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Severities of Transportation Accidents Involving Large Packages

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Sandia Laboratories

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SEVERITIES OF TRANSPORTATION ACCIDENTS
INVOLVING LARGE PACKAGES*

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ABSTRACT

The abnormal environments to which a large package—for example, a spent reactor fuel shipping cask—may be subjected during land transportation are defined quantitatively. The material presented should provide one component required in the evaluation of risks associated with the shipment of hazardous materials. In Part I the study results are summarized; in Part II the physical parameter of truck transport accidents are discussed; and in Part III the physical parameters of train transport accidents are examined.

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PART I
SEVERITIES OF TRANSPORTATION ACCIDENTS—SUMMARY

SEVERITIES OF TRANSPORTATION ACCIDENTS — SUMMARY

Introduction

This study was undertaken to define in a quantitative nonjudgmental technical manner the abnormal environments to which a large package (total weight over 2 tons)* would be subjected as the result of a transportation accident. Because of this package weight, air shipment was not considered as a normal transportation mode and was not included in the study. The abnormal transportation environments for shipment by motor carrier (Part II) and train (Part III) were determined and quantified. In all cases the package was assumed to be transported on an open flat-bed truck or an open flat-bed railcar. In an earlier study,¹ referred to in this report as SLA-74-0001, the small-package environments were investigated. The primary purpose of SLA-74-0001 was to quantify the abnormal environment to which a small package (total weight under 2 tons) would be subjected as the result of a transportation accident. A third transportation study, related to the abnormal environment involving waterways transportation, is now under way at Sordis Laboratories and should complete the description of abnormal transportation environments.

Five abnormal environments were defined and investigated:

1. Fire
2. Impact
3. Crush
4. Immersion
5. Puncture

The primary interest of this study was directed toward the type of large package used to transport radioactive materials; however, the findings are not limited to this type of package but can be applied to a much larger class of material shipping containers.

This report is not intended to be an evaluation of current radioactive material shipping practices, package design, or regulatory standards. It is intended, rather, to serve as

*Units of measure in this report are expressed according to the English gravitational system because (1) the document is a companion to SLA-74-0001, which uses English units and (2) data in this document will be compared with Federal regulatory standards (e.g., 10-CFR-71), which uses English units.

one of the principal steps in determining the risk to the public associated with the land transportation of hazardous materials. W. W. Lorange in his recent book Of Acceptable Risk delineates the basic elements of a risk evaluation as follows:

1. Define the conditions of exposure
2. Identify the adverse effects
3. Relate exposure with effect
4. Estimate overall risk

This report provides one of the variables necessary to define the condition of exposure for large shipping containers; namely, a technical description of the land transportation accident environment. Other variables that must be considered include the response of the package to the accident conditions (damage), the quantity of hazardous material released (if any), the radius of effect of any release, the number of people exposed to the hazard due to any release, and the intensity of exposure. A detailed definition of exposure would entail these and other factors; hence, it is not feasible to attempt to establish package specifications solely on the basis of the information contained in this report.

Discussion of Environments

The description of abnormal transportation environments is complicated because the experimental data, such as those used for the detailed description of normal transportation environments, is not available. The environmental descriptions found to be suitable for abnormal environments are:

Fire

The optimum description of the abnormal thermal environment would be a set of temperature/time profiles in which each profile would have an associated probability of occurrence and a known lower-bound confidence level. The thermal environmental information contained in the report is divided into two regimes. The first is the expected fire-temperature regime, the second is the expected fire-duration regime. Neither of these regimes could be defined if this study were limited to only published accident data. Consequently, in both regimes, assumptions based on information garnered from nonaccident-related sources were required for obtaining the environmental descriptions. Although this may at first appear to be a serious shortcoming, it does not preclude an acceptable prediction of the fire threat. To apply the information to a specific package, one must be able to identify those thermal environments that may result in an undesirable response of the material contained in the package. The fire-temperature distribution and the fire-duration distribution presented in Parts II and III of this report can then be used to estimate the expected frequency of situations that may be of concern.

Impact

The description of the impact environment, like that of the fire environment, is not optimal. Ideally, the reader would be presented with a set of shock pulses defined by (a) the shape of the shock pulse (e.g., square wave, triangular pulse), (b) the amplitude in terms of acceleration units, and (c) the pulse duration. Each of these pulses would be accompanied by an expected probability of occurrence and lower-bound confidence level. Realistically, one can never expect the information necessary for establishing this type of description to be available from the historical accident records.

The velocity change that the shipment vehicle is expected to experience can be conservatively calculated if it is based on the principle of Conservation of Momentum and existing accident records. The reader should note that the value of the velocity change that the vehicle experiences is actually the value of the integral of the acceleration time history—the shock pulse—applied to the system by the impact. For any particular system the total mass of the loaded shipment vehicle is known and the expected fraction of accidents in which a given velocity change will be exceeded can be determined from Parts II and III. If the pulse is to be completely defined, its characteristics may be determined analytically.

Two governing force levels must be considered in any analysis: the minimum force level necessary to produce an undesired consequence, as determined by capabilities of the shipment system, and the maximum force level that the target can sustain. If a class of targets is not capable of sustaining this minimum force level, these targets and all lesser targets should be eliminated from consideration. For example, in the motor-carrier environment, if passenger autos and all lesser targets (from force-level considerations) are excluded, over 80 percent of all motor-carrier collision accidents become relatively unimportant. If only massive stationary objects and railroad trains are found to challenge the transport system, almost 99 percent of all motor-carrier collision accidents can be excluded from consideration. Because of the inability to prejudge what strength capabilities the transportation systems may possess, the complete impact parameter distributions are presented in the Appendix to this report.

Crush

The crush environment is one that frequently occurs in accident situations, but is normally not singled out as significant enough to merit reporting. The data used in this report relating to the crush environment has been inferred from accident reports containing photographs of or line drawings of accident scenes. Additionally, conservative assumptions that are in agreement with the known physical parameters of crush situations have been utilized to predict the expected crush loadings.

Immersion

Because immersion is a very infrequent environment, no accident reports that specified the depth of the immersion were found. Evaluation of this environmental severity was based solely on the frequency of occurrence of water hazards and the expected depth profile associated with these hazards.

Puncture

The threat of puncture is directly related to package construction. Consequently, to obtain a measure of the threat of puncture, it is necessary to assume basic package construction features. Most studies of the mechanics of puncture are empirical, and are applicable only to ballistic (2 to 3 times sonic velocity) or higher-velocity projectiles. In this much lower region of interest, the best that can be done in the general situation is to obtain an order-of-magnitude estimate of the likelihood of puncture, given an accident. This has been done, and the results are presented in terms of the equivalent mild-steel package wall thickness. The puncture environment is discussed in detail in Part III of this report and is correlated with recorded railroad tank car puncture accident reports.

Discussion of Results

The results of this study are presented in a series of graphs and tables that describe the expected environmental levels that a package or system may experience as the result of a land transportation accident. Figures 1-1 and 1-2 are examples of these results stated in terms of the expected number of occurrences at a given level for each one-billion shipment miles. Figure 1-1 deals with expected fire environment, and Figure 1-2 depicts the expected impact environment.

The response of the item being shipped to the environment imposed on the shipment, rather than the environments themselves, determines the significance of the environment. For example, if immersion will cause an unacceptable response of the material being shipped (e.g., nuclear criticality), it is an environment of primary consequence. If, however, immersion will not result in an unacceptable response, regardless of depth, then immersion is obviously of little concern. Similar statements may be made about each of the other four environments considered.

If one proceeds from the least complex to the most complex environmental description, the results of this study may be summarized as follows.

Immersion

This environment is characterized by the probability of the package being immersed to a depth less than or equal to a given depth.

Figure 1-1. Expected frequency of occurrence per billion transport miles of a fire exceeding a given duration.

Figure 1-2. Expected range in frequency of occurrence of an impact-caused velocity change greater than or equal to the velocity change shown.

Crush

This environment is characterized by the probability of the total crush loading being equal to or less than a given total load.

Puncture

This environment is characterized by the probability of puncture as a function of package wall thickness.

Fire

This environment is characterized by two probability descriptions: the expected fire-temperature distribution and the expected fire duration. The reader must determine those temperature/time profiles that may cause an unacceptable system response. Given this information and the fire-temperature and fire-duration probabilities, an estimate can be made of the probability of the temperature/time profiles occurring in accident situations.

Impact

The evaluation of this environment requires a knowledge of the complete shipment system (i.e., the shipment vehicle), the tie-down system, the package, and the material shipped. The environment is characterized by the expected system velocity change resulting from the most severe single impact experienced in a collision accident. For example, consider a rear-end truck/truck collision where the shipment truck traveling at 55 mph overtakes and collides with a second truck. During the impact the shipment truck is slowed from 55 mph to 25 mph. It then proceeds along the shoulder of the highway and comes to rest. A 30-mph velocity change would be recorded for this accident.

Velocity change was chosen to characterize the impact environment because it (1) is a quantity that is understandable to most readers and (2) will generally provide a conservative damage estimate if a massive, essentially unyielding target is assumed and the velocity change value is used as the impact velocity. The transport vehicle structure, the package tie-down system, and the target impacted will all affect the severity of the impact environment. Extensive data summaries are included in the appendix of this report to aid the serious investigator in determining those impact environments that may be of concern and to obtain a reasonable estimate of the probability of occurrence of each.

PART II
MOTOR-CARRIER ENVIRONMENTS

Chapter 1

DEFINITIONS AND ACCIDENT RATES

Accident Definition

The definition of "accident" as used in Part II is consistent with the definition for Classes I and II Interstate Motor Carriers of Property as set up by the Bureau of Motor Carrier Safety, Federal Highway Administration, U. S. Department of Transportation. For consistency with *SLA-74-0001*, this definition, which includes all accidents that result in fatalities, injuries, or property damage of \$250 or more,²⁻⁶ has been retained for the current study.

Accident Rate

Accident rates in accordance with the above accident definition are reported annually⁴⁻⁶ for intercity shipments by Classes I and II Interstate Motor Carriers of Property (Table II-1).

TABLE II-1
Accident Rates

<u>Year</u>	<u>Accident Rate (accidents per mile)</u>
1966	2.4×10^{-6}
1967	2.4×10^{-6}
1968	2.5×10^{-6}
1969	2.4×10^{-6}
1970	2.7×10^{-6}
1971	2.2×10^{-6}
1972	2.3×10^{-6}

No attempt is made in this study to define a rigorous accident rate statistically. Rather, selection of a representative rate is subject to the constraint that (1) the rate, (2) the accident definition, and (3) the environment probabilities—given an accident—are consistent. The rate selected for this study is

$$R = 2.5 \times 10^{-6} \text{ accidents per mile.}$$

This is the same rate as that used in Reference 1, which describes the small-package transportation environment. Here, the rate equals the probability of a truck accident for 1 mile of travel.

Accident Environment Definitions

Interactions between a shipping container and its surroundings during an accident are labeled "accident environments." The five accident environments are defined below. The terms "fire," "impact," "crush," "puncture," and "immersion" are not to be interpreted by their dictionary meanings, but rather according to the specific definitions given below.

Accident Environments

Fire. Subjection to a high-temperature environment produced by combustion. Example: The interaction of a container with a fire following an overturn.

Impact. Striking or being struck by an object that has no sharp projections. Example: Collision with a highway overpass bridge pier.

Crush. Subjection to structural loads that may be either highly localized or spanning a large area of the container but that cannot be categorized as impact, puncture, or immersion. Example: The interaction of a container with the ground when the container rests between the trailer and ground after an accident.

Puncture. Striking or being struck by an object that has a potential for penetrating the container. Example: The impalement of a container on a structural member of the truck.

Immersion. Submersion in a liquid medium. Example: The interaction of a container with water after the truck plunges off a bridge into a river.

Historical Data Base

The data base used in this study to determine accident frequency of occurrence by type of accident was prepared by the Bureau of Motor Carrier Safety, Federal Highway Administration, U. S. Department of Transportation.²⁻⁶ This bureau issues an annual report entitled Accidents of Large Motor Carriers of Property. This report is a compilation of individual reports by interstate motor carriers having annual operating revenues of \$300,000 or more. These carriers are subject to the Federal Motor Carrier Safety Regulations (Code of Federal Regulations, Title 49, Parts 390 to 397) and report as required by these regulations. A reportable accident for the selected study period (1969 through 1972), as defined by these regulations, is an accident resulting in a fatality, an injury, or property damage of \$250 or more. Although more recent statistical

data are available, they were disregarded because the cost basis for reporting was changed from \$250 to \$2000, making any combination or integration of these data with other data questionable.

The railroad grade-crossing accident, which accounts for approximately 0.7 percent of the collision accidents, was of particular interest because of its potential severity. The data base for this type of accident was obtained from the reports presented in Highway Grade-Crossing Accidents for the period 1969 through 1972.⁷⁻¹⁰ These statistical reports, which are issued by the Office of Safety, Federal Railroad Administration, Department of Transportation, are based upon rail-carrier reports filed with the Federal Highway Administration pursuant to the Accident Reports Act of 1910 (as amended).

The traveling speed of a motor vehicle immediately before an accident has a substantial effect upon the severity of the accident. Unfortunately, preaccident vehicle speed is not reported by the Bureau of Motor Carrier Safety (BMCS); however, it is reported by the Federal Railroad Administration (FRA) both for the trains and for the motor vehicles involved in grade-crossing accidents. The severity of highway accidents by type of accident is discussed in Appendix A.

Appendix B of this report contains a detailed description of the methods used to obtain the estimated truck-accident distribution by type of accident. The distribution, stated in Table II-II, was used in the analysis. The accident types identified in Table II-II are stated in a shorthand notation. The designation #1 refers to the truck of interest (the truck transporting the package). The designation #2 refers to the other principal vehicle in the accident. Thus, "Rear-end, #1 into #2, truck 0.0856" would be interpreted to mean "The truck transporting the package overtook and collided with another truck in 8.56 percent of the accidents."

The fire environment and the rates associated with this environment are described in detail in Chapter II-2 of this report.

TABLE II-II
Frequency of Collision Accident Types

<u>Accident Type</u>	<u>Frequency</u>
<i>The truck is decelerated along its axis</i>	
Head-on, truck	0.0031
Rear-end, #1 into #2, truck	0.0256
Side-on, #1 into #2, truck	0.0086
Head-on, auto	0.0327
Rear-end, #1 into #2, auto	0.2245
Side-on, #1 into #2, auto	0.0151
Run into train	0.0018
Object	0.1030
Subtotal	0.5003
<i>The truck is decelerated along its axis</i>	
Rear-end, #2 into #1, truck	0.0006
Rear-end, #2 into #1, auto	0.1842
Subtotal	0.2648
<i>The truck is accelerated perpendicular to its axis</i>	
Side-on, #2 into #1, truck	0.0183
Side-on, #2 into #1, auto	0.1211
Struck by train	0.0054
Subtotal	0.1448
TOTAL	1.000

Chapter 2 FIRE ENVIRONMENT

Introduction

This section of the report follows very closely the results reported in Vol. III of Reference 1. The present analysis differs from the earlier study chiefly in the assumption that the package is carried alone and, therefore, that there is no cargo available on the transporting vehicle that can contribute fuel to the fire. All assumptions referring to combustible cargo apply only following a truck-truck collision, i.e., all noncollision fires involving a cargo source are eliminated.

Data from summaries^{2-4, 11, 12} of accident reports filed by commercial carriers indicate that fires occur in approximately 1.6 percent of all truck accidents. These accidents, however, account for nearly 10 percent of the total property damage in commercial carrier accidents. This indicates that, when fire does occur, the accidents are much more serious than the average accident. Although it is not possible to predict the details of events occurring during any particular accident or group of accidents, probabilistic descriptions of the frequency and severity of truck accidents involving fire can be made. Based on engineering approximations, data evaluation, and analytical models, reasonable and useful approximations of the expected environmental levels are possible.

The major sources of data for fire accidents are the summary reports of accidents compiled by the Department of Transportation (DOT) Bureau of Motor Carrier Safety.^{2-4, 11, 12} These quantitative data are very complete in terms of accident type, frequency of fire, cause of fire, property damage, and other related information. Such information is useful in predicting frequency of fires and relative severity (property damage) of accidents. The reports do not, however, provide the information required for describing such expected environment levels in a fire accident as fire size, intensity (temperature), location, duration, and combustible materials. Occasionally, the individual accident reports of the more severe accidents filed by the National Transportation Safety Board (NTSB) provide qualitative estimates of some of the necessary fire parameters. In general, however, it was necessary to use vehicle and accident parameters in conjunction with theoretical modeling to develop a reasonable description of the expected thermal environment.

A truck-fire accident has a large number of variables that affect the resultant fire. Included among these are fuel tank involvement, the amount and type of fuel available, the kind of cargo in

truck/truck accidents (flammable or nonflammable) and how it is packaged, the possibility of collision with a tanker truck, the extent to which the vehicle becomes involved in the fire, the availability of firefighting equipment, and the effects of all possible combinations of these and other considerations. It has not appeared feasible, or even possible, to develop a model which could readily incorporate all the possible combinations of events into a single analytic expression that would provide a description of the fire environment. It has been concluded that a "Monte Carlo" technique for describing the truck accident involving fire is one possible approach to the problem of multiple variables.

Data Base

References 2, 3, and 4 indicate that of 115,363 truck accidents causing approximately \$230 million in property damage, 1835 involved fire. These 1835 fires resulted in about \$20 million in damage. Approximately 50 percent of the truck accidents involve collision with an auto, 35 percent are single-vehicle accidents, and 15 percent involve a collision with another truck. Table II-III shows the relative frequency of various types of accidents, how often fire occurs in those accidents, and the percentage of the total fires according to type of accident. It is interesting to note that only about 25 percent of the fires result from collision-type accidents and that over 75 percent of the fires are caused by fire only and by noncollision-type accidents. These data are useful in determining frequency of fires and average property damage per accident. They do not, however, provide any information regarding the accident severity distribution or the description of the thermal environment. References 11 and 12 yield some additional insight into the fire accident by providing data on cause of fire, location of fire origin, method of extinguishment (if any), fuel tank involvement, and broad category descriptions of the commodity (cargo) classification of the carrier. In addition, Reference 12 gives some indication of property damage distribution by showing the property damage that occurs for each of various extinguishment methods.

TABLE II-III
Truck Accident Data²⁻⁴

Accident Type	Percent of Total Accidents	Frequency of Fire (%)	Percent of Total Fires
Collision With Auto	49.7	0.3	10.4
Collision With Truck	15.0	0.8	7.8
Collision With Fixed Object	14.1	0.4	3.7
Other Collision	5.1	0.9	3.0
Ran Off Road	7.1	1.1	4.9
Overturns	2.7	1.2	2.1
Other Noncollision	6.0	13.0	48.8
Fire Only	0.3	100.0	19.3
Total	100.0	-	100.0

Fire Description

A truck accident that results in a fire can create cargo environments ranging from essentially no thermal exposure to severe thermal exposure, depending upon the fire size, location, temperature, and duration. In addition to the diesel fuel or gasoline in the fuel tanks, truck fires can involve a wide variety of combustible materials, such as combustible cargo, cab interior, electrical and brake systems, and tires.

The expected temperature of the resulting fire will depend upon the combustible materials involved. It is apparent both from experimental work and from theoretical work that exact predictions of temperatures in any particular fire cannot be made. However, most hydrocarbon fuels—such as JP-4, diesel, and gasoline—yield measured flame temperatures for open burning that are approximately the same, generally falling in the range from 1400° to 2400°F.¹³⁻¹⁵ Furthermore, the flame temperatures of most of the other expected combustibles fall in that same range, generally toward the lower end.¹⁶⁻¹⁷ Therefore, the probability distribution of truck-accident fire temperatures can be reasonably represented by the same distribution determined in Reference 1. The probability density function (pdf) is given by

$$f(T) = 1.77 \times 10^{-5} (T - 1400)^{0.83} e^{-\left(\frac{T-1400}{550}\right)^{1.83}}, \quad (II.1)$$

where T is measured in °F. The associated cumulative distribution function (cdf) is given by

$$F(T) = \int_{1400}^T f(T) dT = 1 - e^{-\left(\frac{T-1400}{550}\right)^{1.83}}. \quad (II.2)$$

The distributions obtained from Eqs. (II.1) and (II.2) are shown in Figure II-1.

Figure II-1. Probability distribution of truck-accident fire temperatures.

From previous analyses¹ the fire can be considered to be essentially a blackbody radiation source for a flame thickness of 4 feet or more. For smaller flames the effective emissivity drops off very rapidly. The convective heat transfer from the flame to a container engulfed in the fire (optically thick) is approximately a factor of 10 lower than the radiative heat transfer¹ and therefore can be neglected in heat-transfer tests or analyses of containers. The assumption that the fire radiates as a blackbody tends to compensate for neglecting the convective transfer.

A significant fraction of the fire accidents presents little thermal threat to the cargo, since the fires are confined to a small area, are of short duration, or both. The small local fires are not optically thick, put out a relatively small total heat and, unless they spread, are of minor consequence.

Fire Duration

Since the available fire-accident data do not provide quantitative information sufficient for a statistical basis of fire duration, modelling of the expected fire duration had to be based on various parameters expected to influence the fire and its burn time. The large number of variables involved and the numerous combinations and interactions of these variables precluded a closed-form description of the expected fire burn time; therefore, a Monte Carlo prediction scheme was used. The model includes the available data coupled with engineering predictions of fire duration based on probabilistic availability of combustibles from various types of accidents. It considers the interaction and probabilistic involvement of fuel tanks, tires, cargo, brakes, electrical system, and cab as well as the effects of fire-fighting efforts.

A simplified schematic flow chart of the computer program used to predict the probability distribution of fire durations is shown in Figure II-2. Only those accidents where a fire occurs are simulated in the program; the number of simulated accidents required to obtain a good statistical sample is thereby greatly reduced. From the information shown in Table II-III, the frequency of fire is known for each type of accident. Random numbers are selected in the various blocks. Decisions are based on the value of each random number so that after a large number of such events the probability distributions for each event, obtained either from the data or from modeling, will be followed; a composite or net probability distribution for the fire duration is obtained by tabulating the results. There is considerable interaction between the blocks of Figure II-2; however, for simplicity, this interaction is not shown. For example, the probabilistic involvement of fuel tanks in a fire and the probable amount of fuel available to burn are different for each type of accident.

Figure II-2. Simplified flow chart of Monte Carlo fire-duration program.

A list of the major assumptions and probability distributions used in the program (not necessarily in the sequence used) follows. Where the greatest degree of uncertainty exists, the intent is to err on the conservative side (i.e., to maximize the fire duration). Again it should be emphasized that truck cargo assumptions apply only after a truck/truck collision.

1. Frequency of various fire-accident types is as shown in column 3 of Table II-III.
2. Ninety-nine percent of the truck cargo weights are between 0 and 20 tons, with an average weight of 10 tons and a cdf of

$$1 - e^{-\left(\frac{W}{22862}\right)^{2.73}}, \quad (II.3)$$

where W is cargo weight in pounds.

3. All tanker truck shipments are flammable.
4. The fraction (f) of cargo that will burn, if flammable, can be represented by the distribution (cdf)

$$1 - e^{-\left(\frac{f}{0.268}\right)^{1.25}} \quad (II. 4)$$

which gives an average or expected value of 20 percent. This distribution was obtained from DOT's OHM data bank container-failure incidents coupled with a qualitative review of numerous individual fire-accident reports.

5. If a collision or overturn fire accident occurs, the fuel tank of one or more of the vehicles is always involved.
6. The fuel available in the fuel tank of a single-vehicle truck accident varies from 0 to 200 gallons, with an expected value of 120 gallons and a cdf given by

$$1 - e^{-\left(\frac{f_u}{132}\right)^{3.68}} \quad (II. 5)$$

where f_u is fuel in gallons. Furthermore, the fuel is distributed uniformly over an area that can vary with uniform probability from 25 to 125 ft². It should be noted in this and all other fuel dispersion area assumptions that the area is, in general, somewhat less than the area over which the accident occurs and over which wreckage may be distributed. The fuel from the fuel tank tends to be concentrated in and around the fuel tank. Furthermore, the fuel tends not to be uniformly distributed, as assumed, but rather forms in puddles in depressions, gouge marks, gutters, ditches etc., or remains in the fuel tank (or its wreckage). The small uniform dispersion area tends to account for the fact that the fuel is concentrated near the fuel tank and compensates for the fact that the fuel puddles in local areas rather than uniformly over a large area.

7. Fuel available in a truck/auto collision varies from 0 to 250 gallons, with an expected value of 150 gallons, and the cdf is given by

$$1 - e^{-\left(\frac{f_u}{166}\right)^{3.73}} \quad (II. 6)$$

The fuel is distributed uniformly with equal probability over an area from 25 to 125 ft².

8. A truck/truck (nontanker) collision has fuel availability ranging from 0 to 500 gallons, with an expected value of 300 gallons. The corresponding cdf is given by

$$1 - e^{-\left(\frac{r_u}{331}\right)^{3.70}} \quad (11.7)$$

The fuel is distributed uniformly with equal probability over 40 to 200 ft².

9. A truck/truck collision has a 2-percent chance that one or more of the trucks is a tanker carrying flammable goods. This number is based upon relative mileage data of tanker trucks and conventional trucks.
10. A truck/tanker collision has available fuel which can vary from 0 to 10 000 gallons, with an expected value of 5000 gallons. The fuel cdf is given by

$$1 - e^{-\left(\frac{r_u}{5718}\right)^{2.73}} \quad (11.8)$$

The fuel is distributed uniformly with equal probability over 50 to 500 ft².

11. Noncollision fires originate as follows: 14 percent in the fuel system; 36 percent in the area of tires, brakes, and wheel bearings, 21 percent in the electrical system; 12 percent in the cab; and 17 percent in other areas or from unknown causes. This information is consistent with fire-accident data¹¹⁻¹² after deleting cargo origin fires.
12. Noncollision fires that start in the fuel system have a 20-percent probability of involving the fuel tank; otherwise, the fire duration is uniformly distributed from 0 to 10 minutes.
13. Noncollision fires that start in the area near the tires, brakes, and wheel bearings have a 10-percent probability of involving fuel; otherwise, the fire duration is uniformly distributed from 0 to 15 minutes.
14. Noncollision fires originating in the electrical system have a 10-percent chance of involving the fuel tank; otherwise, the fire duration is uniformly distributed from 0 to 10 minutes.
15. Noncollision fires starting in the cab have a 10-percent probability of fuel tank involvement; otherwise, the fire is uniformly distributed from 0 to 20 minutes.

16. Other (unknown source) noncollision fires have a 10-percent probability of fuel tank involvement; otherwise, the fire duration is uniformly distributed from 0 to 15 minutes.
17. The liquid hydrocarbon fuels from fuel tank or cargo have a burn rate of $0.65 \text{ lb/ft}^2 \text{ min}$, which corresponds, in general, to a surface recession burn rate of 0.16 in/min .¹⁴
18. For fuel purposes, wood or other cellulosic material is considered to be representative of nonliquid combustible cargo with a representative burn rate of $0.16 \text{ lb/ft}^2 \text{ min}$ for the first 30 minutes (linear decrease from 0.24 to $0.09 \text{ lb/ft}^2 \text{ min}$) and $0.09 \text{ lb/ft}^2 \text{ min}$ thereafter.^{18,19}
19. Combustible surface area of nonliquid combustible cargo is uniformly distributed from 100 to 1000 ft^2 .
20. The char density (material remaining after burning) is 35 percent of the original density of the nonliquid combustible cargo.^{20,21}
21. According to values confirmed by accident reports and compilations,¹² no fire-fighting capability is available for 30 percent of the fire accidents, a local fire department may be summoned for 30 percent, and hand extinguishers are utilized in 10 percent. In the remaining 30 percent, "other" firefighting efforts are either minimal or unknown. The relative merit of the last category is based on a comparison of property damage estimates and those from fire department or hand-extinguisher firefighting efforts.
22. Hand extinguishers are ineffective against fires if more than 75 gallons of fuel or 1000 pounds of solid combustible cargo become involved. Otherwise, hand extinguishers, if available (10 percent), control the fire duration, which is then uniformly distributed between 0 and 10 minutes.
23. Local fire departments, if available (30 percent), are effective against all fires. Unless a fire burns out before they arrive, they control the duration, which is uniformly distributed from 15 to 45 minutes.
24. Other (unknown or unreported) firefighting efforts, if available (30 percent), are ineffective against fires if more than 200 gallons of fuel or 2500 pounds of other combustible cargo becomes involved. Otherwise, this firefighting effort controls the duration, which is uniformly distributed from 5 to 30 minutes.

It should be mentioned that many of the foregoing assumptions and/or probability distributions went through several iterations. This was necessary to obtain overall results that were consistent with such qualitative available data as frequency of fuel tank involvement, frequency of combustible

cargo involvement, frequency of complete burnout, and fire durations proportional to property damage estimates.

Several series consisting of 10 000 fire accidents were simulated on the computer. The repeatability of the results was excellent and indicated that 10 000 simulations constituted a statistical sample sufficiently large to prevent variations of greater than 1 percent in the results.

The sensitivity of the results to certain of the key (and most uncertain) assumptions was also examined. Following a truck/truck collision, the probability that the other truck (nontanker) involved in the collision carried flammable goods was varied from 10 to 100 percent, with a nominal value of 30 percent. Also, the probability of the flammable cargo being involved in the fire was varied ± 50 percent from a nominal value of 0.2. Furthermore, the probability of fuel tank involvement in all noncollision fires was varied by ± 50 percent from the assumptions listed previously.

The results of the Monte Carlo prediction scheme are shown in Figure II-3 as a cumulative distribution function. The sensitivity of the results to the variations mentioned in the previous paragraph was remarkably low. At the end of 5 minutes the distribution varied ± 3 percent; beyond 20 minutes the variation was less than ± 1 percent, even when all the sensitivity parameters acted together to shorten or lengthen the predicted fire duration.

Conclusions

The predicted probability per truck mile of exceeding a specified fire environment is shown in Figure II-4. These results are based on a truck accident rate²⁻⁵ of 2.5 per million miles, a fire frequency per accident of 1.6 percent, and the predicted durations shown in Figure II-3. The temperature selected as representative for the truck fire environment is 1850°F.

Figure II-3. Cumulative distribution of fire-accident duration for truck transport of large packages.

Figure II-4. Probability per truck mile of fire exceeding a given duration.

Chapter 3

IMPACT ENVIRONMENT

Introduction

The impact environment is assumed to be present in each truck-collision accident. The impact environment associated with a single vehicle running-off-the-road accident or overturning-on-the-road accident has also been considered. This environment is discussed in detail in Appendix A. The effects of a truck accident on a large package are difficult to quantify. For example, in low-velocity collision accidents the truck structure will act to mitigate the environment and to maintain the cargo response to levels below those normally associated with "rough handling" environments. In high-velocity collisions, the mitigation provided by the truck structure may be negligible.

The existing accident data allow the computation of the maximum velocity change attributable to the most severe single impact in a collision accident with a minimum number of assumptions. Hence, this quantity, velocity change, was chosen as the parameter that best describes the impact environment. The time history associated with this velocity change is dependent upon both the transport system characteristics and the characteristics of the second vehicle or object in the accident. If it is desirable to be highly conservative (to predict greater package damage than that realistically expected) an object both massive and rigid may be assumed to be representative of the second vehicle or object in the collision.

Collision and Noncollision Accidents

Truck accidents have been divided into two major categories, which parallel the BMCS reporting system.²⁻⁸ Appendix A of this report contains a detailed discussion of accident severities, and Appendix B contains the accident frequencies and distributions by type used in this study. The distribution of accident types as stated in Table B-VI is used. The primary abnormal cargo environment is due to overturning and running off the road in 19.8 percent of the expected accidents. Collision with other vehicles, trains, or stationary objects produces an impact environment in the remaining 80.2 percent of the expected accidents.

The overturn and running-off-the-road accident was found to provide a very severe environment for the truck driver, Appendix A. The severe environment and frequent occurrence of this type of accident requires its consideration. It is believed, however, that no severe single impacts are included in this type of accident; rather, it is a gradual slowing of the vehicle by a

series of low-level impacts and ground friction. The speed at which the truck overturns or leaves the road can be estimated by the vehicle speed distribution developed in Appendix C and shown in Figure C-2.

The impact analysis that follows is limited to collision accidents where the transport vehicle is involved in an accident with a second vehicle, train, or stationary object.

Analysis of Truck-Collision Accidents

The analytical approach employed is to study each component of the collision accident situation in its most clearly definable configuration and to determine the parameters that characterize this situation. Each parameter is expressed by a function that represents its frequency of occurrence. A Monte Carlo analysis technique is then employed for random sampling of each parameter distribution, to determine the parameters of a single accident, and to determine the impact parameters. This procedure is repeated until a sufficient number of trials have been made to allow calculation of the distribution of the accident impact characteristics.

The analysis of the collision accident situation is based upon the following assumptions:

1. The vehicle collisions are inelastic.
2. The initial and final velocity of the shipment truck; the direction of the velocity change relative to the shipment truck's path; and a description of the second vehicle, train, or object involved in the collision are sufficient to define the accident environment.
3. The distribution of basic parameters developed in Appendices B, C, and D are sufficient for the purpose of this analysis.
4. The collision environment is a random process and can be analyzed by the Monte Carlo technique.

Environmental Description

Computations of the velocity change experienced by the truck and container as a result of an impact are based upon the principle of conservation of momentum. This principle can be stated as

$$m_1 v_1 + m_2 v_2 = (m_1 + m_2) v \quad (II.9)$$

or

$$v = \frac{1}{(m_1 + m_2)} (m_1 v_1 + m_2 v_2) , \quad (11.10)$$

where

- m_1 is the mass of the shipment truck, the package, and the tiedown system (i.e., the gross mass of the loaded shipment vehicle).
- m_2 is the gross mass of the second vehicle or the effective mass of a train or stationary object.
- v_1 is the preaccident velocity of the shipment vehicle.
- v_2 is the preaccident velocity of the second vehicle or train. ($v_2 = 0$ for stationary objects.)
- v is the postaccident velocity of the shipment vehicle and second vehicle.

The velocity change that the shipment vehicle and package will experience as a result of a collision can be expressed as the difference between the postaccident and preaccident shipment vehicle velocity.

$$\delta v = v - v_1 , \quad (11.11)$$

where

- δv is the impact velocity change experienced by the shipment vehicle and the package.

The above equations were combined to yield the velocity change (δv) directly as a function of preaccident vehicle velocities and vehicle gross weight. The velocity change equation can now be stated as

$$\delta v = \frac{W_2}{W_1 + W_2} (v_2 - v_1) , \quad (11.12)$$

where

- W_1 is the gross over-the-road weight of the shipment vehicle.
- W_2 is the gross over-the-road weight of the second vehicle or the effective weight of a train or stationary object.

The analysis procedure involves random selection of the following parameters:

1. Type of accident. This variable is selected from the accident distribution shown in Appendix B, Table B-VIII.
2. Preaccident speed of the shipment vehicle. This variable is selected from the speed distribution shown in Appendix C, Figure C-2.
3. Weight of the second vehicle, train, or stationary object. This value is selected from the appropriate distribution in Appendix D.
4. Preaccident speed of train or second vehicle. This value is selected from the appropriate distribution in Appendix C.

The above preaccident speeds are then modified as follows:

1. In rear-end collisions the higher speed is assigned to the striking vehicle.
2. In side-on collisions the struck vehicle velocity is set equal to zero.

The gross over-the-road weight of the shipment truck is assumed to be known and is held constant for each set of calculations.

With the Monte Carlo simulation technique, used 500 000 randomly chosen accidents were evaluated for each of seven gross over-the-road shipment vehicle weights. The velocity change was computed and recorded in each simulated accident, and the cumulative distribution was determined. Typical shipment vehicle weights are:

1. 10 to 15 tons. This weight represents an empty tractor-trailer truck, four to six axles.
2. 15 to 30 tons. This weight range is included for cargo other than spent reactor fuel.
3. 30 to 40 tons. This weight represents the typical gross weight of spent reactor fuel highway shipments (tractor, trailer, package, spent fuel, and tie-down system).
4. 40 to 50 tons. This weight represents the normal overload permit range and upper legal weight limits for interstate highway transportation.

Collision Accident Impact Configurations

The following configurations were selected for use in the collision analysis of truck/truck, truck/passenger auto, and truck/train accidents. The truck/object collision configuration is discussed in the Distribution of Stationary Objects, Unreported Objects, and Other Objects (Appendix D). The configurations selected for these collisions are worst-case examples. That is, their use will result in a maximum predicted value of velocity change. The configurations are also simple and readily amenable to analysis.

1. Head-On Truck/Truck and Truck/Passenger Auto Collision.

The vehicle centerlines are coincident, and the vehicles are traveling in opposite directions.

2. Side-On Truck/Truck and Truck/Passenger Auto Collision.

The struck vehicle is not in motion (its preaccident motion is not of interest). The line of travel of the striking vehicle passes through the centroid of the struck vehicle and is perpendicular to it.

3. Rear-End Truck/Truck and Truck/Passenger Auto Collisions.

Identical to head-on except that the vehicles are traveling in the same direction.

4. Truck Into Train Collisions. Identical to side-on truck/truck collisions, with the truck as the striking vehicle.

5. Train Into Truck Collisions. Identical to side-on truck/truck collisions, with the train as the striking vehicle.

Results

The results of this study are presented both in graphical and in tabular form. The graphical presentation allows a quick visual comparison of the data for all weight categories, whereas the tabular form may prove useful in future studies. In Figure II-5 the computed velocity change is plotted as a function of its cumulative frequency of occurrence. The shape of this curve is similar to those derived in SLA-74-0001.¹ To facilitate the evaluation of the results at moderate and high velocities, the cumulative distribution of the velocity change that is greater than or equal to a given velocity change has been plotted on a semilogarithmic scale. This information is presented in Figure II-6.

Table II-IV contains the basic information plotted in Figures II-5 and II-6. The values in Figure II-6 are computed as 1 minus the value listed in Table II-IV.

Figure II-5. Impact velocity change as a function of cumulative frequency of occurrence for highway transportation.

Figure II-6. Velocity change due to impact in a highway transportation collision accident.

TABLE 11-15

Velocity Change Due to Impact in a Highway Transportation Collision Accident

Velocity Change Due to Impact (mi/hr)	Cumulative Fraction of Sample With a Velocity Change Less Than or Equal to Indicated Velocity Change for Each Over-the-Road Transport Vehicle Weight (in tons)						
	10	15	20	25	30	40	50
5	0.5038	0.6220	0.7146	0.7915	0.8213	0.8711	0.8962
10	0.7641	0.8429	0.8951	0.9104	0.9256	0.9454	0.9575
15	0.8759	0.9171	0.9366	0.9520	0.9610	0.9721	0.9782
20	0.9244	0.9503	0.9642	0.9723	0.9775	0.9834	0.9872
25	0.9523	0.9697	0.9782	0.9828	0.9859	0.9895	0.9923
30	0.9701	0.9819	0.9875	0.9900	0.9911	0.9946	0.9965
35	0.9809	0.9876	0.9910	0.9931	0.9945	0.9959	0.9966
40	0.9878	0.9921	0.9945	0.9950	0.9965	0.9973	0.9978
45	0.9922	0.9951	0.9965	0.9973	0.9977	0.9983	0.9987
50	0.9951	0.9970	0.9978	0.9983	0.9986	0.9990	0.9994
55	0.9970	0.9982	0.9987	0.9990	0.9996	0.9996	0.9998
60	0.9981	0.9989	0.9992	0.9995	0.9998	0.9998	0.9999
65	0.9989	0.9994	0.9996	0.9997	0.9999	0.9999	
70	0.9993	0.9996	0.9997	0.9999			
75	0.9996	0.9998	0.9999				
80	0.9997	0.9999					
85	0.9998						
90	0.9999						

Computation of Rates Associated With a Given Velocity Change

Using the above information, the rate of accident occurrence associated with a given velocity change can be computed. Compute, for example, the expected accident rate with a velocity change less than or equal to 30 miles per hour for the following highway transportation system.

Item	Weight (lb)
Spent Reactor Fuel Cask	55 000
Tiedown System	2 500
Trailer	12 000
Tractor	15 000
Total	84 5000

Data for the 40-ton, over-the-road weight group will be used.

$$\begin{array}{lll}
 \text{Accident Rate} & 2.5 \times 10^{-6} & \frac{\text{truck accidents}}{\text{transport mile}} \\
 \text{Collision Rate} & 0.8020 & \frac{\text{collision accidents}}{\text{truck accidents}} \\
 \text{Velocity Change Rate} & 0.0036 & \frac{\text{collisions with } \delta v \leq 30 \text{ mph}}{\text{collision accident}}
 \end{array}$$

or

$$\text{Velocity Change Rate } (1. = 0.0036) \quad 6.40 \times 10^{-3} \quad \frac{\text{collisions with } \delta v \leq 30 \text{ mph}}{\text{collision accident}}$$

The expected rate of occurrence, R, is then

$$R = (2.5 \times 10^{-6})(0.8020)(6.4 \times 10^{-3})$$

$$R = 1.28 \times 10^{-8} \frac{\text{collisions with } \delta v \leq 30 \text{ mph}}{\text{transport mile}}$$

The above ratio may be inverted to obtain the expected mileage per transportation accident involving this velocity change.

Conclusions

The large-package motor-carrier impact environment has been evaluated and the probability of a given velocity range for a system has been determined. The large packages (minimum weight, 2 tons) are normally shipped on open vehicles. A typical example of this type of package is the reactor spent-fuel cask. For this type of package the probability of a collision accident that results in a velocity change of 30 miles per hour due to impact is approximately 10^{-8} per transport mile, or once every 100 000 000 package-transportation miles. The transport vehicle structure, the package tie-down system, and the target impacted will all effect the severity of the impact environment to which the package will be subjected. Extensive data summaries are included in the appendix of this report to aid the serious investigator in determining those impact environments which may be of concern and to obtain a reasonable estimate of their probability of occurrence.

Chapter 4 CRUSH ENVIRONMENT

Introduction

The truck crush environment is difficult both to define and to quantify. The designation itself possesses a rather vague connotation of a hydrostatic pressure while permitting some degree of dynamic, nonsymmetric load application. We have, for this study, rather arbitrarily defined crush to be "essentially static forces acting on a container because of the latter's position underneath the truck." The crush environment (due to other cargo), which is generally severe for small packages, is insignificant for packages that are carried singly or in small numbers. The environment resulting from the trailer rolling over on the package is considered to be impact, and therefore is not analyzed here; the only load considered is that resulting from the trailer coming to rest on the package.

This chapter presents the procedures required for calculating crush loads in motor-carrier accidents and discusses the variations that can be expected when differing load configurations are considered.

Analysis

The result sought in this analysis is the calculation of the probability of a container encountering accident-related crushing forces during transport and the estimate of the severity of these forces. The probability that the package ends up underneath the trailer (p_c) was calculated by use of the collocation model developed for aircraft accident analysis of Reference 1, Volume II. An 8- x 40-foot (320 ft²) trailer bed was assumed as the crushing area. Dimensions within which the container and overturned trailer were assumed to lie varied in width between 40 and 50 feet and in length between 75 and 100 feet. With these variations both in dimensions and in models, p_c was calculated to be in the range of 2×10^{-2} to 9.5×10^{-2} . A value of 5×10^{-2} was selected as being representative.

$$p_c \text{ (probability of crush, given a collision or overturn)} = 5 \times 10^{-2} \quad (II.13)$$

This value is very conservative. In accidents where the large package breaks loose, the collocation model assumes that the final position of the trailer and package are independent; however, they are not. If the package does not separate from the trailer, the foregoing probability of crush states that 1 of 20 accidents will result in the trailer resting on the package. Available accident data indicate a lower rate.

The probability distribution of crush load, given that a crush occurs, was modeled with the assumptions that (a) the trailer is overturned and (b) the container lies between the trailer bed and the ground. Beam analysis was used, and two beam-loading configurations were investigated. These configurations are shown in Figure II-7. For loading configuration 1 (trailer bed supported by container and ground), the force on the container (F) is given by

$$F = \frac{wbL^2}{2l} \quad (II. 14)$$

where

- F is the crushing force (lb/ft)
- w is the unit average trailer weight (lb/ft²)
- L is the total trailer length (ft)
- l is the distance from the point of support to the package (ft)
- b is the nominal width of the trailer (ft).

Since the entire trailer weight (W, lb) is equal to wbl, Eq. (II. 14) may be rewritten as

$$F = W \frac{L}{2l} \quad (II. 15)$$

For loading configuration 2 (trailer bed supported by container and rigid connection to trailer chassis), the container force is given by

$$F = \frac{wb}{8l} \left[6L^2 - 4Ll + l^2 \right] \quad (II. 16)$$

The foregoing description is parallel to that in Reference 1, Volume III. The major differences in the large-package environment are

1. The absence of other cargo on the trailer.
2. The absence of dynamic crush environment caused by other cargo.
3. The crush load capacity typically found in accident-resistant containers.

The crush environment can be adequately specified by a single load value. It can be noted from the above equations that the maximum value of F is

$$F_{\max} = wbl = W \quad (II. 17)$$

Figure 11-7. Beam-analysis loading configurations.

This value may be used as the expected maximum static crush loading. The typical shipment of large packages (e.g., spent reactor fuel casks) is by means of large flat-bed trailers with rigid tiedown systems. The larger trailer and tiedown system weight is normally less than 15 000 pounds, and the trailers are nominally 8 feet wide. Based on these figures, the maximum static crush loading, F , is 15 000 pounds and the distributed crush loading can be estimated as F/b , or 1875 pounds per lineal foot of loaded area.

For convenience, this value is rounded to 2000 pounds per lineal foot.

Conclusions

The static crush environment can be described by its estimated frequency of occurrence and by the maximum expected crush value:

$$P(\text{probability of crush, given } \geq \text{ collision or overturn}) = 5. \times 10^{-2} .$$

Maximum expected crush force $\leq$ 2000 pounds per lineal foot over an 8-foot length .

PART II

Chapter 5 IMMERSION ENVIRONMENT

Introduction

As compared with many of the other environments, no actual data are available from which it is possible to infer the probability of cargo being immersed. It is, however, possible to use some indirect data which, when coupled with models of river beds and ditches, can lead to an estimate of the relative significance of the immersion environment in terms of its probability of occurrence and depth of immersion. With regard to duration of immersion, no indirect data such as that utilized for fire duration estimations presently appears to exist.^{55, 56}

Analysis

Three separate types of events are considered: (1) accidents that occur during bridge crossings, (2) roadside ditch immersions resulting from rollovers or cargo ejected from a trailer in collisions, and (3) accidents in which the motor carrier leaves the road and enters adjacent water.

a. Bridge-Crossing Accidents

This analysis is based on the assumption that the occurrence probability of accidents on bridges is equal to motor-carrier accident rates in general. Although arguments either to increase or to decrease this rate can be made, any other assumption is no less difficult to justify quantitatively. With the equivalence assumption, the probability of a bridge accident is simply the ratio of bridge miles in the continental U. S. to total road miles times the highway accident rates.

Reference 22 lists the notable highway bridges in the U. S., a total of about 37.9 bridge miles. Although this mileage includes some bridges under which the water flow is minimal over the entire year, it does not include the large number of shorter bridges in which a real immersion threat can exist. Rather arbitrarily, therefore, a total of 100 miles of bridge length was chosen to represent the threat.*

*As shown later, the probability of an immersion threat to large packages is relatively small in comparison to the probabilities of fire, impact crush, and puncture.

Similar problems exist in defining the highway mileage corresponding to this length of bridge. Conservatively, as most of the bridges are on federal highways, the value of 150 000 miles of roads under federal control²³ was used. This leads to a probability of 7×10^{-4} that, if an accident occurs, it takes place on a bridge. This figure could easily be in error by at least a factor of 5.

As most accidents are of a relatively minor nature and most deep-water bridges are rather heavily protected, the occurrence of an accident on a bridge is not tantamount to an immersion incident. As an order of magnitude estimate, it is assumed that 1 percent of the containers involved in an accident on a bridge will be immersed. This assumption is based both on the probability of the entire trailer dropping into the water and on the probability of a detached package falling off the bridge.

The accident rate for trucks was assumed to be 2.5×10^{-6} per mile. Combining this with the probability of the accident occurring on the bridge and, if this happens, the probability of the package becoming immersed leads to an estimate of about 1.8×10^{-11} immersions per mile.

With this figure used as the immersion rate for bridges, the depths were estimated by assuming a mean water depth of 10 feet and by assuming that only 5 percent of the depths equal or exceed a dredged channel value²⁴ of 40 feet. Therefore, the probability per package mile of being immersed is 1.3×10^{-11} ; of being immersed in greater than 10 feet of water is 9×10^{-12} ; and of being immersed to depths greater than 40 feet is 9×10^{-13} . These data are graphically depicted in Figure II-8.

Figure II-8. Probability of package being immersed in a depth greater than depth given for bridge accidents.

b. Vehicular Roll-Over and Cargo Ejected Into Roadside Ditch

The overturn rate for motor carriers is tabulated by the Bureau of Motor Carrier Safety (see Chapter 1 and, for example, Reference 4). This rate, averaged over 3 years, is about 1.9×10^{-8} per mile. Again, an assumption of the probability of immersion for a given package, given an overturn, is required and again an arbitrary order of magnitude value of 0.01 has been chosen. The probability of immersion due to roll-over is, therefore, about 1.9×10^{-10} per mile.

The depth of the water in ditches must be estimated. Certainly, the probability of a ditch containing appreciable water is no greater than the 0.01 value when averaged over the entire U.S.; in some areas, it probably is less than 10^{-4} . Use of the 0.01 value leads to a maximum immersion probability, per mile, resulting from roll-over of 1.9×10^{-10} per mile. When water is present, the assumption that it has an average depth of 0.5 feet and a 5-percent probability of a depth greater than 3 feet leads to the data shown in Figure II-9.

Figure II-9. Probability of package being immersed in a depth greater than depth given for ditch accidents.

c. Runoffs

From Appendix B (Tables B-V & B-VI), about 17 percent of the major highway accidents involve departure of the truck from the driving surface. Certainly, no more than 0.1 percent of these accidents will result in the out-of-control vehicle driving into adjacent streams or lakes. This results in an immersion probability for runoffs of about 4×10^{-10} per mile. The vehicle is assumed to overturn in the water when maximum depth is reached, and the depth is assumed to vary linearly up to a maximum of 5 feet. These results are shown in Figure II-10.

Figure II-10. Probability of package being immersed in a depth greater than depth given for runoff accidents.

Summation

From these data the probability of immersion, given an overturn or collision, is simply the sum of a, b, and c divided by the rate of overturn and collisions, or

$$(1.8 \times 10^{-11} + 1.9 \times 10^{-10} + 4 \times 10^{-10}) \left[(2.5 \times 10^{-6}) (0.9) \right] = 1.7 \times 10^{-4} \quad (\text{II.10})$$

Most of these are relatively minor, however, as can be seen from Figure II-11, which is the environmental description for immersion achieved by adding the results of Figures II-8, II-9, and II-10. Figure II-11 shows that only about 0.001 of the immersion accidents or 3.4×10^{-7} overturn or collision accidents result in a depth greater than that specified in Reference 25. The total immersion rate, per mile, is shown in Figure II-12.

Figure II-11. Probability of immersion at a depth greater than that shown, given immersion.

Figure II-12. Probability, per mile, of immersion in a depth greater than depth given in a motor-carrier accident.

Conclusions

The immersion environment is expected to occur very infrequently. It has been estimated that (1) only 1 accident in 3 000 will involve immersion of the package and (2) the probability of immersion to depths greater than 4 feet is of the order of 10^{-10} per package transport mile.

Chapter 6 Puncture Environment

Introduction

"Of all the potential threats to radioactive or hazardous material cargo, none is more difficult to describe, more uncertain, and more random in nature than the potential puncture of a container by portions of the deformed trailer, by other cargo, or by external sources. Because of the complexity of this threat, it is probably safe to state that it is not possible, regardless of the amount of expended effort, to define accurately the puncture environment." This statement was used to describe the puncture environment in Reference 1, volume III. The data base for puncture of packages in highway accidents has not been expanded.

An analysis of the puncture threat in large-package railroad accidents has been achieved by use of railroad tank car puncture data. This analysis is discussed in Chapter 6 of Part III of this report. The puncture threat in the rail environment is considered to be greater than that in the highway environment (given a puncture situation) because of the presence of the railcar coupler as a potential probe in each such situation. The response of truck transported packages to puncture threats has been estimated based upon the analysis of the railroad transportation environment. The readers are encouraged to familiarize themselves with the railroad puncture analysis, Chapter 6 of Part III, before applying any of the motor carrier findings to a specific problem.

Puncture Threat

This analysis will utilize the same method that was developed in the rail transport puncture investigation. The method is applicable to determining the order-of-magnitude of the puncture threat. A search of truck accident records did not establish any potential puncture probes such as the rail-car coupler which would serve as a basis for the analysis. Therefore, it was necessary to assume a probe and an associated probe failure model. The probe chosen was one which is identical to the Model 1 rail-car coupler (Figure III-18). This assumption lead to the results, which are shown in Table III-XII. The effective impact velocities for puncture were estimated to be the same as the single vehicle preaccident velocities. These velocities obtained from equation C.1 and are shown in Figure C-2. It was further assumed that no situations leading to package puncture would occur in collision accidents involving passenger autos, light stationary objects, or terrain features. These items are defined in Appendix D, pages D-4 and D-7. These three classes of collisions account for 73% of all truck accidents involving collisions.

The probability of a puncture situation given a truck accident has been calculated as the product of three events: (1) the probe does not fail, (2) the impact velocity is sufficient to penetrate given a nonfailing probe, and (3) the collision does not involve passenger autos, light stationary objects, or terrain features. This probability is tabulated in Table II-V for selected package wall thicknesses.

TABLE II-V
Probability of Occurrence of a Puncture Situation
Given a Truck Transport Collision Accident

Package Wall Thickness (mild steel) _____ (in.)	Probability of Puncture Situation
0.4375 (7/16)	2.21×10^{-1}
0.50	2.18×10^{-1}
0.75	2.04×10^{-1}
1.00	1.64×10^{-1}
1.25	9.38×10^{-2}
1.50	2.88×10^{-2}
1.75	3.97×10^{-3}
2.00	2.31×10^{-3}
2.50	4.36×10^{-8}
3.00	5.56×10^{-12}

Probability of Puncture

The probability of puncture given a puncture situation must be determined. It can be seen from the above, that a puncture situation is deemed to occur in every collision accident where effective impact velocity is above the puncture threshold velocity and the collision does not involve passenger autos, light stationary objects, or terrain features. This probability (puncture given a puncture situation) will be estimated to be the same for truck accidents as for railroad accidents. The available railroad tank-car puncture data, discussed in Chapter III-6, indicates that no more than 1 out of 100 collision situations in the railroad environment resulted in tank-car punctures. It will be assumed for track accidents that the probability of puncture given a puncture situation is 10^{-2} .

Conclusion

The results of this analysis are presented in Table II-VI. In addition to the above factor, the probability of a collision accident given a reportable truck accident has been determined to be 0.80, Table B-6. The probability of a reportable truck accident given a mile of track has been estimated to be 2.5×10^{-6} .

TABLE II-VI
Probability That a Package Will Be Punctured

Package Wall Thickness (a) (in.)	Probability per Transport mile	Probability per Reportable Accident	Probability Truck Coll- ision Accident	Probability per Accident Where Probe Failure Controls
0.4375	4.42×10^{-9}	1.77×10^{-3}	2.21×10^{-3}	1.
0.50	4.36×10^{-9}	1.74×10^{-3}	2.18×10^{-3}	1.
0.75	4.08×10^{-9}	1.63×10^{-3}	2.04×10^{-3}	0.99
1.00	3.28×10^{-9}	1.31×10^{-3}	1.66×10^{-3}	0.84
1.25	1.88×10^{-9}	7.50×10^{-4}	9.38×10^{-4}	0.50
1.50	5.76×10^{-10}	2.30×10^{-4}	2.80×10^{-4}	0.16
1.75	7.04×10^{-11}	3.18×10^{-5}	3.07×10^{-5}	0.023
2.0	4.62×10^{-11}	1.85×10^{-5}	2.31×10^{-5}	0.014
2.5	---	---	4.35×10^{-10}	2.9×10^{-7}
3.0	---	---	---	4.0×10^{-11}

(a) Mild Steel Package Wall Assumed

PART III
TRAINING ENVIRONMENTS

Chapter 1

DEFINITIONS AND ACCIDENT RATES

Accident Definition

The definition of "accident" as used in this study is consistent with the definition of "train accident" as set up by the United States Code of Federal Regulations²⁶ in that it includes accidents associated with the operation or movement of trains, locomotives, or cars that result in railroad equipment, track, or roadbed damage in excess of \$750.

Accident Rate

The accident rate appropriate for this study is that for freight trains only. The breakdown of freight train accidents on Class I and Class II line-haul railroads in 1972²⁷ is given in Table III-1.

TABLE III-1
Number of Class I and Class II Line-Haul Railroad Train Accidents
to Freight Trains in 1972

Accident Classification ^a	Number of Train Accidents ^b
Collisions (one freight)	172
Collisions (two freight)	68
Deraillments	3880
Other	465

^aFor definition of accident classifications, see Reference 28.

^bFrom Table 123 of Reference 27. Also listed in Reference 2 are about 2500 highway grade crossing accidents which are classified as "train service" accidents. This number is composed of accidents that (1) are either less than \$750 in severity or (2) do not involve personal injury or derailment or result in collision with another train. Because of the lack of threat to cargo in these accidents, they were not considered in determining the accident rate.

Doubling the number of two-freight collisions and adding the second column gives a total of 4653 freight trains involved in accidents in 1972. The total Class 1 freight train mileage²⁹ in 1972 was 451×10^6 . Since Class 1 railroads represent 99 percent of the railroad industry in terms of traffic, the train accident rate, R, is

$$R = 10^{-5} \text{ train accident per mile.}$$

For R small, as is the case here, the rate equals the probability of a train accident in 1 mile of travel.

Accident Environment Definitions

Interactions between a railcar or package and its surroundings during an accident are labeled "accident environments." The five accident environments—fire, impact, crush, puncture, and immersion—as used in this study should be interpreted according to the specific definitions given below.

Fire. Exposure to a high-temperature environment produced by combustion. Example: the interaction of a package with a fire following a derailment.

Impact. Striking or being struck by an object that has no sharp projections. Example: the interaction of a railcar with an adjacent railcar in a collision.

Crush. Subjection to structural loads that may either be highly localized or be extended over a large area of the exposed package but that cannot be categorized as impact or puncture. Example: the forces on a package that rests between the freight car and ground after an accident.

Puncture. Striking or being struck by an object that penetrates the protective structures of the package. Example: the impalement of a package by the coupler of a freight car.

Immersion. Submersion in a liquid medium. Example: the submersion of a package in water after a car derails on a bridge and falls into a river.

The environments as specified in this report are transportation vehicle environments, not package environments, because the available abnormal environmental data deal with transport vehicles rather than with their cargos. The vehicles in this case are railroad flat-bed freight cars. Specific analysis of particular package design and tiedown structures, if any, is necessary for further reduction of data to the package response. The data in this report were developed to facilitate these follow-on detailed analyses.

The most common rail accident (83 percent of all rail accidents) is derailment of a section of the cars in a train having no prior collision. In this case the lead car of the derailment separates from the preceding car and leaves the tracks. At separation from the preceding car, the brake system is activated over all cars in the train and both sections of the train are brought to a halt. Derailment thus involves a series of cars, each leaving the track at a successively slower speed. Because of the increased resistance to movement after leaving the track, the lead cars are decelerated at faster rates than the following cars and a series of low differential velocity impacts results. Because high inertial forces are involved (owing to the weight of the loaded cars), it is not unusual to encounter reports of one car overriding another as a result of a low differential velocity impact.

The differential velocities of impacting cars in collision accidents are typically much higher than those of cars in derailment accidents. However, these large differential velocity changes experienced by cars near the impact point rapidly diminish to velocities that are within the normal impact capabilities of freight cars. This point is established by the fact that many of the cars in trains involved in a collision will remain on the rails with their structure intact. Extreme equipment damage is usually limited to the locomotives and lead cars in head-on collisions and to the locomotives, caboose, and adjacent cars in rear-end collisions.

Chapter 2

FIRE ENVIRONMENT

Introduction

Fires resulting from train accidents have a wide variety of causes and a range of severities that extends from inconsequential (less than \$100 property damage) to multimillion-dollar holocausts. The data sources³⁰⁻³² are helpful in providing information related to type of accident (collision, derailment, etc), frequency of fire, cause of fire, and property damage estimates. However, the accident records do not provide the information required to describe the environment levels expected in a fire accident, such as fire size, intensity (temperature), location, duration, and fuel source. The lack of commonality of railroad fires and the paucity of specific data make the development of a reasonable probabilistic description of the fire environment a somewhat subjective exercise.

In contrast to an aircraft accident,³³ where the postcrash fire can be described almost exclusively in terms of the fuel situation, the train fire has a large number of variables that can affect the resultant fire. Such variables are accident type (collision, derailment, rail crossing, vandalism, etc), type and amount of cargo (flammable or nonflammable), type of car(s) involved (boxcar, tanker car, etc), involvement of locomotive fuel, and availability of firefighting equipment and personnel. The large number of variables and the lack of specific data led to the use of a Monte Carlo technique for developing a description of the train-accident fire environment. A brief description of this procedure can be found in Reference 34. The Monte Carlo approach utilizes the available data, along with engineering judgments and theoretical predictions, to determine the consequences of certain events or the sequence of events.

The resulting fire description has a degree of uncertainty because of lack of data. Qualitative comparisons of the fire severity and duration with the property damage distributions can be made, however, to adjust the more sensitive input parameters until reasonable agreement is obtained.

Data Base

The primary data sources for determining the frequency and severity of train-accident fires were Reference 30 (for the years 1969, 1971, and 1972) and Reference 31 (also for 1972). Unfortunately, the two data sources for 1972 have a large discrepancy in the reported number of fires experienced by rail transport. It was assumed that Reference 31 contained the correct information, since compiling fire-accident data was the specific purpose of that study; in Reference 30 the fact that a fire occurred in connection with an accident may have gone unrecorded and some "fire only" accidents may not have been reported.

Reference 31 is a compilation of fire accidents for 1972 of 13 U. S. railroads, representing 99 113 track miles, and two Canadian railroads, representing 41 304 track miles. Since there are approximately 200 000 track miles (excluding parallel tracks) in this country,²⁰ the experience of the railroads reported in Reference 31 is taken to be representative of the U. S. railroad industry as a whole. In 1972 the 15 railroads reported 2152 fires with property damage losses of \$8 754 282. Fire losses of \$1000 or less were reported for 1378 of the accidents and of less than \$10 000 for 1941 of the accidents.

Freight trains and/or their contents were involved in 897 of the fires. Approximately 1 percent of the collision and derailment accidents resulted in a fire, with an average property damage of \$82 000. Including only those accidents where property losses exceed \$1000, Table III-II shows the relative frequency of various types of freight train accidents, how often fire occurs in those accidents, and the percentage of the total fires accounted for by each type of accident. As shown, fires due to accidents other than collision and derailment account for most fires. These accidents have a wide range of severity and, although they are much more frequent, generally are much less destructive than fires following collision or derailment. The unusually high frequency of fires from "other" accidents is a result of the data discrepancy between References 30 and 31. It is not believed that fires actually occur in 90 percent of all "other" accidents but rather, as mentioned previously, that this apparent rate stems from the differences in reporting in the two sources. Using the National Fire Protection Association (NFPA) data as representative would indicate that in 1972 there were 420 accidents other than collision and derailment where fire was involved and damage exceeded \$1000, whereas data for the same year from the Federal Railroad Administration (FRA)³⁰ shows a total of 465 "other" accidents where damage exceeded \$750. The frequency of fire in these "other" accidents cannot be determined from the FRA data alone. However, since 420 fires (excluding collision and derailment) were reported by NFPA, the resulting fire frequency from "other" accidents is 90 percent, as shown in the table. A more plausible explanation, however, is that the two references are not reporting the same accidents. It is assumed that the NFPA data are correct; hence, the total number of fires is consistent and fire frequency of "other" accidents will not affect the results. For all freight train fires from accidents of various causes (including those with less than \$1000 damage), Table III-III shows the percentage of fires, the percentage of the property damage, and the average cost per accident.

TABLE III-II

Railroad Accident Fire Rates
(freight trains, damage > \$1000)

<u>Accident Type</u>	<u>Percent of Total Accidents</u>	<u>Percent of Fire Frequency</u>	<u>Percent of Total Fires</u>
Collision	6.62	1	0.74
Derailment	83.39	1	9.38
Other	9.99	90 ^a	89.88

See discussion in text concerning data discrepancy.

TABLE III-III

Causes and Costs of Freight Train Fires
(includes all fires with monetary damage)

<u>Cause of Fire</u>	<u>Percent of Fires</u>	<u>Percent of Cost</u>	<u>Average Cost/Accident</u>
Heating Units	7.86	2.79	\$ 1,869
Brake Shoe Sparks	26.91	17.84	3,491
Hot Boxes	6.95	3.54	2,671
Power-Related Sources	2.21	0.78	1,863
External Sources	25.92	7.83	1,501
Derailment, Collision	2.46	46.58	51,712
Spontaneous	1.96	0.83	2,221
Unknown, Other	25.93	19.81	4,024

Data on the commodities carried by the railroads, typical loadings, and amount of flammable goods, as well as the train makeup (average number of boxcars, tankers, flat cars, etc) were obtained from References 29 and 35. In addition, Reference 35 was used to determine the amount of potential flammable material available from the car construction materials of certain cars (such as wooden floors) and typical fuel capacities of the locomotives.

In summary, the data sources provide a reasonable base for determining the cause and frequency of railroad fires and also the availability of combustible materials. However, they do not provide information necessary for a description of the resulting thermal environment. It is necessary, therefore, to model the expected environment by use of analytical techniques to predict the fire severity based on a probabilistic availability of combustible materials from various types of accidents.

Fire Description

Since the accident data do not contain the quantitative information necessary to describe the train-accident fire environment, other theoretical and experimental information was utilized. It is apparent both from theory and from experiments that exact predictions of temperatures in any particular fire cannot be made. Expected temperatures are a function of the fuel, oxygen supply, geometric configuration, and other variables, most of which can only be estimated in an accident situation. However, most liquid hydrocarbon fuels yield approximately the same measured flame temperatures for open burning and, in general, fall in the range from 1400° to 2400°F .¹³⁻¹⁵ Furthermore, the flame temperatures of most of the other expected combustibles fall in that same range, generally toward the lower end.^{16, 17} The probability distribution of the train-fire temperature was assumed, therefore, to be represented by the distribution determined previously for aircraft fires (described in Volume 1 of Reference 1).³³

From previous analyses,³³ the fire can be considered to be essentially a blackbody radiation source for a flame thickness of 4 feet or more and the convective heating can be neglected.

Fire Duration

From accident to accident, the wide variety of types and of amounts of combustible material available to provide fuel for the fire precluded a closed-form analytic description of the probable burn time, and the lack of detailed data prevented a statistical representation of the duration. A Monte Carlo prediction scheme was used, therefore, to obtain the expected distribution for the fire duration. The procedure and justification follow those explained in Reference 34.

A simplified schematic flow chart of the computer program used to predict the fire-duration distribution is shown in Figure II-1. Simulated accidents are limited to those where a fire occurs; such a limitation greatly reduces the number of simulated accidents required for obtaining a good statistical sample.

A list of the major assumptions, as well as the probability distributions used in the program, is given here. The assumptions and distributions were obtained from a combination of qualitative and quantitative data; analytical models; engineering approximations; and, occasionally, intuition. As in the previously discussed mode of transport (truck), wherever uncertainty exists the intent is to err on the side of conservatism; e.g., to maximize the fire duration. Only fires causing over \$1000 damage are considered.

1. Frequency of various fire-accident types are as shown in column 3 of Table III-JI.

Figure III-1. Simplified flow chart of Monte Carlo train-fire-duration program.

2. As obtained from the accident data,³¹ the distribution of fire causes other than collision and derailment are as follows: unknown, other, and grade crossing (27.2 percent); spontaneous ignition (2.1 percent); external sources (vandalism, etc., 27.2 percent); hot boxes (7.1 percent); brake-shoe sparks (28.2 percent); and heating units (8.2 percent).
3. When collision results in fire, the locomotive is involved in the fire 26 percent of the time.^{31,32}
4. Boxcars are involved in 72 percent of the fires.³¹
5. Loaded tank cars are involved in 14 percent of the fires.³¹
6. Refrigerator and other cars are involved in 14 percent of the fires.³¹

7. Diesel fuel on board the locomotives³⁵ varies from 1000 to 5000 gallons, with an expected value of 2000 gallons and a cumulative distribution function (cdf) given by

$$1 - e^{-(f-1000/1415)^{1.06}}, \quad (III. 1)$$

where F is fuel in gallons.

8. When diesel fuel from locomotives is involved in the fire, it is dispersed uniformly over 500 to 1000 ft², with an expected value of 700 ft² and a cdf given by

$$1 - e^{-(A-500/252)^{1.6}}, \quad (III. 2)$$

where A is area in ft².

9. When one car becomes involved in a fire, the probability of adjacent cars (if flammable) catching fire is 20 percent.
 10. Fifty-six percent of the freight cars are loaded.^{25, 35}
 11. Five percent of the commodities carried in refrigerator and "other" cars (not boxcars or tankers) are combustible.^{29, 35}
 12. Fourteen percent of the commodities carried in boxcars are flammable.^{29, 35}
 13. Average cargo weight of loaded boxcars is 46.7 tons, with a distribution from 10 to 90 tons given by

$$1 - e^{-(W-10/44.6)^{1.88}}, \quad (III. 3)$$

where W is cargo weight in tons.^{29, 35}

14. The fraction of flammable goods in boxcars that will burn varies from 0 to 100 percent, with an expected value of 20 percent and a cdf given by

$$1 - e^{-(f/0.268)^{1.25}}, \quad (III. 4)$$

where f is fraction that will burn.^{31, 36}

15. Char density of solid combustible cargo is 35 percent of virgin density.^{19, 20}

16. Loaded tank cars carry 100 percent flammables, with capacities ranging from 10 000 to 40 000 gallons³⁵ and a cdf given by

$$1 - e^{-(C-10\,000/17\,842)^{2.11}} \quad (III.5)$$

where C is capacity in gallons.

17. Tank car fuel, when involved, is spread uniformly over an area varying from 800 to 5000 ft², averaging 2000 ft²; a cdf is given by

$$1 - e^{-(A-500/1465)^{1.26}} \quad (III.6)$$

where A is area in ft².

18. Locomotive fuel and tank-car contents have a mass burn rate¹⁴ of 0.65 lb/ft²·min, which corresponds, in general, to a surface recession burn rate of 0.16 in./min.
19. For fuel purposes, wood or other cellulosic material is considered to be representative of the solid flammable material, with a representative burn rate of 0.16 lb/ft²·min for the first 30 minutes (linear decrease from 0.24 to 0.05 lb/ft²·min) and 0.09/ft²·min thereafter.^{19,20}
20. The boxcar flooring³⁵ consists of 2.25 inches of yellow pine or Douglas fir decking with a density of 35 lb/ft³.
21. Firefighting efforts are available for all fires started from external sources (since this is mostly vandalism and occurs in the railyards) and for one-third of the remainder of the fires. Firefighting is ineffective against tanker-car fires.
22. When firefighting efforts are available and effective, fire duration is controlled by the firefighting efforts and is uniformly distributed between 15 and 60 minutes.

The program was used to simulate several series of accidents involving 10 000 fires. The repeatability of the results was excellent and indicated that a statistical sample of 10 000 simulations was sufficiently large to prevent variations in the predicted duration distribution of more than 1 percent.

The results of the Monte Carlo prediction method are shown in Figure III-2 as both a density function and a cumulative distribution function.

Figure III-2. Duration probability of train-fire accidents involving large packages.

Although there are no data with which the results in Figure III-2 can be compared, an indirect and qualitative comparison can be made with the distribution of property damage in fire accidents. The limited data from Reference 31 are shown in Figure III-3. Since Reference 31 reports only "average damage" values for each type of accident, the average dollar values have been uniformly distributed by $\pm 75\%$ to produce the figure. As a qualitative comparison, data points from the Monte Carlo duration prediction based upon an arbitrary scaling factor of \$167 property damage per minute are shown. The arbitrary cost per time value was selected to place the Monte Carlo data points in the same region of the abscissa and thus show the qualitative comparison in the trends of the curve; it is not intended to be used as a predictive tool for estimating damage from fire times. Although such a prediction is very artificial, since property damage is closely related to the initial value of the train and cargo, the comparison shows a definite qualitative correlation and adds credibility to the duration prediction method.

Figure III-3. Distribution of property damage from railroad fires.

Conclusions

Based on a train-accident rate of one every 10^5 train miles and taking into account the frequency of various types of accidents and the probable number of cars involved, Figure III-4, which shows the probability per car mile of exceeding any specified duration fire environment, uses the following base:³¹ The average number of cars involved in a fire following collision and/or derailment is 10 and the average number of cars involved in "other" train accidents where fire occurs is 1.2, resulting in a fire accident rate of 2.8×10^{-8} car fire accidents per car mile.

No attempt is made in Figure III-4 to address the question of how frequently a large package will be exposed to the fire. It is conservatively estimated that, given the fact that a package is on a train, close exposure will occur no more often than once in every ten fires. Since 90 percent of the fires involve only a single car and since the heat flux drops off very rapidly with distance,³³ it would appear that the only possibilities for direct package exposure would be (1) following a severe collision and/or derailment where several cars are bunched together, (2) in a railyard when a fire starts in a car or cars on a nearby parallel track, and (3) following a grade-crossing accident involving a tanker truck, with the train stopping and the package in the middle of the ensuing fire. Almost any other fire accident would likely offer very little threat to the package because of the distance between the package and the fire.

Figure III-4. Probability per car mile that a fire will occur and exceed the duration shown for train accidents.

PART III

Chapter 3 IMPACT ENVIRONMENT

Introduction

The general procedure used in this analysis is the same as that used in the truck transportation analysis. The principal difference lies in the reduced amount of detail available in the rail-accident descriptions. Two types of accidents are defined: the train derailment accident and the train collision accident. In this analysis, as in the truck analysis, it is the vehicle (the railcar in this case) environment that is predicted. The difference between railcar impact and package impact is significant for those containers that are more frail than the railcar structures. For containers that are stronger than railcar structures the abnormal environments predicted can be considered as the package environments. An example of the latter condition can be found in the spent reactor fuel shipping cask designed to meet the testing requirements of 10-CFR-71 Appendix B. In this case, railcar effects can be disregarded and the package can be thought of as either impacting an adjacent car or being impacted by an adjacent car. It must be remembered, however, that railcars are deformable structures, not rigid targets.

Deraillment Analysis

A computer program, which utilizes a Monte Carlo analysis technique, was prepared to study the derailment problem. A train with 66 cars was utilized to model the typical shipment train.¹ It was assumed that the shipment car was randomly placed in the train. The lead car in the derailment was randomly chosen. One-hundred-thousand derailment accidents were considered for each derailment distribution. In each case, the velocity change of the shipment car due to impact, given that the train experiences a derailment, is computed.

Computations of Velocity Change

The procedure used for computing the velocity change of a shipment car in a derailment accident consists of

1. Selecting the car of interest randomly from the 66 freight cars in the train.
2. Selecting randomly the lead car in the derailment group.
3. Selecting the speed of the train randomly from the appropriate speed distribution (Appendix E).

4. Selecting the number of cars derailed (based upon the train velocity and the derailment model used, Appendix E, Models 1, 2, and 3).
5. Determining whether the car of interest is in the group of cars derailed.
6. If the car of interest is not in the group of cars derailed, recording a zero velocity change and proceeding to the next accident simulation.
7. If the car of interest is in the derailment group, computing its most significant velocity change due to impact as follows:
 - a. Reduce the preaccident velocity linearly, depending upon the car's derailment position in the string of derailed cars. This is done by computing a car impact factor (CIF) as follows:

$$CIF = 1 - \frac{\text{car position number in derailment}}{1 + N \text{ (number of cars derailed)}}$$

(III.7)

Figure III-5 is a graph of this function. It is known that the lead car in a derailment leaves the tracks at a velocity near the train's prederailment velocity. The car following the last car in the derailment group stops on the tracks. Hence, because of the necessity for reducing the car velocity from preaccident velocity to impact velocity, a linear variation is chosen.

Figure III-5. Car impact factor.

- b. Determine the severity of accident factor (SAF). Cars that leave the tracks in a derailment accident may or may not experience a significant collision. If they do experience a collision it may be with a standing car on an adjacent track, a track side structure, another car in the derailment group, or similar objects. In order to account for this, a severity of accident factor was chosen randomly from a uniform distribution on the 0-1 interval and applied to the derailment velocity to obtain a velocity change due to impact. This is a conservative assumption because it assumes that all derailed cars will be involved in some impact and, further, that mean value of this impact will be half of the maximum available impact velocity. This distribution is shown in Figure III-6. The velocity change δV due to impact is computed as follows:

$$\delta V = (SAF)(CIF) (\text{train preaccident velocity})$$

Figure III-6. Severity of accident factor.

8. The impact velocity computed is recorded, and calculations proceed to the next accident.

The results of this derailment analysis, presented in Table III-IV for three different models, as discussed in Appendix E, have been converted to give the expected frequency of occurrence for a velocity change equal to or less than a given velocity change and plotted as Figure III-7.

TABLE III-IV
Derailment Accident Findings - Impact

Velocity Change (mph)	Cumulative Number of Shipment Cars of Interest Expected to Experience a Velocity Change Less Than or Equal to the Indicated Velocity Change, Given 100 000 Train Derailment Accidents With One Shipment Car of Interest per Train		
	Model #1	Model #2	Model #3
No derailment	00463	80211	80134
5	96530	95132	95461
10	99217	97152	97564
15	99904	98257	98650
20	99953	98840	99213
25	99970	99362	99587
30	99983	99610	99735
35	99994	99758	99807
40	99995	99870	99841
45	99997	99926	99867
50	99999	99955	99896
55	99999	99980	99921
60	99999	99989	99955
65	99998	99996	99983
70	100000	99998	100000
75		100000

Figure III-7. Train derailment accidents.

Collision Analysis

A computer program similar to that used for the derailment analysis was developed for the collision analysis. One-hundred-thousand computer simulated accidents were evaluated to determine the velocity change distribution associated with the collision environment.

The procedure for computing the velocity change in a collision accident consists of

1. Selecting the type of collision randomly based upon the collision-accident distribution (Appendix F, Figure F-1).
 - a. Head-on collision
 - b. Rear-end collision
 - c. Side or raking collision and collision with cars not in train (analyzed as head-on or rear-end collisions).
 - d. Broken-train collisions (analyzed as derailments).
2. Selecting preaccident train velocities for each train in the collision from the appropriate train speed distribution or select the derailment speed for broken-train accidents from the broken-train speed distribution (Appendix F).
3. For broken-train accidents, proceeding to the derailment analysis.
4. For collision accidents, randomly choosing the train with the car of interest.
5. Randomly choosing the location of the train car of interest by car number.
6. Assigning collision distribution model to be used. Model 1, all cars involved in collision, or Model 2, only damaged cars involved in collision (Appendix E).
7. Calculating net impact velocity for the collision by type of collision.

8. Calculating velocity change due to impacts. Calculation of this velocity change is based upon a linear reduction in net impact velocity, as a function of car position, in a manner similar to that in derailment accidents.

The severity of accident factors is assumed to be 1 in all collision accidents except broken-train accidents.

9. Proceeding to next accident simulation.

The results of the collision analysis, presented in Table III-V, have been converted to give the expected frequency of occurrence for a velocity change equal to or less than a given velocity change and plotted as Figure III-8.

TABLE III-V
Collision Accident Findings - Impact

Velocity Change (mph)	Cumulative Number of Shipment Cars Expected to Experience a Velocity Change Less Than or Equal to the Indicated Velocity Change, Given 100 000 Train Collision Accidents With One Ship- ment Car of Interest per Train	
	Model #1	Model #2
No collision	12848	88409
5	91276	96365
10	91989	98000
15	96112	98758
20	97999	99197
25	98926	99457
30	99474	99658
35	99699	99777
40	99823	99841
45	99894	99905
50	99940	99946
55	99971	99973
60	99989	99989
65	99995	99995
70	99999	99999
75	100000	100000

Figure III-8. Train collision accidents.

Other Train Accidents

No significant impact conditions have been found in this category. The category has been retained in the analysis to maintain compatibility with the accident rates used in Reference 1. In the analysis of the complete train accident (derailment, collision, and other), the car of interest is considered to suffer no velocity change attributable to "other" accidents.

Train-Accident Analysis

The term "train accidents" refers to the accidents discussed in Part III, Chapter 1, and listed in Table II-I. Analysis of the train accident used the derailment, collision, and "other" accident models discussed above. There are six possible permutations of the three derailment and two collision models. The results of the simulation of 100 000 train accidents, from the accident distribution shown in Figure E-1, are presented in Table III-VI for the upper and lower bound cases. These cases have been designated Case 1 (upper bound) and Case 2 (lower bound). Figure III-8 is a graphic presentation of the data.

TABLE III-VI
Train Accident Findings - Impact

Velocity Change (mph)	Cumulative Number of Shipment Cars of Interest Expected to Experience a Velocity Change Less Than or Equal to the Indicated Velocity Changes, Given 100 000 Train Accidents With one Shipment Car of Interest per Train	
	Case 1	Case 2
No impact	85077	91270
5	94615	96924
10	97102	98395
15	98301	99081
20	98990	99489
25	99386	99705
30	99631	99817
35	99780	99896
40	99878	99943
45	99935	99972
50	99970	99985
55	99983	99990
60	99990	99992
65	99995	99995
70	99997	99998
75	99999	100000
80	100000	

Conclusions

The train-accident impact environment has been investigated, and the distribution of the parameter governing the environments has been determined. The information contained in Table III-VI combined with the expected train-accident rate can be utilized to determine the expected frequency of occurrence of a given velocity change due to impact. For example, a 30-mph or greater velocity change is associated with an expected rate of occurrence of 1 every 27-million package rail transport miles. The impact situations evaluated here are railcar environments, which may also be conservatively assumed to be container environments. With this method of analysis, velocity changes due to impact in a derailment accident or in a collision accident are treated as similar occurrences.

Figure III-9. Train accidents, all types.

Chapter 4 CRUSH ENVIRONMENT

Introduction

It is difficult both to define and to quantify the train-crush environment. As was noted in the truck section of this report, the word itself possesses a rather vague connotation similar to a hydrostatic pressure, but acknowledges that some degree of dynamic, nonsymmetric load application is permissible. We have, for this study, rather arbitrarily defined crush to be considered "the essentially static forces acting on a package as a result of its position underneath derailed cars." Again, the dynamic loads involved in achieving this state are treated as impacts.

The desired result of this analysis is the determination of the frequency, per mile of transport, that a package will encounter crushing forces and the expected severity of these forces. The results presented in this section are similar to those for the static crush portion for trains in SLA-74-0031.

Crush Description

The crush environment is the result of a package resting between the ground and a derailed car or locomotive. In our consideration of crush, other cargo is neglected except for the distributed load it applies to a derailed car when the package rests beneath that car.

Frequency of Static Crush

To estimate the probability of crush, it is necessary to estimate the number of derailed cars and the size of the area which they occupy. To estimate the number of derailed cars, data were obtained from a major railroad on all accidents occurring on its most traveled line for the years 1971, 1972, and 1973. In this sample there are 83 derailments. The average number of derailed cars versus train speed at derailment is shown in Figure III-10.

Obtaining data on areas occupied by derailed cars proved to be very difficult. The derailed accident reports of the National Transportation Safety Board, however, sometimes contain diagrams that permit this information to be inferred. The data shown in Table III-VII were obtained from References 37 through 41.

Figure III-10. Average number of cars derailed versus speed at the time of derailment accident.

TABLE III-VII

Dimensions of Areas Occupied by Derailed Cars in Selected Accidents

Type of Accident	Length of Derailment Area (ft)	Width of Derailment Area (ft)	Area of Derailed Cars (ft ²)
Derailment at 40 mph ¹⁰	333	128	4.3×10^4
Derailment at 52 mph ¹¹	435	140	6.1×10^4
Derailment at 90 mph ¹²	650	114	7.4×10^4
Head-On Collision ¹³	153	165	2.5×10^4
Train 1, 40 mph			
Train 2, 3 mph			
Head-On Collision ¹⁴	250	100	2.5×10^4
Train 1, 30 mph			
Train 2, 30 mph			

The data of Table III-VII indicate that, for derailments, the length of the derailed car area is very nearly proportional to speed. It is assumed for analysis that the width of the derailed car area is constant (125 feet) and that the length varies linearly from 100 feet at zero velocity to 650 feet at 80 mph. For collisions, a constant area, independent of velocity, of 2.5×10^4 for two trains (1.25×10^4 per train) will be assumed. This assumption is based on data shown in Table III-VII.

The probability of crush is calculated as one-half the probability of collision of the package and a derailed car. In the accidents of Table III-VII, gross overlapping of derailed cars was not noted. If it is assumed that the package has equal probability of being anywhere within the area of derailed cars, the probability of crush is given by

$$\Pr\{\text{crush}|\text{derailment accident}\} \\ = C \sum_{i=1}^4 n_i a_i / 2A_i \quad (III-8)$$

where

- C = correction factor (explained below)
- n_i = average number of derailed cars in velocity interval i
- a = crush area of railroad cars
- f_i = fraction of derailments in velocity interval i
- A_i = derailment area in velocity interval i .

Some explanation of C , the correction factor, is necessary. From conversations with railroad officials and from such accident reports as References 37 through 41, it appears reasonable to assume that it is much more difficult to pin a package beneath an upright car than beneath a car on its side. Therefore, the collision model will be assumed valid for cars on their sides, but an order of magnitude high for upright cars. The resulting value of C , which must be applied to the pure collision model, is determined by assuming that three of every four derailed cars remain upright. This assumption leads to

$$C = 0.25 + 0.75 (0.1) = 0.325.$$

The quantity " a " in Equation (III.8) was calculated from car dimensions⁴² weighted by the fraction of particular car types in the typical freight train. These weighted areas, both for upright derailed cars and for cars on their sides, were nearly equal, and 540 ft² was used. The result for derailment accidents was

$$\Pr\{\text{crush}|\text{derailment}\} = 0.022 \quad (III, 9)$$

For collisions, the analogous probability was calculated from the equation.

$$\Pr\{\text{crush}|\text{collision with derailment}\} \\ = C \sum_{i=1}^4 f_i (n_i a + n_i' a') / 2A_i \quad (III-10)$$

where

C , f_i , n_i , a , and A_i are as defined before

n_i^d = number of locomotives derailed in velocity interval i

a^d = locomotive crush area = 715 ft^2

A typical average, " A_i ," in the case of collisions, is $1.25 \times 10^4 / \text{ft}^2$, independent of velocity. Both n_i and n_i^d are, for collisions, functions of net collision velocity. The assumption was made that n_i for collision was identical to n_i for derailment based on one-half the net collision velocity, n_i versus velocity is shown in Figure III-11. Equation (III.10) yields the following results:

$$\Pr\{\text{crush} | \text{head-on collision with derailment}\} = 0.046 \quad (\text{III.11})$$

$$\Pr\{\text{crush} | \text{rear-end collision with derailment}\} = 0.039 \quad (\text{III.12})$$

For broken-train collisions, the same basic procedure was used. The assumptions were as follows: (1) same number of cars (no locomotives) derailed versus velocity as for pure derailments and (2) A_i = constant = $2.5 \times 10^4 / 2$ as for collisions. The result was

$$\Pr\{\text{crush} | \text{broken train collision with derailment}\} = 0.042 \quad (\text{III.13})$$

Figure III-11. Average number of cars and locomotives derailed per train in a collision that produces derailment as a function of net collision speed.

^a This assumption has been discussed in greater detail in SLA-74-0001.¹

Collisions of trains or cars, with cars not in trains, is modeled exactly as rear-end collisions; since the velocity distributions for both accident types are identical, the results are the same.

$$\Pr\{\text{crush}|\text{collision of train or cars, with cars not in trains, with derailment}\} = 0.039 \quad (\text{III. 14})$$

The probabilities of a single car (the car carrying the container of interest) being derailed, given that derailment occurs on the train, are calculated with the equation

$$\Pr\{\text{specified single car derails}|\text{accident type } i\} = \sum_{j=1}^4 \frac{f_j n_j}{N} \quad (\text{III. 15})$$

where

- j = index on speed interval (four intervals used)
- f_j = fraction of accident types in speed interval j
- n_j = average number of derailed cars of accident type in speed interval j
- N = total number of cars in typical freight trains (66).

When these calculations are performed, the results are

$$\Pr\{\text{single car derails}|\text{derailment}\} = 0.103 \quad (\text{III. 16})$$

$$\Pr\{\text{single car derails}|\text{head-on collision with derailment}\} = 0.087 \quad (\text{III. 17})$$

$$\Pr\{\text{single car derails}|\text{rear-end collision with derailment or collision of train or car, with car not in train, with derailment}\} = 0.080 \quad (\text{III. 18})$$

$$\Pr\{\text{single car derails}|\text{broken-train collision with derailment}\} = 0.093 \quad (\text{III. 19})$$

With the above probabilities, it is now possible to calculate the probability of crush, given the various accident types. It is assumed here that all probabilities calculated for head-on collisions are valid for side or raking collisions that occur from a head-on direction and similarly for rear-end collisions. It is also assumed that side or raking collisions are equally divided between head-on and rear-end directions. All probabilities are presented in Table III-VIII, along with the final results.

The results for the collision types may be weighted by the relative frequencies of the collision types (Appendix E, Figure E-1) to get the probability of crush, given a collision. The final results are

$$\Pr\{\text{static crush}|\text{derailment accident}\} = 2.2 \times 10^{-3} \quad (\text{III.20})$$

$$\Pr\{\text{static crush}|\text{collision accident}\} = 1.5 \times 10^{-3} \quad (\text{III.21})$$

TABLE III-VIII

Calculation of Probabilities of Crush, Given Various Accident Types

Train Accident Type	$\Pr\{\text{derailment} \text{Accident Type}\}$	$\Pr\{\text{Car of Interest Derails} \text{Derailment}\}$	$\Pr\{\text{Static Crush} \text{Crush} \text{Container Released}\}$	$\Pr\{\text{Static Crush to Container in Single Car Train Accident Type} \text{Other 3 Probabilities Multiplied Together}\}$
Derailment	1	0.1	0.022	2.20×10^{-3}
Head-On Collision; Side or Raking; Collision in Head-On Direction	0.36	0.097	0.046	1.44×10^{-3}
Rear-End Collision; Side or Raking; Collision in Rear-End Direction; Collision of Train or Cars, With Cars Not in Trains	0.36	0.080	0.039	1.12×10^{-3}
Broken-Train Collisions	0.36	0.093	0.042	1.41×10^{-3}

This calculation makes the assumption that the package will break the tie-down restraints and free itself from the railcar. The alternative behavior that could lead to a static crush is that the package remains integral with the railcar, and the final position is with the car resting on the package. It has been estimated that one-fourth of the derailed cars overturn. Of these, it is improbable that more than one-tenth of the cars are wheels-up at the end of the encounter. This suggests an upper limit of 0.025 for the crush probability if the container is retained. This condition is comparable to the 0.022 to 0.046 values shown in Table III-VIII. The conclusion is, therefore, that no major difference in crush probability should be expected whether the large package stays with the railcar or is thrown free.

Crush Severities

In the typical freight train defined for this study, 56 percent of the cars are full and 44 percent are empty.¹ Further, according to crush probability assumptions made in calculating the correction factor of Equations III-9 and III-10, 77 percent of the static crushes are from cars on their sides and 23 percent from upright cars. The resulting fractions of different types of crush are given in Table III-N. Note that the crush potential results from all cars in the department; not just the car in which the large package is carried.

TABLE III-N

Fractions of Crush in Various Categories

	<u>Empty Car</u>	<u>Full Car</u>
Car on Side	0.33	0.43
Car Upright	0.10	0.14

The crush force probability distribution was calculated for each of the four types of crush according to a simple beam model and an assumed density function for container location beneath the car. These models and density functions are shown in Figure III-12. For full cars, the distributed cargo load was assumed to be the average load of 46.7 tons. Full gondolas and open hoppers on their sides were assumed to have lost half this load. Typical empty weights, heights, and lengths of different car types were obtained from Reference 35. For each of the four static crush types, the F distribution was then calculated for each car type and a final distribution was obtained by weighting each car distribution by the fraction of that car in the typical freight train. Results of these calculations are shown in Figure III-13. When the distributions of Figure III-13 are weighted by the fractions presented in Table III-N the result, given crush, is the probability of a given crush load. This result is shown in Figure III-14.

It should be noted that Figure III-14 does not incorporate any calculations for yielding of the car structure. For static crush beneath upright cars, because the underframe of the car is capable of supporting the loads calculated, no error occurs from this source. For crush from cars on their sides, however, there will be some container load, depending on container position, where the side of the car will deform significantly and not be able to exert further force on the container. Therefore, the cumulative force distributions for cars on their sides are conservatively high, as they do not incorporate this effect. In gondolas and open hoppers, because the reinforcing hat sections are vertical, they do not provide much strength in bending about a vertical (with respect to the car) neutral axis when the car is on its side. Furthermore, even though the sides of these car types are very rigidly attached to the underframe, they have no similar rigid roof attachment and their sides are therefore more susceptible to bending. In view of the many assumptions incorporated into the entire static crush analysis and of the complexity of folding the yield calculations correctly into the force distribution, these calculations were not felt to be worth while. Neglect of this effect makes the crush force predictions higher than expected.

Conclusions

It has been estimated that the probability of any container in a rail shipment being subjected to a static crush load is about 2×10^{-3} per car accident and that the severity of these loads is equal to or less than those given in Figure III-14. When these values are combined with the probability of a railcar being involved in an accident per mile traveled, it is seen that the probability of a container experiencing any static crush load in excess of, for example, 100,000 pounds is less than 10^{-5} per car mile.

EMPTY CAR ON SIDE

Beam Configuration

- F = container force
- G = ground force
- W = empty car weight
- L = car length
- c = coupler height

$$F = W \frac{f}{L}$$

Density Function on f

FULL CAR ON SIDE

Beam Configuration

$$F = \left[c^2 W + \frac{w}{2} (L^2 - c^2) \right] / f$$

Density Function on f

EMPTY CAR UPRIGHT

Beam Configuration

Beam configuration is identical to "empty car upright" except that w is distributed weight of empty car plus cargo.

Density function on f is identical to "empty car upright."

FULL CAR UPRIGHT

$$F = \frac{wL^2}{2f}$$

Density Function on f

- F = container force
- G = ground force
- w = distributed empty car weight
- L = car length

Figure 11-12. Beam configurations and container location density functions for crush types.

EMPTY CARS ON SIDE

Force (thousands of pounds)

FULL CARS ON SIDE

Force (thousands of pounds)

EMPTY CARS UPRIGHT

Force (thousands of pounds)

FULL CARS UPRIGHT

Force (thousands of pounds)

Figure III-13. Cumulative F distributions for types of crush.

Figure III-14. Cumulative distribution of total crush load.

PART III

Chapter 5 IMMERSION ENVIRONMENT

Introduction

Immersion as an accident environment is defined in Chapter 1 of Part III. As explained in Reference 33 the environmental parameter considered is hydrostatic pressure, which is interchangeable with depth.

Immersion resulting from a rail accident is an occurrence for which insufficient accident data are available. Through use of indirect data, however, one potential immersion accident can be modeled to give a perspective with regard to its probability of occurrence and immersion depth. With regard to immersion duration, no indirect data presently appears to be available which would lead to reasonable estimations.^{55, 56}

Immersion Probability Model

The immersion accident considered is that which occurs as a result of car derailment off a bridge that crosses a principal stream. If it is assumed that a train accident is as probable on a bridge as on any other section of main track, then an estimate for the probability of an accident on a bridge, given an accident, is the quotient of bridge mileage spanning principal rivers divided by the total railroad line mileage. The total mileage for the 33 major U. S. railroad bridges is 3.7 miles;²² total railroad line mileage is 204 000 miles.²⁹ Multiplying this quotient by an arbitrary factor of 5 to account for bridges over main rivers and streams not included in the major 33 gives the following result:

$$\Pr\{\text{accident on bridge} | \text{accident}\} = 9.0 \times 10^{-5} \quad (\text{III}, 22)$$

where the notation of a vertical separation line indicates the word "given."

Since it is assumed that only derailed cars can be immersed, it is necessary to calculate the probability of derailment, given the various accident types (Table III-X). The probability of immersing a single car, given that it is derailed on a bridge, is assumed to be 0.25, as some derailed cars will naturally remain on the bridge and some will be restrained by the bridge structure.

TABLE III-X

Calculation of Probability of Immersing a Single Car,
Given Various Accident Types

Train Accident Type	Pr{Derail- ment Accident Type}	Pr{Single Car Derailed Derailment}	Pr{Single Car Immersed Derail on Bridge}	Pr{Single Car Immersed Accident Type on Bridge}	Other Three Probabilities Multiplied Together
Derailment	1	0.103	0.25		0.026
Head-On Collision; Side or Raking Collision in Head- On Direction	0.16	0.007	0.25		0.0073
Rear-End Collision; Side or Raking Collision in Rear- End Direction; Collision of Trains or Cars With Cars Not in Trains	0.36	0.080	0.25		0.0072
Broken-Train Collisions	0.36	0.093	0.25		0.0084

The calculations outlined in Table III-X give the following results:

$$\Pr\{\text{single car immersed}|\text{derailment accident on bridge}\} = 0.026 \quad (\text{III.23})$$

$$\begin{aligned} \Pr\{\text{single car immersed}|\text{derailment}\} &= 0.026 \times 9.0 \times 10^{-5} \\ &= 2.3 \times 10^{-6} \end{aligned} \quad (\text{III.24})$$

When the probabilities for the three categories of collision accidents are weighted by their frequencies of occurrence, given a collision, the following numbers result:

$$\Pr\{\text{single car immersed}|\text{collision on bridge}\} = 0.0075 \quad (\text{III.25})$$

$$\begin{aligned} \Pr\{\text{single car immersed}|\text{collision}\} &= 0.0075 \times 9.0 \times 10^{-5} \\ &= 0.7 \times 10^{-6} \end{aligned} \quad (\text{III.26})$$

The total probability of immersion, given an accident, may be found by multiplying probability (III.24) by 0.83 (probability of a derailment, given an accident), multiplying probability (III.26) by 0.066 (probability of a collision, given a train accident), and adding. The result is

$$\Pr\{\text{immersion}|\text{accident}\} = 1.96 \times 10^{-6} \quad (\text{III.27})$$

Depth Probability Model

The average bridge length of the 33 major railroad bridges²² is 590 feet. To calculate a depth distribution, given immersion, water depth was assumed as a function of length along the bridge. A representative bridge/river pair is shown in Figure III-15. With the assumption that derailment resulting in immersion is equally likely on any section of the bridge, the cumulative depth distribution, given immersion, is given by Figure III-16. The curve (Figure III-17) for probability, per car mile, of being immersed at a depth greater than a given value may be generated from a combination of three factors: data from Figure III-16; the probability of immersion, given an accident (1.98×10^{-6}); and the probability of a train accident per mile (10^{-5}).

Figure III-15. Bridge and river.

Figure III-16. Cumulative probability according to immersion depth.

Figure III-17. Probability, per car mile, of being immersed at a depth greater than that shown.

Conclusions

The estimated probability of immersion due to accidents occurring on railroad bridges over deep rivers is 2×10^{-11} per car mile. When depths are incorporated into the calculation, the probability of exceeding a 50-foot depth is about 5×10^{-12} . Although it is possible to envision other types of accidents and accident locations that might result in immersion in rail accidents, these are primarily shallow-water occurrences and, at most, might increase the 5×10^{-12} figure to 5×10^{-11} per car mile. If the rail bridge mileage were underestimated here by a factor of 10, the immersion probability value would still be less than 5×10^{-10} per car mile.

PART III

Chapter 6 PUNCTURE ENVIRONMENT

Introduction

The hazard associated with the puncture phenomenon could not be established either from historical data or from currently available analytical methods. An estimate of the hazard can be inferred, however, by the use of available information relating to the puncture of railroad tank cars in train accidents. Although this type of accident has a lower frequency than other rail accidents, the tank cars are often laden with flammable materials and their puncture often results in fires. These fires change otherwise minor accidents into major accidents, which lead to detailed accident investigation reports. References 43 through 48 are typical reports of accidents involving puncture.

The procedure used in the following presentation is one that is applicable to the probabilistic evaluation of a design. It is always desirable to have actual test results available for establishing the reliability of each of the system's components. In this case estimates of the reliabilities must be used.⁴⁹

The factors that control the puncture threat are

1. Differential velocity of the cars at the time of impact.
2. Capacity of the probe to sustain impact loading without significant mechanical failure.
3. The equivalent thickness (equivalent of mild steel) in this case) of the item that is subject to penetration.

At this point it is necessary to consider a particular type of item subjected to the penetration threat. The item considered here is the large spent reactor fuel shipping cask. The casks considered are those meeting the requirements of 10 CFR-71 Appendix B.⁵⁰ Typical weights are 20 to 150 tons. The casks are generally constructed of multiple concentric steel structural shells, with lead and/or depleted uranium shield materials between the shells. These casks provide a formidable target for any penetrator and the strength of the penetrator must be considered in the analysis.

Puncture Threat

The following assumptions will be applied to the probe:

1. The coupler located at either end of a railcar is representative of potential railroad puncture threats.
2. Coupler failure strength is a normally distributed random variable.
3. Coupler failure occurs when the coupler/car connection is broken and the inertial force of the car is no longer transmitted to the cask through the coupler.
4. Coupler loading is directly related to differential impact velocity.

Design of couplers vary, but a representative coupler specification is the AAR M-921 specification.⁵¹ Specifically, the differential velocity requirement is that the coupler car connection be able to sustain a 14-mph impact without car damage. It is assumed for the first failure model, Model 1, that essentially no failures occur below a 14-mph differential velocity and that essentially all couplers fail at differential velocities above 30 mph unless penetration occurs. The kinetic energy possessed by a car at 30 mph is 4.6 times greater than that possessed by the car at 14 mph.

Figure III-18 is a plot of the assumed normal probability density function for the failure threshold velocity of car couplers when impacted against massive nonpenetrating targets. This is a plot of a normal distribution with a mean value of 22 mph and a standard deviation of 2 mph. The probability that the coupler will fail in a given interval equals the area contained between any two velocity values. By integrating this curve, it can be shown that the probability of failure below 14 mph, and the probability of nonfailure above 30 mph are both 3.2×10^{-5} . Another way of stating this is that 99.9936 percent of all failures are expected to occur between the 14- and 30-mph impact velocities.

A second estimate, Model 2, was made by using the 14-mph point at one end and doubling the energy of impact at the high end. It is assumed in this case, therefore, that essentially all couplers fail between 14 and 42.4 mph when striking a massive nonpenetrating target. The kinetic energy of the car travelling at 42.4 mph is 9.4 times that of the car traveling at 14 mph. In this case, the normal distribution is governed by a standard deviation of 3.55 mph and a mean of 28.2 mph. The probability density function for Model 2 is shown in Figure III-18. These two distributions are felt to be representative of the upper and lower bounds of expected coupler strengths.

Figure III-18. Assumed probability density functions for failure threshold velocity of train car couplers impacting massive nonpenetrating targets.

Puncture Resistance

The next step in this problem is to develop an acceptable relationship between the puncture resistance of the tank car and that of a large shipping container. Puncture resistance can be gained in two ways. The first is physical separation distance. The typical tank car has the tank head located just above the front/rear trucks with a nominal 2 to 3 feet between the car coupler and the tank head.³⁵ Thus, when a second car overrides the coupler of the tank car, impact between the second car coupler and the tank head is certain, even at low relative override velocities (5-10 mph). Figure III-19 is an example of such a condition.

Figure III-19. Coupler override, tank car collision.

The length of a large package, such as a spent nuclear fuel shipping cask, is always less than the railcar length. This leads to a situation such as is shown in Figure III-20. In this case much higher relative velocities are required for achieving impact between the coupler and the container.

Figure III-20. Coupler override, package car

This point is difficult to quantify, but is significant since the majority of tank car punctures reviewed are the result of override conditions.

The second factor that may be used to relate puncture resistance of large containers to that of tank cars is the actual structure to be penetrated. This can be done by estimating a minimum relative velocity to puncture a tank car with a known wall thickness and estimating the relative velocity required for puncturing a container with a different wall thickness. A puncture analysis developed in SLA-74-0001 was based on energy relations. This approach is used in the current analysis. Equation (42) from Volume II of SLA-74-0001 relates the approximate wall thickness necessary to prevent puncture to the impact velocity:

$$r = \frac{M}{\pi Y} \frac{V^2}{R} \quad (III. 20)$$

where

- r is the thickness of the material subject to puncture
- M is the effective mass of the container
- V is the relative velocity between the probe and the container
- R is the radius of a probe with a circular cross section that is equivalent to the actual probe
- Y is the yield strength of the material subject to puncture.

For spent nuclear fuel shipping casks, the weight of the cask and the weight of the tank car are comparable. The yield strengths of the steels, carbon and stainless, are also comparable. Since the probe under consideration is the same for tank car and for cask, the R term is constant. Rewriting the above equation, we have

$$\tau = \left(\frac{V}{\alpha} \right)^2 \quad (III. 29)$$

The dimensions used in this case are

τ - inches

V - mph

α - mph/ $\sqrt{\text{inches}}$ (a constant).

The assumptions made in obtaining Eqs. (III. 28) and (III. 29) may be questioned by some readers. Indeed, it could be shown that a number of factors not considered above affect the penetration of a given target by a given probe; however, the purpose of the relationship is to obtain a value to be used in an-order-of-magnitude evaluation of the puncture threat and it should be used only for this purpose.

The constant α can be estimated for mild steel from existing tank car accident reports³⁷⁻⁴¹ and typical tank car construction details.³⁵ From available accident reports, it is estimated that $\alpha = 25$ may be used for assured puncture of tank car heads and shells. It is assumed that 80 percent of this value can be used as a puncture threshold. Based on this assumption, Table III-XI gives the estimated threshold velocities computed for puncture of packages.

TABLE III-XI
Estimated Puncture Threshold Velocity for Packages With Mild Steel Walls

Equivalent Mild Steel Target Thickness (in.)	Puncture Threshold Velocity (mph)
0.4375	13
0.50	14
0.75	17
1.00	20
1.25	22
1.50	24
1.75	26
2.00	28
2.50	32
3.00	35
4.00	40
5.00	45
6.00	49

Probability of Puncture

We can now estimate the probability of puncture based either on (1) the assumption that a puncture situation exists in every abnormal environment impact situation or on (2) the assumption that a puncture situation exists only in a fraction of the impact situations. The probability of puncture per train accident and the probability of puncture per transport mile can then be calculated.

A zero-one step function probability is assumed for package-perforation resistance. If, for example, the impact velocity is equal to or greater than the penetration threshold velocity, the package can be perforated provided that the coupler does not fail. Using (1) this assumption, (2) the threshold velocities (Table III-XI), and (3) the probability density functions (Figure III-16), we can compute the probability of a coupler perforating the target, given a puncture situation with velocity equal to or greater than puncture threshold velocity. These probabilities are listed in Table III-XII.

TABLE III-XII

Probability of Perforation, Given a Puncture Situation With the Impact Velocity Equal to or Greater Than Puncture Threshold Velocity

Mild Steel Target Thickness (in.)	Perforation Threshold Velocity (mph)	Probability of Perforation ^{a)}	
		Case 1	Case 2
0.4375	13	1.	1.
0.50	14	1.	1.
0.75	17	9.9×10^{-1}	1.
1.00	20	8.4×10^{-1}	9.9×10^{-1}
1.25	22	5.0×10^{-1}	9.6×10^{-1}
1.50	24	1.6×10^{-1}	8.3×10^{-1}
1.75	26	2.3×10^{-2}	7.3×10^{-1}
2.00	28	1.4×10^{-2}	5.2×10^{-1}
2.50	32	2.9×10^{-7}	1.4×10^{-1}
3.00	35	4.0×10^{-11}	2.8×10^{-2}
4.00	40	-	4.4×10^{-4}
5.00	45	-	1.1×10^{-7}
6.00	49	-	2.3×10^{-10}

NOTE: a. This value is the same as the probability that the coupler will not fail given an impact at or below the perforation threshold velocity.

The velocities listed in Table III-XII are based on the assumption that one car is standing and the other is in motion at the stated velocity or on the assumptions that the velocity is the relative impact velocity and that both cars are in motion. These velocities were not directly available from the impact calculations; hence, a conservative assumption is made. It is assumed that the relative velocity at impact is equal to the car's preaccident velocity. The cumulative probability of occurrence of given velocities, as determined by the upper-bound impact model, are listed in Table III-XIII.

TABLE III-XIII
Car Preaccident Velocities

Car Preimpact Velocity (mph)	Cumulative Probabilities of Occurrence of Car Preimpact Velocities
5	0.2669
10	0.4220
15	0.5587
20	0.6700
25	0.7600
30	0.8271
35	0.8780
40	0.9153
45	0.9418
50	0.9603
55	0.9735
60	0.9823
65	0.9881
70	0.9922
75	0.9953
80	0.9989

With this information, the probability that a puncture situation will occur given a package is involved in an impact with a rail car can be computed. The basic assumption here is that all such impacts will result in a package-puncture situation if (1) the relative velocity is above the puncture threshold velocity and (2) the probe (coupler) does not fail. The probabilities calculated for these assumptions are recorded in Table III-XIV.

TABLE III-XIV
Probability That a Potential Package Puncture Will Occur Given
the Package is Involved in an Impact with a Railroad Car

Package Wall Thickness (in.)	Potential Puncture Probability-Model 1	Potential Puncture Probability-Model 2
0.4375	4.96×10^{-1}	4.96×10^{-1}
0.50	4.69×10^{-1}	4.69×10^{-1}
0.75	3.86×10^{-1}	3.93×10^{-1}
1.00	2.77×10^{-1}	3.22×10^{-1}
1.25	1.45×10^{-1}	2.78×10^{-1}
1.50	4.08×10^{-2}	2.24×10^{-1}
1.75	5.10×10^{-3}	1.62×10^{-1}
2.00	2.73×10^{-3}	1.01×10^{-1}
2.50	1.35×10^{-5}	2.10×10^{-2}
3.00	---	3.13×10^{-3}
4.00	---	3.70×10^{-5}
5.00	---	6.30×10^{-9}

The expected frequency of a puncture situation, given a train accident, may be estimated by using available data on tank-car punctures. Reference 52 is a summary of 121 major railroad accidents investigated by FRA during the period July 1, 1971 through June 30, 1972. Of these, 110 were train collision or derailment accidents. The remaining 11 were rail-highway (grade-crossing) accidents.

Of the 110 train accidents, 11 involved the perforation of one or more tank cars. These 11 accidents resulted in an estimated \$1 222 000 damage to railroad property, or an average of \$111 000 per accident. The average cost per accident during 1971 and 1972 was \$15 000 and \$14 300, respectively. It is clear that these 11 accidents represent major railroad accidents.

Of the 110 accidents, 9 involved the perforation of one tank car, one involved the perforation of two tank cars, and one involved the perforation of an indeterminate number between one and seven tank cars. The number is indeterminate because the report on this latter accident does not distinguish between car puncture and car rupture due to other causes. Two additional tank-car perforations during this period have been reported in Reference 53. In each of these accidents

one car was perforated. Between 14 and 20 tank-car perforations were reported during this period. It must be assumed that others occurred during this same period, but that the reports of these punctures have not been found.

With this information (the 1972 train mileage⁶¹ and the average number of tank cars per train (Table E-1V)), the tank car puncture rate can be estimated.

$$R_T = \frac{N}{n \cdot M} \frac{\text{tank car punctures}}{\text{tank car mile}} \quad (\text{III, 30})$$

Where

N = number of tank-car punctures per year = 20

n = average number of tank cars per train = 7

M = train mileage per year = 4.51×10^8

$$R_T = 6.3 \times 10^{-9} \frac{\text{tank-car punctures}}{\text{tank-car mile}} \quad (\text{III, 31})$$

The expected exposure rate of a package to puncture can also be estimated using: (1) the train accident rate, 10^{-5} per train mile; (2) the probability of puncture for 9,4375-in.-thick mild steel plate, 0.496; and (3) the rate of involvement of car in impacts given a train accident, 0.15. Combination of these values yields an expected exposure rate of 7.44×10^{-7} per train transport mile. The rate for puncture given a puncture situation can be estimated as follows:

Let β = punctures per puncture situation

$$\text{Then } \beta = \frac{6.3 \times 10^{-9}}{7.44 \times 10^{-7}} = 0.47 \times 10^{-3} \quad (\text{III, 32})$$

or $\beta \approx 1$ puncture in 100 exposures

It is likely that not all tank cars which were punctured during 1972, the base period, are included in the 20 considered above. It is also likely that not all of the 20 punctures reported were due to coupler action. It will therefore be assumed that, by not reducing the likelihood of puncture due the differences in coupler override conditions (Figures II-19 and 20) and also by using the upper-bound puncture Model (Model 2), the desired conservatism is retained in the analysis.

Equivalent Wall Thickness

The final point in this analysis is to determine an equivalent steel thickness for other materials. The numbers are based on the relative target efficiencies of 1-in.-thick plates in stopping 100-grain compact steel projectiles.⁵⁴ The ratio used was that of the projectile impact energy required for perforating the plate of interest to that required for perforating a mild steel plate. The relative thickness results are, at best, first-order estimates and should be applied with caution. If a problem is particularly sensitive to this value, a more detailed investigation should be made. For estimation purposes, the equivalent steel thickness of various container material can be determined by

$$T_s^* = \beta T_m$$

where

T_s^* is the equivalent mild steel thickness of the material

T_m is the material thickness

β is a constant for each material as listed in Table III-XV

TABLE III-XV
Constants for Equivalent Steel Thickness Estimation^a

Material	β
2024 T-3 Aluminum	0.25
Mild Steel ^b	1.0
Copper	1.56
Lead	0.0625
Tuballoy ^c	2.2

^a It is assumed that all material other than mild steel rests upon a substantial steel base.

^b Mild steel, for the purpose of this study, is defined as a carbon steel with a published yield point below 60,000 psi and a Brinell hardness number of 150 or less.

^c Cast depleted uranium is sometimes used as a shield material in the design of radioactive materials packages. Information on this particular material was not available in the reference document.⁵⁴ Information available on Tuballoy, which can be depleted uranium in any manufactured form, is included here for estimation purposes.

Summary of Results

The puncture situation has been defined in terms of railroad tank-car puncture accidents. The analysis is limited and is believed to be conservative; however, in cases where puncture resistance is a major factor and the rates listed in Table III-XVI are not sufficient, an extensive test program may be required to establish a puncture threshold value for a given probe and package.

TABLE III-XVI
Probability of Puncture

Package Wall Thickness (in.)	Probability per Transport Mile	Probability per Reportable Accident	Probability per Reportable Collision or Derailment Accident	Probability per Accident where Probe Failure Controls
0.4375	7.44×10^{-9}	7.41×10^{-4}	8.23×10^{-4}	1.
0.50	6.9×10^{-9}	6.80×10^{-4}	7.67×10^{-4}	1.
0.75	5.85×10^{-9}	5.85×10^{-4}	6.50×10^{-4}	1.
1.00	4.90×10^{-9}	4.93×10^{-4}	5.44×10^{-4}	0.99
1.25	4.18×10^{-9}	4.18×10^{-4}	4.54×10^{-4}	0.96
1.50	3.37×10^{-9}	3.37×10^{-4}	3.74×10^{-4}	0.88
1.75	2.43×10^{-9}	2.43×10^{-4}	2.70×10^{-4}	0.73
2.00	1.52×10^{-9}	1.52×10^{-4}	1.69×10^{-4}	0.52
2.50	3.15×10^{-9}	3.15×10^{-5}	3.50×10^{-5}	0.14
3.00	4.70×10^{-11}	4.70×10^{-6}	5.22×10^{-6}	0.028
4.00	5.54×10^{-13}	5.54×10^{-8}	6.16×10^{-8}	4.4×10^{-4}
5.00	9.41×10^{-17}	9.41×10^{-12}	1.05×10^{-11}	1.7×10^{-7}
6.00	---	---	---	2.3×10^{-10}

APPENDIX A
COMMERCIAL MOTOR-CARRIER ACCIDENTS
(Relative Severities and Frequencies)

Appendix A

COMMERCIAL MOTOR-CARRIER ACCIDENTS (Relative Severities and Frequencies)

Introduction

This study was undertaken to obtain background material for use in a subsequent investigation of the quantitative abnormal environment severities experienced by a large single cargo item shipped by commercial truck within the continental United States. This study investigates the available sources of truck accident data, selects the data deemed most suitable, and qualitatively assesses the severities of the reported accidents. The study findings are reported in the form of bar graphs for quick visual interpretation and in tabular form for use in subsequent studies.

Truck-Accident Data

Data available on vehicle accidents are directed primarily toward (1) determining cause (2) counting fatalities and injuries, and (3) determining economic loss. The severity of the accident as it relates to cargo damage is not addressed in any of the state or national vehicle accident reports obtained in prior work,¹ in the current study, or in studies with similar interests^{55, 56} being conducted at Sandia Laboratories. Leimkuhler⁵¹ employs available accident cost data to obtain economic justification for route selection, speed control, and scheduling of shipments, but does not address the question of relative accident severity. The point which must be clearly made at the outset is that there appears to be no complete compilation of detailed historical information regarding the effects on cargo of real transportation accidents. Possible exceptions to this statement are records kept by the ERIA and DOT OHSI on actual incidents involving radioactive and other hazardous materials.^{1, 58, 59} The problem with using this information is that very few potentially serious (from a large-package truck cargo standpoint) accidents occurred in these data sets.

The truck-accident data that appear to be most comprehensive are those compiled by the Bureau of Motor Carrier Safety (BMCS) in their annual reports.²⁻⁶ BMCS accident reports for large trucks were reviewed for the period 1968 through 1973. The 1969, 1970, 1971 and 1972 BMCS reports, which have a consistent accident definition, were used as the primary data sources. The data contained in the BMCS reports are discussed in detail later in this appendix; at the outset, however, four significant points must be kept in mind:

1. BMCS Accident Reports do not include information dealing with vehicle speeds either preceding or at the time of the accident.

2. Reporting of accidents, required by law, is the responsibility of the individual carrier.
3. There are significant pieces of information missing in the data; e.g., collisions with "fixed objects" represent about 15 percent of all accidents, but no specific information is given about the objects.
4. There is no generally accepted method by which HMCS accident reports can be correlated with national and/or state accident statistics.⁶⁰

Basic Data Used in Analysis

The data base (HMCS Data) contained information relating to

1. Truck accident rates.
2. Fatalities and injuries resulting from truck accidents.
3. Dollar costs associated with truck accidents.
4. Items 1, 2, and 3 by type of cargo (e.g., General Freight, Liquid Petroleum Products).
5. Truck-accident statistics by time of day and day of week.
6. Truck-accident statistics by age of driver (preventable accidents).
7. Items 1, 2, and 3 by type of accident (e.g., head-on collision, truck with auto; truck collision with fixed object).
8. Items 1, 2, and 3 by geographic region.

A number of these items, although of interest from an administrative standpoint for the development of procedural controls (e.g., as related to type of cargo, time of day, day of week, age of driver, and geographical region), are not germane to this study.

The injury and fatality rates pertinent to this study are those associated with the reporting vehicle's driver rather than the totals for given types of accidents. The items of especial significance are

1. Item 2, with specific reference to reporting vehicle driver injury and fatality rates.
2. Item 3, dollar costs associated with each accident category.
3. Item 7, accidents categorized by type.

A truck accident, as considered in this report, is either

1. A single vehicle accident with the truck in motion; e.g., running off the road, overturning, and collisions with objects.

2. A multiple vehicle accident with at least one of the vehicles in motion;
e.g., head-on and rear-end collisions.

Types of Vehicle Accident

The BMCS reports categorize large-truck accidents in the manner described below:

Collision

Collision is defined as an accident of (1) two or more vehicles involving at least one in motion or (2) a single vehicle striking a stationary object.

1. Pedestrian - The reporting truck is involved in an accident with a pedestrian.
2. Property - The reporting truck is involved in an accident with a carrier of property (commercial truck).

(Each of the following is defined similarly)

3. Passenger Auto.
4. Motor Bus.
5. Other Motor Vehicle (motorcycle).
6. Railroad Train (grade-crossing accidents).
7. Streetcar.
8. Bicycle.
9. Animal/Animal-Drawn Vehicle
10. Fixed Object.
11. Other Object.
12. Unreported Object.
13. Driverless Vehicle.

Noncollision

Noncollision is defined as a single-vehicle accident where the vehicle is in motion.

1. Overturned on Road - The reporting vehicle overturned.
2. Ran off Road - The reporting vehicle ran off the road.
3. Driverless Vehicle - The reporting vehicle rolled away.
4. Other Noncollision.

Other Accidents

In this category the vehicle is not in motion.

1. Fire Only.
2. Injured In/on Standing Vehicle.
3. Fallen from Standing Vehicle.
4. Thrown Against Standing Vehicle.
5. Stolen (standing) Vehicle.
6. Not Elsewhere Classified.

The Category III accidents will not be considered further. With the exception of fire these accidents do not offer potential to harm the truck cargo. Fire-accident environments have been discussed in Reference 1, which also uses the HMCS data as its basis.

Accident-Severity Measures

The HMCS reports³⁻⁵ contain data sufficient for a direct calculation of distributions in accident type. They do not, however, have any information that will allow a direct calculation of severity of environments experienced by cargo. Therefore, three indirect qualitative severity measures are used:

1. The number of reporting-vehicle driver fatalities in each type of accident.
2. The number of reporting-vehicle drivers injured in each type of accident.
3. The estimated dollar cost of the property damage in each type of accident.

The foregoing information can be used to infer the relative accident severity.

The following coefficients defining distribution factors and frequencies are used in the severity calculations.

Accident Distribution Factor

This is a ratio of the number of reported accidents in a given classification to the total number of accidents reported.

Example: Categories I and II reported 179 070 accidents during the 1969-1972 period. Of those, 149 803 were collision accidents and 29 267 were noncollision accidents.

Hence,

$$\text{Collision accident distribution factor} = \frac{149,807}{175,070} = 0.85$$

$$\text{Noncollision accident distribution factor} = \frac{29,267}{175,070} = 0.16$$

Driver Fatality Frequency

This is a ratio of the number of driver fatalities reported in a given classification to the total number of driver fatalities reported.

Example: Categories I and II reported 1007 driver fatalities during the 1969-1972 period. Of these, 550 were collision fatalities and 457 were noncollision fatalities.

Hence,

$$\text{Driver fatality frequency, collision} = \frac{550}{1007} = 0.55$$

$$\text{Driver fatality frequency, noncollision} = \frac{457}{1007} = 0.45$$

The foregoing calculations indicate that 45 percent of the driver fatalities occurred in only 16 percent of the vehicle accidents. The following ratio may be used as a measure of accident severity.

$$\text{Driver fatality ratio} = \frac{\text{Driver fatality frequency}}{\text{Accident distribution factor}}$$

Example: For the above data,

$$\text{Driver fatality ratio, collision} = \frac{0.55}{0.85} = 0.65$$

$$\text{Driver fatality ratio, noncollision} = \frac{0.45}{0.16} = 2.81$$

It is learned, therefore, that only one out of six accidents will be noncollision, but the driver is 4 times more likely to be killed in the noncollision accident than in the collision accident. The inference drawn here is that, as a group, noncollision accidents are potentially more dangerous to the driver than collision accidents are. The injury ratios and cost ratios, defined similarly to the foregoing fatality ratios, show the same trend. A severity relation by accident classification can now be inferred from the data.

By carrying this concept further, one can compute severity ratios (fatality, injury, and cost) for each type of accident to identify those accidents that require detailed study. Table A-I is a year-by-year compilation of the accident distributions expressed in terms of percentages. Table A-II is a year-by-year compilation of the driver fatality frequencies expressed in terms of percentages. These tables show that the data for the 4-year period being considered exhibit a year-to-year consistency. Collision with passenger autos make up 50 percent of all moving vehicle accidents each year and account for 10 percent of the fatalities each year. Accidents with railroad trains account for 0.50 percent of the accidents and 2.5 to 3 percent of the fatalities.

Table A-III is a year-by-year compilation of the driver fatality ratios. Table A-IV is a composite compilation of the driver fatality ratios and the accident cost ratios for the 4-year period. Table A-V is a compilation of the driver injury ratios for the same 4-year period. Table A-VI is a compilation of the various types of accidents listed in decreasing severity; i.e., line 1 is most severe and line 17 is least severe.

The information shown in these tables is depicted graphically in Figures A-1, A-2, and A-3. Figure A-1 is a plot of the normalized accident-severity rating based on the truck driver fatality ratio derived for the 17 principal types of accidents listed in the Collision and Noncollision categories. Figures A-2 and A-3 depict the same information based upon truck driver injuries and accident cost information.

It is indicated that several of the items can be combined to reduce the number of categories that must be considered:

1. Collision With Pedestrian and Collision With Bicycle are similar and will be combined (Pedestrian/Bicycle).
2. Collisions With Property (Truck), Motor Bus, and Streetcar are similar and will be combined (Commercial Truck).
3. Passenger Auto will remain unchanged (Passenger Auto).
4. Collision With Other Motor Vehicle (Motorcycle) and Collision With Animal/Animal-Drawn Vehicle have similar severities and will be combined (Motorcycle/Animal).
5. Railroad Trains will remain unchanged (Grade Crossing).
6. Collision With Fixed Object, Collision With Unreported Object, and Collision With Other Object will be combined (Stationary Object).
7. Rollaway/Collision and Rollaway/Noncollision will be combined (Rollaway).
8. Return-on-Road and Ran-off-Road are similar and will be combined (Overturn).
9. Other (noncollision) will remain unchanged (Other).

These combinations are referred to as the Revised Accident Categories. Table A-VII contains the data summary for the revised categories. Table A-VIII contains the revised severity ratings for each of the three accident parameters (driver fatalities, driver injuries, and accident costs). The revised accident categories are ordered from the most severe category to the least severe. Figures A-4, A-5, and A-6 are graphic representations of the nine categories for each of the three parameters. In these representations all the categories have been normalized by dividing the ratio associated with each accident category by the largest ratio in its associated category. Figure A-7 is a graphic representation of the frequency of occurrence of the accident types.

Conclusions

Severities of different types of truck accidents were compared on a relative basis by using truck driver fatality and injury information and accident cost data. The accident severity ratings for each of the major types are in good agreement.

The noncollision environments described by Run-off-Road and by Overturn-on-Road as reported by HMC's have a high severity and a high frequency. They, therefore, constitute two of the major abnormal environments. In general the results of this study may be summarized as follows:

1. Railroad train collisions are very severe, but infrequent (about 0.6 percent of all accidents).
2. Single-vehicle overturning and running-off-the-road accidents are both very severe and frequent (about 10 percent of all accidents).
3. Truck/truck collision accidents are less severe than the foregoing, but occur frequently (about 16 percent of all accidents).
4. Truck/passenger auto collision accidents do not, as a group, provide a severe environment, but are the most frequent (about 50% of all accidents).
5. The classifications Collision With a Stationary Object and Other (noncollision) are of moderate severity, are not well defined and are relatively frequent (about 22 percent of all accidents).

Figure A-1. Normalized driver fatality ratio.

Figure A-2. Normalized driver injury ratio.

Figure A-3. Normalized accident cost ratio

Figure A-4. Normalized driver fatality ratio for revised accident types.

Figure A-5. Normalized driver injury ratio for revised accident types.

Figure A-6. Normalized accident cost ratio for revised accident types.

Figure A-7. Accident frequency by revised accident types.

TABLE A-1

Summary of Moving Vehicle Accidents, 1969-1972 BMCS Reports

Accident Classification	Percent of Total Moving Vehicle Accidents Reported			
	1969	1970	1971	1972
Collision With				
Pedestrian	0.99	0.84	0.84	0.86
Property ^a	15.60	15.13	15.92	15.93
Passenger Auto ^a	47.58	46.54	48.22	47.82
Motor Bus	0.48	0.40	0.44	0.44
Other Motor Vehicle ^b	0.61	0.57	0.60	0.57
Railroad Train	0.59	0.66	0.52	0.55
Streetcar	0.01	0.00	0.00	0.00
Animal/Animal-Drawn Vehicle	0.80	0.75	0.79	0.68
Bicycle	0.13	0.11	0.08	0.09
Fixed Object	14.04	14.02	14.59	15.07
Unreported Object	0.11	0.14	0.12	0.11
Other Object	0.13	0.07	0.20	0.20
Rollaway	1.38	1.29	1.05	1.03
Noncollision				
Ran off Roadway	6.87	6.89	6.40	6.47
Other	6.02	6.65	7.33	7.17
Rollaway	0.03	0.02	0.06	0.04
Overturn on Road	2.65	2.92	2.84	2.88
TOTAL	100.00	100.00	100.00	100.00

^a Property refers to medium and large trucks; light trucks such as pickups, panels, and vans are classified as passenger autos.

^b Motorcycles are the majority vehicle in this category.

TABLE A-II
Summary of Driver Fatalities for Moving Vehicle Accidents,
1969-1972 .MICS Reports

Accident Classification	Driver Fatalities by Class as a Percentage of Total Driver Fatalities			
	1969	1970	1971	1972
Collision With				
Pedestrian	0.42	0.83	0.79	0.74
Property ^a	24.69	21.31	24.31	22.88
Passenger Auto ^a	9.62	10.74	11.76	11.07
Motor Bus	0.00	0.00	1.18	0.37
Other Motor Vehicle ^b	0.84	0.41	0.39	0.74
Railroad Train	3.77	2.48	2.35	2.95
Streetcar	0.00	0.00	0.00	0.00
Animal/Animal-Drawn Vehicle	0.84	1.65	1.18	0.37
Bicycle	0.00	0.00	0.00	0.00
Fixed Object	12.55	11.57	14.90	17.71
Unreported Object	0.00	0.00	0.00	0.37
Other Object	0.00	0.42	0.00	0.00
Rollaway	0.00	0.42	0.00	0.36
Noncollision				
Ran off Roadway	34.72	39.67	33.73	34.32
Other	4.60	2.09	1.57	2.95
Rollaway	0.42	0.00	0.00	0.00
Overturn on Road	7.53	6.61	7.84	5.17

^a Property refers to medium and large trucks; light trucks such as pickups, panels, and vans are classified as passenger autos.

^b Motorcycles are the majority vehicle in this category.

TABLE A-III

Summary of Driver Fatality Accident Ratios for Moving Vehicle Accidents,
1969-1972 BMCS Reports

Accident Classification	Driver Fatalities as a Percentage of Total Driver Fatalities Percentage of Total Moving Vehicle Accidents Reported			
	1969	1970	1971	1972
Collision With				
Pedestrian	0.42	0.99	0.93	0.93
Property	1.58	1.47	1.53	1.43
Passenger Auto	0.19	0.22	0.24	0.23
Motor Bus	0.	0.	2.68	0.84
Other Motor Vehicle	1.78	0.72	0.65	1.30
Railroad Train	6.39	3.76	4.52	5.36
Streetcar	0.	0.	0.	0.
Animal/Animal-Drawn Vehicle	1.05	2.20	1.49	0.54
Bicycle	0.	0.	0.	0.
Fixed Object	0.89	0.83	1.02	1.14
Unreported Object	0.	0.	0.	3.36
Other Object	0.	2.93	0.	0.
Rollaway	0.	0.32	0.	0.36
Noncollision				
Ran off Roadway	5.06	5.76	5.27	5.30
Other	0.76	0.43	0.21	0.11
Rollaway	14.00 ^a	0.	0.	0.
Overturn on Road	2.84	2.26	2.76	1.80

^a This apparently high number is the result of one driver fatality and a small number of accidents.

TABLE A-IV

Summary of Driver Fatality and Accident Cost Ratios for Moving Vehicle Accidents,
1969-1972 BMCS Reports

Accident Classification	Number of Accidents	Driver Fatalities	Dollar Cost Thousand	Driver Fatality Ratio	Accident Cost Ratio
Collision With					
Pedestrian	1520.	7	224.6	0.82	0.08
Property	20101.	237	82192.6	1.50	1.49
Passenger Auto	87280.	109	106899.0	0.22	0.62
Motor Bus	787.	4	1721.5	0.90	1.11
Other Vehicle	1049.	6	1748.7	1.02	0.85
Railroad Train	1027.	29	7283.8	5.02	3.60
Streetcar	9.	--	6.4	--	0.36
Animal/Animal-Drawn Vehicle	1344.	10	2633.1	1.32	1.01
Bicycle	182.	--	30.0	--	0.08
Fixed Object	25934.	144	41307.6	0.39	0.81
Unreported Object	216.	1	198.4	0.82	0.47
Other Object	270.	1	279.8	0.66	0.53
Rollaway	2096.	2	2534.5	0.17	0.61
Noncollision					
Overturn on Road	5065.	68	27014.7	2.39	2.71
Ran off Road	11878.	358	60358.8	5.36	2.58
Other	12259.	30	17780.6	0.44	0.74
Rollaway	67.	1	83.7	2.66	0.71
TOTAL	170 079.	1007	362 453.9		
Collision Accidents	149 803.	550	247 217.0	0.87	0.84
Noncollision Accidents	20 267.	457	105 246.9	2.73	1.83

TABLE A-V
Driver Injury Ratio, 1969-1972 B'SCS Reports

Accident Classifications	Numbers of Drivers Injured					Number of Accidents	Driver Injury Ratio
	1969	1970	1971	1972	Total		
Collision With							
Pedestrian	5	6	9	5	25	1520	0.14
Property	1205	943	1215	1266	4632	26461	1.42
Passenger Auto	1230	1196	1157	1163	4746	27268	0.47
Motor Bus	28	25	29	25	107	787	1.17
Other Vehicle	29	17	21	14	81	1045	0.67
Railroad Train	69	67	68	77	281	1027	2.76
Streetcar	1	0	0	0	1	9	0.06
Animal/Animal-Drawn Vehicle	27	37	49	38	142	1344	0.91
Bicycle	0	0	1	1	2	162	0.09
Fixed Object	475	447	517	548	1987	25934	0.66
Unreported Object	16	11	7	8	42	216	1.68
Other Object	16	1	35	27	90	270	2.87
Rollaway	17	14	11	6	50	2096	0.21
Noncollision							
Overturn on Road	493	550	573	669	2290	5065	3.90
Ran off Road	1170	1157	1204	1379	4910	11876	3.57
Other	369	300	339	359	1367	12259	0.96
Rollaway	0	0	1	0	1	67	0.13
TOTAL	5159	4789	5231	5587	20766	179070	

TABLE A VI
Accident Severity Ratios

Severity	Other Fatality Ratio	Driver Injury Ratio	Accident Cost Ratio
1. Most Severe	Ran off Road, NC	Overturn	Railroad Train, C
2.	Railroad Train, C	Ran off Road, NC	Overturn, NC
3.	Rollaway, NC	Other, Object, C	Ran off Road, NC
4.	Overturn, NC	Railroad Train, NC	Property, C
5.	Property, C	Unreported Object, C	Motor Bus, C
6.	Animal ... , C	Property, C	Animal ... , C
7.	Other Vehicle, C	Motor Bus, C	Other Vehicle, C
8.	Fixed Object, C	Streetcar, C	Fixed Object, C
9.	Motor Bus, C	Other, NC	Other, NC
10.	Pedestrian, C	Animal, C	Rollaway, NC
11.	Unreported Object, C	Other Vehicle, C	Passenger, Auto
12.	Other Object, C	Fixed Object, C	Rollaway, C
13.	Other, NC	Passenger Auto, C	Other Object, C
14.	Passenger Auto, C	Rollaway, C	Unreported Object, C
15.	Rollaway, C	Pedestrian, C	Streetcar, C
16.	Streetcar	Rollaway, NC	Pedestrian, C
17. Least Severe	Bicycle	Bicycle, C	Bicycle, C

Note: C = Collision; NC = Noncollision

TABLE A-VII
Accident-Severity Ratios for
Revised Accident Categories

	Driver Fatalities Total	Driver Injuries Total	Driver Cost Thousands	Number of Accidents	Driver Fatality Ratio	Driver Injury Ratio	Accident Cost Ratio
Collision With							
Pedestrian/Bicycle	7	27	254.5	1 702	0.73	0.14	0.08
Truck	241	4750	83 920.5	28 897	1.48	1.42	1.48
Passenger Auto	105	4748	106 995.0	87 268	0.22	0.47	0.63
Motorcycle/Animal	16	223	4 431.8	2 393	1.19	0.80	0.94
Railroad Train	29	281	7 283.8	1 027	5.02	2.36	3.60
Object	146	2119	41 782.8	26 420	0.98	0.69	0.80
Rollaway	3	51	2 629.2	2 163	0.25	0.20	0.62
Noncollision							
Overturn on Road	426	7200	87 372.5	16 941	4.47	3.68	2.62
Other	30	1367	17 780.6	12 259	0.44	0.96	0.74
TOTAL	1007	20 766	352 453.9	179 070			

TABLE A-VIII
Revised Accident-Severity Ratings

Severity	Driver Fatality Ratio	Driver Injury Ratio	Accident Cost Ratio
1. Most Severe	Railroad Train	Overturn	Railroad Train
2.	Overturn	Railroad Train	Overturn
3.	Truck	Truck	Truck
4.	Motorcycle/Animal	Other Noncollision	Motorcycle/Animal
5.	Object	Motorcycle/Animal	Object
6.	Pedestrian/Bicycle	Object	Other Noncollision
7.	Other Noncollision	Passenger Auto	Passenger Auto
8.	Rollaway	Rollaway	Rollaway
9. Least Severe	Passenger Auto	Pedestrian/Bicycle	Pedestrian/Bicycle

APPENDIX B
MOTOR-CARRIER ACCIDENT DISTRIBUTIONS

Appendix B

MOTOR-CARRIER ACCIDENT DISTRIBUTIONS

Introduction

The analysis of abnormal highway environments by Monte Carlo techniques requires a knowledge of the frequency of occurrence of each of the events. This appendix addresses the question of frequency of occurrence of the different types of commercial truck accidents.

Truck/Truck and Truck/Auto Accident Distribution

In an analysis of the type being attempted, it is necessary to classify accident situations and to employ the classifications for computing the expected response of the vehicle cargo to the given situation. The collision accident situations have been classified as follows:

1. Head-On. Vehicle centerlines coincident and vehicles traveling in opposite directions.
2. Rear-End. Vehicle centerlines coincident and vehicles traveling in the same direction.
3. Side-on. Vehicle traveling paths that form a right angle and intersect at the centroid of the vehicle that is struck.

It becomes a matter of judgment to distribute the known accident population²⁻⁶ into the designated categories. It is desired to maintain a degree of conservatism in the chosen distribution and to maintain a measure of this conservatism.

Bureau of Motor Carrier Safety (BMCS) reports, 1969 through 1972, were used to establish three of the four distributions considered and to evaluate the conservatism associated with each of the four distributions.

1. Proportional Assignment of Unknowns. Those accidents that can be definitely identified as belonging to one of the five collision categories (head-on, rear-end #1 into #2, rear-end #2 into #1, side-on #1 into #2, and side-on into #1)^{*} are assigned to that category. Collisions of unknown categories are assigned to the five categories in the same proportion as the accidents of known categories.

^{*}In the BMCS reports vehicle #1 always refers to the reporting vehicle; in this study vehicle #1 is assumed to be the vehicle transporting the cargo.

2. Equal Assignment of Unknowns. The same procedure as above is used for collisions of known categories. The collisions of unknown categories are divided into five equal groups and assigned to the five known categories.
3. Equal Likelihood. All five known categories are considered equally likely to occur. This distribution is not based on BMCS reports.
4. SLA-74-0001 Distribution - The distribution used in Reference 1. This distribution is also based on BMCS reports.

Inasmuch as a conservative approach is used in this study, angle collisions are disregarded even though most of the actual collision accidents are of this type. The reason is that a data set sufficient for establishing angles and their associated frequencies could not be found.

The BMCS reports, which form a basis for the first two distributions, contain information on the number of reporting-vehicle drivers killed or injured in a given type of collision. For example, in the 1969-1972 period, 29 drivers of reporting vehicles were killed in 435 head-on truck/truck collisions. Similar statistics are available for fatalities and injuries in each of the five collision categories noted. This information was employed to compute driver fatalities per accident and driver injuries per accident for truck/truck and truck/auto collision, shown in Table B-I. The four accident distributions are shown in Table B-II.

TABLE B-I
1969-1972 BMCS Accident Data - Injury and Fatality Rates

Type of Accident	Total Driver Fatalities	Total Driver Injuries	Total Number of Accidents	Driver Fatalities per Accident	Driver Injuries per Accident	Fraction of Accidents Considered
Truck						
Head-On	29	162	435	0.0667	0.3724	0.0405
Rear-End #1 into #2	77	1130	4573	0.0168	0.2471	0.4255
Rear-End #2 into #1	7	1103	4303	0.0016	0.2563	0.4004
Intersection #1 into #2	2	77	459	0.0044	0.1678	0.0427
Intersection #2 into #1	5	164	978	0.0051	0.1881	0.0910
Auto						
Head-On	13	489	1 803	0.0072	0.2712	0.0538
Rear-End #1 into #2	12	396	12 303	0.0010	0.0320	0.3695
Rear-End #2 into #1	2	496	10 169	0.0002	0.0485	0.3032
Intersection #1 into #2	3	170	2 490	0.0012	0.0683	0.0742
Intersection #2 into #1	9	611	6 684	0.0013	0.0914	0.1993

Total reported truck/truck collisions, 1969-1972 = 28 897 (includes streetcars and motor buses)

Total reported truck/auto collisions, 1969-1972 = 87 879

TABLE B-II
Accident Distribution Factors

Type of Accident	Accident Distribution Factors based on			
	Proportional Assignment of Unknowns ^a	Equal Assignment of Unknowns	Equal Likelihood	SLA-74-0001 ^a
Truck				
Head-On	0.0405	0.1467	0.2000	0.2922
Rear-End #1 into #2	0.4255	0.2335	0.2000	0.2670
Rear-End #2 into #1	0.4004	0.2745	0.2000	0.2765
Side-On #1 into #2	0.0427	0.1415	0.2000	0.2061
Side-On #2 into #1	0.0910	0.1505	0.2000	0.1121
Auto				
Head-On	0.0534	0.1434	0.2000	0.1010
Rear-End #1 into #2	0.3605	0.2651	0.2000	0.2277
Rear-End #2 into #1	0.3012	0.2197	0.2000	0.2160
Side-On #1 into #2	0.0742	0.1517	0.2000	0.1741
Side-On #2 into #1	0.1001	0.1702	0.2000	0.1370

^aThe discrepancy in these values is due to an erroneous interpretation in SLA-74-0001 of the BMCS side-on collision category.

The conservatism associated with each distribution was estimated by using the injury and fatality information, the assumed collision distribution, and the total number of accidents to predict the number of driver injuries and fatalities that would have resulted from the assumed distribution. The predicted driver injuries and fatalities were divided by the number of injuries and fatalities reported by BMCS. This ratio is considered a measure of the conservatism of the assumed distribution. Predicted injuries and fatalities, recorded injuries and fatalities, and the ratios are shown in Table B-III. For the purpose of this study, the distribution using proportional assignment of unknowns was chosen as being most representative of actual collision environment.

TABLE B-III
Truck Driver Fatalities and Injuries, Actual and Predicted

Type of Distribution	Predicted Driver Fatalities	Predicted Driver Injuries	Actual Driver Fatalities	Actual Driver Injuries	Ratio of Predicted to Actual the Fatalities	Ratio of Predicted to Actual Driver Injuries
Truck						
Proportional Assignment of Unknowns	322	7 141	241	4750	1.34	1.50
Equal Assignment of Unknowns	463	7 127	241	4750	1.92	1.50
Equal Likelihood	547	7 110	241	4750	2.27	1.50
SLA-74-0001	638	7 688	241	4750	2.65	1.61
Auto						
Proportional Assignment of Unknowns	102	5 620	109	4740	0.94	1.17
Equal Assignment of Unknowns	156	7 655	109	4740	1.43	1.51
Equal Likelihood	100	8 926	109	4740	1.74	1.62
SLA-74-0001	229	10 465	109	4740	2.10	2.20

Truck/Train Accident Distribution

There are two cases that must be considered in the truck/train collision or ident:

1. Truck is struck by the train.
2. Truck runs into side of the train.

Table B-IV contains information for the period 1969 through 1972 by type of collision.⁷⁻¹⁰ It can be observed that in 75 percent of the accidents the truck is struck by the train. In the remaining 25 percent, the truck runs into the side of the train. This is the distribution used in the analysis.

TABLE B-IV
Truck/Train Accident Statistics, 1969-1972^a

Type of Accident	Reporting Year				Total for 1969-1972 Period
	1969	1970	1971	1972	
Trucks ^b Struck by Train	566	572	540	591	2269
Trucks ^b Ran Into Side of Train	198	162	193	213	766
Total Accidents Considered	764	734	733	804	3035

^a Fraction of occurrences truck struck by train, 0.75; fraction of occurrences truck ran into side of train, 0.25.

^b Pickup trucks and panel trucks included in sample.

Distribution of All Truck Accidents for Analysis

The basic data set can be broken down into two general categories, Collision Accidents and Noncollision Accidents. Collision accidents involve a primary impact with another vehicle, a pedestrian, a bicyclist, a train, an animal, or an object other than the road and roadside terrain. Noncollision accidents involve fire, running off the road, overturning, and other such accidents.

The noncollision accidents may include impacts with roadside ditches, banks, the roadway, and other roadside terrain features. Table B-V contains the basic accident distribution obtained from the BMCS data set, which is used in this study.

TABLE B-V
Distribution of Accidents by BMCS Categories, 1969 -1972

Accident Classification	Number of Accidents	Fraction of Total
Collision With		
Pedestrian	1 520	0.0085
Property	28 101	0.1569
Passenger Auto	87 268	0.4873
Motor Bus	787	0.0044
Other Vehicle	1 049	0.0059
Railroad Train	1 027	0.0057
Streetcar	9	0.0001
Animal/Animal-Drawn Vehicle	1 344	0.0075
Bicycle	182	0.0010
Fixed Object	25 934	0.1440
Unreported Object	216	0.0012
Other Object	270	0.0015
Rollaway	2 096	0.0117
		<u>0.8365</u>
Noncollision		
Overturn on Road	5 065	0.0283
Ran off Road	11 876	0.0663
Other	12 259	0.0685
Rollaway	67	0.0004
		<u>0.1635</u>
TOTAL	179 070	1.0000

The basic accident distribution was revised as follows for use in the analysis:

1. It is assumed that loss of control of the vehicle when the driver is taking evasive action causes the most damage in pedestrian, other vehicle (motorcycle), animal/animal-drawn vehicle, and bicycle accidents. For the purpose of this study, the running-off-the-road/overturn type of accident best describes these collision accidents.
2. The term "property" refers to carriers of property (commercial trucks). This category was combined with the categories Motor Buses and Streetcars to form a single new collision category, Trucks.

3. Fixed Objects, Unreported Objects, and Other Objects were combined into a single category, Objects.
4. Collision Rollaway and Noncollision Rollaway were combined into a single category, Rollaway.
5. A new category, Overturn/Ran Off Road, was established to include both collision and noncollision accidents where the primary cargo damage was due to overturning or running off the road.

Table B-VI contains a listing of the BMCS accident data in the revised categories.

TABLE B-VI
Distribution of BMCS Data by Revised Categories

Accident Classification	Number of Accidents	Fraction of Total
Collision Only		
Truck		
Property	28 897	0.1614
Motor Bus		
Streetcar		
Passenger Auto	87 268	0.4873
Railroad Train	1 027	0.0057
Object	26 420	0.1476
Fixed Object		
Unreported Object		
Other Object		
Collision and Noncollision		
Overturn/Ran off Road	35 458	0.1980
Pedestrian		
Other Vehicle		
Animal/Animal-Drawn Vehicle		
Bicycle		
Rollaway (collision)		
Overturn on Road		
Other		
Rollaway (Noncollision)		
Total	179 070	1.000

It can be observed that about 20 percent of the accidents fall in the new Overturn/Ran off Road category. It is assumed that this category can be conservatively represented by overturning and running-off-the-road accidents, except for those accidents in which the fire effects are a major cargo damage mechanism.

The collision-only accidents are listed in Table B-VII, along with the distributions selected for each category. It can be seen from this table that the collision accident with the lowest expectation is a truck running into the side of a train. The collision accident with the greatest expectation of occurrence is a truck running into the rear of an auto. It should be remembered that these are derived distributions and not actual distributions. The distributions are such that the number of truck driver fatalities and injuries suffered in actual accidents is conservatively approximated by the derived distributions.

TABLE B-VII
Distribution of Revised Categories by Type of Vehicle,
Collision-Only Accidents

	Fraction of Collision-Only Accidents	Distribution Factor	Distribution for Analysis
Truck	0.2012		
Head-on		0.0405	0.0081
End-on #1 into #2		0.4235	0.0856
End-on #2 into #1		0.4004	0.0806
Side-on #1 into #2		0.0427	0.0086
Side-on #2 into #1		0.0910	0.0183
Auto	0.5076		
Head-on		0.0538	0.0327
End-on #1 into #2		0.3695	0.2245
End-on #2 into #1		0.3032	0.1842
Side-on #1 into #2		0.0742	0.0451
Side-on #2 into #1		0.1993	0.1211
Railroad Train	0.0072		
Struck by train		0.7500	0.0054
Ran into train		0.7500	0.0018
Object	0.1840	1.0000	0.1840

The distribution shown in Table B-VII is again presented in Table B-VIII, which contains a reorganization of the data by effect on truck. Only three truck motions are permitted:

1. The truck is decelerated along its line of travel; i.e., the vehicle is slow or is stopped by the collision.
2. The truck is accelerated along the line of travel; i.e., the vehicle speed is increased by the collision.
3. The truck is accelerated perpendicular to the line of travel; i.e., the vehicle is moved sideways by the collision.

TABLE B-VIII
Collision Accident Distribution by Direction of Acceleration
Vector on Shipment Truck

Direction of Acceleration Vector on Package	Distribution Factors	Normalized Sets of Distribution Factors
Truck Decelerated Along Its Axis		
Head-on, truck	0.0081	0.0137
End-on #1 into #2, truck	0.0856	0.1450
Side-on #1 into #2, truck	0.0086	0.0146
Head-on, auto	0.0327	0.0554
End-on #1 into #2, auto	0.2245	0.3803
Side-on #1 into #2, auto	0.0451	0.0764
Ran into train	0.0018	0.0030
Object	0.1840	0.3116
	<u>0.5904</u>	<u>1.0000</u>
Truck Accelerated Along Its Axis		
End-on #2 into #1, truck	0.0808	0.3044
End-on #2 into #1, auto	0.1842	0.8958
	<u>0.2650</u>	<u>1.0000</u>
Truck Accelerated Perpendicular to Its Axis		
Side-on #2 into #1, truck	0.0183	0.1264
Side-on #2 into #1, auto	0.1211	0.8363
Struck by train	0.0054	0.0373
	<u>0.1448</u>	<u>1.0000</u>

These three distributions will be used to compute the maximum velocity change of the vehicle and cargo and the associated maximum energy change resulting from a collision accident. If the cargo tie-down strength is less than that required to maintain the cargo on the vehicle, the tie-downs will fail and release the cargo. In this case the cargo velocity change will be less than the predicted maximum.

APPENDIX C
MOTOR VEHICLE AND TRAIN SPEED DISTRIBUTIONS FOR
MOTOR-CARRIER ACCIDENTS

Appendix C

MOTOR VEHICLE AND TRAIN SPEED DISTRIBUTIONS FOR MOTOR-CARRIER ACCIDENTS

Motor Vehicle Speed Distributions

The difficulty of determining vehicle speed distributions has been pointed out earlier.¹ No data that correlate vehicle speeds and accident severity have been found. Sandia Laboratories is currently engaged in a program to obtain, at the state level, data that will link accident speed and accident severity.^{55, 56} The five speed data distributions used in this report were obtained from the following sources:

1. SLA-74-0001¹ which presents local data (Alabama, 1970, and Texas, 1969) for speeds at which accidents occurred on rural highways.
2. Reference 60, which presents local data (Texas 1969) for passenger-auto-accident speed distributions and for truck-accident distributions. These data cover both urban and rural highways.
3. References 7-10 (FHWA data), which present data for the speeds of vehicles involved in railroad-highway grade-crossing accidents.
4. Reference 61, which presents data on the actual speed of vehicles recorded on tangent sections of main rural highways during off-peak hours. This sample is free-flowing highway traffic and does not reflect any accident involvements. A review of the BMCS data for 1969-1972 allows the following speed inferences:
 - a. Approximately 10 percent of the accidents listed reflect very low speed for one or both vehicles. These include backing, stopped-in-traffic, and rollaway accidents.
 - b. Approximately 30 percent of the accidents are low- to moderate-speed accidents. These include turning, intersection, and skidding accidents (inclement weather conditions assumed for the last case).
 - c. The balance, approximately 60 percent of the accidents, are moderate- to high-speed accidents. These include head-on, rear-end, passing, and sideswipe accidents.

¹Rural here means all highways outside of city limits and excludes intracity accidents.

Table C-1 contains a list of each of the speed distributions. Figure C-1 is a graphic representation of the data in Table C-1 for the five distribution data sets mentioned.

TABLE C-1
Vehicle-Accident Speed Distributions

Speed mph	Fraction of Accidents At or Below This Speed					Analysis Values
	Texas Auto	Texas Truck	FRA Data	SLA-74-0001	Free Flow, No Accident	
0	0.1230	0.0580		0.05		0.0
10	0.3606	0.3774	0.0675	0.19		0.1386
20	0.5436	0.5393	0.1923	0.29		0.2772
30	0.7809	0.6544	0.3784	0.39		0.4157
40	0.8750	0.8072	0.5000	0.51	0.02	0.5543
50	0.9321	0.9225	0.7561	0.60	0.15	0.6929
60	0.9731	0.9843	0.8866	0.87	0.50	0.8315
70	0.9932	0.9955		0.97	0.84	0.9701
80				0.99		0.9900
90						0.9950
100						1.0000

Figure C-1. Vehicle-accident speed distribution.

It should be noted that the data from Reference 61, free-flowing highway traffic, requires that almost all accidents (85 percent) occur at relatively high speeds; this contradicts the BMCS data. Conversely, the Texas truck-accident data from Reference 60 reflects that the majority of accidents (92 percent) occur at moderate to low speeds. Low speed is assumed to be 15 mph or less, moderate speed to be 15 to 50 mph, and high speeds to be greater than 50 mph. The data from References 1 and 7 through 10 seem to fit the BMCS data best. For calculational convenience, the following speed distribution function, based on the data in Reference 1, was chosen for use in the analysis.

Let x be a random variable in the 0-1 interval. The velocity associated with any value of x will then be given by

$$V = 72.16x, 0 \leq x \leq 0.21$$

$$V = 500(x - 0.21) + 70, 0.21 \leq x \leq 0.69 \quad (C-1)$$

$$V = 2000(x - 0.69) + 80, 0.69 \leq x \leq 1.00$$

This function is plotted as a straight line between the origin and the 70-mph point. It then follows the Reference 1 data to the 80-mph point and extends linearly to the 100-mph point. The distribution, shown in Table C-1 under Analysis Values, is also shown in Figure C-2. For this distribution, 21 percent of the velocities will be at or below 15 mph, 69 percent at or below 50 mph, and 31 percent above 50 mph. The distribution appears to offer a reasonable fit to the known conditions.

Figure C-2. Vehicle-accident speed distribution used in the analysis.

Train Speed Distribution

The Federal Railroad Administration (FRA) data for the years 1969 through 1972⁷⁻¹⁰ form the basis for this distribution. Table C-II contains a year-by-year breakdown of train speeds for cases where the train struck the vehicle. Figure C-3 is a plot of these data. The train speed distribution used in the grade-crossing accident analysis is determined by the following relationships:

$$V = \frac{10}{0.0899} x, \quad 0 \leq x < 0.0899$$

$$V = \frac{40}{0.7265} (x - 0.0899) + 10, \quad 0.0899 \leq x < 0.8164$$

$$V = \frac{10}{0.1067} (x - 0.8164) + 50, \quad 0.8164 \leq x < 0.9231$$

$$V = \frac{10}{0.0491} (x - 0.9231) + 60, \quad 0.9231 \leq x < 0.9722 \quad (C.2)$$

$$V = \frac{10}{0.0240} (x - 0.9722) + 70, \quad 0.9722 \leq x < 0.9962$$

$$V = \frac{10}{0.0026} (x - 0.9962) + 80, \quad 0.9962 \leq x < 0.9988$$

$$V = \frac{10}{0.0012} (x - 0.9988) + 90, \quad 0.9988 \leq x \leq 1.00$$

where x is a random variable whose value is between zero and one.

TABLE C-II
1969-1972 FRA Rail-Highway Accident Data, Giving
Speed of Train at Time of Accident

Speed of Train (mph)	Number of Accidents					Fraction of Total
	Vehicle Struck by Train					
	1969	1970	1971	1972	Total	
1-9	253	179	202	192	926	0.0899
10-19	348	362	354	342	1406	0.1530
20-29	454	452	483	488	1877	0.2032
30-39	455	444	483	467	1829	0.1990
40-49	372	370	401	431	1574	0.1713
50-59	272	252	237	220	981	0.1067
60-69	140	111	109	91	451	0.0491
70-79	82	77	32	30	221	0.0240
80-89	7	10	5	2	24	0.0026
90 & over	6	2	3	--	11	0.0012
TOTAL	2389	2289	2269	2263	9100	1.0000

Figure C-3. Train/vehicle grade-crossing accident data, giving speed of train at time of accident (from 1969-1972 FRA Rail-Highway Accident Data - 9190 accidents).

Table C-III is a comparison of the FRA data and the continuous-speed distribution assumed in this analysis. Figure C-4 is a plot of the train speed distribution function. All velocities are in miles per hour.

TABLE C-III
Grade-Crossing Accident Data, Giving Speed
of Train at Time of Accident

Speed of Train (mph)	Fraction of Accidents Below this Speed (FRA data)	Fraction of Accidents Below this Speed (assumed distribution)
0	0.	0.
10	0.0899	0.0899
20	0.2429	0.2715
30	0.4461	0.4532
40	0.6451	0.6348
50	0.8164	0.8164
60	0.9231	0.9231
70	0.9722	0.9722
80	0.9962	0.9962
90	0.9988	0.9988
100	--	1.0000

Figure C-4. Railroad train speed distribution used in grade-crossing analysis.

APPENDIX D
WEIGHT DISTRIBUTIONS FOR
MOTOR CARRIERS INVOLVED IN ACCIDENTS

Appendix D
WEIGHT DISTRIBUTIONS FOR
MOTOR CARRIERS INVOLVED IN ACCIDENTS

Motor Vehicle Weight Distribution

Introduction

The weight of the vehicle is one of the principal variables in this analysis. Although it might be possible to determine the weight distribution for all passenger autos and trucks in the United States, the work involved would outweigh any advantages that might be gained in accuracy. One possible problem, however, involves identification of passenger autos and trucks as reported in the BMCS accident statistics. The data for the year 1972 will be considered to point out the reason for concern in this area. The information displayed in tabular form in Tables D-I and D-II was obtained from References 5 and 61.

TABLE D-I

Motor Vehicle Statistics, 1972

	Number of Vehicles ($\times 10^{-3}$)	Vehicle Mileage ($\times 10^{-9}$)	Percent of Total Vehicles	Percent of Total Mileage
Passenger Auto	86 850	1003.5 ^a	79.20	86.08
Bus	1 901	5.1	1.55	0.41
Pickup/Panel Truck	14 462	155.7	11.62	12.42
Trucks (excluding pickup/panel trucks)	5 283	88.8	4.32	7.09
Motorcycles	3 798		3.11	
TOTAL	122 304	1253.1	100.0	100.0

^a Includes motorcycles.

TABLE D-II
Percent of Collision Accidents by Type of Motor Vehicle
1972 BMCS Report

Type of Vehicle	Total Collision Accidents	Percent of Total Collision Accidents
Passenger Autos, Taxis, Pickup Trucks, Panel Trucks	25 239	73.88
Trucks (excluding pickups and panels)	8 393	24.57
Motor Bus	230	0.67
Other Motor Vehicles (motorcycles)	297	0.87
TOTAL	34 159	99.99

The BMCS category "Property" contains only collisions between two carriers of property (commercial trucks). These truck/truck collisions are further defined by BMCS to exclude pickup trucks and panel trucks.⁶² Pickups and panels represent over 10 percent of total vehicle registrations and almost 75 percent of truck registrations. Thus, the shift of these vehicles from the truck/truck collision to the truck-passenger auto collision category is significant. Trucks (excluding pickups and panels) represented 4.3 percent of the total registered motor vehicles and 7.1 percent of the total vehicle mileage in 1972, but 24.6 percent of the motor vehicle collision accidents reported to BMCS were truck/truck collisions. The BMCS data contain a more complete and detailed report of large-truck accidents than any other data set known to the author. A further discussion of BMCS data dealing with the 1969 report can be found in Reference 60 and in Appendix A. The method of analysis used is such that a collision with a truck (as defined by BMCS) will produce a more severe environment than collision with a pickup or panel-type vehicle. The accident analysis will then be conservative if collisions with trucks are overrepresented.

Passenger Autos, Pickup and Panel Trucks

The gross vehicle weights for different types of light vehicles were obtained from Reference 63. Curb weight of passenger cars generally ranged from 1800 to 5000 pounds, with a few models outside this range. The maximum recommended load for these vehicles generally ranged from 800 to 1200 pounds. The 4000- to 5000-pound curb weight appears to be predominant. For this study it was assumed that the weight of passenger cars could be conservatively represented by the function

$$W = 3000x + 3400 \text{ pounds,}$$

(D.1)

where x is a random variable in the 0-1 interval.

Pickup trucks present a problem somewhat greater than do autos, since the options selected by the buyer can substantially affect the curb weight of the vehicle. Most of the pickup trucks are one-half-ton vehicles with a basic weight in the 5000- to 6000-pound range. The weight of panel trucks was assumed to be the same as that of pickups. The following function was used to represent weight of pickup and panel trucks.

$$W = 5000x + 5000 \text{ pounds} , \quad (D.2)$$

where x is a random variable chosen in the 0-1 interval.

Trucks (excluding pickups and panels)

The weight distribution for trucks was determined by use of registration information from Reference 61 and maximum legal weight information from Reference 64. This information is presented in Table D-III. The weight distribution function chosen to represent trucks is

$$W = \frac{18,000}{0.7310} x + 10,000 , \quad 0 \leq x < 0.7310$$

$$W = \frac{48,000}{0.2540} (x - 0.7310) + 28,000 , \quad 0.7310 \leq x < 0.9850 \quad (D.3)$$

$$W = \frac{24,000}{0.0150} (x - 0.9850) + 76,000 , \quad 0.9850 \leq x \leq 1.0 ,$$

where x is a random variable chosen in the 0-1 interval.

TABLE D-III

Distribution and Weights of Medium and Heavy Trucks

Type of Truck (number of axles)	Registrations (1000s)	Percent of Total Registrations	Cumulative % of Total Reg.	Maximum Legal Weight (1000 lb)
2-axle	3862	73.10	73.10	26
3-axle	852	12.34	85.44	44
4-axle	273	5.17	90.61	60
5-axle	417	7.89	98.50	76
All others	79	1.50	100.00	100 ^a
TOTALS	5283	100.00		

^a Assumed maximum weight for this study.

Train Weight Distribution

An earlier study, Reference 65, found that the total weight of the train is not significant so long as it is substantially greater than the weight of the container and transport truck. In this study the train is assigned a weight sufficient to ensure that the package velocity change approximates

1. The preaccident train speed for cases where the train strikes the truck.
2. The preaccident truck speed for cases where the truck strikes the train.

Object Weight Distribution

Three BMCS object classifications have been included in this distribution. The BMCS classifications "Fixed Objects," "Unreported Objects," and "Other Objects" have been combined to form a single new classification, "Stationary Objects." This category accounts for 14 percent of all collision accidents, 26 percent of collision fatalities, 17 percent of collision injuries, and 17 percent of collision dollar costs. Collision with an object can range from hitting a sign post to colliding with a bridge pier or abutment. It is the author's opinion that the degree of hazard associated with object impacts is generally overemphasized. This type of collision ranks below Railroad Train, Truck, and Motorcycle/Animal collisions in severity and above Pedestrian/Bicycle, Passenger Auto, and Rollaway collisions (Appendix A).

The term "Bridge Abutment," frequently found in object impact discussions, is often misused or misunderstood. The bridge abutment serves to transmit the load from the bridge superstructure to the foundation and also acts as a retaining wall to hold back the earth fill behind it. Consequently, the bridge superstructure is placed above the top of the abutment. The abutment generally does not project above the bridge deck and hence is not the object impacted by a vehicle crossing the bridge.

It is possible for a vehicle to collide with the abutment of a bridge (overpass) that is over the vehicle's roadway. In this case, however, it is common to place the breastwall of the abutment parallel to the highway and the wingwalls of the abutment at an angle (not perpendicular) to the highway. Good design practice calls for setting the abutments back from the roadway to minimize the hazard to vehicles. In general, it is very difficult for a vehicle to hit a bridge abutment in a right-angle (or near-right-angle) impact situation. Bridge piers, supports placed between abutments, are quite a different matter. Piers take many forms, but are commonly seen as intermediate supports of interstate highway bridges. The principal differences between the piers and abutments, from a collision severity viewpoint, are that the piers are generally much less massive than the abutments and the piers are not earth backed.

The description of a fixed object was based on data obtained from the State of Colorado. These data were limited to vehicle-collision accidents that involved fatalities. Its use is only to identify objects and to obtain an estimate of their frequency of occurrence.

The Colorado data provide a listing of stationary objects that were struck in accidents involving fatalities. The 1974 Colorado data cite 209 objects struck in 129 accidents resulting in 156 fatalities. Multiple impacts are included in these statistics; for example, a vehicle may have struck a guard post on the right-hand-side of the highway; crossed the traffic lanes and struck the median barrier; and recrossed the highway, coming to rest against an embankment. Three object collisions would be recorded for this accident.

The accuracy of the Colorado data depends upon the individual responsible for the initial accident report. An example of this is the reference to an accident where the vehicle struck a "bridge abutment" located in the median. Such an accident is possible if the highway has a very wide median, but unlikely. It is probable that the vehicle struck a large bridge pier. Some accident reports may contain a detailed description of each object struck, whereas others may report only the first or last object struck. It was assumed that these data are representative of object collisions and, therefore, this data set was used in the analysis.

The Colorado data have been divided into five groups:

1. Massive Objects. Included in this group are bridge abutments, tunnel faces, and similar objects.
2. Substantial Objects. Included in this group are concrete wing walls, concrete bridge piers, boulders, and other such items.
3. Heavy Objects. Included in this group are brick walls, median barriers, guard posts, guard rails, bridge rails, trees, and similar objects.
4. Light Objects. Included in this group are signs, curbs, fences, utility poles, delineator posts, mail boxes, and similar objects.
5. Terrain Features. Included in this group are backslopes, embankments, ravines, gravel stockpiles, and similar objects. Note that although the mass of any of these items is large, compared with Massive Objects or Substantial Objects, none will provide severe impact environment for the cargo.

Table D-IV contains a listing of these five environments and their frequencies of occurrence. Four of the five environments are related to other accident conditions:

1. Massive Objects. Analyzed as a collision of a shipment truck into a train.

2. Substantial Objects. Analyzed as a collision of a shipment truck into a truck.
- 3.4. Heavy Objects and Terrain Features. Analyzed as a collision of a shipment truck into a passenger auto.
5. Light Objects. Have the weight of the object assigned by the function

$$W = 3400x$$

(D. 4)

where x is a random variable in the 0-1 interval and W is the weight of the object.

TABLE D-IV
Frequency of Occurrence of Object Collisions by Group
Based Upon 1974 Colorado Statistics on Object
Collisions Which Involved Fatalities

Group	Number of Occurrences	Fraction of Total
Massive Objects	8	0.0383
Substantial Objects	18	0.0861
Heavy Objects	44	0.2105
Light Objects	112	0.5359
Terrain Features	27	0.1292

This distribution was felt to be overly conservative, since it produced more severe environment than the truck/truck collision. Hence, it was further modified to include the effect of collision angle. The angle between the object and the truck was assumed to vary between zero and 90° , with all angles having an equal likelihood. The component of the truck velocity normal to the object surface was then employed as the effective impact velocity.

APPENDIX E
TRAIN ACCIDENTS

Appendix E TRAIN ACCIDENTS

Frequencies of Train-Accident Types

The probabilities of a derailment, a collision, or an "other" accident, given a train accident, were estimated from the figures in Table III-I. For these probabilities the notation of Reference 67, where Pr represents a probability and a vertical line represents a condition on that probability, was used.

$$\text{Pr (derailment|train accident)} = 0.834 \quad (\text{E. 1})$$

$$\text{Pr (collision|train accident)} = 0.066 \quad (\text{E. 2})$$

$$\text{Pr (other|train accident)} = 0.100 \quad (\text{E. 3})$$

Collisions are further broken down into the following categories:²⁸ rear-end, head-on, broken-train, side or raking, at railroad crossings (highway grade-crossing accidents are not included in this category), trains with cars not in trains, switching, and those not elsewhere classifiable.²⁹ Data on relative frequencies of these categories for freight trains only were obtained from the FRA "T Sheets" (train-accident report forms)³² for all train accidents to Class 1 railroad freight trains during the months of March and September 1973, a total of 1025 accidents. For the purposes of this study, "switching" and "not elsewhere classifiable" were not useful categories. Therefore, these accidents were placed, according to accident descriptions, into appropriate categories (e.g., a switching collision that was head-on was placed in the head-on category). The resulting estimates of probabilities are given:

$$\text{Pr (rear-end collision|collision)} = 0.191 \quad (\text{E. 4})$$

$$\text{Pr (head-on collision|collision)} = 0.067 \quad (\text{E. 5})$$

$$\text{Pr (broken-train collision|collision)} = 0.157 \quad (\text{E. 6})$$

$$\text{Pr (side or raking collision|collision)} = 0.315 \quad (\text{E. 7})$$

$$\text{Pr } \left(\begin{array}{l} \text{collision of train or cars with} \\ \text{cars not in trains} \end{array} \middle| \text{collision} \right) = 0.270 \quad (\text{E. 8})$$

It was also determined from the data that about 36 percent of the collisions involved derailment. Therefore,

$$\text{Pr}(\text{derail} | \text{collision}) = 0.36$$

(E.9)

All these data are summarized in the block diagram of Figure E-1.

Figure E-1. Class I freight-train accident rates and frequencies.

Net Velocity Distributions

From the FRA data, the train-speed distribution was found for collision accidents. This distribution is given in Table E-1.

TABLE E-I
Differential and Cumulative Distributions
of Freight Train Speed for Collision Accidents

Speed (mph)	Fraction of Accidents	Speed (mph)	Fraction of Accidents Below This Speed
0-5	0.418	5	0.418
5-10	0.214	10	0.632
10-15	0.116	15	0.748
15-20	0.048	20	0.796
20-30	0.097	30	0.893
30-40	0.058	40	0.951
40-50	0.029	50	0.980
50-60	0	60	0.980
60-70	0.010	70	0.990
70-80	0.010	80	1.000

From the same data, the speed distribution was found for derailments (not including derailments resulting from collisions). This distribution is given in Table E-II.

TABLE E-II
Differential and Cumulative Distributions
of Freight Train Speed for Derailment Accidents

Differential Distribution		Cumulative Distribution	
Speed (mph)	Fraction of Accidents	Speed (mph)	Fraction of Accidents Below This Speed
0-5	0.187	5	0.187
5-10	0.223	10	0.410
10-15	0.174	15	0.584
15-20	0.064	20	0.646
20-30	0.148	30	0.796
30-40	0.082	40	0.878
40-50	0.075	50	0.953
50-60	0.027	60	0.980
60-70	0.010	70	0.990
70-80	0.010	80	1.000

The broken-train collision is a special case of the collision accident. The following is a sequence of events leading to this accident:

1. At some point in the train the cars uncouple. The motive power on the leading cars draws them away from the trailing cars.
2. Automatic braking systems are activated by the opening of air line connection at the point of separation.
3. The leading cars slow more quickly than the trailing cars, then the trailing cars catch up to the leading cars and collide with them.

The relative velocity at the time of the collision is controlled by effectiveness of braking in each section of the train. It is assumed that its magnitude is low and that the primary accident effects are caused by derailment of cars subsequent to the collision. On the aforementioned "T" forms, the speed at which the break occurred was all that was reported for the broken-train collisions. This distribution, with "unknowns" arbitrarily placed in the 70- to 80-mph category, is given in Table E-III. Although this distribution is not statistically significant inasmuch as it represents only 12 accidents, it does represent the best estimate available.

TABLE E-III
Distribution of Train Speed at Time of Break
for Broken-Train Accidents

Speed (mph)	Fraction of Accidents
0-10	0
10-15	0.083
15-20	0.083
20-30	0.250
30-40	0.250
40-50	0.167
50-60	0
60-70	0.083
70-80	0.083

Typical Train Definition

For this study, it is necessary to define a "typical" freight train according to average figures for numbers of cars, types of cars, and fractions of cars loaded.²⁰ Statistics from Reference 67 result in the typical freight train assumed throughout this study (see Table E-IV).

TABLE E-IV

Definition of Typical Freight Train as Used in This Study

Type of Car	Number Full	Other	Number Empty
Locomotive		3	
Plain Boxcar	7		6
Equipped Boxcar	4		3
Gondola	4		3
Open Hopper	8		6
Covered Hopper	4		3
Flat Car	3		2
Refrigerator Car	2		2
Tank Car	4		3
Other Car	1		1
Caboose		1	

Accident Rate per Car Mile

The environments to be described here are those to which an individual railcar will be subjected, given a train accident. Car damage due to impact in accidents other than collisions or derailments was assumed negligible. It is believed that these accidents primarily involved casualties, fire, and/or minor equipment damage.

The average number of cars involved in derailment accidents appears to increase rapidly with derailment velocity, as does the number of cars affected by collision accidents. There are also indications from the available data that the number of cars involved in derailments increases as train length increases.⁶⁸ Both these factors were considered in derailment and collision models.

Preaccident Train Speed

To achieve the continuous distribution required for the analytical treatment, the train speed data shown in Tables E-I and E-II were fitted with Weibul distribution curves of the form

$$F(V) = 1 - e^{-\frac{V^\alpha}{\beta}} \quad (E-10)$$

where

V is the preaccident train velocity.

x is a random number selected from a uniform distribution in the 0-1 interval.

α and β are constants.

Figure E-2 is a plot of the data contained in Table E-I and the continuous speed distribution used in the analysis for collision accidents. Figure E-3 is a plot of the data contained in Table E-II and the continuous speed distribution used in the derailment analysis. In each case the values of α and β were selected to obtain a reasonable curve fit to the discrete data sets. The speed distribution for broken-train accident, Table E-III, was approximated by a piecewise linear function. Figure E-4 is a plot of the discrete data and the piecewise linear function.

Figure E-2. Cumulative distribution of freight train speeds for collision accidents.

Figure E-3. Cumulative distribution of freight train speeds for derailment accidents.

Figure E-4. Distribution of train speeds at times of break, broken-train accidents.

Car-Derailment Models

Three different models were formulated to determine the number of cars that would be involved in a derailment accident, given that such an accident occurred. A number of factors^{68,69} appear to influence the number of cars that will be involved in any given derailment:

1. **Train Speed.** The number of cars derailed per accident appears to increase significantly with train speed.
2. **Train Length.** The number of cars derailed per accident appears to increase significantly as the number of cars approaching the derailment point increases.
3. **Train Composition.** The effect of a mixed train composed of cars of substantially different lengths and weights affects the derailment pattern.
4. **Car Characteristics.** Car length and weight appear to affect the number of cars derailed in a given accident.
5. **Ground Friction.** Ground friction affects the rate at which the derailed cars slow to a stop.
6. **Braking.** Upon derailment, the brakes are automatically applied to all cars. This affects the rate at which cars remaining on the track slow to a stop.

Of these six items, only train speed at the time of derailment was considered as a basis for construction of each derailment model. The effect of train length was considered separately and is discussed below. The effects of the train composition and individual car characteristics were not considered in determining the number of cars derailed, given a derailment accident. In the determination of the car velocity following derailment, however, both ground friction and braking were considered.

Derailment Model 1 was taken directly from Reference 1 and is identical to that used in determining small-package environments (Figure E-5). Derailment Model 2 was designed to give a continuously varying distribution of cars derailed as a function of derailment speed. The relation was established so that the four cases considering speed dependence⁶⁸ would be compatible with the chosen function. In Figure E-6, where Derailment Model 2 is shown, the four points of correspondence are indicated by small circles.

Figure E-5

Average number of cars derailed as a function of train speed at time of derailment (Model 1).

Figure E-6

Average number of cars derailed as a function of train speed at time of derailment (Model 2).

An additional item of data dealing with the speed dependence of the number of cars derailed is available from Reference 69. In this case the average number of cars damaged as a result of derailment is reported. The average number of cars damaged versus derailment speed,⁶⁹ identified as Derailment Model 3, is shown in Figure E-7. To aid in comparison of the three different derailment models, the expected number of cars that will derail is plotted as a function of pre-accident train speed in Figure E-8.

Figure E-7. Average number of cars damaged per accident (Model 3).

Figure E-8. Comparison of Derailment Models 1, 2, and 3.

Car-Collision Models

Two collision models were considered. In Model 1 all cars in the train were assumed to be affected by a head-on or rear-end collision.¹ In Model 2 the average number of cars damaged by the collision were considered.⁶⁹ In both models the broken-train collision was handled as a derailment accident, with the train speed selected from the broken-train speed distribution. Side or raking collisions and collisions with cars not in train were handled as head-on or rear-end collisions. In both models there were possibilities of the car escaping involvement in the collision because of the method of evaluation of broken-train results.

The distribution used in Model 2 is shown in Figure E-9. As stated above, all cars are assumed to be involved in the accident in Model 1.

Figure E-9. Accidents involving collision of any kind (Model 2).

Train-Length Effect

The length of the train affects the expected number of derailed cars if all other factors are constant.^{58,69} To determine the effect of train length by using the three proposed derailment models, the numbers of cars in the train were varied between 20 and 200 in increments of 20. The probability that the shipment car was in the derailed string of cars was calculated and recorded. Calculations were made by use of a Monte Carlo process and the derailment analysis for each model and each train length. The results are presented in Figure E-10. It can be seen that the probability of a selected car being involved in a derailment drops rapidly as the length of the train is increased. Probability based on a typical train of 66 cars will be conservative if the 66 car results are applied to longer trains. No information which would permit the direct determination of a derailment model that is both length- and speed-dependent is currently available.

Figure E-10. Probability that a given car is derailed, given that the train consists of N cars, three locomotives, and a caboose.

REFERENCES

1. R. K. Clarke et al., Severities of Transportation Accidents, SI-A-74-0001, Sandia Laboratories, Albuquerque, NM, July 1976.
2. 1968 Accidents of Large Motor Carriers of Property, Bureau of Motor Carrier Safety, Federal Highway Administration, U.S. Department of Transportation, Washington, D.C., December 1969.
3. 1969 Accidents of Large Motor Carriers of Property, Bureau of Motor Carrier Safety, Federal Highway Administration, U.S. Department of Transportation, Washington, D.C., December 1970.
4. 1970 Accidents of Large Motor Carriers of Property, Bureau of Motor Carrier Safety, Federal Highway Administration, U.S. Department of Transportation, Washington, D.C., March 1972.
5. 1971-1972 Accidents of Large Motor Carriers of Property, Bureau of Motor Carrier Safety, Federal Highway Administration, U.S. Department of Transportation, Washington, D.C., May 1974.
6. 1973 Accidents of Large Motor Carriers of Property, Bureau of Motor Carrier Safety, Federal Highway Administration, U.S. Department of Transportation, Washington, D.C., July 1975.
7. Rail-Highway Grade-Crossing Accidents (For the year ended December 31, 1969), Bureau of Railroad Safety, Federal Railroad Administration, U.S. Department of Transportation, Washington, D.C.
8. Rail-Highway Grade-Crossing Accidents (For the year ended December 31, 1970), Bureau of Railroad Safety, Federal Railroad Administration, U.S. Department of Transportation, Washington, D.C.
9. Rail-Highway Grade-Crossing Accidents (For the year ended December 31, 1971), Office of Safety, Federal Railroad Administration, U.S. Department of Transportation, Washington, D.C.
10. Rail-Highway Grade-Crossing Accidents (For the year ended December 31, 1972), Office of Safety, Federal Railroad Administration, U.S. Department of Transportation, Washington, D.C.
11. 1969 Analysis of Accident Reports Involving Fire, U.S. Department of Transportation, Federal Highway Administration, Bureau of Motor Carrier Safety.
12. 1971 Analysis of Accident Reports Involving Fire, U.S. Department of Transportation, Federal Highway Administration, Bureau of Motor Carrier Safety, March 1973.
13. B. E. Bader, "Heat Transfer in Liquid Hydrocarbon Fuel Fires," Chemical Engineering Progress Symposium Series, Vol. 61, No. 58, 1965, p. 7840.
14. W. de L. M. Messenger, The Transport of Radioactive Materials, United Kingdom Atomic Energy Authority, January 1962.
15. L. H. Russell and J. A. Canfield, "Experimental Measurement of Heat Transfer to a Cylinder Immersed in a Large Aviation Fuel Fire," Trans. ASME, Series C, J. Heat Transfer, 95, August 1973, pp. 397-407.

REFERENCES (cont.)

16. D. Gross, "Experiments on the Burning of Cross Piles of Wood," J. Research National Bureau of Standards 65C, No. 2, 1962, pp. 99-105.
17. H. W. Emmens and T. Shen, "Fire Spread in Paper Arrays," 13th Symposium (International on Combustion, The Combustion Institute, 1971, pp. 917-927.
18. D. W. Larson, Unpublished Data, Sandia Laboratories, Albuquerque, New Mexico.
19. Charring Rates of Selected Woods, U.S. Forest Service Research Paper FPL 69, Madison, Wisconsin, April 1967.
20. Review of Information Related to the Charring Rate of Wood, U.S. Forest Service Research Note FPL-0145, Madison, Wisconsin, November 1966.
21. P. L. Blackshear, Jr., and A. M. Kanury, "Heat and Mass Transfer to, From, and Within Cellulosic Solids Burning in Air," Tenth Symposium (International) on Combustion, The Combustion Institute, Pittsburgh, PA, 1965, pp. 911-923.
22. 1968 Centennial Edition - The World Almanac and Book of Facts, Luman H. Long, ed, Newspaper Enterprise Association, Inc., p. 438.
23. *Ibid*, p. 573.
24. Waterborne Commerce of the United States, Parts 1-5 Calendar Year 1972, Department of the Army Corps of Engineers.
25. Regulations for the Safe Transport of Radioactive Materials, IAEA Safety Series No. 6, Vienna, Austria, 1967, p. 18.
26. Code of Federal Regulations, Part 225, Section 225.21, October 1, 1974.
27. Accident Bulletin No. 141, Summary and Analysis of Accidents on Railroads in the United States, Calendar Year 1972, Department of Transportation, Federal Railroad Administration, Bureau of Railroad Safety.
28. Code of Federal Regulations, Part 225, Section 225.22, October 1, 1973.
29. Yearbook of Railroad Facts, 1973 edition, Economics and Finance Department, Association of American Railroads, L. C. Card No. Abb-7305.
30. Summary and Analysis of Accidents on Railroads in the United States, Department of Transportation, Federal Railroad Administration, Bureau of Railroad Safety, published annually.
31. "Report of Fire Losses for Calendar Year 1972," National Fire Protection Association--Railroad Section, private communication with John Ottosen, Fire Record Department, March 1974.
32. Rail Accident Reports (Form T), maintained by Federal Railroad Administration.
33. R. K. Clarke, J. T. Foley, W. F. Hartman, and D. W. Larson, Severities of Transportation Accidents, Vol. II - Aircraft, SLA-74-0001, Sandia Laboratories, July 1976.
34. R. K. Clarke, J. T. Foley, W. F. Hartman, and D. W. Larson, Severities of Transportation Accidents, Vol. III - Motor Carrier, SLA-74-0001, Sandia Laboratories, July 1976.
35. Car and Locomotive Encyclopedia, Compiled for the Association of American Railroads, Simmons-Boardman Publishing Co., New York, 1970.

REFERENCES (cont.)

36. Computer Listing of Hazardous Material Incidents, Data Maintained by Department of Transportation, Office of Hazardous Materials, July 1973.
37. Railroad Accident Report - Derailment of Missouri Pacific Railroad Company's Train 54 at Houston, Texas, October 19, 1971, NTSB-RAR-72-6, National Transportation Safety Board, December 13, 1972.
38. Railroad Accident Report - Chicago, Burlington and Quincy Railroad Company Train 64 and Train 824 Derailment and Collision with Tank Car Explosion at Crete, Nebraska, February 14, 1969, NTSB-RAR-71-2, National Transportation Safety Board, February 24, 1971.
39. Railroad Accident Report - Derailment of Amtrak Train No. 1 While Operating on the Illinois Central Railroad Near Salem, Illinois, June 10, 1971, NTSB-RAR-72-5, National Transportation Safety Board, August 30, 1972.
40. Railroad Accident Report - Texas and Pacific Work Extra 523/Missouri Pacific Extra 1902 East Head-on Collision at Taft, Louisiana, February 21, 1973, NTSB-RAR-73-6, October 25, 1973.
41. Railroad Accident Report - Head-on Collision of Two Penn Central Freight Trains at Herndon, Pennsylvania, March 22, 1972, NTSB-RAR-73-3, National Transportation Safety Board, March 14, 1973.
42. E. J. Albano and P. Seide, "Bifurcation of Rings Under Concentrated Central Directed Loads," JAM, June 1973, p. 553.
43. Sequence of Events Following Crescent City Derailment (8/10/70), RA-01-1-1, Association of American Railroads, Chicago Research Center.
44. Sequence of Events Following Houston, Texas, Derailment (10/19/71), RA-01-3-9, Association of American Railroads, Chicago, Research Center.
45. Railroad Accident Report - East St. Louis, Illinois Yard Collision, NTSB-RAR-73-1, January 22, 1972.
46. Railroad Accident Report - Hazardous Materials Accident in the Railroad Yard of the Norfolk and Western Railway at Decatur, Illinois, NTSB-RAR-75-4, July 10, 1974.
47. Railroad Accident Report - Hazardous Materials Accident at the Southern Pacific Transportation Company's Englewood Yard in Houston, Texas, NTSB-RAR-75-7, September 21, 1974.
48. Railroad Accident Report - Derailment and Subsequent Burning of Delaware and Hudson Railway Freight Train at Oneonta, New York, NTSB-RAR-74-4, February 12, 1974.
49. E. B. Hagen, Probabilistic Approach to Design, John Wiley and Sons, New York, 1968.
50. Code of Federal Regulations, Part 71, Title 10, Chapter 1, April 30, 1975.
51. Specifications for Design Fabrication and Construction of Freight Cars, Association of American Railroads, Chicago, Illinois, 1964.
52. Summary of Accidents Investigated by the Federal Railroad Administration in Fiscal Year 1971-1972, Department of Transportation, Federal Railroad Administration.
53. Summary of Ruptured Tank Cars Involved in Accidents, RA-01-2-7, Association of American Railroads, Revised July 1, 1972, Chicago, IL.

REFERENCES (cont)

54. The Resistance of Various Metallic Materials to Perforation by Steel Fragments, Project Thrur Technical Report No. 47, Ballistic Analysis Laboratory, Baltimore, Maryland, April 1967.
55. J. T. Foley et al., Truck Route Survey for LMFBR Spent Fuel Shipping Hazard Analysis, SAND76-0313, Sandia Laboratories, Albuquerque, NM, November 1976.
56. W. F. Hartman et al., Statistical Description of Heavy Truck Accidents on Representative Segments of Interstate Highway, SAND76-0409, Sandia Laboratories, Albuquerque, NM, November 1976.
57. F. Leimkuhler, Trucking of Radioactive Materials, The Johns Hopkins Press, Baltimore, MD, 1963.
58. D. E. Patterson and A. Mehn, A Summary of Incidents Involving USAEC Shipments of Radioactive Material, Division of Operational Safety, AEC, TID-16764 (Suppl. 1), November 1963.
59. A Summary of Incidents Involving USAEC Shipments of Radioactive Materials, 1963-1964, Division of Operational Safety (AEC), Industrial Safety and Fire Protection Branch, Washington, D. C., TID-16764 (Suppl. 2), April 1966.
60. R. E. Scott et al., Statistical Analysis of Truck Accident Involvements, The University of Michigan Highway Research Institute, Ann Arbor, MI, December 1971.
61. Statistical Abstract of the United States 1974, Bureau of the Census, U. S. Department of Commerce, 95th Edition, Washington, D. C., 1974.
62. Conversation between J. T. Foley and C. A. Davidson, Sandia Laboratories, Division 1285, and Russell Kidwell, Bureau of Motor Carrier Safety, May 1976.
63. NADA Official Used Car Guide, Vol. 44, No. 1, National Automobile Dealers Used Car Guide Co., McLean, VA, January 1977.
64. State Size, Weight, and Speed Maximums for Trucks and Truck Trailers, Rockwell-Standard Company, Detroit, MI, August 1971.
65. A. W. Dennis, Analytical Investigation of a Grade-Crossing Accident Between a Railroad Train and a Spent Reactor Fuel Cask, SAND74-0317, Sandia Laboratories, Albuquerque, NM, January 1975.
66. Fatal Traffic Accident Summary, State of Colorado, 1974.
67. K. A. Brownlee, Statistical Theory and Methodology in Science and Engineering, Second Edition, John Wiley and Sons, New York, 1965.
68. Railroad Tank Car Safety Research and Test Project, Phase 08, Report on Computer Derailment Study, RA-08-1-12, Association of American Railroads, Chicago, Research Center, February 17, 1972.
69. M. F. Meigs, Study of Freight Train Accidents Experienced by Class I Railways, SCR-111, TID-4500, Sandia Laboratories, Albuquerque, NM, August 1959.