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A Monte Carlo Model of Uncertainty in a Deterministic Hazardous Waste Transportation Risk Assessment

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A Monte Carlo Model Of Uncertainty In A Deterministic

Hazardous Waste Transportation Risk Assessment

(TITLE)

BY

Michael A. Cowen

THESIS

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ABSTRACT

This thesis is aimed at developing and applying advanced modeling tools in the prediction of risk to the general public from transportation of chemical waste on public highways. The modeling tools developed can then be used to compare alternative waste management scenarios. The application considered is related to the transport of hazardous waste generated by the United States Department of Energy (DOE) to current treatment, storage, and disposal facilities. DOE is currently considering four different scenarios.

The application considered can be more specifically defined as an analysis of the risk to the general public from transporting the 63 shipments of DOE generated hazardous waste designated as "poison by inhalation hazards" (PIH), potentially resulting in fatality, by the United States Department of Transportation (DOT) [Title 49, Code of Federal Regulations (Part 173.132)] in the 1992 fiscal year. The analysis is based on current transportation practices employed by DOE. Once the modeling tools have been developed to perform this analysis, similar analysis can be routinely carried out for other health end-points (carcinogenic effects and other adverse health effects other than cancer and lethality) and other waste management scenarios.

Two types of tools have been developed, deterministic and probabilistic. Using the probabilistic modeling tool, a cumulative probability distribution of number of people impacted can be developed (for this application impacted means number of individuals experiencing potentially life-threatening health effects due to inhalation of a DOE generated PIH released as a result of a truck transportation accident). The probabilistic modeling tool developed is based upon a Monte Carlo analysis accounting for the uncertainties in the variables involved in the modeling process.

The deterministic tool developed provides a simplified version of the probabilistic model such that the prediction will be one risk value which should approximate the mean of the cumulative probability distribution developed by the probabilistic model. Both the deterministic and probabilistic modeling tools require the modeling of the consequence of

a release of hazardous waste. The consequence is the result of source term accident modeling (i.e., resulting from a truck accident spill) along with dispersion modeling.

The source term modeling employs the use of (1) distributions of meteorological data supplied by the National Weather Service at over 60 locations uniformly distributed around the continental United States and (2) a detailed study on the US DOT HMIRS (Hazardous Materials Information Reporting System) database which encompasses information on thousands of hazardous material transportation accidents since the 1970's. The study of the HMIRS database led to probability distributions on the release amounts (by transport container), breach fractions and accident time (by hour and month). A health criteria, presented at WM-94 by Hartman et. al. (1994), is used in the dispersion modeling to define human health impacts from the concentration history at each downwind location.

Reasonable single values for all modeling parameters were used in the deterministic model, whereas probability distributions for release estimates and accident meteorological conditions were used for release amounts and meteorology in the probabilistic model. Realistic scenarios for the transportation accident itself were developed accounting for mixtures of chemicals released as is likely to occur.

It was found that the cumulative probability distribution of the number of individuals with potentially life-threatening health effects, is highly skewed. The probability that no individuals will have potentially life-threatening health effects from these 63 shipments is greater than 99%. Therefore the median (the 50-th percentile) of the distribution is 0, and all of the non-zero potentially life-threatening health effects are contained in the upper tail of the cumulative probability distribution (less than 1% chance of occurrence). Table 1 below presents some summary statistics compiled from the distribution.

Only 3 (of the 63) shipments had the potential to affect more than 500 people in a single accident. Furthermore, only 14 shipments had the potential to affect more than

100 people. Eliminating, or at least altering the waste management of these shipments, could dramatically reduce risks by reducing the probabilities for a catastrophic accident in which more than 100 people are affected.

Table 1 Summary Statistics from the Cumulative Probability Distribution of Number of Individuals with Potentially Life-Threatening Health Effects

Number of People with Potentially Life-Threatening Health Effects (N)	0.001	0.01	0.1	1	10	100	500
Probability that More than N Individuals are Impacted	4.2E-4	2.4E-4	1.2E-4	3.6E-5	5.4E-6	5.8E-7	1.7E-8

An additional observation is that the mean of the cumulative probability distribution, 3.48E-4, is located at the 99.947-th percentile and the result of the deterministic calculations of risk, 1.74E-4 ($^1/_2$ of the mean), is located at the 99.941-th percentile.

The Monte Carlo analysis helped to provide a great deal of perspective on the deterministic risk value. The fact that there is such a large probability of zero risk and an extremely small probability of a high risk scenario can be very useful in the decision making process.

1. INTRODUCTION

1.1. Background

This thesis is aimed at developing and applying advanced modeling tools in the prediction of risk to the general public from transportation of chemical waste on public highways. The application to be considered is the transport of hazardous waste generated by the United States Department of Energy. An accurate prediction of risk allows for a comparison of a number of management alternatives to determine the relative risk among the management alternatives considered for study.

The United States Department of Energy (DOE) has approximately 45 sites within the United States which produce hazardous waste from their research and production processes. This waste must be transported on public roads to commercial permitted treatment, storage or disposal facilities (TSDs). During the course of travel, there is the possibility of an accidental release of hazardous waste resulting from a truck accident. Life-threatening, carcinogenic or other adverse health effects can result from inhalation of toxic fumes or poisons spread downwind from the accident site. As the generators of the waste, the Department of Energy must assume partial liability for the consequences resulting from such an accident.

The Department of Energy is considering alternative waste management scenarios that may reduce the risks of human health effects from transportation of DOE generated waste to final treatment and disposal facilities. The basic question to be evaluated is "how much should DOE rely on outside commercial facilities for treatment "? A decision by the Department of Energy on how to handle offsite waste treatment involves a comparison of four alternatives which considers several issues including human health risks, cost of treatment and transportation, ecological impacts, land use and socioeconomic impacts. The current cases under consideration include the following:

(1) <u>Baseline (no action)</u> - The baseline or no action alternative refers to the continuation of nearly 100% use of outside commercial facilities for

treatment, storage and disposal of the DOE hazardous waste. Currently, the DOE treats some of their generated wastes on-site, transporting the rest to commercial facilities for treatment and/or disposal. This thesis will focus on the hazardous waste currently sent to outside commercial vendors.

(2) Decentralized - Under this alternative on-site treatment activity would increase between 5 and 10 percent. As a result of this increase, use of commercial TSD vendors will decrease, likely reducing the risk from transportation.

(3) Regionalized - This alternative builds upon the decentralized alternative by treating, storing and disposing on DOE sites approximately 50 percent of the waste that is currently treated, stored and disposed of offsite. This waste would then be transported to one of five designated regional DOE-owned-and-operated hazardous waste treatment facilities.

(4) Centralized - Under this alternative, 90 percent of all hazardous waste (non-wastewater hazardous waste) presently treated by commercial TSD vendors would be transported to one of two DOE-owned-and-operated hazardous waste treatment facilities. The two DOE sites selected for this treatment are Idaho National Engineering Laboratory and Oak Ridge Reservation in Oak Ridge, Tennessee.

For each alternative the total number of miles required to transport hazardous waste to treatment and disposal facilities is different. Similarly, the routes traveled will be different for each alternative. These changes from the baseline alternative will alter potential accident scenarios possibly leading to an increase or decrease in risk.

This thesis will present results of risk predictions only for the no action alternative with the health endpoint of "lethality," better described as the "number of people with potentially life-threatening health effects." Predictions for the other alternatives and for the two additional human health endpoints of "carcinogenicity" and "any effects" (other than carcinogenicity) can be carried out routinely with the computer models available as part of this thesis.

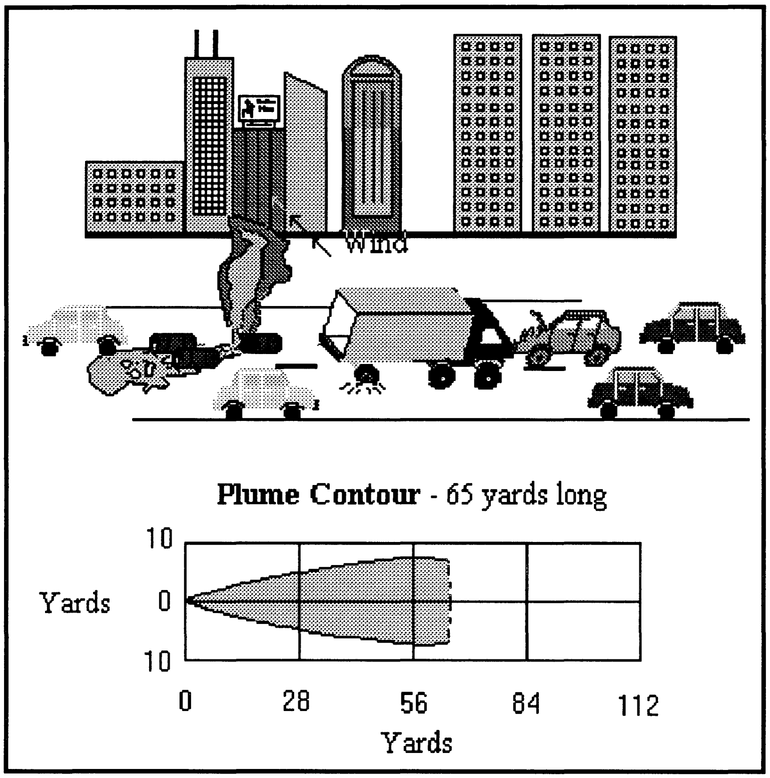
1.2. Transportation Risk and Affecting Factors

The risk of transporting chemical waste for one mile in a truck is the product of the probability of a release (during that one mile) and the consequence of the release that may occur during that one mile. The probability of a release is itself the product of the probability of an accident (during that one mile) and the probability of a release given that an accident occurred in that one mile. Once the risk for one mile of travel can be computed, the risk for an entire DOE scenario is computed as the sum of risk for each mile traveled in the entire scenario.

There are a number of factors influencing these risk calculations. Some of them are illustrated in the following two figures. Figures 1.1 and 1.2 depict some potential accident scenarios that can happen for the DOE waste. These figures show some of the factors which can increase or decrease risks during the course of transportation including meteorological conditions, accident severity (affects how much is released and magnitude of release rate), chemical released and the number of people in the vicinity of the accident (population density).

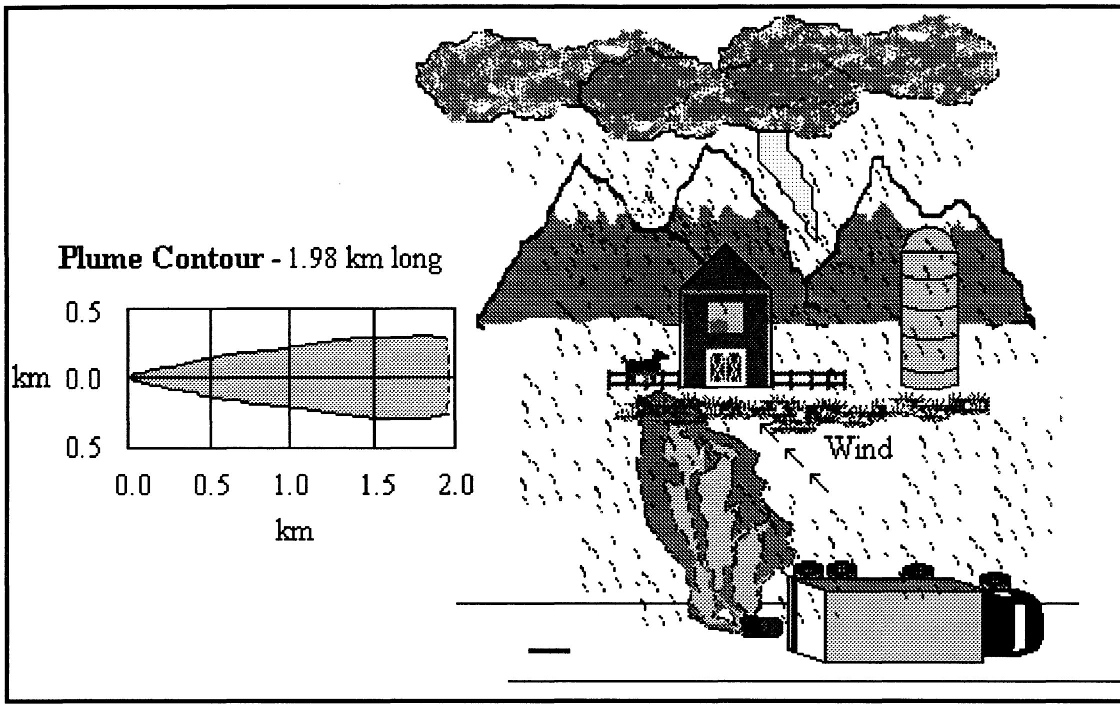
In Figure 1.1 a single unit truck transporting 55 gallon drums of bromine from Livermore California to Los Angeles California gets a flat tire while in Los Angeles. The driver temporarily looses control of the truck and hits a motor vehicle in another lane. It is a hot summer day with complete cloud cover and 50% humidity. The wind is blowing at 4 m/s. The accident results in ruptures in several of the drums. Subsequently, 77 pounds of bromine are spilled onto the pavement forming a pool on the ground which takes approximately one hour to evaporate. During the evaporation, fumes spread downwind toward the downtown area. The plume contour in Figure 1.1 represents an area downwind where any location within the gray contour has an air concentration which exceeds 11 parts per million bromine. Any individual within this area for more than one hour may suffer lethal effects. The downtown area is over 100 yards from the road and the plume contour is only 65 yards in length. Emergency response personnel are able to quickly and easily evacuate the general public from the vicinity of the spill and no deaths result from inhalation of bromine fumes.

Figure 1.1 Continuous Liquid Release of Bromine



In the scenario in Figure 1.1, high traffic volumes increase the probability of an accident, and large population densities increase the number of potential deaths per unit area within the plume contour. However, the bromine is released as a liquid. Liquid releases generally do not pose as great a danger to the general public as do gaseous releases. When gases are released into the atmosphere, plumes are formed with higher concentrations over a shorter period of time than those formed from evaporating pools of liquid. Although the duration of the inhalation danger is shorter for gaseous releases than it is for liquid releases, the human body can become overwhelmed by the higher concentrations in such short periods time.

Figure 1.2 Instantaneous Gaseous Release of Hydrogen Selenide



In Figure 1.2, a single unit truck transporting hydrogen selenide, selenium hexafluoride and tellurium hexafluoride from Argonne, Illinois to Clarence, New York overturns in a bad storm in the mountains of New York. A steel pressurized cylinder of hydrogen selenide is ruptured instantaneously releasing one gallon of the chemical in a gaseous state into the atmosphere. Hydrogen selenide is extremely toxic and it is estimated that inhalation of the gas for 15 minutes at a concentration of 0.17 parts per million will result in lethality. The temperature is 43° F and there is a rain storm with high speed winds blowing out of the south at 11 m/s. Due to the low lethal concentration threshold and high speed winds, the plume contour is 1.98 kilometers in length despite the small amount released (one gallon). However, other than the occupants of the nearby farm house, no communities exist within the plume contour and consequently only the driver and farm house occupants are in danger.

In each of these scenarios the plume contour was computed using the CASRAM computer dispersion model **[1]**. The CASRAM model has been used in both the deterministic and probabilistic methods and will be discussed further in chapters 4 and 5 on the deterministic and probabilistic models. This model requires as input the time of day, time of year, CAS numbers for each chemical released, amount released of each chemical , release duration for each chemical (possibly instantaneous), lethal concentration thresholds as a function of release duration for gas releases and evaporation time for liquid releases, and a number of meteorological parameters including wind speed, ambient temperature, ground roughness and stability class.

When predicting the risk associated with transporting any particular DOE shipment of hazardous waste there is a distribution of possible values for each of the CASRAM input parameters. When applying the deterministic method to the prediction of risk in each of the scenarios in Figures 1.1 and 1.2, fixed values would have been assumed for each of the CASRAM inputs. For this thesis, average or conservative values are assumed. The actual values used are discussed in Chapter 3 on the deterministic method. However, in the probabilistic method, a distribution of values for each of the CASRAM inputs will be recognized resulting in a distribution of plume contours. More importantly, a distribution of exposed areas (area contained in the plume contour) will be provided, ultimately providing a distribution of risk.

The probabilistic model can be used to quantify the uncertainty in deterministic predictions as well as provide additional information that the deterministic model cannot provide. This additional information will lead to improved comparisons between future alternative management scenarios for waste transport. The parameters where probability distributions will be recognized in the probabilistic model are presented in Table 1.2

The remaining chapters of this thesis discuss the DOE shipments, the U.S. Department of Transportation's Hazardous Materials Information Reporting System (HMIRS) database and provide more details on the deterministic and the development of the probabilistic methods used in this study. Table 1.2 lists three parameters or categories of parameters which contribute to the risk calculations. Two of these, fraction of maximum shipment capacity released and temporal conditions, are based upon an investigation of the accident data contained in the HMIRS database maintained by the

Research and Special Programs Administration of the United Stated Department of Transportation. This database contains data on releases from thousands of hazardous waste accidents that have occurred since the early 1970's.

Table 1.2 Parameters of Risk which have Probability Distributions (for the purposes of this thesis)

(a)	Percent of maximum or actual shipment capacity released depending upon container type
(b)	Meteorological conditions
(c)	Temporal conditions including month, day and hour

The third category of parameters, the meteorological conditions, are based upon a study of 5 years of data from each of 62 National Weather Service sites in the country. The amount of data collected is sufficient to provide accurate distributions of winds, temperatures and stabilities as a function of both time and location.

The modeling in this thesis does not account for variability in health criteria. Future work could involve the inclusion of this uncertainty in health criteria for each chemical that may be involved in a toxic gas release due to the transport of DOE hazardous chemical waste. Inclusion of that variation was beyond the scope of this thesis. The remaining two main sources of uncertainty (release amounts and meteorology) are included in this thesis. The sequence of the remaining chapters is given below -

Chapter 2: The DOE Shipments
Chapter 3: The HMIRS Database
Chapter 4: The Deterministic Method
Chapter 5: The Probabilistic Method
Chapter 6: Results and Discussion

2. THE DOE SHIPMENTS

In order to analyze risk from treatment technology operations and transportation accidents, the hazardous waste risk assessment modeling (HaWRAM) database **[7]** has been developed at Argonne National Laboratory. This database is structured to manage information related primarily to DOE generated hazardous waste transported to commercial facilities for treatment and/or disposal during the 1992 fiscal year. However, the DOE hazardous waste manifests sheets, from which the HaWRAM database is constructed, do not document truck configuration or route information and often provide limited data on packaging and commodity physical state. These limitations will result in some uncertainty in the models developed in this thesis. During the course of discussing the deterministic and probabilistic models in Chapter 4 and Chapter 5, these uncertainties will be pointed out and our efforts to minimize this uncertainty will be discussed.

There were 63 shipments in the HaWRAM database transported on public highways to commercial facilities for treatment and/or disposal which have been designated as "poison inhalation hazards" (PIH's) by the U.S. Department of Transportation (DOT) [Title 49, Code of Federal Regulations, Part 173.132]. Only liquids and gases are designated as PIH substances. Two criteria must be met for designation as PIH: (1) high toxicity, on the basis of animal 50% lethal concentrations (LC_{50}); and (2) for liquids, medium to high volatility. For this study, the modeling tools developed are applied to these 63 shipments, (all 63 are listed in Appendix A) which will serve as the no-action alternative case data with a health end point of potentially life-threatening health effects. Table 2.1 contains a sample shipment from the 63 listed in Appendix A.

Note that Table 2.1 does not show all the information available in the HaWRAM database for this shipment, but it also shows additional information which is not supplied in the database. All data in Table 2.1 other than the 15 minute exposure, 30 minute exposure and 60 minute exposure time concentration thresholds, are supplied by the HaWRAM database and comprises the information in the database which was used in applying the deterministic and probabilistic methods.

Table 2.1 Sample Shipment

Generator: Lawrence Livermore National Laboratory			Destination Facility: ENSCO, Inc			
Generator Location: Livermore, California			Destination Location: El Dorado, Arizona			
Departure Date: 7/10/92						
Shipment Contents:						
Commodity Name	CAS number	Container type	Original quantity	Lethal concentration (PPM) thresholds as a function of exposure duration		
				≤ 15 min	(15, 30] min	> 30 min
Phenyl Isocyanate	103-71-9	Large Drum	177 pounds	11	5.4	2.7
Titanium Tetrachloride	7550-45-0	Large Drum	13 pounds	3.7	2.6	1.8

2.1. Potentially Life-Threatening Concentration Thresholds

The potentially life-threatening concentration thresholds for PIH substances are defined to be air concentrations above which exposed persons are at risk of potentially life-threatening health effects. Two possible toxicity values that are often available in the literature for estimating potential human life-threatening health effects are the LC_{50} and the LC_{LO}. The LC_{50} is defined as that concentration of gas or vapor that causes death in half of the animals tested when administered by continuous inhalation. The LC_{50} is obtained only from animal tests; consequently, results must be extrapolated for application to humans. The LC_{LO} is defined as the lowest concentration of gas or vapor that causes death in any exposed species. The LC_{LO} values may be obtained from animal tests or from accidental human exposure occurrences. When obtained from the latter, the lethal concentration measurement may not be accurate.

For this thesis, the deterministic and probabilistic methods have only been applied to the transportation of the 63 potentially life-threatening shipments of DOE generated hazardous waste for no-action alternative. However, the modeling tools developed will be applied to all four alternatives for all three health end-points (fatality, cancer and other adverse effects). For further details on the development of the potentially life-threatening concentration thresholds and the concentration thresholds for carcinogenic and other adverse health effects refer to WM-94 [7].

2.2. Routes Traveled

Routing information has been predicted using the HIGHWAY 3.1 - *Enhanced Highway Routing Model* [6] developed at Oak Ridge National Laboratory. The model takes as input the origin and destination cities, and supplies a detailed output of population densities at several locations defined by latitude and longitude angles. The model also supplies detailed information about the interstate and local road names as well as corresponding mileage for those roads. Although the road and highway specific information was not used in the application of the deterministic and probabilistic methods, it was useful in testing the quality or applicability of the HIGHWAY 3.1 predicted routes to the actual routes traveled.

Although these routes are predicted, they are good approximations to the actual routes taken. The routes predicted for by the HIGHWAY 3.1 model have been spot checked for accuracy by contacting the carriers and obtaining actual route information.

For the deterministic method this detailed output is simplified to a distribution of miles traveled in 13 different population zones, and then further simplified to a table of three weighted average population densities and corresponding mileage for each of the three general population zones - rural, suburban and urban. Table 2.2 contains the summarized route predicted information for the sample shipment in Table 2.1.

Table 2.2 HIGHWAY 3.1 Predicted Route from Livermore, California to El Dorado, Arizona

Population Zone	Miles	People / Mi^2
Rural	1,763	12
Suburban	157	948
Urban	19	5,660

Appendix B contains a sample detailed output used in the probabilistic method.

2.3. Containers Used by the DOE

The DOE hazardous waste can be divided into two main categories. The first category includes gases, compressed gases, liquefied gas, and compressed liquids. Hazardous wastes in this category are generally shipped in pressurized steel cylinders and pose a greater potential consequence when exposed to the general public than the hazardous wastes in the second category. The second category includes liquids which are not under pressure. These hazardous wastes are generally shipped in 55 gallon steel or fiber drums. There are also some smaller steel and fiber drums commonly used to package the liquid wastes in this second category. These smaller drum sizes include those which have a capacity of 5 gallons, 10 gallons, 15 gallons and 30 gallons.

Approximately 65% of the hazardous waste listed in Appendix A have been packaged in cylinders and the rest in large drums. Although none of the hazardous waste listed in Appendix A is packaged in large single unit bulk containers such as a tanker truck, or the smaller fiber and steel drums, these containers must be considered as well. The modeling tools developed must be applicable to the DOE generated hazardous waste with the potential to cause carcinogenic or other adverse health effects. Some of the shipments of hazardous wastes in the HaWRAM database with the potential to cause carcinogenic or other adverse health effects have been packaged in the smaller drums and bulk containers.

3. THE HMIRS DATABASE

The Hazardous Materials Information System database (HMIRS) was developed and is currently maintained by the Research and Special Programs Administration of the United States Department of Transportation. This database contains thousands of records of actual hazardous materials accidents occurring during loading, unloading, temporary storage and transportation. The transportation incidents include enroute accidents by highway, rail, water and air.

Using these data, probability distributions of release fractions resulting from an accident and probability distributions for time of accident (month and hour) will be constructed. These distributions will later be applied in the probabilistic method. Average values of these distributions will be applied to the deterministic model.

3.1. Reporting Requirements

The Hazardous Materials Incident Reporting System (HMIRS) was established in 1971 to fulfill the requirements of the Hazardous Materials Control Act of 1970. General reporting requirements apply to all modes of transport including air, rail, water, and highway. These requirements mandate that if any of the conditions listed in Table 3.1 exist as a direct result of a hazardous materials incident occurring during transportation, the carrier must file a telephonic report at the earliest practical moment and submit a completed written copy of DOT form 5800.1 (see Appendix D) within thirty days.

Table 3.1 Conditions which Mandate HMIRS Reporting

1. As a direct result of hazardous materials -
   - (i) A person is killed
   - (ii) A person receives injuries requiring hospitalization
   - (iii) The estimated property damage exceeds $50,000
   - (iv) An evacuation of the general public occurs lasting one or more hours
   - (v) One or more major transportation arteries or facilities are closed or shut down for one hour or more

(Table 3.1 Continued)

(vi) The operational flight pattern or routine flight of an aircraft is altered

2. Fire, breakage, spillage or suspected contamination occurs involving a shipment of radioactive material

3. Fire, breakage, spillage or suspected contamination occurs involving shipments of etiologic agents

4. A situation exists of such a nature that, in the judgment of the carrier it should be reported though not meeting any of the above conditions.

3.2. The Subset of the HMIRS Database Used in Distribution Construction

As of January 1985, the DOT Research and Special Programs Administration (RSPA) established a rigorous qualification program on incoming copies of the written reports (DOT form 5800.1) to be entered into the HMIRS database. To date, the 1993 data qualification is not complete. The 1985 - 1992 subset of the HMIRS database has therefore been selected as the data set from which to construct probability distributions of release fractions and time of accident. However, the 1985-1989 data are not as descriptive as the 1990 to 1992 data. In 1990 additional fields of information were added to form DOT 5800.1. As a result, the reports filed during and beyond 1990 are more descriptive of the incidents than those filed prior to 1990. The only additional field added which is useful to this study is called the *PHASE* field. The *PHASE* field identifies whether an accident occurred while enroute, during loading or unloading or while in temporary storage.

The definition of transportation supplied by the Department of Transportation states that loading, unloading and temporary storage are a part of the transportation process. This thesis is only concerned with accidents occurring while enroute. Disaggregating the 1990 through 1992 incidents into enroute and loading/unloading incidents is simply a matter of checking the appropriate fields. However, the 1985 through 1989 data do not identify the phase of transportation. In order to categorize the 1985 to 1989 data into enroute and loading/unloading releases, incidents occurring in the same city as the origin or destination cities are categorized as loading/unloading incidents. This may lead to misclassification of some incidents because enroute accidents can occur in the origin or destination cities and temporary storage incidents may occur in locations other than the origin and destination cities. However, the number of such cases is small.

The scope of this analysis does not include dust dispersion, radiological waste or releases resulting from loading, unloading or temporary storage incidents and is only concerned with highway related incidents. In constructing distributions of release fractions, time of day and month of year, only those events in the HMIRS database satisfying all of the conditions given in Table 3.2 are considered applicable to this study. There are **17,838** incidents in the database satisfying these conditions.

Throughout the remainder of this section, all results and discussion based on events in the HMIRS database are assumed to reflect only those events which satisfy all of the above conditions in Table 3.2.

Table 3.2 Requirements for Incident Inclusion in Sample Space of Events Used to Construct Probability Distributions.

1. Mode of transport used is highway
2. A release of non-radioactive hazardous waste occurred.
3. The released materials are in a liquid or gaseous state.
4. The incident occurred while enroute.

3.3. Containers

In the event of an accidental release of hazardous waste resulting from a truck accident, some fraction of the shipment contents may be discharged. This fraction can range from a value near zero where a small leak from a damaged receptacle on a drum to 100% of a pressurized cylinder's contents bursting out almost instantaneously from a puncture. The actual value of this fraction depends upon the severity of the accident and the type of container used. Some accidents may involve a collision with another vehicle, while others may involve overturning of a truck or even a collision with a train. There are other factors besides the cause or type (overturn, collision, etc.) of accident which affect the accident severity. Table 3.3 gives a list of several factors which may affect the severity of a truck accident.

Table 3.3 Factors Affecting the Severity of a Truck Accident

- Type and severity of accident (collision, overturn, etc.)

• Driver reaction	• Road conditions
• Truck configuration	• Traffic
• Weight of truck	• Weather
• Truck dimensions	• Geography

All of the factors listed in table 3.3 affect the damage incurred by the hazardous waste containers inside the truck. The severity of this damage to the containers can be different in otherwise identical accident conditions for each different container type. For example, a puncture to a pressurized cylinder will usually result in a total release of the cylinder contents whereas a puncture in a 55 gallon drum containing liquids will result in some portion of the contents spilling out depending on the location of the hole and the orientation (standing upright or fallen over) of the drum. Table 3.4 gives a list of container types identified in the HMIRS database.

Table 3.4 lists the possible categories of containers from which to construct distributions of release fractions. Because of limitations in the number records in each of the of the HMIRS data, these categories have been generalized into six categories. Table 3.5 gives a basic description of each of these six categories. Note that each category is identified as package freight or bulk. Bulk containers are large containers which are generally shipped by themselves; for example tanker trucks are considered bulk containers. The DOE generated hazardous waste is rarely shipped in bulk containers, in particular, none of the PIH waste is shipped in bulk containers. Package freight containers are smaller and several of these are generally shipped together on one truck.

Table 3.4 List of Containers Identified in the HMIRS Database

Bulk containers:		
• Tank car	• Steel cylinder tank	• Portable steel tanks
• Cryogenic tank	• Portable rubber tank	
Package-freight containers:		
• Drums	• Pressurized cylinders	• Kegs / Barrels
• Cans	• Aerosol cans	• Flasks
• Jars	• Pails	• Pallets
• Jugs	• Tubes	• Cloth bags (solids only)
• Carboys	• Jerricans	• Bottles

Table 3.5 General Container Type Categories

Category	Descriptions
Small drums (*) (package freight)	Small drums are generally 5, 10, 15 or 30 gallon steel or fiber drums used to transport chemicals in a liquid state. Approximately 79% of the small drum incidents recorded in the HMIRS database involve 5 gallon drums.(*)
Large drums (*) (package freight)	Large drums are generally 55 gallon steel or fiber drums carrying chemicals in a liquid state. Other common sizes include 30, 35 and 50 gallon drums. However, the 55 gallon drums account for more than 92% of the large drum incidents recorded in the HMIRS database. It was found that 35% of the 63 PIH hazardous waste shipments in Appendix A are packaged in large drums (mostly 55 gallon drums).(*)
Pressurized cylinders (*) (package freight)	Pressurized cylinders are generally used to transport gases, compressed gases, or liquefied gases under pressure. Furthermore, hazardous materials packaged in cylinders generally present a greater hazard to human health than materials packaged in other package freight containers. It was found that 65% of the PIH hazardous waste shipments in Appendix A are packaged in cylinders. (*)

(Table 3.5 Continued)

Category	Descriptions
Pressurized bulk containers (bulk)	Pressurized bulk containers include large pressurized cylinders, and cryogenic tanks. Most incidents in the HMIRS database involving these containers are related to releases of hydrogenated compounds or chloride compounds. Although these containers are not used in packaging any of the hazardous waste listed in Appendix A, these containers are used in packaging some of the DOE generated hazardous waste which when released can lead to carcinogenic or other adverse health effects.
Non-pressurized bulk containers (bulk)	Non-pressurized bulk containers include non-pressurized cargo tanks and portable tanks. Although these containers are used for highly toxic chemicals such as anhydrous ammonia, they are most commonly used for fuels and oils. These containers do not apply to the DOE generated hazardous wastes in this study.
Other small containers (package freight)	Other small containers are generally small containers which can be constructed from plastic, glass or metal including bottles, jars, pails and cans. Hazardous materials packaged in these containers generally present a low level of human health hazard. These containers do not apply to the DOE generated hazardous wastes in this study.

(*) The original data supplied by DOE do not always document the container size. Furthermore, when cylinders are packaged inside of drums it is often indicated that the container type is a drum. Therefore it is assumed that any hazardous waste which is in a gaseous state or is a compressed liquid or liquefied gas has a pressurized cylinder as its inner container. Furthermore, because 55 gallons is the most frequently used drum size it has been assumed in this study that all drum packagings are 55 gallons in capacity when no information about the size is given.

3.3.1. Container Requirements

The Title 49, Code of Federal Regulations, Part 172.101 provides precise details on how to determine the acceptability of a container for the packaging of a specific hazardous material offered for transportation. The basis for determining acceptability involves rating individual containers based upon performance in simulated transportation accident scenarios. These performance based tests include drop, leak, hydrostatic pressure and vibration tests. For example, one type of container may leak when dropped from 5 feet while a second type of container will not leak until it is dropped from 25 feet. The second container type will then receive a higher rating. The following section presents the distributions of the six generalized container categories and some discussion specific to each category.

3.4. Release Fractions

One limitation of the HMIRS database is that the total volume or weight of a hazardous material shipped as package freight is not recorded. However, the number of containers shipped for each hazardous material and the maximum capacity of those containers is entered into the database so that the maximum physical capacity for the hazardous material can be calculated. For example, a truck carrying ten 55 gallon drums of chlorine and three cylinders with a maximum capacity of 8 ft^3 filled with anhydrous hydrochloric acid has a maximum capacity of 550 gallons (10 x 55) of chlorine and a maximum capacity of 24 ft^3 (3 x 8) of anhydrous hydrochloric acid.

The records of the HMIRS database also include an entry for the total quantity released of each hazardous material in transit. For each chemical in each record of the database, the release quantity is divided by the associated maximum capacity providing a release fraction. These release fractions have been grouped into the six generalized container categories defined in section 3.2, from which release fraction distributions have been constructed. Figure 3.1 contains the cumulative probability distributions for the drum and cylinder categories and Figure 3.2 contains the cumulative probability distributions for both the pressurized bulk and non-pressurized bulk container categories. Table 3.6 contains some summary statistics from these same distributions.

The package freight distributions in Figure 3.1 have release fractions along the abscissa. These numbers represent the percentage of the maximum physical capacity of the container used to transport any one hazardous commodity which will be released. For example, according to the large drum release fraction distribution, there is a 25% chance that more than 4.5% of the drums capacity will be released and therefore a 25% that more than 2.475 gallons will spill out of a 55 gallon drum (2.475 gallons = 4.5% x 55 gallons). This probability is the same whether the drum is filled to the top or only half way.

Figure 3.1 Cylinder and Drum Container Release Fraction Cumulative Probability Distributions

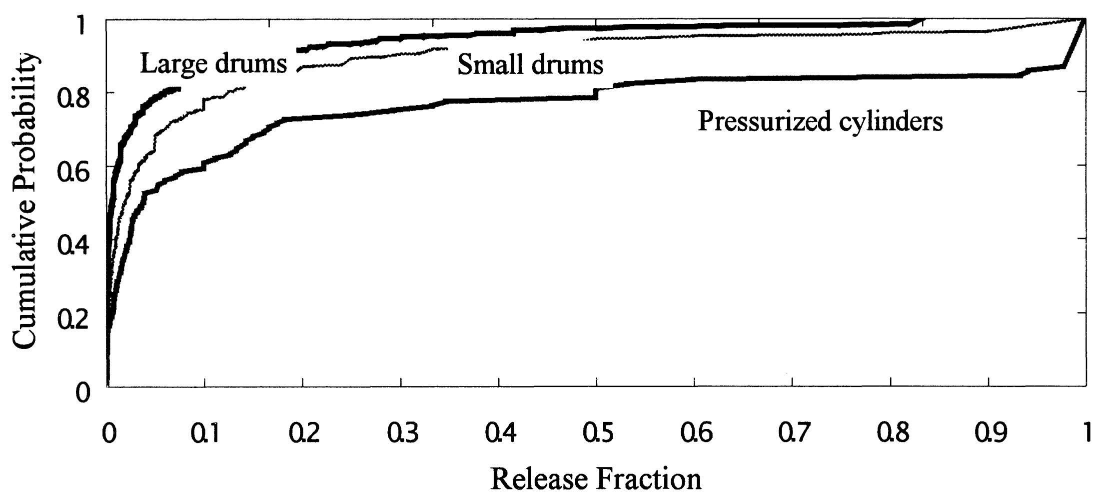
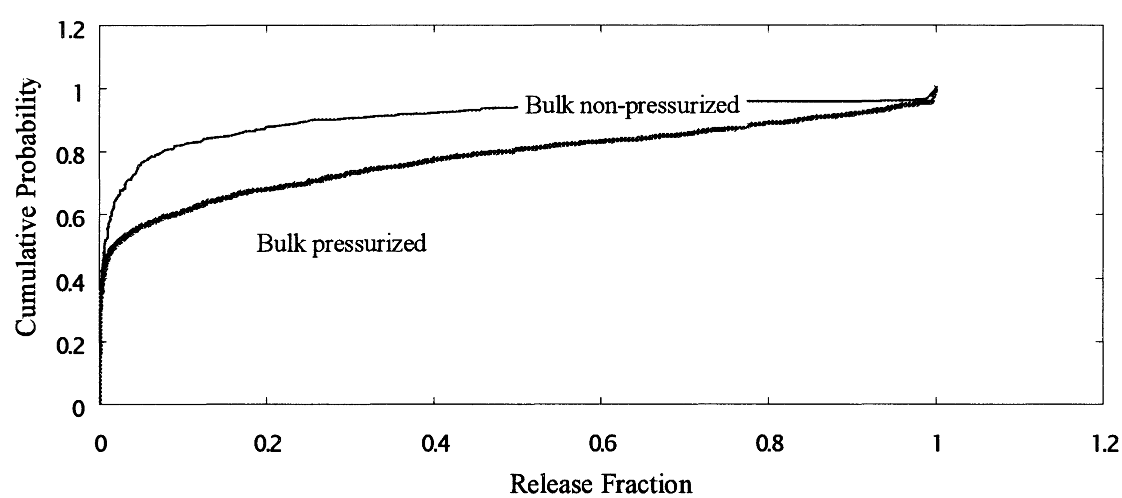


Figure 3.2 Bulk Pressurized and Bulk Non-Pressurized Container Release Fraction Cumulative Probability Distributions.



The records in the HMIRS database relating to <u>bulk container</u> releases record the actual amount shipped instead of the physical capacity of the containers. The bulk container distributions are distributions of the percent of amount shipped which will be released. For example, suppose two identical portable tanks (non-pressurized) with a maximum capacity of 5,000 gallons are filled such that one of them contains 2,000 gallons of hexane and the other 3,000 gallons of petroleum. Using the bulk non-pressure curve in Figure 3.2, it can be seen that there is a 25% chance that more than 34% of the quantity shipped **(not 34% of the maximum physical capacity)** will be released. This leads to a 25% chance that more than 680 gallons (34% x 2,000 gallons) of hexane will be released and 1,020 gallons (34% x 3,000 gallons) of petroleum will be released.

Table 3.6 Summary Statistics for Container Release Fractions

Container Category	Number of incidents	Distribution mean	Cumulative Probability Distribution %-iles: 25th percentile	Median (50th %-ile)	75th percentile
Pressurized bulk[(a)]	353	9%	0.1%	0.7%	4.7%
Non-pressurized bulk[(a)]	1,676	22%	0.1%	1.8%	34.0%
Large drums[(b)]	5,866	7%	0.1%	0.7%	4.5%
Small drums[(b)]	1,603	11%	0.4%	2.0%	9.3%
Pressurized cylinders[(b)]	84	24%	0.8%	3.8%	29.3%

(a) Bulk container distributions are distributions of the percent of the actual amount shipped which will be released.

(b) Package freight distributions are distributions of the percent of the maximum physical capacity of the containers used to ship a hazardous material which will be released.

The data from Table 3.6 is obtained from the distributions plotted in Figures 3.1 and 3.2. This table shows that for all five distributions the median is located to the left of the mean, that is, these distributions are heavily skewed to the right. The location of the median to the left of the mean results from the fact that most release amounts account for a small fraction of the maximum capacity (package freight) or quantity shipped (bulk); however, a cluster of releases near the 100% release fraction exist in all five distributions. Even in the bulk pressurized container distribution there is a 3.4% chance that 100% of the contents will be released. For example, consider the pressurized cylinder distributions. There is a 13% chance that 100% of the maximum capacity is released and a 50% chance that less than 3.8% of the maximum capacity is released. This 13% chance of 100% of the maximum capacity being released pulls the mean of the distribution to the right of the median skewing the distribution to the right.

Figure 3.1 shows that cylinders generally release a higher percentage of their maximum capacity than drums. This should be expected since the pressure inside cylinders is generally higher than it is in drums, resulting in higher release rates. Small drums generally release a higher percent of their capacity than large drums. There are several potential reasons for this. The most dominant reason is that smaller drums are much more likely to be filled to their maximum capacity more often than large drums.

It may seem peculiar that the distributions have such low means, especially for cylinders. It seems reasonable to expect that when cylinders release their contents, the average fraction released would be close to 1. However, most of the cylinder-related incidents involve small releases from a leaky valve. When drums are used to package liquids, overpacks are placed around the drums which have the ability to absorb liquids which have been released. Many of the drum releases involve leaks from a damaged receptacle or spills where a portion of the released quantity is absorbed in the overpacking.

Bulk containers exhibit the opposite behavior of the drums and cylinders. The bulk pressurized containers generally release a smaller fraction of their maximum capacity than the bulk non-pressurized. This results from the construction of the bulk pressurized containers. A large portion of these containers are cryogenic cargo tanks. Cryogenic tanks are constructed by placing a steel vessel within another steel vessel. Each of these vessels is comparable in sturdiness to a typical non-pressurized bulk container. In order for a release to occur, both vessels must be damaged. The cumulative probability distributions for the bulk container release fractions are given in Figure 3.2.

The cylinder and large drum distributions in Figure 3.1 are applied to the probabilistic method in Chapter 5 and their averages in table 3.6 are applied to the deterministic method in Chapter 4. The small drum and bulk probability distributions in

Figures 3.1 and 3.2 respectively, will be applied when this study is extended to include the carcinogenic and other adverse health effect end-points.

3.4.1. Application Uncertainty

In both the probabilistic and deterministic methods, the probability distributions of release fractions will be applied to determine the amount of hazardous waste released when a release is modeled. When the containers used are package freight containers there is a conflict. The shipment data supplied lists the actual quantity shipped and the maximum physical capacity is not always known. The release fraction probability distributions constructed from the HMIRS database which are applicable to package freight containers are based upon maximum physical capacity. For the purposes of continuing with the development of the modeling tools this thesis is to supply, release amounts have been modeled in both the deterministic and probabilistic methods by applying the maximum physical capacity release fractions to the actual amounts shipped. This will result in an artificial reduction in the calculated risks numbers.

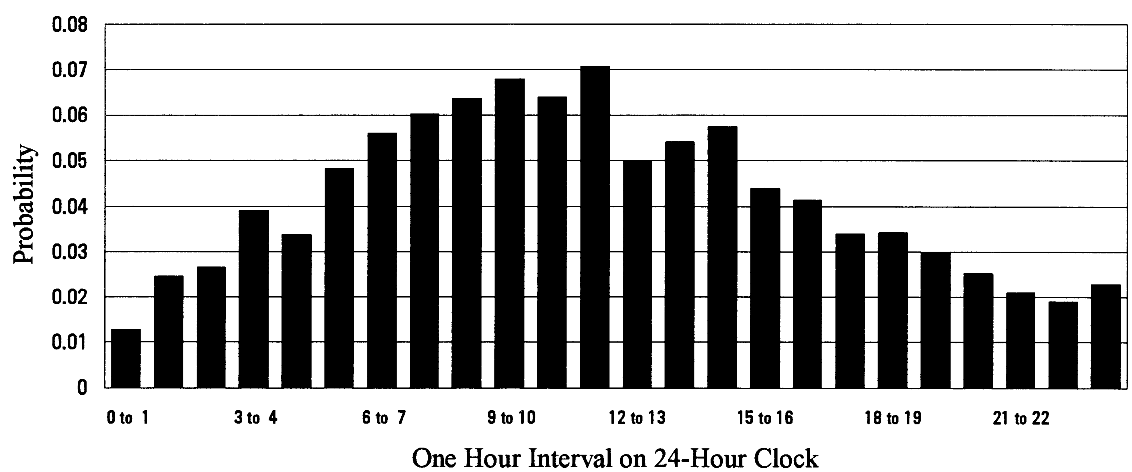
However, future improvements will include recalculating the deterministic results and reconstructing the risk distribution resulting from the probabilistic method using the assumption that any unknown package freight container size has a 55 gallon capacity. This assumption will allow for the determination of the maximum physical capacities for each chemical in each shipment and subsequently more accurate results.

Also it should be noted that many of the release incidents in the HMIRS database are releases of hazardous waste generated in private industry or other agencies which have no association with the U.S. Department of Energy. Hazardous waste produced by these agencies which are not affiliated with DOE may not be entirely representative of the DOE waste in terms of performance capabilities of containers used to package their waste. For example, there are several hundred releasing incidents in the subset of the HMIRS database applied to this study which involve paint related chemicals shipped in 55 gallon drums. Keep in mind that not all 55 gallon drums perform at the same level (see section 3.3.1) and overpacks which provide additional protection against releases may or may not be used depending upon the regulations for the chemical of concern. As a result, the release fraction distributions may be a bit conservative.

3.5. Time of Accident (Month and Hour)

This section contains a description of the probability distributions of the time period in which a truck accident involving a release of hazardous waste may occur. These distributions include the hour of the day and the month of the year. These distributions are given in Figures 3.3 and 3.4 .

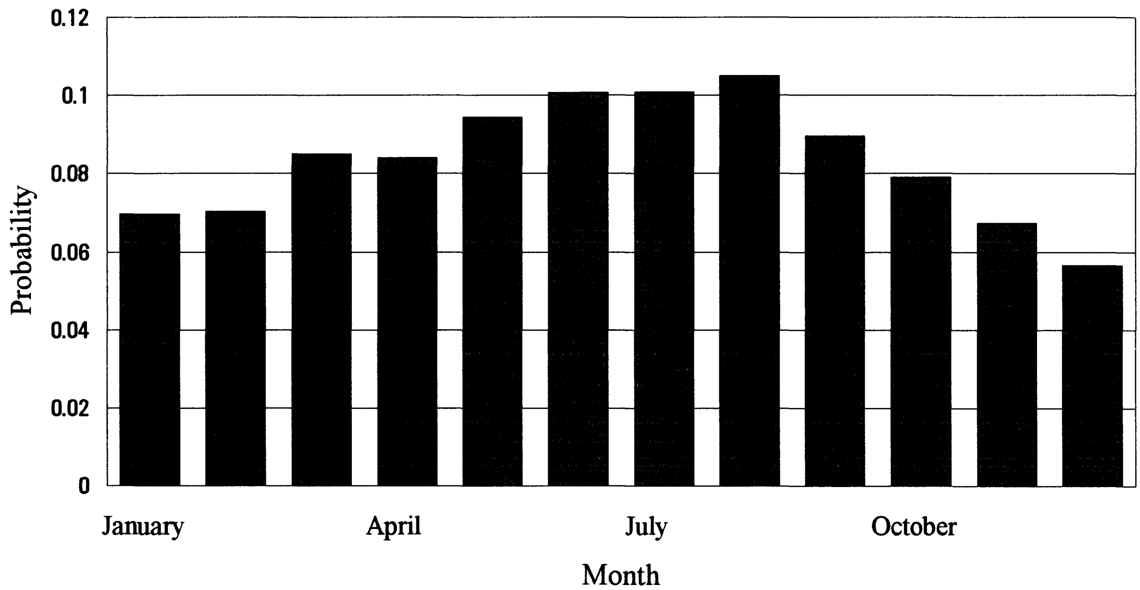
Figure 3.3 Probability that a Release of Hazardous Materials Resulting from a Truck Accident Occurs in a Given Hour.



The distribution of accidental releases by hour of day is broken up into one hour time intervals on a 24 hour clock where the hour 0 to 1 represents the hour from midnight to 1 A.M.. This distribution indicates that releases are less frequent during nighttime hours. This is most likely a direct result of the fact that truck and traffic volumes are lower at night.

The distribution of releases by month indicate that releases are more frequent in the warmer months than in winter time. Again, this is most likely a result of higher traffic volumes in the spring and summer months.

Figure 3.4 Probability that a Release of Hazardous Materials Resulting from a Truck Accident Occurs in a Given Month.



Appendix E contains other results from the HMIRS database including a description of the algorithm used to construct a cumulative probability distribution from a sample of release accidents. The distributions and results presented in this section and in Appendix E have applications in studies similar to this thesis. One example is the determination of downwind protective action distances from a transportation accident. The Research and Special Programs Administration of the United States Department of Transportation publishes the *Emergency Response Guidebook* [6] for emergency response personnel who are responsible for protecting people near an accident site where hazardous materials, which produce poisonous effects when inhaled, have been released. The Guidebook allows for emergency response personnel such as firemen and policemen to quickly and easily determine protective action distances based upon the chemical released, general container size, and daytime/nighttime release period.

4. THE DETERMINISTIC METHOD

This section contains a detailed discussion about the deterministic method including input parameters, model algorithm and a summary of results. Section 4.1 thru 4.4 discuss the risk formula and each of its parameters. Section 4.5 gives a detailed case study in which the risk associated with one of the shipments in Appendix A is determined using the deterministic method. Detailed results of the annual risk associated with the 63 potentially life-threatening DOE shipments of hazardous waste listed in Appendix A calculated based upon the deterministic method are given in Appendix F. No discussion of those results are given in Appendix F. A discussion will be presented in chapter 6 where they are compared against the results of the probabilistic method.

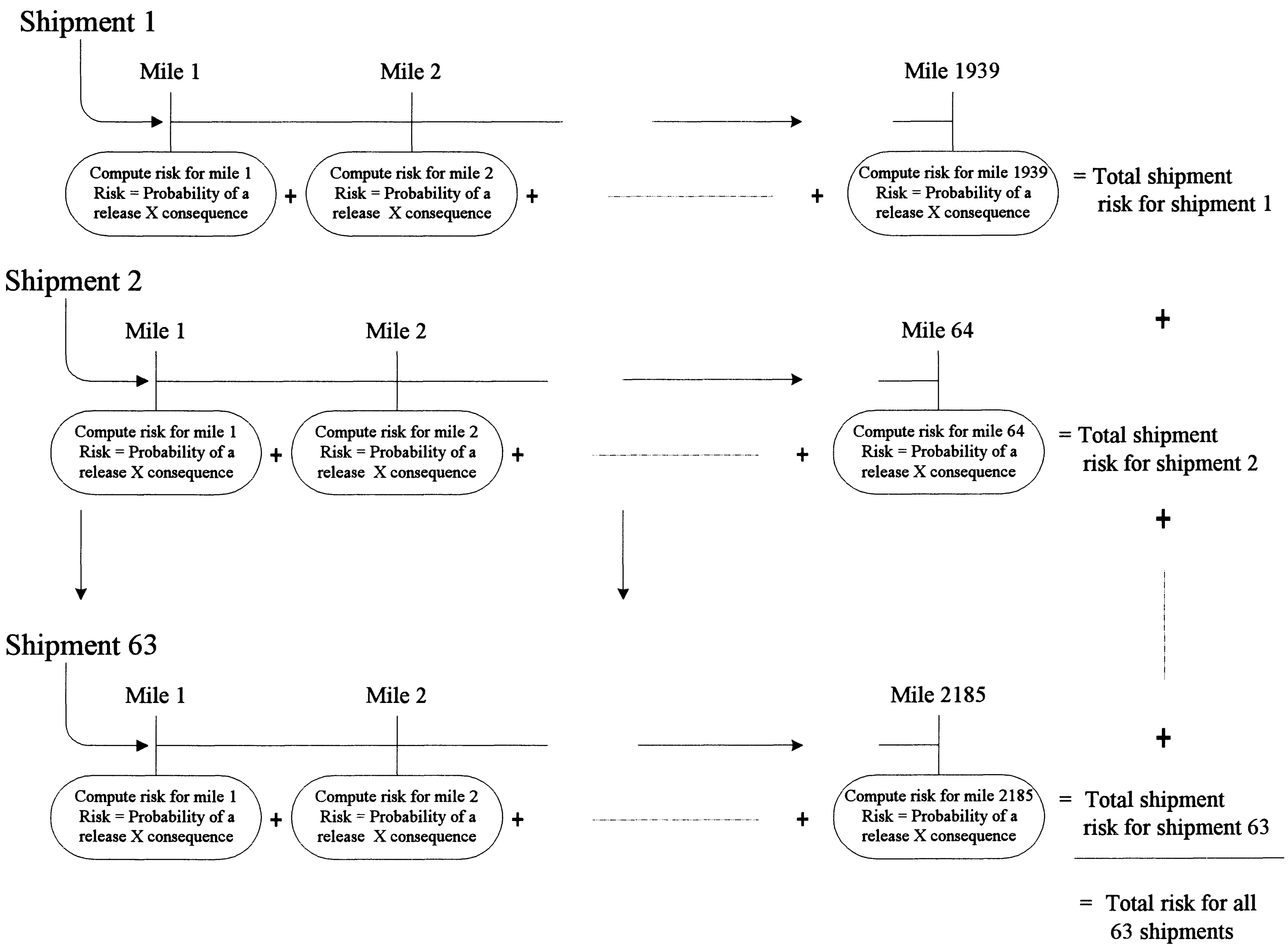
4.1. The Risk Formula

The risk associated with the transportation of one shipment of hazardous materials at any given point along the route traveled is defined as the product of the probability of a release at that point multiplied by the resulting consequence (fatalities are the only consequence within the scope of this thesis). The individual shipment risk is then computed by dividing the route traveled into 1 mile segments, computing risk at one point in each segment and summing these point risks. Finally, the annual risk is taken as the sum of the individual shipment risks. This process defines the annual risk formula shown in Equation 4.1. Figure 4.1 depicts this process graphically to facilitate your understanding.

$$RISK = \sum_{s}\sum_{p}\underbrace{\left(AR_p \times PR_s\right)}_{\text{Probability of Release}} \times \underbrace{\left(EA_s \times PD_p\right)}_{\text{Consequence}} \qquad \textbf{\textit{(Equation 4.1)}}$$

The **s** subscript denotes the shipment number. Any factor in the equation 4.1 whose value depends on shipment contents is subscripted by the **s**. **s** ranges from 1 to 63 for the 63 potentially life-threatening DOE shipments.

Figure 4.1 The Deterministic Calculation Process



The **p** subscript denotes the p-th mile along the route traveled for the s-th shipment. Any factor in the risk equation whose value depends upon population densities or demography at a specific mile is subscripted with the **p**. **p** ranges from one up to the number of miles for the route traveled.

AR_p denotes the accident rate at the p-th mile. This value is a function of demographic region. These regions are rural, suburban and urban.

PR_s denotes the conditional probability of a release given an accident. The conditional release probability is a function of packaging type (package freight or bulk). Package freight containers are generally 55 gallon drums filled with liquids or cylinders filled with compressed liquids, gases or liquefied gases whereas bulk containers are generally large portable tanks or tanker trucks.

EA_s denotes the exposed area resulting from a release. This area is modeled from shipment data assuming fixed meteorological conditions, hour of day and month of year.

PD_p denotes the population density at the p-th mile. Population densities are attained from predicted routes.

4.2. Accident Involvement Rates

A cross classification study conducted in California **[2]** is the only known source of information that accurately matches accident data and corresponding shipment miles for selected sites statewide to generate accident involvement rates by demographic category and truck configuration. These rates are given in Table 4.2.

As mentioned before, the HaWRAM database does not provide details of truck configuration. However, the DOE hazardous waste is shipped predominantly in consignments of multiple drums with maximum capacities of each drum less than or equal to 55-gallons. These types of shipments are conveyed mostly in single-unit trucks. Therefore, only the single-unit truck configuration accident rates have been employed in the deterministic calculations.

Table 4.2 California Accident Involvement Rates, 1979-1983

	Accident rates per million vehicle miles traveled (VMT)					
Truck Configuration	Rural freeway	Rural non - freeway	Suburban* freeway	Suburban* non - freeway	Urban freeway	Urban non - freeway
Single unit	0.56	0.68	0.79	0.86	1.01	1.04
Single-trailer combination	0.94	1.91	1.56	1.97	2.18	2.03
Double-trailer combination	1.18	1.63	1.41	3.48	1.63	5.33
All configurations	0.90	1.49	1.19	1.57	1.48	1.64

* Suburban accident rates are not given by Graf and Archuleta **[2]**. They have been computed by averaging the rural and urban accident rates.

Additionally, only the freeway accident rates have been used in the deterministic calculations. The Federal motor carrier safety regulations demand that unless no practical alternative exists, hazardous materials be transported over routes which do not go through or near heavily populated areas, places where crowds are assembled, tunnels, narrow streets or alleys. Furthermore, DOE facilities are generally located in rural areas. This suggests that in the urban and suburban categories, the ratio of nonfreeway to freeway miles is very small or zero. Examining the HIGHWAY 3.1 program output from the 37 unique routes applicable to the 63 DOE potentially life-threatening shipments, indicates that this assumption is correct. In fact, after examining these routes, it is apparent that the majority of the miles traveled in all 37 routes is comprised of rural freeway miles. Most routes had in excess of 900 rural freeway miles and less than 5 miles of rural nonfreeway travel. It is therefore assumed that the impact of delineating the HIGHWAY output into freeway and nonfreeway mileage for the purpose of applying appropriate accident rates is negligible and only freeway, single-unit truck configuration accident rates have been applied to the risk calculations.

4.2.1. Accident Involvement Rates vs. Probabilities of an Accident

Discrete probability is generically defined as the ratio of the number of desirable outcomes over the total number of potential outcomes. The accident involvement rates presented in Table 4.2 are estimators of the actual probabilities of an accident where the number of potential outcomes is served by the number of miles in which an accident could occur and the desired outcomes are served by the number of miles in which an accident did occur. The accident rate in any one of the three general population zones is then an estimate of the probability of an accident in any one mile of travel in that population zone.

It is crucial to realize that the probability of more than one accident occurring during the course of transporting one shipment from its generation point to its treatment and/or disposal facility is negligible. A discussion about this probability is presented in Appendix C.

Another important and interesting result is that for these 37 HIGHWAY predicted routes, a good approximation to the probability of exactly one accident occurring along the entire route traveled from the generator to the disposal facility, in any one population zone, is obtained by multiplying the number of miles traveled in that population zone by the appropriate accident rate. For example, suppose a route consists of 10 rural miles, 10 suburban miles and 10 urban miles. The approximate probabilities of exactly one accident occurring along the entire route for this example, in each of the three generalized population zones, are given below -

(i) Rural population zone: 10 x 0.56E-6 = 5.6E-6

(ii) Suburban population zone: 10 x 0.79E-6 = 7.9E-6

(iii) Urban population zone: 10 x 1.01E-6 = 1.01E-5

A thorough discussion about these approximate probabilities is presented in Appendix C.

4.3. Probability of a release given an accident

The Federal Highway Administration (FHWA) truck accident database, maintained by the Office of Motor Carriers, contains descriptive data of nationwide accidents involving motor carriers of property subject to Title 49, Code of Federal Regulations, Part 394. This database allows for accident categorization by package type and flags whether or not a release occurred. Table 4.3 gives the probability of a release given an accident by package type. These conditional probabilities, based on the FHWA truck accident database, have been calculated by dividing release counts by accident counts for each of the package types.

Table 4.3 Probability of a Release Given an Accident by Cargo Type

Data based on 1984-1985 FHWA-reported truck accidents			
Cargo Type	Number of Accidents	Number of Releases	Release probability given an accident
General Freight	741	61	0.082
Gases in Bulk	259	21	0.081
Liquids in Bulk	1,831	345	0.188
Solids in Bulk	40	12	0.300

4.3.1. Applying the Conditional Release Probabilities to the DOE Shipments

All of the hazardous waste listed in the DOE shipments in Appendix A have been packaged as package freight in drums or cylinders. Therefore only the general freight conditional release probability from Table 4.3 has been applied to this study. The conditional bulk container release probabilities will be applied when the carcinogenic and other adverse health end-points are considered.

One problem with applying the general freight conditional release probability lies in the potential for multiple chemicals to be shipped together in one truck. When truck accidents occur resulting in a release, a fraction of each chemical in transit may be released. On the other hand, a fraction of only one of the chemicals or a few, but not all, of the chemicals in transit will be released. It is assumed that when a release occurs, a fraction of the total quantity of each chemical in transit is released. This assumption may be conservatism in many cases.

4.4. Exposed Areas and the CASRAM Computer Dispersion Model

Exposed area refers to the area covered by a plume with a sufficiently large concentration to cause potentially life-threatening health effects as a result of inhalation. This area is a function of several parameters including meteorological conditions, temporal conditions, fraction of shipment volume released (per hazardous material in transit) and lethal concentration threshold. Conservative or average values are assumed for all of these variables.

One of the difficulties in computing exposed areas, as mentioned in Chapter 2, is accounting for the effects of multiple chemicals being released. The algorithm described in section 4.5.1 has been included in the CASRAM computer model **[1]** which has been used to compute exposed areas for release scenarios involving the DOE shipments in Appendix A. This computer dispersion model includes a source model for determining release rates. The source model and dispersion methodology which CASRAM employs are briefly discussed later in Chapter 5 on the probabilistic method (see Sections 5.2.5 and 5.2.6).

It is assumed that any location within a 100 foot radius of any point on the highway is uninhabited. Exposed areas have therefore been computed using the CASRAM model via numerical integration starting at a location of 100 feet downwind from the release. At each downwind integration step, the three exposure times along with the associated average release rates computed by the CASRAM model, are used to compute three potentially different widths in which the toxicological limits are exceeded. (Recall that exposure times correspond to the 15, 30 and 60 minute toxicological values available in the shipment data for each chemical.) Whichever of these three widths is the largest is used in the incremental area calculation.

4.4.1. Accounting for Multiple Chemical Releases

When an individual is simultaneously exposed to two or more hazardous wastes which act upon the same organ, harmful health effects can result which would not have occurred if exposure occurred individually for each hazardous waste at different times. When modeling a scenario in which multiple chemicals are released, the determination of the width of the plume at each incremental integration step is determined by incrementing the crosswind distance until the inequality given in equation 4.2 fails to be true.

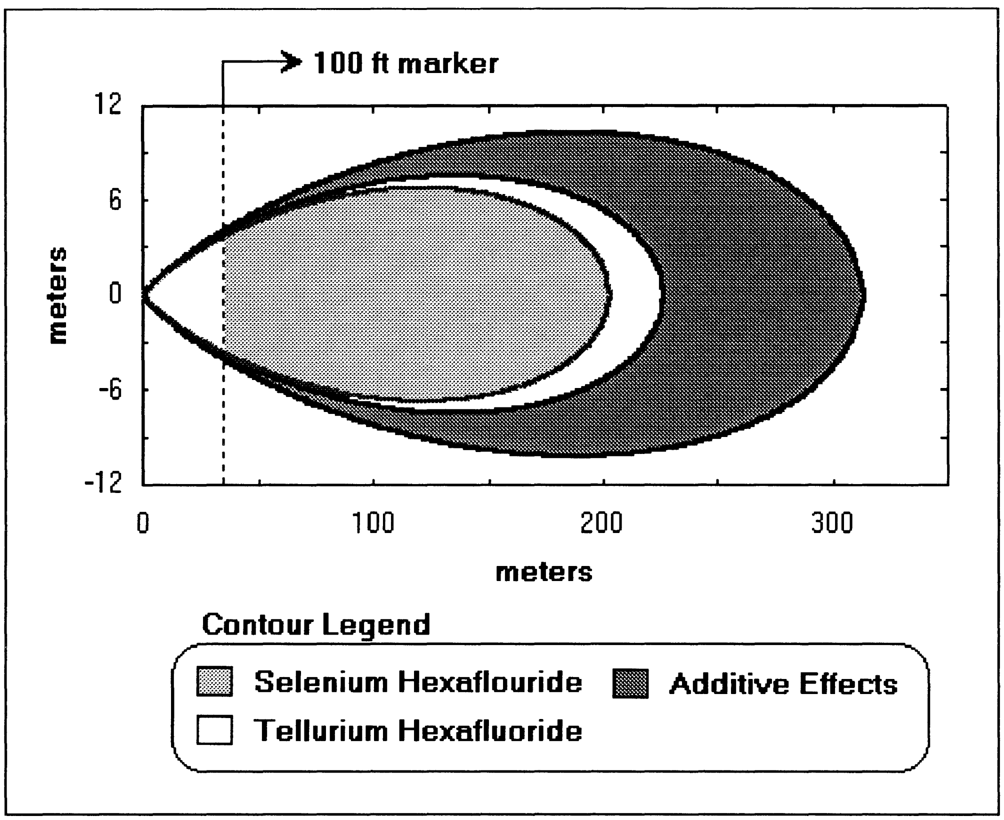
$$\sum_{i=1}^{N} \frac{C_i}{L_i} \geq 1 \qquad \textit{(Equation 4.2)}$$

$\mathbf{L_i}$, in Equation 4.2 represents the concentration threshold (for this study it represents the potentially life-threatening health effects concentration threshold) and $\mathbf{C_i}$, represents the concentration at any particular location (as predicted by a dispersion model such as CASRAM). The summation index, i, is incremented from 1 to N where there are N chemicals released.

Keep in mind that the width at each integration step is computed using equation 4.2 three times. Once for each (exposure time)/(release rate) combination and the largest width is used in the incremental area calculation.

Figure 4.2 shows the results of modeling a one hour, simultaneous release of 10 pounds of selenium hexafluoride and 10 pounds of tellurium hexafluoride. The health end-point under consideration is potentially life-threatening health effects, so that the concentration thresholds for selenium hexafluoride and tellurium hexafluoride are 1 ppm and 0.5 ppm respectively. In the figure, there are three contours. The smallest contour contains an area with a sufficiently large air concentration of ($\geq$ 1 ppm) selenium hexafluoride to produce a potentially life-threatening situation to individuals within the contour. The middle contour contains an area with a sufficiently large air concentration of ($\geq$ 0.5 ppm) tellurium hexafluoride to produce a potentially life-threatening situation for individuals within the contour. If additive effects were ignored, any point outside of the selenium hexafluoride and tellurium hexafluoride contours is designated as a safe location. However, when additive effects are considered, there are additional locations where although the air concentrations of selenium hexafluoride and tellurium hexafluoride are below 1 ppm and 0.5 ppm respectively, the sum of the ratios of the actual concentration divided by the corresponding concentration threshold exceeds unity. These additional locations are contained along with the areas contained in the two smaller contours within the additive effects contour.

Figure 4.2 Plume Contours of Individual and Additive Effects
(Axes Units - Meters)



For each of the 63 shipments of DOE generated hazardous waste listed in Appendix A, all chemicals within one shipment are assumed to be additive. In reality this is not true, however, coding such relationships into the dispersion model can be extremely difficult. As a result, the exposed areas computed by the CASRAM model may be conservative, subsequently leading to potentially conservative risks.

4.5. The Risk Associated with Shipment 53

In this section, the risk associated with the transportation of shipment 53 will be determined. This example will discuss the fine points associated with implementing the deterministic method using the 63 DOE generated potentially life-threatening shipments of hazardous waste. Table 4.4 contains the data for shipment 53.

Table 4.4 Shipment 53

Generator:	Sandia National Laboratory in Albuquerque, NM
Designated Facility:	Rollins Environmental Services in Deer Park, TX

Chemical List:

Chemical Name	Cont. Type	Quantity Shipped	Lethal concentration limits 15 minutes	30 minutes	60 minutes	CAS Number
Ammonia	Cyl	30 lbs	560	280	140	7664-41-7
Boron Trifluoride	Cyl	3 lbs	16	11	8	7637-07-2
Carbon Monoxide	Cyl	15 lbs	560	280	140	630-08-0
Chlorine	Cyl	1 lbs	27	19	14	7782-5-5
Hydrogen Sulfide	Cyl	30 lbs	89	44	22	7783-06-4
Methylamine	Cyl	4 lbs	540	380	270	74-89-5
Phophine	Cyl	3 lbs	4.4	3.1	2.2	7803-51-2
Silicon Tetrafluoride	Cyl	6 lbs	6400	4500	3200	7783-61-1
Sulfur Dioxide	Cyl	2 lbs	330	170	83	7446-09-5

In order to predict the route traveled for this shipment the HIGHWAY 3.1 *Enhanced Routing Model* requires as input the origin and destination cities. This information is supplied in Table 4.4. After inputting this information, the data in Table 4.5 is supplied as output.

At this point we need to be determine the probability of a release and the consequence at each of the 899 miles along the predicted route and add their products. This summation will be the risk for the route. This will be done individually for each demographic region. Afterwards, the risks in each demographic region will be summed.

Table 4.5 HIGHWAY 3.1 Route Summary

Demographic Region	Weighted Average Population Density	Miles Traveled in Region
Rural	12	737
Suburban	112	140
Urban	5790	21
Total	321	899

4.5.1. The Probability of a Release

For every mile traveled in a rural area, the probability of an accident is approximately 0.56E-6 (see Table 4.2). Similarly, for every mile traveled in a suburban area and for every mile traveled in an urban area the probability of an accident is given by 0.79E-6 and 1.01E-6 respectively. Furthermore, all hazardous wastes in the shipment are packaged as general freight and the applicable conditional release probability is therefore 0.082 (see Table 4.3). For every mile in each of the demographic regions, the probability of a release is given in Table 4.6.

Table 4.6 Probability of a Release at Any Given Mile by Demographic Region

Demographic Region	Probability of a Release
Rural	4.59E-8
Suburban	6.48E-8
Urban	8.28E-8

4.5.2. Consequence

The consequence is determined by taking the product of the population density at each mile multiplied by the associated exposed area at that mile. For each mile in any one of the three demographic regions, the population density is approximated by a constant whose value is given above in Table 4.5. These values are weighted average population densities computed by the HIGHWAY 3.1 *Enhanced Routing Model*.

The exposed areas are calculated using CASRAM. The inputs parameters which it requires and the values which have been used in the application of the deterministic model to the 63 shipments of PIH hazardous wastes listed in Appendix A are given below -

1. Chemical List in Table 4.4 - Actual shipment data

2. Wind Speed (**4 m/s**) - Average wind speed around the continental United States

3. Ambient Temperature (**35° C**) - Conservative temperature

4. Stability Class (**D**)- Average stability around the continental United States

5. Release Fraction per Chemical Capacity - The release fraction is used to determine how much of the chemical is released given the maximum physical capacity of the containers used to package the chemical. Table 3.6 in the chapter on the HMIRS database gives a list of average release fractions based on capacity for a chemical shipped in a specific container type. Keep in mind that chemical capacity refers to the maximum amount of chemical that can be shipped within a set of containers. It does not refer to the actual quantity shipped. For example, suppose a total of ten gallons of bromine is shipped such that 5 gallons are packed in each of two different 15 gallon fiber drums. The maximum physical capacity would be 2 X 15 gallons = 30 gallons, even though the actual quantity shipped is only 10 gallons. All hazardous waste for this shipment (shipment 53) is packaged in cylinders so that the applicable release fraction will be 24%. Note, if a container is packaged with less than the appropriate release fraction, a release will be modeled with more being released than physically possible. For example, a 55 gallon drum filled with 2 gallons of chlorine be modeled as releasing 7% X 55 = 3.85 gallons. This type of situation may never occur because the release fractions are small.

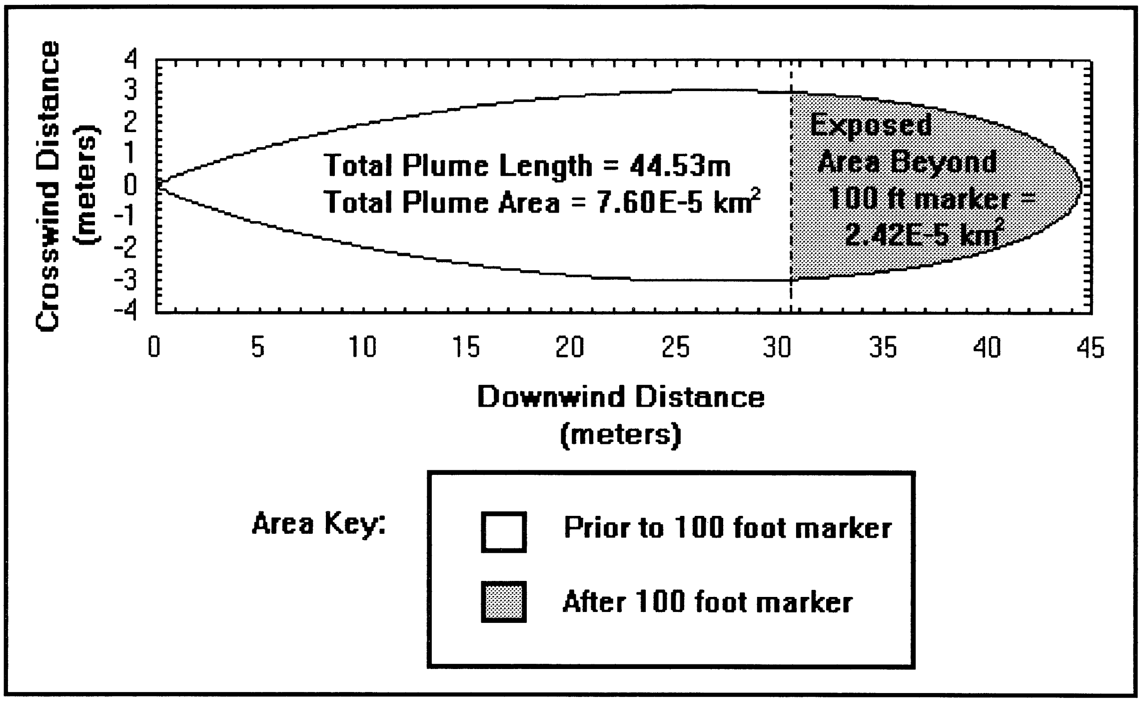
The shipment data does include the exact container size or the number of containers used. Therefore the maximum physical capacity for each of the ten chemicals in this shipment cannot be computed. The average release fractions have been applied to the actual quantity shipped for each chemical. As a result of this, predicted release amounts may be under estimated. This issue was discussed in section 3.4.1.

For the deterministic method, all location related information is constant. Any CASRAM model parameters which are location dependent or location related will therefore be constant for all shipments. Therefore, all exposed areas for this shipment will be the same irrespective of where along the route the accident occurs. In the probabilistic model, distributions of meteorological conditions, time and location will be recognized resulting in location dependent exposed areas. For this particular case the exposed area to be used at all locations along the route is given in Figure 4.3. Furthermore, routes are described by a total mileage count and an associated average population density in each of the three generalized population zones (rural, suburban and urban) and the probability of a release is a constant within each of the generalized population zone. As a result, the product of consequence multiplied by probability of a release is a constant within each of the generalized population zones. Therefore, risk can be computed by summing the three products of (probability of a release) x (consequence) x (total miles in population zone) where the probability of a release and the total miles are a function of population zone. The risk calculation for this shipment is shown below. Note that some unit conversion was necessary to compute the risk and these conversions are not shown.

$$\text{Risk for Shipment 53} = \sum_{i=1}^{N} \left(PR_i[\text{Release}] \times Cnsq_i \right)$$

$$= \sum_{p=\text{rural, suburban or urban}} \left(PR_P[\text{Release}] \times Cnsq_P \times M_P \right) = 1.07E\text{-}7,$$

Figure 4.3 Exposed Area for Shipment 53



4.6. Interpreting the Results of the Deterministic Method

The calculated shipment risk in Figure 4.2, 1.07E-7 people, represents an approximation to the mean or expected value of the distribution of potential outcomes or consequences which result from transporting hazardous waste, and the annual risk is then the sum of the expectations of the the distributions of consequences for each of the shipments of hazardous waste shipped during the year. Appendix C develops shows a mathematical developement of this approximate expectation.

5. THE PROBABILISTIC METHOD

This section illustrates the methodology and operating procedures of the probabilistic model. The goal of the application of this model is to produce one cumulative probability distribution of number of people with potentially life threatening health effects due to the transportation of the 63 shipments of DOE generated PIH wastes (see Appendix A). This distribution will be denoted as PLTHE. The model is based upon a Monte Carlo algorithm which is used to produce, for each shipment of concern, a cumulative probability distribution of consequence given that a release occurs during the course of transporting a shipment of hazardous waste on public highways from its generation point to a designated disposal and/or treatment facility. For this application there are 63 potentially life-threatening shipments of DOE generated hazardous waste under consideration (see Appendix A). Therefore, 63 cumulative probability distributions of consequence given a release have been developed using a Monte Carlo algorithm. To obtain the PLTHE, Monte Carlo techniques are again employed using each of the individual 63 shipment distributions as input, ultimately providing a single cumulative probability distribution (the PLTHE). This process will be explained in detail in the remaining sections of this chapter.

5.1. Introduction to Monte Carlo Algorithms

In general, Monte Carlo techniques are often employed to produce a cumulative probability distribution for a random variable Y, whose cumulative probability distribution is unknown and where this random variable is a function of one or several random variables X_0, X_1, ..., X_n, whose probability distributions are known. Furthermore, the function which maps the random variables X_0, X_1, ..., X_n to Y must be known as well.

For example, the consequence of a release of hazardous waste occurring as a result of a truck transportation accident is a stochastic random variable and is a function of several parameters, each of which is listed below in Table 5.1. There are three columns in Table 5.1. Column 2 flags whether or not the variable is treated stochastically in the determination of the 63 cumulative probability distributions of consequence given a release and column 3 identifies that the stochastic variable is dependent upon the values of other listed stochastic variables.

Table 5.1 Input Parameters for the Determination of Consequence Given a Release

Input Parameters	Stochastic?	Stochastic dependency upon other input parameters
Location	NO	Not applicable, variable not stochastic
Chemical data	NO	Not applicable, variable not stochastic
Population density	NO	Not applicable, variable not stochastic
Health criteria(1)	NO	Not applicable, variable not treated stochastically
Release fraction	YES	Container type - different distribution for each type
Spill cover area(2)	YES	Physical state - Only applicable to liquid spills
Time	YES	None
Date	YES	None
Meteorology	YES	Time, Date and Location

(1) **In reality, health criteria is stochastic, however, this variation is beyond the scope of this thesis and has been treated deterministically.**

(2) **The spill coverage area is only applicable if the chemical is initially released as a liquid.**

The function which maps the input parameters in Table 5.1 to consequence given a release is simply the product of $EA \times PD$, where EA is the exposed area computed by the CASRAM computer dispersion model and PD is the population density supplied by the HIGHWAY 3.1 *Enhanced Routing Model.* Note that the CASRAM dispersion model takes as input all parameters listed in Table 5.1, other than the population density.

The Monte Carlo algorithm is implemented by repeatedly choosing values for each of the input parameters, calculating the value of the function based upon the selected input parameter values, and recording the trial calculation. This processes is repeated several hundred or even thousands of times. At each iteration, the selection of the input parameter values reflects their respective distributions. The process of selecting a value for the input parameters, will be referred to as sampling throughout the rest of the text.

The result of this repetitive process will be a distribution of values from which a cumulative probability distribution may be approximated. Appendix E discusses an algorithm for constructing a cumulative probability distribution from a set of values.

Note that the meteorology is stochastic and is dependent upon other stochastic parameters (time and date). The implication is that the Monte Carlo algorithm employed must be capable of sampling in a manner which accounts for the stochastic dependence of random variables.

The remaining sections of this chapter will provide detailed information on the implementation of the Monte Carlo algorithms used to construct distributions of consequence given a release for each of the 63 potentially life-threatening shipments of hazardous waste listed in Appendix A.

5.2. Distribution of Consequence Given a Release

This sections provides additional details on the implementation of the Monte Carlo algorithm employed to construct a distribution of consequences given that a release occurs. Throughout the discussion of the methodology used in this process, it is important to keep in mind that the distributions constructed do not account for the consequence of multiple accidents occurring along one route as the probability of multiple accidents is negligible (see Chapter 4 and Appendix C). The flowchart in Figure 5.1 illustrates the process. The stochastic components have been identified by the "Random $\rightarrow$" notation.

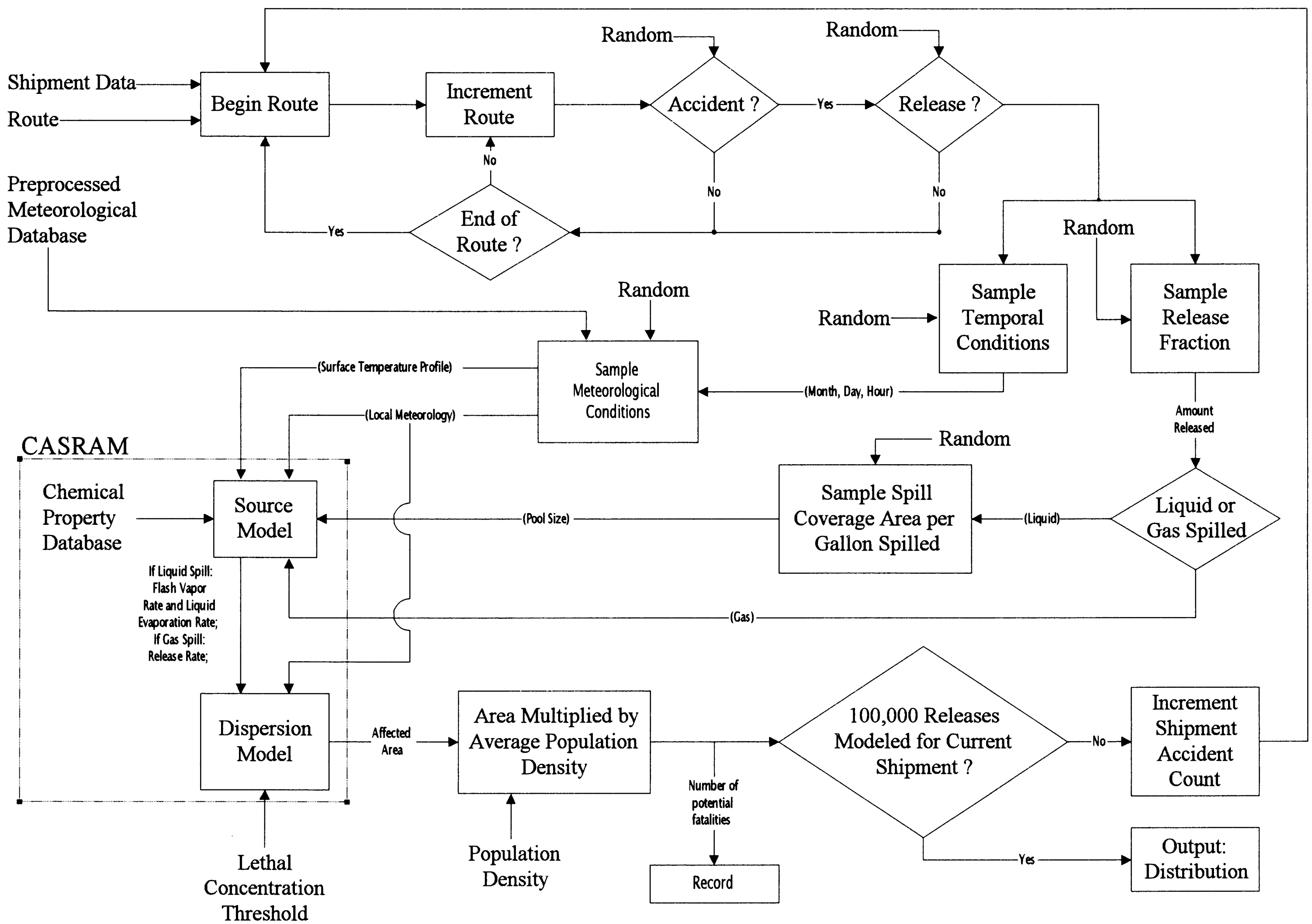


Figure 5.1 Overview of the Monte Carlo Process

As initial data, the model requires the route to be traveled, the shipment contents and the population density at the current location. The model begins by looking at the first location, uniformly sampling a number on the interval [0,1] and determining if an accident occurs based upon the sampled number. If the number sampled is less than the appropriate accident rate (3 possible accident rates - rural, suburban or urban) then an accident occurs. When it is determined that an accident occurs, another random number between zero and one is sampled uniformly. If this number is less than the appropriate probability of a release given an accident then a release occurs, otherwise, the route is incremented to the next location (different latitude and longitude and potentially different population density). When a release occurs, the appropriate sampling of date, time, meteorology, release fraction and spill coverage area (if liquid spill) is performed. Using the sampled values, the source model and dispersion models (CASRAM) are employed to determine the number of number of people experiencing the health end-point under consideration (potentially life-threatening health effects for this thesis). The number of potential impacts (for the health end-point under consideration) is recorded and the whole process starts over. This process is repeated until 100,000 releases have been modeled and recorded.

It is necessary to base the iteration count on releases rather than miles due to the low probability of an accident. It is conceivable that 100,000 miles could be traveled and no release will be sampled. Therefore, to assure a smooth distribution the model continues processing until 100,000 releases have occurred.

5.2.1. Probability of an Accident and Probability of a Release Given an Accident

The probability of an accident is one of three values. There is an associated accident probability at each mile along the route traveled depending upon whether the location is rural, suburban or urban. These three accident probabilities are same values used in the deterministic model (see Section 4.2).

Similarly, the probability of a release depends upon the container type used. These conditional probabilities used are the same as those used in the deterministic method (see Section 4.3). When multiple chemicals are in transit, a potentially different random number between 0 and 1 is uniformly sampled for each chemical included in the shipment. Each of these chemicals is then tested for a release by comparing the appropriate sampled number against the appropriate conditional release probability. Since different chemicals in the same shipment may be packaged in different container types, there could be a different conditional release probability applicable (see Section 4.3) for each chemical.

5.2.2. Sampling Date and Time

The month of the year and the time of day are sampled from the discrete distributions constructed from releasing accidents recorded in the HMIRS database. These distributions are given in the form of a probability histogram in Figures 3.3 and 3.4. and reviewed in tabular format in Tables 5.2 and 5.3.

The sampling algorithm used to determine the month is based upon a random number, call it r, uniformly sampled between [0,1]. For each of the twelve months, an interval whose length is equal to the probability associated with that month, will be assigned. After r, the random number, is uniformly sampled, the month is chosen depending upon what interval r is contained in. For example, suppose r is in the interval [0, 0.070], then the month is January. If r is in the interval (0.070, 0.141], then the month is February. Notice that the left end-point of the interval associated with February is open (not closed) and is equal to the right end-point of the previous month's (January) interval.

Intervals for months following February are defined in a similar manner. The left end-point is open and equal to the right end-point value for the previous month's associated interval. The right end-point is closed and equal to the sum of the left end-point plus the probability associated with that month.

Table 5.2 Discrete Probability Density Function of Month of the Year Given a Release Occurred

Month	Probability	Month	Probability
January	0.070	July	0.101
February	0.071	August	0.105
March	0.084	September	0.085
April	0.082	October	0.078
May	0.095	November	0.068
June	0.101	December	0.057

Sampling for the hour day is done exactly the same as for sampling the month. A random number is uniformly sampled between 0 and 1. This number will fall into one of 24 different intervals, each associated with one specific hour. Each of these 24 distinct non-overlapping intervals will be associated with a specific hour and have a length equal to the probability that the release occurs in the associated hour, given that a release does occur. Once a month is sampled, the day of the month, ranging from 1 to 28, 30 or 31 (depending upon the month), is sampled uniformly.

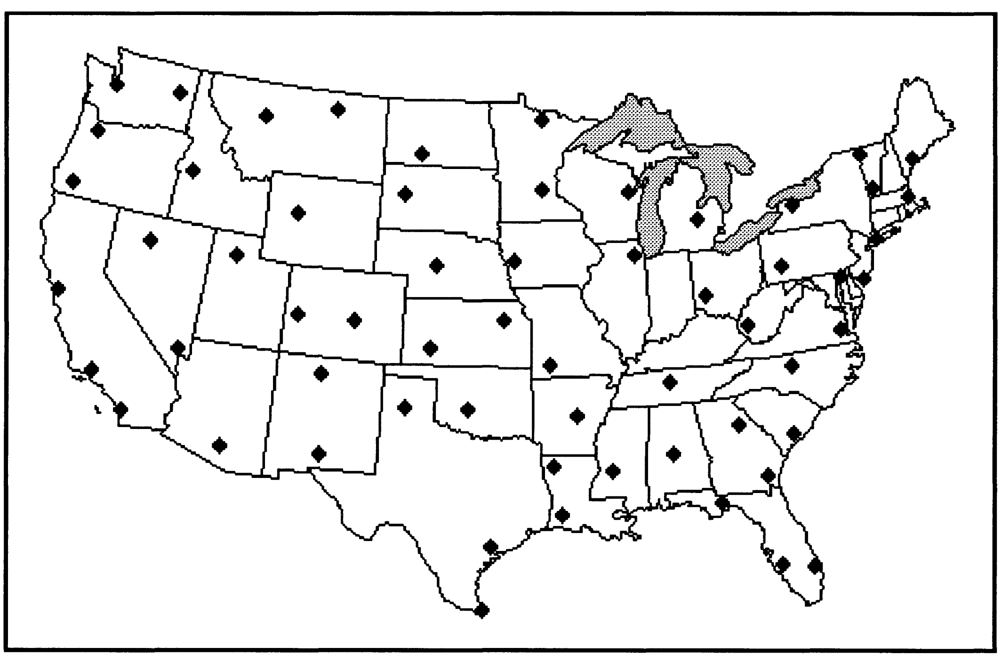
5.2.3. The Meteorological Preprocessor and Sampling the Meteorology

Data from 61 cities well distributed throughout the continental United States (see Figure 5.2) serve to characterize the entire country from a climatological point of view. Two varieties of data are used. The first are surface-airways data which are used to specify the surface turbulence characteristics. These data are organized through the National Solar Radiation Data Base. The second variety are upper-air data. These data are used for specification of the morning temperature profile, necessary for determination of daytime inversion heights.

Table 5.3 Discrete Probability Density Function of Hour of Day Given a Release Occurred

24 Hour Clock Interval	Probability	24 Hour Clock Interval	Probability
0 - 1	0.013	12 - 13	0.050
1 - 2	0.024	13 - 14	0.054
2 - 3	0.026	14 - 15	0.057
3 - 4	0.039	15 - 16	0.043
4 - 5	0.033	16 - 17	0.041
5 - 6	0.048	17 - 18	0.033
6 - 7	0.056	18 - 19	0.034
7 - 8	0.060	19 - 20	0.030
8 - 9	0.063	20 - 21	0.025
9 - 10	0.067	21 - 22	0.021
10 - 11	0.064	22 - 23	0.018
11 - 12	0.071	23 - 24	0.023

Figure 5.2 Distribution of Weather Stations Throughout the Continental United States



Before sampling these data, a meteorological preprocessor takes raw hourly data consisting of wind speed, temperature, humidity and cloud cover measurements, and computes the required meteorological parameters for use in the source and dispersion models. The meteorological preprocessor uses an energy budget model, whereby components of the surface energy budget are parameterized to provide a series of equations which are then solved using the raw meteorological data along with similarity based wind and temperature profiles. For daytime (unstable lapse conditions) the inversion height is calculated using an integral model which relies on the temporal surface turbulence characteristics along with the morning temperature profile. The methods used in the preprocessor represent the state of the art in atmospheric boundary layer characterization and are preferable to the traditionally employed stability class methods.

Given a location and sampled values for the month, day and hour, the most applicable subset of the preprocessed meteorological database is sampled for the necessary values from the four closest cities to the given location. The four sets of sampled values are then interpolated to the current location along the route.

Besides the typically required atmospheric parameters, the meteorological preprocessor must also handle the pavement temperature profile, which is required in the source model. Although the evaporation rate from a pool is a very strong function of its surface temperature, the heat flux from the ground into the evaporating pool is most often the dominant energy source for pool evaporation. As a result of this, accurate determination of the ground temperature profile is important for accurate evaporation estimates because . A ground temperature profile is not computed per se for the source model, but a modified *pavement* temperature profile is computed. The pavement temperature profile differs from a usual ground temperature profile in that the energy balance at the surface does not include evaporation or transpiration from plants. This modification greatly affects the local energy budget, leading to large variations in surface temperature and conductive heat fluxes over those observed on normal ground.

5.2.4. Sampling the Release Fractions

There are five potentially applicable cumulative probability distributions which may be sampled during the Monte Carlo process, depending upon the container type used. The recognized container types include large drums, small drums, pressurized cylinders, pressurized bulk containers and non-pressurized bulk containers.

These five different container types are discussed in detail in Table 3.5. Only the large drum and pressurized cylinder distributions apply to the 63 potentially life-threatening DOE generated shipments of hazardous waste. The algorithms used to sample those distributions is described below.

Sampling from these distributions is done based upon the raw data used to construct the cumulative probability distributions rather than the cumulative probability distributions themselves. The set of release fractions collected from the HMIRS database have been categorized by container type and then sorted within each category in ascending order. Let N_c denote the total number of release fractions (same as number of total incidents) collected for a certain container type. Then within each category, the sorted release fractions are numbered from 0 to N_c-1. Sampling is then done by uniformly sampling a random integer in the range of 0 to N_c-1, where the value of N_c depends upon the container type.

Using the sampled release fraction, a release amount can be calculated. The product of the maximum physical capacity should be multiplied by the release fraction sampled to determine the release amount. Presently, the maximum physical capacities are not always available and release amounts have been calculated by multiplying the actual quantity of hazardous materials shipped by the sampled release fraction. Resulting risks may be under estimated as containers are not always filled to their maximum capacity. However, future improvements to the application of the modeling tools provided in this thesis will include employing an algorithm to estimate maximum physical capacities. It will be assumed that any drums with an unknown capacity, due to lack of information in the HaWRAM database, have a capacity of 55 gallons. Furthermore, any pressurized cylinders with an unknown size will be assumed to have a capacity of 29 gallons. These containers sizes are the most commonly used and generally the largest used in practice as well. Because 29 gallon cylinders and 55 gallon drums are generally the largest sizes for cylinders and drums, resulting risk calculations to be included in future improvements, when these container size assumptions are employed, may be conservative.

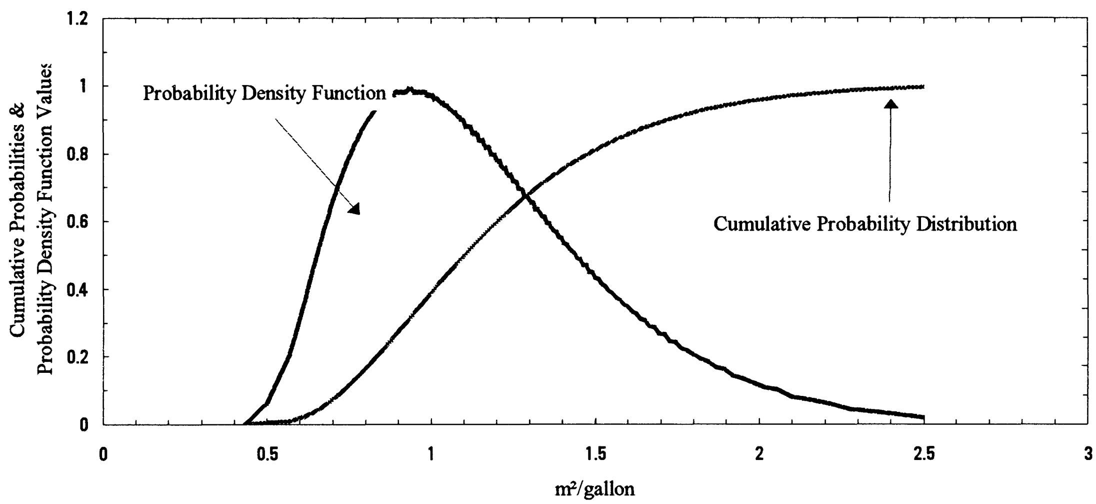
It should be noted that when multiple chemicals are released a release fraction is sampled for each released chemical.

5.2.5. The Spill Coverage Area and Sampling from its Probability Density Function

When a liquid is released, it forms an evaporating pool on the ground, thus releasing the material into the atmosphere. In determining the release rate, the pool size is an important factor because the evaporation rate is directly proportional to the pool size. Unfortunately, models for estimating pool size are not well developed. Additionally, the few existing models either require chemical data that are often not available or yield unrealistically large pool sizes. Adding to this problem is that pool-size data are practically non-existent.

Due to the lack of acceptable techniques, an entirely heuristic scheme for estimating pool size is employed. By considering a few representative chemicals for which data were available, estimates of the equilibrium pool thickness on a flat surface have been derived. These estimates all yielded a unit coverage area of approximately 1 m^2/gallon. However, few spills occur on flat, uniform surfaces, and an arbitrary distribution has therefore been developed to account for a large variation in surface porosity and slope. This distribution is shown in Figure 5.3. The large tail on the distribution is required to model the few cases where the liquid is spilled on strongly sloped, non-porous surfaces. These cases would exhibit large pool areas and consequently, large evaporation rates.

Figure 5.3 Cumulative Probability and Probability Density Functions of Unit Liquid Spill Coverage Area (m^2/gallon)



5.2.6. The Source Model

The source model uses the amount spilled, chemical property data and information sampled from the meteorological preprocessed database to determine the release rates for the spilled chemicals. Two types of releases are considered in the model. For gases, liquefied gases or liquids whose boiling point is below the pavement surface temperature, the released quantities are assumed to be released instantaneously. For cases when the pavement temperature is between zero and ten degrees above the boiling point, some liquid will flash and the rest will form a pool. Due to lack of available data, all released liquid which is not flashed is assumed to form a pool on the pavement surface. Undoubtedly, this does not always occur in real accidents. The implications of this assumption will be more thoroughly explored in section 5.4.

The time dependent evaporation rate from the pool is estimated using a sophisticated energy balance technique. Average evaporation release rates are computed for 15 minute, 30 minute 60 minute time periods. These release rates are simply the amount of material evaporated up to that time divided by the respective time period. If all of the chemical which is spilled evaporates before the 60 minute time period has expired, the evaporation model is terminated, and the release rates for the remaining time periods are simply given as the amount spilled divided by the respective time period.

5.2.7. The Dispersion Model

The dispersion model uses local meteorology data and chemical release rates to determine the area in which the toxicological limits are exceeded. The concentration downwind of the source is determined using a similarity-based method which utilizes non-dimensional relationships for the ground-level crosswind-integrated concentration together with relations for the horizontal plume spread. This method is superior to the Pasquill-Gifford-Turner curves since it appropriately accounts for the atmospheric boundary layer's physical structure and continuously relates the meteorological parameters to the downwind concentration estimates (i.e. no discretization into stability classes). Furthermore, model predictions agree well with a wide variety of field studies, most notably the Prairie Grass Dispersion Experiments. Besides standard plume releases, the dispersion model also has the capability of treating puff releases. Such capability is required since gaseous and flashed liquid releases are instantaneous (forming a puff), whereas evaporation from a liquid pool is continuous (forming a plume). For a more thorough description of the dispersion methodology, the reader is referred to *Statistical Determination of Downwind Concentration Decay* **[1]**.

Note that when multiple chemicals are released, the methodology to account for additive effects is exactly the same as presented in Section 4.4.

5.3. Constructing the PLTHE

Section 5.2 discussed the methodology and operating procedures for determining a cumulative probability distribution of consequence given that a release occurs for any one shipment. This section provides an approach for building upon that method by using the cumulative probability distributions of consequence produced for each shipment, to construct a single cumulative probability distribution representative of all shipments (the

PLTHE). This remainder of this section will discuss the approach used in three steps, numbered 1, 2 and 3 below.

1. For each cumulative probability distribution of consequence given that a release occurs (there are 63 cumulative probability distributions resulting from applying the Monte Carlo process described in section 5.2 to the 63 potentially life-threatening shipments of DOE generated hazardous waste listed in Appendix A), an unconditional cumulative probability distribution of consequence must be determined. The term unconditional here means that a cumulative probability distribution of consequence will be derived given that the shipment is transported on public highways. Since the release condition is not a given, the probability of a consequence of zero is magnified greatly because the probability of a release is so small. The main idea here is that instead of assuming a release occurs somewhere along a route and determining the cumulative probability distribution of consequence, we now simply assume a truck transporting hazardous waste is shipped along a route consisting of public highways. We now examine the cumulative probability distribution of consequence given that the truck is traveling along that route. Doing so, the probability of a release needs to be factored into the cumulative probability distribution of consequence given that a release occurs.

2. Define the random variable $Y = X_1 + X_2 + \ldots + X_N$, where X_i is a random variable whose cumulative probability distribution is represented by the unconditional cumulative probability distribution of consequence for the i-th shipment of hazardous waste. Note that for the application of the risk assessment of the baseline potentially-lethal shipments of DOE generated hazardous waste, N=63.

3. Use another Monte Carlo algorithm to determine the cumulative probability distribution of Y. Note that Y will represent the cumulative probability distribution of the sum of the shipment risks random variables, hence the random

variable Y represents the annual risk and Y's cumulative probability distribution represents the cumulative probability distribution of the annual risk.

5.3.1. Step 1 - Constructing an Unconditional Consequence Distribution

The cumulative probability distributions provided by the Monte Carlo process defined in Figure 5.1, are in a numerical format. That is, they are given in the form of two column table. Column 1 contains a value X, which represents that a consequence given that a release occurs. Column two contains a cumulative probability PR[X], which represents the probability that the consequence of a release is less than or equal to X. Therefore, 1-PR[X] represents the probability that the consequence of a release is greater than X. To illuminate this discussion we will work with a simplified example.

Suppose that consequence is number of potentially life-threatened individuals (which is the case for the application of the modeling tools presented in this thesis). Furthermore, suppose that the output of the Monte Carlo process defined in Figure 5.1, for some particular shipment is represented in Table 5.4. Table 5.4 only shows 10 values, intermediate values must be interpolated. Note, that in reality, the output of the Monte Carlo process will show cumulative probability distributions in much finer detail, in that the numerical representation will contain 100,000 values instead of 10. For simplicity, only 10 values are used. Although the cumulative probability distribution is simplified in that only ten values are used for the numerical representation, the methodology presented to obtain the unconditional cumulative probability distribution of the consequence

From table 5.4 it is seen that the probability that more than 0 individuals are exposed to a potentially life-threatening circumstance is 80%. Furthermore suppose that the probability of a release has been determined for the route to be 8E-5. Then the probability that more than 0 people are impacted is given by the probability of a release multiplied by the probability that more than 0 people are impacted given that a release occurs. This same product corresponding to each of the ten consequence values is computed and recorded in column four of Table 5.4. The fourth column of Table 5.4 now has the probability that more than X people are impacted given only that the shipment was shipped along public roads. However, to determine the cumulative probability distribution the values in the 4-th column of Table 5.4 still must be subtracted from 1. Table 5.5 shows both the conditional and unconditional consequence cumulative probability distributions for this hypothetical shipment and route.

Table 5.4 Cumulative Probability Distribution of Consequence Given a Release for a Hypothetical Shipment and Route

Assume that for this particular shipment and route, the probability of a release is approximately 8.0E-5			
Number of potentially life-threatened individuals X	(Cumulative probability) Probability that consequence is less than or equal to X, given that a release occurs	(1- Cumulative probability) Probability that consequence is greater than to X, given that a release occurs	(8.0E-5 x (1 - Cum Prob)) Probability that consequence is greater than X
0	80%	20%	1.6E-5
1	86%	14%	1.12E-5
2	91%	9%	7.2E-6
3	95%	5%	4.0E-6
4	98%	2%	1.6E-6
5	99%	1%	8.0E-7
6	99.4%	0.6%	4.8E-7
7	99.6%	0.4%	3.2E-7
8	99.7%	0.3%	2.4E-7
9	99.8%	0.2%	1.6E-7
10	99.9%	0.1%	8.0E-8

Table 5.5 Conditional vs. Unconditional Cumulative Probabilities Distributions of Consequence

Consequence	Cumulative Probability Given a Release Occurred	Cumulative Probability
0	0.8	0.99998400
1	0.86	0.99998880
2	0.91	0.99999280
3	0.95	0.99999600
4	0.98	0.99999840
5	0.99	0.99999920
6	0.994	0.99999952
7	0.996	0.99999968
8	0.997	0.99999976
9	0.998	0.99999984
10	0.999	0.99999992

5.3.2. Steps 2 and 3 - Another Monte Carlo Algorithm

Step 2 is simply to define the random variable $Y = \sum X_i$, where each of the X_i have a cumulative probability distribution represented by the cumulative probability distribution of the i-th shipment (as derived in Step 1). Step 3 is to derive the distribution of the random variable Y using a Monte Carlo algorithm. This algorithm proceeds by simply sampling a value corresponding to each of the random variables X_1 , X_2 , ..., then adding up all the sampled X_i , and recording the sum. This process is repeated several hundred or even thousands of times, until enough data is collected to make a smooth distribution.

For the application involving the 63 DOE generated potentially life-threatening shipments of hazardous waste, there are 63 distributions to sample at each iteration, and the number of iterations used is 10,000,000. In this case a smaller number of iterations was not sufficient because for all 63 of the (unconditional) cumulative probability distributions of consequence, all the non-zero consequence is contained in the upper tail (above the 99-th percentile). In order to achieve a sufficient amount of sampling from the upper tail of those distributions an incredibly large number of iterations (10,000,000) had to be executed.

5.4. Results and Discussion

Figure 5.4 shows the (PLTHE) cumulative probability distribution of number of individuals with potentially life-threatening health effects as a result of transporting the 63 DOE generated shipments of hazardous waste listed in Appendix A. This distribution shows that the mean number of individuals exposed to a potentially life-threatening scenario as a result of transporting the 63 DOE generated shipments of hazardous waste, is not always a good indicator of possible outcomes. For instance, although the mean value is 3.48E-4, the probability that zero people will be exposed to a potentially life-threatening situation is greater than 99%, the probability that more than 1 person will be exposed to a potentially life-threatening situation is 3 in 25 thousand, the probability that more than 1,000 people will be exposed to a potentially life-threatening situation is 1 in

50 million. It is quite conceivable that a route on which slightly more people are affected in the mean, may be preferable to an alternative route in which the odds for a catastrophic accident are higher.

5.4.1. Deterministic Results versus Probabilistic Results

The mean of the cumulative probability distribution given in Figure 5.4 is 3.48E-4 people, whereas the results of the deterministic method show a risk of 1.74E-4 (they differ by a factor of 2). Although these numbers differ by a factor of two, their respective locations on the cumulative probability distribution are 99.941% and 99.947%. For this case, the deterministic results provide a good estimator for the mean of the cumulative probability distribution of number of potentially life-threatened individuals.

When these modeling tools are applied to the other alternative waste management scenarios (centralized, decentralized, and regionalized - see section 1.1) and to the other health end-points ("cancer" and "other adverse health effects"), the deterministic results will provide an estimate for the expected value of consequence (risk) for each combination of waste management scenario and health end-point. These numbers will allow for comparison of alternatives only by average values or expected consequence. However, the probabilistic results also provide a probability of zero risk (> 99% for the baseline potentially life-threatening scenario) and some additional information about catastrophic results in the upper tail of the distribution. This type of information can be very useful in the comparison between alternative waste management scenarios.

In addition to Figure 5.4, the cumulative probability distribution of number of potentially life-threatened individuals, Figure 5.5 has been provided. Both these figures are presented with the abscissa in log scale. The ordinate axis of Figure 5.5 represents 1 minus the cumulative probability, in other words, the probability that more than N people are exposed to a potentially life-threatening situation. Figure 5.5 may be easier to interpret than the cumulative probability distribution given in Figure 5.4.

Figure 5.4 Cumulative Probability Distribution of Number of Potenitally Life-Threatening Health Effects as a Result of Transporting the 63 DOE Generated Shipments of Hazardous Waste.

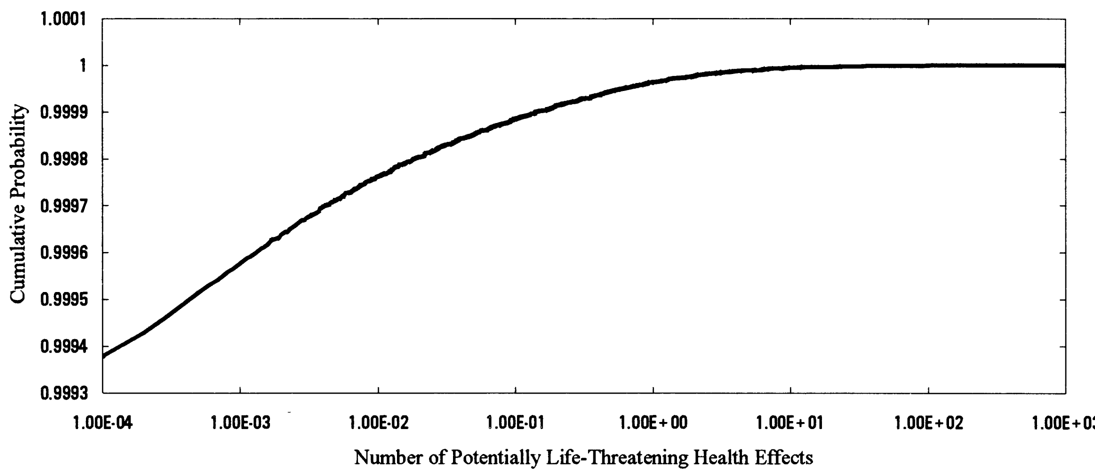
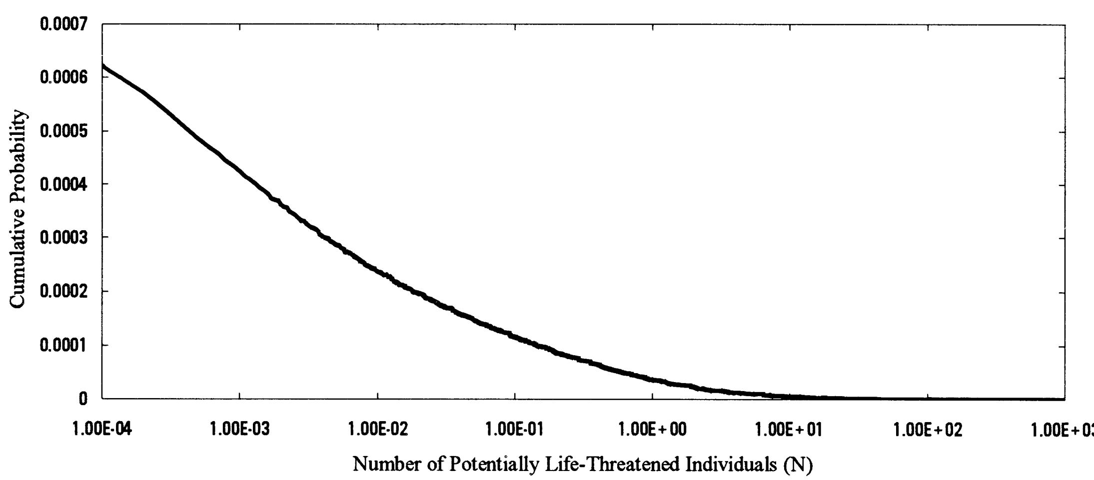


Figure 5.5 Probability that more than N Individuals are Exposed to Potentially Life-Threatening Health Effects as a Result of Transporting the 63 Shipments of DOE Generated Hazardous Waste.



5.4.2. Problem Shipments

The three largest risk shipments, according to the deterministic results, are shipments 3, 12, and 23. Their associated risks, as well as the mean of the associated cumulative probability distribution of number of potentially life-threatened individuals and probability that more than 100 people are potentially life-threatened, are given in Table 5.6.

Table 5.6 Summary Statistics of Deterministic and Probabilistic Results

Shipment number	Deterministic shipment risk	Mean of cumulative probability distribution	Probability of 0 potential fatalities	Probability > 100 potential fatalities	Probability of a release	Shipment miles traveled
3	8.18E-6	2.98E-5	99.999%	4.00E-8	3.97E-6	64.5
12	3.63E-5	8.89E-5	99.996%	1.02E-7	9.43E-5	1905
23	8.26E-5	1.97E-4	99.998%	3.14E-7	3.04E-5	557.2

There are a few interesting points to be made about the table. First note that the deterministic results agree with the probabilistic results in that shipments 2, 12 and 23 have the highest means of all 63 cumulative probability distributions of number of potentially life-threatened individuals, and the highest probabilities that more than 100 lives are potentially threatened. The deterministic risk of shipment 3 differs from the mean of the corresponding cumulative probability distribution by a factor of 3.6. However, both the deterministic result and the probabilistic mean both lie between the 99.90-th percentile and the 99.999-th percentile. Similarly, the deterministic risks for shipments 12 and 23 differ from their corresponding cumulative probability distribution means by a factor of 2.4. However, in each case, the two numbers lie between the corresponding 99.90-th percentiles and the 99.99-th percentiles.

It should also be noted that these three shipments, 3, 12 and 23, are comprised of only either all hazardous wastes in a gaseous state or at least 90% in a gaseous state. Furthermore these three shipments account for 73% of the deterministic risk and are dominant shipments in the determination of the upper tail of the annual cumulative probability distribution of number of individuals potentially life-threatened.

5.4.3. Probabilistic Model Uncertainty

Clearly, one would like a model that was truly accurate and free from bias, whether that bias be conservative or non-conservative. This was a fundamental goal in the development of the probabilistic modeling tools developed in this thesis. However, when faced with lack of information in a particular area, assumptions employed tended to be conservative since non-conservative assumptions historically require more justification. In the remainder of this section, areas of uncertainty in the probabilistic modeling tools and their possible impacts on results are briefly discussed.

1. The specification of the spill coverage area distribution was quite arbitrary and neglected individual chemical properties. Though the distribution is most certainly not entirely accurate, predicted spill areas are very reasonable and, as will become apparent below, not a significant source of uncertainty in the final annual cumulative probability distribution of number of potentially life-threatened individuals.

2. The assumption that liquid spills always occur on the pavement is fairly dramatic. The higher temperatures which can be associated with the pavement surface provide a large reservoir of available energy. This most certainly leads to an overprediction of evaporation rates for spills which do not occur on the pavement surfaces. In these cases, the release rates may be overpredicted by as much as a factor of 2. Additionally, if a spill is confined within the vehicle, additional overprediction may occur since surface transfer coefficients are markedly reduced over what they are for materials the ground. This may seem to be quite a problem. However, the fact that most of the risk comes from gases (in which case the evaporation from pools is not applicable) means that the uncertainties in the final annual cumulative probability distribution arising from the treatment of the liquid spills forming evaporating pools, are small.

3. Using the data in the HMIRS database to predict releasing behavior in accidents involving a release of hazardous waste generated and packaged by DOE may result in conservative distributions. Not all large drum containers provide the same protection to their contents. Furthermore, not all have equivalent protection from additional overpacks as well. The same can be said for cylinders and small drums. The demands on the performance capabilities of the containers used depend upon the level

of danger presented by the hazardous waste being packaged. The application of the modeling tools developed concerns hazardous waste which is potentially lethal. Because of the high level of danger these commodities present, packaging requirements are stringent. Not all of the drum and cylinder incidents found in the HMIRS database and used to construct release fraction distributions, are representative of the DOE containers. Section E.2 (located in Appendix E) provides additional details about this uncertainty.

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APPENDIX A

This section identifies the 63 potentially life-threatening shipments of DOE generated hazardous waste transported for disposal and/or treatment in the 1992 fiscal year. The format of this information is given below -

Row 1: Shipment number

Row 2: Location of generator(city, state) and designated treatment facility(city, state)

Row 3: Date of departure from generation point

The remaining rows for a shipment include the hazardous waste data. The column descriptions for the hazardous waste data rows are given below -

- Column 1 identifies the manifest reported container type. The identification is a 2 character string. A container identification starting with a 'C' indicates that a cylinder container was used and an identification beginning with a 'D' indicates a drum.

- Column 2 contains a 1 character string which provides more detailed information about the packaging used. If column 2 contains a 'C' then a cylinder packaging was used. If column 2 contains an 'L' then a large drum (> 20 gallons in capacity, mostly 55 gallon drums) was used and if column 2 contains an 'S' a small drum was used. If column 1 does not agree with column 2, that is column 1 has 'DM' but column 2 has 'C', this should be interpreted as meaning that the hazardous waste is packaged in cylinders contained inside of drums.

- Column 3 has the value of the original quantity shipped.

- Column 4 contains the units for the original quantity. The units are indicated by a 1 character string . A 'P' indicates pounds, 'G' indicates gallons and 'C' indicates cubic feet.

- Column 5 contains the chemical name
- Columns 6, 7 and 8 contain the potentially life-threatening health effect concentration thresholds for the 15 minute, 30 minute and 60 minute exposure times respectively.
- Column 9 contains the CAS number for the chemical

SHIPMENTS

```
shipment  1
Livermore, CA to El Dorado, AR
 7/10/92
DM L    10 P Phosphorus oxychloride              13     9.1     6.4  10025-87-3
DM L    10 P phosphorus oxychloride              13     9.1     6.4  10025-87-3

shipment  2
Livermore, CA to El Dorado, AR
 9/30/92
DM L   177 P Phenyl isocyanate                   11     5.4     2.7    103-71-9
DM L    13 P Titanium tetrachloride             3.7     2.6     1.8   7550-45-0

shipment  3
Livermore, CA to Gilroy, CA
 1/24/92
DM C   565 P Chlorine                            27      19      14   7782-50-5

shipment  4
Livermore, CA to Gilroy, CA
 2/ 7/92
DM C   200 P Chlorine                            27      19      14   7782-50-5

shipment  5
Livermore, CA to Los Angeles, CA
 5/ 8/92
DM L    77 P Bromine                             45      23      11   7726-95-6

shipment  6
Livermore, CA to Los Angeles, CA
 7/22/92
DF L     5 G Phosphorus oxychloride              13     9.1     6.4  10025-87-3

shipment  7
Livermore, CA to Los Angeles, CA
 8/10/92
CW C    57 P Nitric Acid, fuming                 27      19      13   7697-37-2
DM L   160 P Phenyl isocyanate                   11     5.4     2.7    103-71-9
DM L   160 P Thiophosgene                        23      16      11    463-71-8

shipment  8
Livermore, CA to Greenbrier, TN
 7/ 2/92
DF C     5 G Hydrogen fluoride, Anhydrous        24      17       8   7664-39-3

shipment  9
Livermore, CA to Greenvrier, TN
 7/24/92
DM L    10 P Cyclohexyl isocyanate                6     4.2       3   3173-53-3
```

shipment 10
Livermore, CA to Deer Park, TX
10/ 4/91

DM C	13 P	Nickel carbonyl	1.4	0.96	0.48	13463-39-3

shipment 11
Livermore, CA to Deer Park, TX
10/ 4/91

DM C	10 P	Tungsten hexafluoride	12	6	3	7783-82-6

shipment 12
Livermore, CA to Deer Park, TX
5/ 8/92

DM L	15 P	Bromine or Bromine solutions	45	23	11	7726-95-6
CY C	125 P	Hydrogen fluoride, Anhydrous	24	17	8	7664-39-3

shipment 13
Livermore, CA to Deer Park, TX
6/18/92

CY C	1 P	Sulfur dioxide, liquefied	330	170	83	7446-09-5

shipment 14
Idaho Falls, ID to Clarence, NY
12/17/91

DM C	2 P	SULFURIC ACID, FUMING	23	16	11	7664-93-9
DM C	14 P	TUNGSTEN HEXAFLUORIDE	12	6	3	7783-82-6

shipment 15
Idaho Falls, ID to Clarence, NY
8/17/92

DM L	10 P	Thiophosgene	23	16	11	463-71-8

shipment 16
Idaho Falls, ID to El Dorado, AR
10/25/91

DF L	14 P	Methyl iodide	90	63	45	74-88-4
DF L	76 P	Thiophosgene	23	16	11	463-71-8

shipment 17
Idaho Falls, ID to El Dorado, AR
11/14/91

DF C	41 P	Chlorine	27	19	14	7782-50-5

shipment 18
Idaho Falls, ID to Clarence, NY
4/15/92

DF C	45 P	Boron trifluoride	16	11	8	7637-07-2
DM L	12 P	CYANOGEN BROMIDE	7.7	3.9	1.9	506-68-3

shipment 19
Argonne, IL to El Dorado AR
11/19/91

DM L	5 G	Trimethylacetyl chloride	27	19	14	3282-30-2

shipment 20
Argonne, IL to Clarence, NY
12/ 6/91

DM L	5 G	Bromine or Bromine solutions	45	23	11	7726-95-6

shipment 21
Argonne, IL to Clarence, NY
12/ 6/91

DM L	5 G	Sulfuric Acid, fuming	23	16	11	7664-93-9
DM L	10 G	Titanium tetrachloride	3.7	2.6	1.8	7550-45-0

shipment 22
Argonne, IL to Clarence, NY
4/24/92

DM L	5 G	Allylamine	110	81	57	107-11-9
DM C	30 G	Nitric Acid, fuming	27	19	13	7697-37-2

shipment 23
Argonne, IL to Clarence, NY
7/ 7/92

CW C	1 G	Hydrogen Selenide	0.17	0.12	0.085	7783-07-5
CW C	1 G	Selenium hexafluoride	2	1.4	1	7783-79-1
CW C	1 G	Tellurium hexafluoride	1	0.71	0.5	7783-80-4

shipment 24
Argonne, IL to Houston, TX
9/ 2/92

DM C	1 G	Arsine	5.2	2.6	1.3	7784-42-1
CW C	1 G	Methyl bromide	110	79	56	74-83-9

shipment 25
Kansas City, MO to Deer Park, TX
3/11/92

CW C	35 P	Ammonia, anhydrous	560	280	140	7664-41-7
CW C	2 P	Carbon monoxide	560	280	140	630-08-0

shipment 26
Kansas City, MO to Houston, TX
6/25/92

DM C	50 P	Ammonia, anhydrous	560	280	140	7664-41-7
DM C	20 P	Chlorine	27	19	14	7782-50-5
DM C	20 P	Hydrogen Sulfide	89	44	22	7783-06-4
DM C	20 P	Nitrogen Dioxide	6	4.2	3	10102-44-0
DM C	50 P	Silicon tetrafluoride	6400	4500	3200	7783-61-1
DM C	20 P	Sulfur dioxide, liquefied	330	170	83	7446-09-5

shipment 27
Los Alamos, NM to Baton Rouge, LA
11/27/91

DF L	1 P	Dimethyl sulfate	3.5	2.5	1.7	77-78-1
DF L	1 P	Thiophosgene	23	16	11	463-71-8
DM L	3 P	Cyanogen bromide	7.7	3.9	1.9	506-68-3

shipment 28
Los Alamos, NM to Baton Rouge, LA
12/17/91

DM L	25 P	Bromine	45	23	11	7726-95-6

shipment 29
Los Alamos, NM to Baton Rouge, LA
2/13/92

DF C	60 P	Ammonia, anhydrous	560	280	140	7664-41-7

shipment 30
Los Alamos, NM to Baton Rouge, LA
5/ 5/92

DF L	2 P	Bromine	45	23	11	7726-95-6
DF L	9 P	Nitric Acid, fuming	27	19	13	7697-37-2

shipment 31
Los Alamos, NM to Baton Rouge, LA
8/ 4/92

DF L	10 P	Sulfuric Acid, fuming	23	16	11	7664-93-9

shipment 32
Los Alamos, NM to Baton Rouge. LA
8/27/92

DF L	25 P	Titanium tetrachloride	3.7	2.6	1.8	7550-45-0

shipment 33
Los Alamos, NM to Deer Park, TX
10/30/91

DM C	1 P	Nitric Acid, fuming	27	19	13	7697-37-2

shipment 34
Los Alamos, NM to Deer Park, TX
1/29/92

DF	C	4	P	Nitric Acid, fuming	27	19	13	7697-37-2

shipment 35
Los Alamos, NM to Deer Park, TX
5/ 5/92

DM	L	1	P	Acrolein, inhibited	19	13	6.6	107-02-8
DF	C	10	P	Arsine	5.2	2.6	1.3	7784-42-1
DM	C	2	P	Nitric Acid, fuming	27	19	13	7697-37-2

shipment 36
Los Alamos, NM to Deer Park, TX
5/28/92

CY	C	5	P	Carbon monoxide	560	280	140	630-08-0
CY	C	1	P	Sulfur dioxide, liquefied	330	170	83	7446-09-5

shipment 37
Los Alamos, NM to Deer Park, TX
6/25/92

CY	C	1	P	Chlorine	27	19	14	7782-50-5

shipment 38
Los Alamos, NM to Deer Park, TX
7/16/92

CY	C	10	P	Carbon monoxide	560	280	140	630-08-0
CY	C	6	P	Chlorine	27	19	14	7782-50-5
DF	C	1	P	Nitric Acid, fuming	27	19	13	7697-37-2
CY	C	20	P	Sulfur dioxide, liquefied	330	170	83	7446-09-5

shipment 39
Los Alamos, NM to Deer Park, TX
8/ 4/92

CY	C	2	P	Arsine	5.2	2.6	1.3	7784-42-1
CY	C	3	P	Carbonyl fluoride	72	51	36	353-50-4
CY	C	2	P	Phosgene	5.6	2.8	1.4	75-44-5
CY	C	1	P	Phosphine	4.4	3.1	2.2	7803-51-2
CY	C	2	P	Sulfuryl fluoride	400	280	200	2699-79-8

shipment 40
Los Alamos, NM to Deer Park , TX
8/13/92

CY	C	2	P	Chlorine	27	19	14	7782-50-5

shipment 41
Los Alamos, NM to Deer Park, TX
9/24/92

CY	C	2	P	Chlorine	27	19	14	7782-50-5
CY	C	4	P	Hydrogen Sulfide	89	44	22	7783-06-4
CY	C	400	P	Sulfur dioxide, liquefied	330	170	83	7446-09-5

shipment 42
Albuquerque, NM to El Dorado, AR
10/ 8/91

DF	C	5	P	Nitric Acid, fuming	27	19	13	7697-37-2

shipment 43
Albuquerque, NM to El Dorado, AR
2/17/92

DF	L	10	P	Methyl chloroformate	14	10	7	79-22-1

shipment 44
Albuquerque, NM to Fremont, CA
4/21/92

DF	C	27	P	Chlorine	27	19	14	7782-50-5
DF	C	24	P	Hydrogen Sulfide	89	44	22	7783-06-4
DM	C	7	P	Nitric oxide	350	250	170	10102-43-9
DF	C	47	P	Nitrogen Dioxide	6	4.2	3	10102-44-0

shipment 45

Albuquerque, NM to Baton Rouge, LA
11/27/91

CW C	25 P	Nitric Acid, fuming	27	19	13	7697-37-2
DF L	25 P	Phosphorus oxychloride	13	9.1	6.4	10025-87-3
CW L	25 P	Sulfuric Acid, fuming	23	16	11	7664-93-9
CW L	25 P	Thionyl chloride	100	71	50	7719-09-7

shipment 46
Albuquerque, NM to Baton Rouge, LA
1/13/92

DF C	60 P	Arsine	5.2	2.6	1.3	7784-42-1

shipment 47
Albuquerque, NM to Baton Rouge, LA
2/ 3/92

DF L	4 P	Methyl iodide	90	63	45	74-88-4

shipment 48
Albuquerque, NM to Baton Rouge, LA
4/21/92

DF L	7 P	Allylamine	110	81	57	107-11-9
DF L	12 P	Methyl vinyl ketone	0.79	0.56	0.4	78-94-4
DF C	10 P	Nitric Acid, fuming	27	19	13	7697-37-2

shipment 49
Albuquerque, NM to Baton Rouge, LA
5/26/92

DF C	159 P	Hydrogen Sulfide	89	44	22	7783-06-4

shipment 50
Albuquerque, NM to Clarence, NY
7/16/92

CY C	3 P	Hydrogen Sulfide	89	44	22	7783-06-4
CW C	68 P	Nitric oxide	350	250	170	10102-43-9
CY C	10 P	Nitrogen Dioxide	6	4.2	3	10102-44-0

shipment 51
Albuquerque, NM to Deer Park, TX
10/14/91

DF L	5 P	Thionyl chloride	100	71	50	7719-09-7

shipment 52
Albuquerque, NM to Deer Park, TX
3/31/92

CY C	38 P	Ammonia, anhydrous	560	280	140	7664-41-7
CY C	3 P	Carbon monoxide	560	280	140	630-08-0
CY C	1 P	Chlorine	27	19	14	7782-50-5
CY C	4 P	Methylamine, Anhydrous	540	380	270	74-89-5
CY C	10 P	Nickel carbonyl	1.4	0.96	0.48	13463-39-3
CY C	1 P	Nitrosyl chloride	6	4.2	3	2696-92-6
CY C	3 P	Silicon tetrafluoride	6400	4500	3200	7783-61-1
CY C	2 P	Sulfur dioxide, liquefied	330	170	83	7446-09-5
CY C	1 P	Titanium tetrachloride	3.7	2.6	1.8	7550-45-0
CY C	3 P	Tungsten hexafluoride	12	6	3	7783-82-6

shipment 53
Albuquerque, NM to Deer Park, TX
5/21/92

CY C	30 P	Ammonia, anhydrous	560	280	140	7664-41-7
CY C	3 P	Boron trifluoride	16	11	8	7637-07-2
CY C	15 P	Carbon monoxide	560	280	140	630-08-0
CY C	1 P	Chlorine	27	19	14	7782-50-5
CY C	30 P	Hydrogen Sulfide	89	44	22	7783-06-4
CY C	4 P	Methylamine, Anhydrous	540	380	270	74-89-5
CY C	3 P	Phosphine	4.4	3.1	2.2	7803-51-2
CY C	6 P	Silicon tetrafluoride	6400	4500	3200	7783-61-1
CY C	2 P	Sulfur dioxide, liquefied	330	170	83	7446-09-5

shipment 54
Albuquerque, NM to Deer Park, TX
7/22/92

CW C	1 P	Hydrogen Selenide	0.17	0.12	0.085	7783-07-5

shipment 55
Albuquerque, NM to Deer Park, TX
7/31/92

CY C 190 P Carbon monoxide	560	280	140	630-08-0
CY C 3 P Hydrogen Sulfide	89	44	22	7783-06-4

shipment 56
Albuquerque, NM to Deer Park, TX
9/ 1/92

CY C 12 P Ammonia, anhydrous	560	280	140	7664-41-7
CY C 3 P Carbon monoxide	560	280	140	630-08-0
CY C 5 P Hydrogen fluoride, anhydrous	24	17	8	7664-39-3

shipment 57
Amarillo, TX to Sauget, IL
4/ 3/92

DM L 900 G Sulfuric Acid, fuming	23	16	11	7664-93-9

shipment 58
Amarillo, TX to Carlyss, LA
2/14/92

DF L 5 G Thionyl chloride	100	71	50	7719-09-7

shipment 59
Richland, WA to El Dorado, AR
11/19/91

DM L 60 P Chlorine	27	19	14	7782-50-5

shipment 60
Richland, WA to El Dorado, AR
4/29/92

DM L 85 P Bromine or Bromine solutions	45	23	11	7726-95-6
DM L 11 P Sulfur trioxide, inhibited	4.5	3.2	2.2	7446-11-9

shipment 61
Richland, WA to El Dorado, AR
7/31/92

DM L 10 P Dimethyl sulfate	3.5	2.5	1.7	77-78-1
CF L 20 P Sulfuric Acid, fuming	23	16	11	7664-93-9
DM L 54 P Titanium tetrachloride	3.7	2.6	1.8	7550-45-0

shipment 62
Richland, WA to El Dorado, AR
8/20/92

DM L 14 P Phosphorus Trichloride	20	14	10	7719-12-2

shipment 63
Richland, WA to El Dorado, AR
9/23/92

DM L 10 P Chloropicrin	3.9	2.8	2	76-06-2

APPENDIX B

This section contains both a detailed and a summarized version of a sample HIGHWAY 3.1 route prediction for traveling from Lawrence Livermore National Laboratory in Livermore, CA to Laidlaw Environmental Services in Greenbrier, TN.

HIGHWAY 3.1 summary

Population Zone	(people/mile^2)	Average People/Sq. Mile	Miles Traveled
Rural	(< 139)	15.14	2051.6
Suburban	(139-3326)	884.99	215.7
Urban	(> 3,326)	5639.674	29.8

HIGHWAY 3.1 Detailed Output Description

Routes predicted by the HIGHWAY 3.1 program are given by a series of latitude, longitude pairs followed by a distance from the previous latitude, longitude pair followed by a discrete distribution of miles traveled in each of twelve different population density categories. The column descriptions given below describe these categories. Note that latitude and longitude pairs are absolute values in the western hemisphere.

Column 1	degrees of latitude.
Column 2	degrees of longitude.
Column 3	distance in miles from the last latitude, longitude pair.
Column 4	miles traveled in an area with 0 people per square mile.
Column 5	miles traveled in an area with 0 - 5 people per square mile.
Column 6	miles traveled in an area with 5 - 22.7 people per square mile.
Column 7	miles traveled in an area with 22.7 - 59.7 people per square mile.
Column 8	miles traveled in an area with 59.7 - 139 people per square mile.
Column 9	miles traveled in an area with 139 - 326 people per square mile.
Column 10	miles traveled in an area with 326 - 821 people per square mile.
Column 11	miles traveled in an area with 821 - 1861 people per square mile.
Column 12	miles traveled in an area with 1861 - 3326 people per square mile.
Column 13	miles traveled in an area with 3326 - 5815 people per square mile.
Column 14	miles traveled in an area with 5815 - 9996 people per square mile.
Column 15	miles traveled in an area with > 9996 people per square mile.

HIGHWAY 3.1 detailed output

86.717	36.350	1.9	0.0	0.0	0.0	0.0	0.1	0.3	0.9	0.6	0.0	0.0	0.0	0.0
86.706	36.308	6.1	0.0	0.0	0.0	0.0	0.1	0.3	1.0	4.1	0.6	0.0	0.0	0.0
86.751	36.246	2.1	0.0	0.0	0.0	0.0	0.0	0.1	0.5	0.9	0.3	0.3	0.0	0.0
86.779	36.208	1.9	0.0	0.0	0.6	0.1	0.0	0.1	0.6	0.5	0.0	0.0	0.0	0.0
86.781	36.189	1.9	0.0	0.1	0.0	0.0	0.0	0.0	0.1	0.3	1.0	0.2	0.2	0.0
86.818	36.163	0.9	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.4	0.1	0.1	0.3
86.835	36.157	24.7	0.0	3.3	3.1	0.9	4.4	6.6	1.7	1.7	1.7	0.8	0.5	0.0
87.177	36.028	10.0	0.0	0.1	2.4	3.9	3.3	0.3	0.0	0.0	0.0	0.0	0.0	0.0
87.337	36.019	9.0	2.9	0.3	1.0	1.8	0.8	1.2	1.0	0.0	0.0	0.0	0.0	0.0
87.486	35.990	20.0	0.0	6.5	13.5	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
87.802	35.881	17.0	0.0	1.2	15.8	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
88.083	35.840	18.0	0.0	11.8	3.0	1.1	0.5	1.6	0.0	0.0	0.0	0.0	0.0	0.0
88.392	35.787	21.0	0.0	1.2	5.3	10.8	3.7	0.0	0.0	0.0	0.0	0.0	0.0	0.0
88.744	35.682	4.9	0.0	0.3	1.8	0.4	1.2	0.1	0.5	0.6	0.0	0.0	0.0	0.0
88.829	35.669	2.0	0.8	0.0	0.0	0.0	0.0	0.0	0.1	1.1	0.0	0.0	0.0	0.0
88.856	35.664	1.0	0.2	0.0	0.0	0.0	0.0	0.1	0.3	0.4	0.0	0.0	0.0	0.0
88.875	35.654	13.0	0.0	0.0	2.7	8.8	0.2	1.3	0.0	0.0	0.0	0.0	0.0	0.0
89.093	35.586	9.9	0.0	1.2	3.0	5.7	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
89.247	35.539	38.0	0.9	6.0	14.4	7.7	3.5	2.7	2.8	0.0	0.0	0.0	0.0	0.0
89.772	35.204	7.9	0.2	0.0	0.1	0.2	0.6	0.5	0.9	3.8	0.6	1.0	0.0	0.0
89.884	35.151	3.9	0.2	0.1	0.0	0.0	0.2	0.4	1.0	0.9	1.0	0.1	0.0	0.0
89.928	35.189	4.9	0.7	0.0	0.1	0.1	0.7	0.4	0.8	1.5	0.6	0.0	0.0	0.0
90.016	35.190	2.1	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.7	0.6	0.6	0.2	0.0
90.020	35.159	1.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.1	0.8	0.1	0.0
90.020	35.148	1.1	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.1	0.5	0.2	0.3
90.040	35.150	0.9	0.3	0.0	0.0	0.0	0.0	0.0	0.1	0.0	0.1	0.2	0.2	0.0
90.067	35.151	4.1	0.8	1.1	0.4	0.0	0.1	0.2	0.8	0.3	0.1	0.3	0.0	0.0
90.149	35.153	2.9	0.7	0.2	0.0	0.0	0.0	0.1	0.1	0.4	0.9	0.5	0.0	0.0
90.192	35.171	12.1	0.4	4.6	0.8	3.7	1.3	0.7	0.5	0.1	0.0	0.0	0.0	0.0
90.401	35.149	23.9	1.1	8.0	12.9	0.7	0.5	0.2	0.2	0.3	0.0	0.0	0.0	0.0
90.790	35.034	25.1	0.4	5.1	8.2	10.5	0.4	0.0	0.1	0.4	0.0	0.0	0.0	0.0
91.195	34.911	23.1	9.3	11.1	1.2	0.1	0.2	0.8	0.4	0.0	0.0	0.0	0.0	0.0
91.566	34.821	35.0	4.4	5.3	10.1	8.8	3.9	1.9	0.6	0.0	0.0	0.0	0.0	0.0
92.167	34.782	4.1	0.1	0.0	0.4	0.9	0.8	0.4	0.5	0.9	0.1	0.0	0.0	0.0
92.232	34.782	2.0	0.0	0.0	0.0	0.0	0.0	0.0	0.4	0.6	0.4	0.5	0.1	0.0
92.262	34.778	6.1	0.2	0.0	0.7	0.6	0.4	1.2	1.0	0.6	1.2	0.2	0.0	0.0
92.342	34.824	19.9	1.6	0.4	0.6	2.2	10.2	2.9	1.1	0.7	0.1	0.1	0.0	0.0
92.433	35.092	2.1	0.0	0.0	0.0	0.0	0.0	0.4	0.4	0.3	0.8	0.2	0.0	0.0
92.439	35.110	17.0	0.0	2.9	4.4	4.6	0.6	2.5	0.9	1.1	0.0	0.0	0.0	0.0

92.734	35.163	27.0	0.3	1.3	9.0	6.9	2.3	2.4	4.0	0.8	0.0	0.0	0.0	0.0
93.138	35.306	6.9	0.4	0.5	0.7	1.2	2.2	1.6	0.3	0.0	0.0	0.0	0.0	0.0
93.257	35.339	39.0	2.8	7.7	7.3	10.5	7.7	1.5	0.3	1.2	0.0	0.0	0.0	0.0
93.843	35.500	22.1	1.4	1.0	5.2	5.7	3.5	3.4	0.8	0.9	0.2	0.0	0.0	0.0
94.226	35.489	5.8	0.6	0.1	0.7	0.5	0.9	2.3	0.2	0.2	0.3	0.0	0.0	0.0
94.319	35.455	7.0	1.8	1.5	0.5	0.1	0.7	0.1	0.2	0.4	1.6	0.1	0.0	0.0
94.442	35.453	6.1	0.2	1.8	0.5	0.8	0.5	0.9	1.3	0.1	0.0	0.0	0.0	0.0
94.597	35.392	13.9	0.0	0.4	4.1	7.2	0.1	0.7	0.6	0.5	0.3	0.0	0.0	0.0
94.758	35.451	3.0	0.0	0.0	0.0	0.1	0.4	0.4	0.7	1.0	0.4	0.0	0.0	0.0
94.806	35.447	9.9	0.0	3.5	3.6	0.5	0.6	0.9	0.8	0.0	0.0	0.0	0.0	0.0
94.972	35.493	12.0	0.0	5.6	2.1	1.9	1.6	0.3	0.2	0.3	0.0	0.0	0.0	0.0
95.169	35.488	8.0	0.0	0.0	1.9	2.8	3.2	0.1	0.0	0.0	0.0	0.0	0.0	0.0
95.307	35.478	12.9	0.0	1.6	4.8	4.4	0.4	1.0	0.7	0.0	0.0	0.0	0.0	0.0
95.545	35.459	24.9	0.0	4.2	15.2	5.5	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
95.971	35.432	8.9	0.1	1.2	4.4	2.1	0.1	0.1	0.2	0.4	0.3	0.0	0.0	0.0
96.124	35.431	32.0	2.6	6.6	13.0	8.0	0.8	0.3	0.3	0.4	0.0	0.0	0.0	0.0
96.670	35.385	13.9	1.3	2.9	1.3	4.4	2.7	1.3	0.0	0.0	0.0	0.0	0.0	0.0
96.912	35.384	4.9	0.0	0.0	0.6	1.5	0.5	0.8	1.4	0.1	0.0	0.0	0.0	0.0
96.998	35.382	16.0	0.5	3.1	0.8	0.8	6.8	2.4	1.6	0.0	0.0	0.0	0.0	0.0
97.289	35.403	8.0	1.1	0.2	0.1	0.1	0.0	4.1	1.8	0.3	0.3	0.0	0.0	0.0
97.405	35.436	1.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.3	0.2	0.5	0.0	0.0
97.424	35.446	2.9	0.2	0.4	0.0	0.0	0.0	0.0	0.0	0.4	1.2	0.7	0.0	0.0
97.465	35.468	2.0	0.0	0.5	0.0	0.1	0.1	0.2	0.9	0.2	0.0	0.0	0.0	0.0
97.491	35.464	1.9	0.0	0.0	0.1	0.2	0.2	0.6	0.2	0.1	0.3	0.2	0.0	0.0
97.531	35.468	2.9	0.0	0.0	0.0	0.3	0.1	0.1	1.0	1.4	0.0	0.0	0.0	0.0
97.576	35.463	4.1	0.0	1.6	0.8	0.8	0.8	0.1	0.0	0.0	0.0	0.0	0.0	0.0
97.637	35.462	8.0	0.0	1.6	0.4	0.7	0.1	1.2	1.0	0.9	0.2	1.1	0.8	0.0
97.761	35.488	11.0	0.0	6.1	2.0	2.4	0.4	0.0	0.0	0.1	0.0	0.0	0.0	0.0
97.936	35.502	18.0	1.8	4.2	5.9	1.6	0.7	0.7	2.3	0.8	0.0	0.0	0.0	0.0
98.240	35.534	7.0	3.8	0.1	1.6	1.5	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
98.350	35.530	37.0	1.1	10.3	18.7	3.7	0.8	1.6	0.3	0.5	0.0	0.0	0.0	0.0
98.965	35.499	12.9	0.6	5.4	1.8	1.6	2.0	0.5	0.5	0.5	0.0	0.0	0.0	0.0
99.171	35.446	12.0	2.9	0.8	6.1	1.3	0.9	0.0	0.0	0.0	0.0	0.0	0.0	0.0
99.366	35.423	20.9	1.3	7.1	3.5	6.5	1.2	0.8	0.5	0.0	0.0	0.0	0.0	0.0
99.646	35.264	21.0	2.3	9.5	4.6	3.5	1.1	0.0	0.0	0.0	0.0	0.0	0.0	0.0
100.002	35.227	14.9	1.0	13.2	0.2	0.1	0.1	0.1	0.2	0.0	0.0	0.0	0.0	0.0
100.251	35.230	20.1	0.0	18.4	1.4	0.3	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
100.610	35.235	19.0	0.0	17.3	1.7	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
100.909	35.181	4.0	0.0	4.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
100.975	35.183	35.0	0.0	35.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
101.584	35.222	7.0	2.1	4.2	0.7	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0

101.698	35.193	2.0	1.1	0.0	0.1	0.2	0.3	0.3	0.0	0.0	0.0	0.0	0.0	0.0
101.724	35.191	6.0	0.0	0.0	0.0	0.0	0.4	0.7	1.1	1.0	2.1	0.7	0.0	0.0
101.838	35.192	32.9	0.0	2.7	24.2	0.6	0.0	0.1	0.3	1.0	1.4	2.5	0.1	0.0
102.429	35.242	37.0	1.4	35.6	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
103.042	35.184	33.0	13.2	19.8	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
103.612	35.173	7.0	4.7	0.7	0.6	0.8	0.2	0.0	0.0	0.0	0.0	0.0	0.0	0.0
103.724	35.152	3.0	1.6	0.6	0.0	0.0	0.0	0.1	0.7	0.0	0.0	0.0	0.0	0.0
103.777	35.150	52.0	8.7	43.3	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
104.642	34.949	4.0	0.0	1.4	0.6	0.1	0.1	0.2	0.3	1.0	0.3	0.0	0.0	0.0
104.692	34.938	17.0	5.4	11.4	0.0	0.0	0.0	0.1	0.1	0.0	0.0	0.0	0.0	0.0
104.989	34.976	38.0	0.0	38.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
105.665	35.008	54.1	4.7	20.9	7.2	8.6	7.2	0.3	0.2	0.6	0.5	1.4	2.0	0.5
106.550	35.092	4.9	0.1	0.1	0.2	0.0	0.0	0.1	0.2	0.7	1.6	0.9	1.0	0.0
106.627	35.110	0.9	0.0	0.0	0.0	0.0	0.0	0.0	0.3	0.3	0.3	0.0	0.0	0.0
106.646	35.112	2.8	0.0	0.1	0.0	0.1	0.0	0.0	0.1	0.2	0.5	1.8	0.0	0.0
106.703	35.110	29.1	7.0	13.9	0.3	4.9	0.4	0.9	0.3	0.7	0.7	0.0	0.0	0.0
107.171	34.984	12.9	4.5	3.5	1.7	2.1	0.8	0.3	0.0	0.0	0.0	0.0	0.0	0.0
107.381	35.039	32.0	3.3	4.6	13.0	6.5	2.5	0.8	0.8	0.3	0.2	0.0	0.0	0.0
107.874	35.153	19.1	1.0	0.5	12.6	3.0	0.4	0.1	0.8	0.7	0.0	0.0	0.0	0.0
108.055	35.365	43.0	3.1	8.9	21.1	5.7	2.1	0.3	0.4	0.3	0.4	0.6	0.1	0.0
108.803	35.528	4.0	0.0	1.9	0.9	1.2	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
108.831	35.505	16.0	1.4	1.8	7.0	4.3	1.3	0.2	0.0	0.0	0.0	0.0	0.0	0.0
109.044	35.368	20.0	3.4	3.3	11.6	1.7	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
109.331	35.217	6.0	0.0	0.0	6.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
109.436	35.193	47.0	18.9	23.5	2.3	0.0	0.1	0.5	1.7	0.0	0.0	0.0	0.0	0.0
110.157	34.912	28.9	26.3	1.6	0.0	0.0	0.0	0.1	0.9	0.0	0.0	0.0	0.0	0.0
110.641	35.009	4.9	2.1	0.0	0.0	0.1	0.3	0.6	0.6	0.3	0.6	0.3	0.0	0.0
110.731	35.033	50.9	8.9	32.8	4.2	1.7	1.2	0.8	1.3	0.0	0.0	0.0	0.0	0.0
111.581	35.215	6.0	1.8	0.0	0.2	0.2	0.4	0.5	0.4	0.9	1.0	0.4	0.2	0.0
111.663	35.172	28.9	12.5	11.5	4.1	0.1	0.0	0.0	0.1	0.5	0.1	0.0	0.0	0.0
112.149	35.259	18.0	7.4	9.6	0.2	0.8	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
112.473	35.222	23.0	0.0	23.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
112.855	35.312	52.0	0.0	52.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
113.696	35.161	17.9	5.2	12.1	0.4	0.2	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
114.008	35.219	4.0	0.6	0.4	0.4	0.5	0.6	0.3	0.8	0.4	0.0	0.0	0.0	0.0
114.094	35.207	40.1	9.1	27.7	3.3	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
114.306	34.732	18.1	9.6	1.6	6.9	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
114.477	34.717	1.0	0.0	0.0	1.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
114.485	34.717	11.1	1.8	2.2	3.8	3.3	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
114.594	34.821	11.0	7.9	0.1	0.2	0.1	0.2	0.9	1.0	0.6	0.0	0.0	0.0	0.0
114.749	34.880	120.0	19.9	92.4	5.7	2.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0

116.803	34.843	12.0	1.2	1.0	2.6	0.7	1.6	1.2	2.4	0.2	0.7	0.3	0.1	0.0
117.005	34.886	3.0	0.5	0.6	0.1	0.3	0.7	0.0	0.0	0.1	0.1	0.2	0.4	0.0
116.969	34.908	33.8	0.0	17.8	5.5	2.4	4.0	2.5	1.6	0.0	0.0	0.0	0.0	0.0
117.541	34.991	20.0	5.0	2.8	5.4	1.1	3.8	0.8	1.1	0.0	0.0	0.0	0.0	0.0
117.840	35.007	17.0	5.5	3.1	5.2	0.7	1.2	0.1	0.8	0.4	0.0	0.0	0.0	0.0
118.169	35.048	1.0	0.6	0.0	0.1	0.1	0.0	0.1	0.1	0.0	0.0	0.0	0.0	0.0
118.176	35.069	60.9	15.8	15.8	10.1	10.0	1.9	1.2	2.5	0.8	0.5	1.6	0.7	0.0
119.041	35.353	1.9	0.1	0.7	0.0	0.0	0.0	0.0	0.1	0.1	0.2	0.3	0.3	0.1
119.047	35.383	22.0	1.0	2.4	1.6	9.7	1.3	1.4	3.2	0.3	0.6	0.5	0.0	0.0
119.400	35.403	21.0	0.0	9.0	9.0	2.1	0.9	0.0	0.0	0.0	0.0	0.0	0.0	0.0
119.652	35.617	32.0	10.3	17.2	2.3	2.2	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
119.958	35.982	24.8	0.0	16.6	3.1	3.3	0.4	1.4	0.0	0.0	0.0	0.0	0.0	0.0
120.243	36.254	69.0	8.5	28.0	31.6	0.9	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
120.968	37.054	25.0	0.3	4.6	14.8	5.3	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
121.137	37.398	19.0	0.0	7.4	7.1	4.5	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
121.334	37.591	8.1	0.0	3.0	4.8	0.3	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
121.456	37.673	8.0	0.0	4.2	2.4	1.3	0.1	0.0	0.0	0.0	0.0	0.0	0.0	0.0
121.562	37.742	8.9	0.0	4.3	3.4	0.8	0.4	0.0	0.0	0.0	0.0	0.0	0.0	0.0
121.724	37.709	1.0	0.0	0.0	0.0	0.0	0.0	0.1	0.1	0.3	0.3	0.2	0.0	0.0
121.739	37.703	1.9	0.3	0.1	0.1	0.1	0.1	0.1	0.1	0.3	0.1	0.3	0.3	0.0

APPENDIX C

This appendix contains a mathematical proof of three statements made in Chapter 4 on the deterministic method. The assertions made in that section are summarized in statements 1, 2 and 3 below.

1. The probability that more than one accident might occur during the course of transportation for any one shipment of DOE generated hazardous waste is negligible.

2. The probability of one accident occurring during the course of transportation of any one shipment of DOE generated hazardous waste in a specific population zone (rural, suburban, urban) is given as follows -

   Let AR_R, AR_S and AR_U denote the probability of an accident in any one mile of travel in a rural, suburban and urban population zone respectively, and let m_R, m_S and m_U denote the mileage within the rural, suburban and urban population zone respectively . Then the probability that exactly 1 accident occurs, an it occurs within a

   a) rural population zone is given by

   $$m_R \times (1 - AR_R)^{(m_R - 1)} \times (1 - AR_S)^{m_S} \times (1 - AR_U)^{m_U} \times AR_R$$

   b) suburban population zone is given by

   $$m_S \times (1 - AR_R)^{m_R} \times (1 - AR_S)^{(m_S - 1)} \times (1 - AR_U)^{m_U} \times AR_S$$

   c) urban population zone is given by

   $$m_U \times (1 - AR_R)^{m_R} \times (1 - AR_S)^{m_S} \times (1 - AR_U)^{(m_U - 1)} \times AR_U$$

3. The calculated risk associated with any one shipment is approximately the mean or expected value of the distribution of potential outcomes or consequences which may

result from transporting the shipment from its generation point to a prospective designated treatment/disposal facility.

C.1. The Probability of Multiple Accidents

It is crucial to realize that the probability of more than one accident occurring during the course of transporting one shipment from its generation point to its treatment and/or disposal facility is negligible for the routes traveled in transporting the 63 shipments of PIH hazardous wastes generated by the United States Department of Energy.

There are 37 unique HIGHWAY predicted routes traveled in transporting the 63 shipments of DOE generated hazardous waste listed in Appendix A. All of these routes are less than 3,000 miles long and are more than 70% of each routes total mileage is comprised of rural mileage. The probability of an accident is the lowest in the rural population zone and the highest in the urban population zone. Therefore, the probability of more than one accident occurring while transporting any one of the 63 potentially life-threatening shipments of hazardous waste listed in Appendix A is less than the probability of more than one accident occurring while transporting one shipment of hazardous waste across a 3,000 mile route comprised of all urban mileage. This latter probability will be developed and will be shown to be negligible in an intuitive sense. It is not clear how to define the term negligible mathematically, however, it seems to reasonable to treat probabilities of less than 1.0E-4 as negligible.

Now, let a route consists of 3,000 miles of urban mileage. Then the probability of an accident in any one of those 3,000 miles is equal to 1.01E-6, denoted AR, and the probability that an accident will not occur in any one of those 3,000 miles, denoted (1-AR) is equal to 0.999999.

If no accident occurs then no accident occurred in any of the 3,000 miles along the route and this event has probability $(1\text{-}AR)^{3000} \approx 0.996975$. If one accident occurs then it either it happened at the first, second, third, ..., or 3,000-th mile. It is assumed for simplicity that if an accident occurs then the hazardous waste must still be shipped from the accident point to the designated treatment facility along the remainder of the route. If N is an integer in the interval [1, 3000], then the probability that exactly one accident happens at the N-th mile is given by

$$\underbrace{(1-AR)^{N-1}}_{\substack{\text{First N-1}\\ \text{miles safely}\\ \text{travelled}}} \times \underbrace{AR}_{\text{Accident}} \times \underbrace{(1-AR)^{3000-N}}_{\substack{\text{Remaining miles}\\ \text{safely travelled to}\\ \text{desginated treatment}\\ \text{facility}}} \quad , \text{ where } \quad AR = 1.01E-6$$

$$= \ (1-AR)^{2,999} \ \times \ AR \qquad \text{for every N in } [1,\ 2,\ \ldots,\ 3000]$$

Furthermore, there are 3,000 different miles in which the accident can occur and the probability that exactly one accident occurs is then given by $3{,}000\cdot(1\text{-AR})^{2999}\cdot\text{AR} \approx 0.002991$. Furthermore, the three events of (1) no accident, (2) exactly one accident and (3) more than one accident are mutually exclusive and collectively exhaustive so that the probability of more than one accident is given by

$$\text{1-PR[0 accidents] - PR[1 accident]} \approx 3.4\text{E-}5.$$

It is helpful to view these three probabilities together in a table. Table C.1 contains the probability of zero accidents, exactly one accident and multiple accidents occurring while transporting one shipment of hazardous waste across 3,000 miles of urban mileage.

When examining the numbers in table C.1 it is important to realize that the probability of more than one accidents for this example is significantly higher than it is any one actual route. For the 37 unique HIGHWAY 3.1 predicted routes, all are less than 3,000 miles in total length and over 70% of those miles in each route is comprised of rural miles only. Furthermore, the probability of an accident in any one mile within a rural area is less then the probability of an accident in any one mile of a urban area. In other words if $P_{multiple}$ denotes the probability of more than one accident occurring along any one of the 37 unique HIGHWAY 3.1 predicted routes, then $P_{multiple} < 0.000034 < 1.0E\text{-}4$, thus $P_{multiple}$ is negligible.

Table C.1 Probabilities of Number of Accidents Occurring Along a 3,000 Mile Route Comprised of all Urban Mileage

Event	Probability of event
Zero Accidents	0.996975
Exactly One Accident	0.002991
More Than One Accident	0.000034

It should also be noted that it is really a release we are interested in because no release means zero risk. Now given that the probability of more than one accident occurring is less than 3.4E-5 we also have, based upon the probability of a package freight release given an accident (0.082), that the probability of more than one release is less than 2.79E-6 = 3.4E-5 x 0.082. Therefore, not only is the probability of multiple accidents for one shipment occurring along a route negligible, but more importantly, the probability of multiple releases for one shipment along a route is negligible.

C.2. The Probability of Exactly One Accident in a Specific Population Zone

The probability of exactly one accident occurring along a route and occurring in a rural population zone, is now developed. The following notation will be (same notation used in statement 2 above).

AR_I - Probability of an accident in any one mile of travel in the I-th population zone, where I can be one of - Rural, Suburban or Urban.

m_I - Number of miles along the route which are representative of the I-th population zone, where I can be one of - Rural, Suburban or Urban.

Suppose exactly one truck accident occurs while transporting a shipment of hazardous waste. Furthermore, let this accident occur in a rural population zone. Now the route traveled is ordered from the generation point to the designated treatment and/or disposal facility as follows -

$$(m_{R1}, m_{S1}, m_{U1}), (m_{R2}, m_{S2}, m_{U2}), \ldots, (m_{Rn}, m_{Sn}, m_{Un}) \quad ,$$

$$\text{where } \sum_{i=1}^{n}(m_{Ri} + m_{Si} + m_{Ui}) = m_R + m_S + m_U$$

This ordering listed above implies that the first m_{R1} miles traveled pass through a rural area, and the next m_{S1} miles traveled pass through a suburban area, etc.. Note that this ordering of the miles traveled is general because some of the m_{Ii} may be zero, where $I \in (R, S, U)$ and $i \in (1, 2, ..., n)$. Now suppose that the at the i-th mile an accident occurs, where the i-th mile is one of the m_{Rj} miles. With this ordering defined it is clear that the probability of an accident occurring in a rural population zone at the i-th mile is given by

$$\underbrace{\prod_{k=1}^{i-1}\left[(1-AR_R)^{m_{Rk}} \times (1-AR_S)^{m_{Sk}} \times (1-AR_U)^{m_{Uk}}\right] \times (1-AR_R)^{m^*}}_{\text{No accident occurs in the first (i) miles. Note that since the i-th mile occurs within the one of the } m_{Rj}\text{, there is some number } m^* \text{ which represents the number of miles within the } m_{Rj} \text{ miles but prior to the i-th mile, in which no accident occurs.}} \times \underbrace{AR_R}_{\text{Accident occurs at the i-th mile}}$$

$$\times \underbrace{(1-AR_R)^{m^`} \times \prod_{k=j+1}^{n}\left[(1-AR_R)^{m_{Rk}} \times (1-AR_S)^{m_{Sk}} \times (1-AR_U)^{m_{Uk}}\right]}_{\text{No accident occurs after the i-th miles. Note that since the i-th mile occurs within the one of the } m_{Rj}\text{, there is some number } m^` \text{ which represents the number of miles within the } m_{Rj} \text{ miles but after the i-th mile, in which no accident occurs.}}$$

The above expression looks somewhat complex. Basically this expression simply multiplies the probability of no accident occurring in the first i-1 miles, multiplied by the probability of an accident at the i-th mile, multiplied again by the probability of no accident occurring in any of the remaining miles which are traveled following the i-th mile. Furthermore, due to the commutitivity of multiplication these terms can be rearranged and simplified so that the probability of exactly one accident happening at the i-th mile, given that the i-th mile is in a rural population zone, is given by Equation C.1.

$$(1 - AR_R)^{(m_R - 1)} \times (1 - AR_S)^{m_S} \times (1 - AR_U)^{m_U} \times AR_R \qquad \textit{(Equation C.1)}$$

Note that Equation C.1 is independent of which particular rural mile is chosen. In other words, the probability of exactly one accident occurring in a rural area at the i-th mile, where the i-th mile is in a rural population zone, is the same for all rural miles. Furthermore, since there are a total of m_R different miles in which this accident may happen, we have that the probability of exactly one accident occurring along the route, where this accident occurs in a rural area is given by Equation C.2.

$$m_R \times (1 - AR_R)^{(m_R - 1)} \times (1 - AR_S)^{m_S} \times (1 - AR_U)^{m_U} \times AR_R \qquad \textit{(Equation C.2)}$$

$$m_S \times (1 - AR_R)^{(m_R - 1)} \times (1 - AR_S)^{m_S} \times (1 - AR_U)^{m_U} \times AR_S \qquad \textit{(Equation C.3)}$$

$$m_U \times (1 - AR_R)^{(m_R - 1)} \times (1 - AR_S)^{m_S} \times (1 - AR_U)^{m_U} \times AR_U \qquad \textit{(Equation C.4)}$$

Equations C.3 and C.4 represent the probability of exactly one accident happening for the route traveled, where the accident occurs in a suburban and urban population zone respectively. No proof is given for Equations C.3 and C.4. The proof of rural case is easily applied to the suburban and urban cases. The theories used to develop the proofs of statements 1 and 2 can include mutual exclusion, stochastic independence and binomial distributions. These topics can be found in any undergraduate text on mathematical probability theory.

C.3 Interpreting the Results of the Deterministic Method

For each shipment the set of potential outcomes or consequences as a result of transportation is given by the set whose members are the three different consequences (consequence of a release in each of the three generalized population zones) resulting from exactly one release occurring due to an accident plus the no release consequence. Note that this true because we are assuming no accident or only one accident occurs along the route because the probability of more than one accident occurring along a route is negligible.

Furthermore, these four consequences will occur exactly when a release occurs in the associated population zone (insofar as the determinisitc method, in the probabilistic method there will be an infinite number of consequences recognized at each potential release location) or when no release occurs. Therefore, the probability of a release in a specified population zone (or the probability of no release) is exactly the probability of the associated consequence in that population zone (or thye no release consequence). In interpreting the results of the deterministic method, it will be important to keep in mind that that there are only four potential consequences which result from transporting a shipment of hazardous waste (insofar as the deterministic method), and that the probability of these four consequences (consequence of a release in a rural, suburban or urban population zone or no release) is given by the probability of a release in the associated population zone or the probability of no release.

Therefore, the expected value or mean value of this distribution of four potential consequences is given by summing each of the four consequences multiplied by their respective probabilities. That is the mean value or expected value of the distribution of consequences (insofar as the deterministic calculations) is given by (Note that the following developement makes use of statements (1) and (2)):

$$\text{Mean Value} = \sum_{P=(\text{rural, suburban, urban})} \left(PR_P[\,CNSQ_P\,] \times CNSQ_P \right) + \left(PR[\text{No Release}] \times CNSQ \right)$$

$$= \sum_{P=(\text{rural, suburban, urban})} \left(PR_P[\,CNSQ_P\,] \times CNSQ_P \right) + \left(PR[\text{No Release}] \times 0 \right)$$

$$= \sum_{P=(\text{rural, suburban, urban})} \left(PR_P[\,CNSQ_P\,] \times CNSQ_P \right)$$

$$\approx \sum_{P=(\text{rural, suburban, urban})} \left(\left\{ M_P \times PR_P[\,\text{Release}\,] \right\} \times CNSQ_P \right),$$

where M_P denotes miles in the P - th population zone

$$= \sum_{i=1}^{N\text{ miles}} \left(PR_i[\,\text{Release}\,] \times CNSQ_i \right),$$

where the route travelled is N miles long

= **Shipment Risk**

APPENDIX D

The HMIRS database, discussed in Chapter 3, is constructed from DOT form 5800.1. This Appendix contains a copy of that form which will provide the reader with a general awareness of the information available in the HMIRS database.

DOT Form 5800.1

DEPARTMENT OF TRANSPORTATION
HAZARDOUS MATERIALS INCIDENT REPORT

Form Approved OMB No. 2137-0039

INSTRUCTIONS: Submit this report in duplicate to the Information System Manager, Office of Hazardous Materials Transportation, DHM-63, Research and Special Programs Administration, U.S. Department of Transportation, Washington D.C. 20590. If space provided for any items is inadequate, complete that item under section IX, keying to the entry number being completed. Copies of this form, in limited quantities, may be obtained from the Information Systems Manager, Office of Hazardous Materials Transportation. Additional copies in this prescribed format may be reproduced and used, if on the same size and kind of paper.

I MODE, DATE AND LOCATION OF INCIDENT

1 Mode of transportation ☐ Air ☐ Highway ☐ Rail ☐ Water ☐ Other

2 Date and time of incident (use military time, noon=1200 6pm=1800, midnight=2400) Date: ____ Time: ____

3 Location of incident (include airport name in route/street if incident occurs at an airport)
City: ____ State: ____
County: ____ Route/Street: ____

II DESCRIPTION OF CARRIER COMPANY OR INDIVIDUAL REPORTING

4 Carrier name	5 Carrier address (Principal place of Business)

6 List your OMC motor carrier census number, reporting railroad alphabetic code, merchant vessel name and ID number or other reporting code or number.

III SHIPMENT INFORMATION (from shipping paper or packaging)

7 Shipper name and address	8 Consignee name and address
9 Origin address (if different from shipper address)	10 Destination address (if different from consignee address)

11 Shipping paper / Waybill identification NO

IV HAZARDOUS MATERIAL(S) SPILLED (note: reference 49 CFR section 172.101.)

12 Proper shipping name	13 Chemical/Trade name	14 Hazard class	15 Identification number (e.g. UN2764, NA202)

16 Is material a hazardous substance ? ☐ Yes ☐ No | 17 Was the RQ met ? ☐ Yes ☐ No

V CONSEQUENCES OF INCIDENT, DUE TO THE HAZARDOUS MATERIALS

18 Estimated quantity of hazardous material released (include units)	19 Fatalities	20 Hospitalized Injuries	21 Non-Hospitalized Injuries

22 Number of people evacuated

23 Estimated dollar amount of loss and/or property damage, including cost of decontamination or clean up (round to dollars)

A. Product loss	B. Carrier damage	C. Public/private property damage	D. Decontamination Cleanup	E. Other damage

24 Consequence of the incident ☐ Vapor (gas) dispersion ☐ Material entered waterway / sewer ☐ Spillage ☐ Fire ☐ Environmental damage ☐ None ☐ Other ☐ Explosion

VI TRANSPORT ENVIRONMENT

25 Indicate type(s) of vehicle(s) involved: ☐ Cargo tank ☐ Van truck/trailer ☐ Flat bed truck/trailer ☐ Tank car ☐ Rail car ☐ TOFC/COFC ☐ Aircraft ☐ Barge ☐ Ship ☐ Other ____________

26 Transportation phase during which incident occurred or was discovered ☐ Enroute between origin/destination ☐ Loading ☐ Unloading ☐ Temporary storage/terminal

27 Land use at incident site: ☐ Industrial ☐ Commercial ☐ Residential ☐ Agricultural ☐ Undeveloped

28 Community type at site: ☐ Urban ☐ Suburban ☐ Rural

29 Was the spill the result of a vehicle accident/derailment ? ☐ Yes ☐ No
If yes, answer parts A thru C.

A. Estimated speed	B. Highway Type	C. Total number of lanes	SPACE FOR DOT USE ONLY
	☐ Divided/limited access ☐ Undivided	☐ one ☐ two ☐ three ☐ four or more	

VII PACKAGING INFORMATION: If the package is overpacked (consists of several packages, e.g. glass jars within a fiberboard box), begin with Column A for information on the innermost packaging.

ITEM		Column A	Column B	Column C
30 Type of packaging, include inner receptacles (e.g. steel drum, tank car)				
31 Capacity or weight per unit package (e.g. 55 gallons or 65 lbs)				
32 Number of packages of same type which failed in an identical manner				
33 Number of packages of same type in shipment				
34 Package specification identification (e.g. DOT 17E, DOT 105A100 or none)				
35 Any other packaging markings (e.g., STC, 18/16-55-88, Y1.4/150/87)				
36 Name and address, symbol or registration number of packaging manufacturer				
37 Serial number of cylinders, portable tanks, cargo tanks, tank cars				
38 Type of labeling or placarding applied				
39 If reconditioned or requalified	A. Registration number or symbol			
	B. Date of last test or inspection			
40 Exemption / approval / competent authority number, if applicable (e.g. DOT E1012)				

VIII DESCRIPTION OF PACKAGING FAILURE (Check all applicable boxes for the package(s) identified above)

41 Action contributing to package failure

	A	B	C			A	B	C	
a.	☐	☐	☐	vehicle collision	i.	☐	☐	☐	corrosion
b.	☐	☐	☐	vehicle overturn	j.	☐	☐	☐	metal fatigue
c.	☐	☐	☐	overloading/ overfilling	k.	☐	☐	☐	friction/ rubbing
d.	☐	☐	☐	loose fitting, valve	l.	☐	☐	☐	fire/ heat
e.	☐	☐	☐	defective fitting, valve	m.	☐	☐	☐	freezing
f.	☐	☐	☐	dropped	n.	☐	☐	☐	venting
g.	☐	☐	☐	struck / rammed	o.	☐	☐	☐	vandalism
h.	☐	☐	☐	improper loading	p.	☐	☐	☐	incompatible material
	☐	☐	☐	improper blocking	q.	☐	☐	☐	other

42 Object causing failure

	A	B	C	
a.	☐	☐	☐	other freight
b.	☐	☐	☐	forklift
c.	☐	☐	☐	nail/ protrusion
d.	☐	☐	☐	other vehicle
e.	☐	☐	☐	water/ other liquid
f.	☐	☐	☐	ground/ floor/ road
g.	☐	☐	☐	roadside obstacle
h.	☐	☐	☐	none
	☐	☐	☐	other

43 How package failed

	A	B	C	
a.	☐	☐	☐	punctured
b.	☐	☐	☐	cracked
c.	☐	☐	☐	burst/internal pressure
d.	☐	☐	☐	ripped
e.	☐	☐	☐	crushed
f.				rubbed/ abraded
g.				ruptured
h.				other

44 Package area that failed

	A	B	C	
a.	☐	☐	☐	end, forward
b.	☐	☐	☐	end, rear
c.	☐	☐	☐	side, right
d.	☐	☐	☐	side, left
e.	☐	☐	☐	top
f.				bottom
g.				center
h.				other

45 What failed on package

	A	B	C	
a.	☐	☐	☐	package material
b.	☐	☐	☐	fitting / valve
c.	☐	☐	☐	closure
d.	☐	☐	☐	chime
e.	☐	☐	☐	weld / seam
f.				hose / piping
g.				inner liner
h.				other

IX DESCRIPTION OF EVENTS: Describe the sequence of events that led to the incident, action taken at the time discovered, and action taken to prevent future incidents. Include any recommendations to improve packaging, or transportation of hazardous materials. Photographs and diagrams should be submitted when necessary for clarification. ATTACH A COPY OF THE HAZARDOUS WASTE MANIFEST FOR INCIDENTS INVOLVING HAZARDOUS WASTE, continue on additional sheets if necessary.		
46 Name of person responsible for preparing report	47 Signature	
48 Title of person responsible for preparing report	49 Telephone number (include area code)	50 date report signed

APPENDIX E

This appendix contains a description of the algorithm used to construct a cumulative probability distribution of a continuous random variable based upon a population sample, additional details on the release fraction cumulative probability distributions given in Figures 3.1 and 3.2, and a few additional probabilities determined from the HMIRS database.

E.1 Construction of a Cumulative Probability Distribution

To illustrate the algorithm used to construct a cumulative probability distribution of a continuous random variable from a population sample, an example will be given rather than describing the algorithm explicitly. In particular, the pressurized cylinders data compiled from the HMIRS data will be used for this example to construct the cumulative probability distribution of percent of maximum capacity released from a cylinder, given that a release of hazardous materials from a cylinder occurs.

Suppose X is a continuous random variable (X represents the percent of maximum physical capacity released or in other words the container release fraction), and that column 1 of Table E.1 contains a set of values (84 values to be exact) randomly sampled from the population of X (the sample containing all pressurized cylinder incidents occurring between 1985 and 1992 and entered into the HMIRS database given that the conditions in Table 3.2 are satisfied). These sampled values are then sorted and numbered from 1 to 84. Table E.1 contains the sorted and numbered values. Column 1 of Table E.1 contains the sorted values and column 2 contains the numbering. The third column contains a set of increasing values contained in the interval [0,1]. These numbers have been computed by dividing column 2 by the sample size, 84.

Consider the first value (the value with an entry of '1' in column 2) in Table E.1. There is 1 out of 84 incidents having a release fraction (of maximum physical capacity) less than or equal to 2.8E-5. In other words, for this sample, the probability that a release

Table E.1 Pressurized Cylinder Release Fractions Derived from HMIRS Database

Release %	Release #	Cumulative Prob.
0.000028	1	0.011905
0.00022	2	0.02381
0.0005	3	0.035714
0.000539	4	0.047619
0.000667	5	0.059524
0.0007	6	0.071429
0.000833	7	0.083333
0.000833	8	0.095238
0.001236	9	0.107143
0.00125	10	0.119048
0.001418	11	0.130952
0.001455	12	0.142857
0.001481	13	0.154762
0.002857	14	0.166667
0.005	15	0.178571
0.005	16	0.190476
0.006667	17	0.202381
0.007143	18	0.214286
0.007576	19	0.22619
0.008081	20	0.238095
0.008264	21	0.25
0.01	22	0.261905
0.010667	23	0.27381
0.010965	24	0.285714
0.014286	25	0.297619
0.014286	26	0.309524
0.015006	27	0.321429
0.016667	28	0.333333
0.016667	29	0.345238
0.02	30	0.357143
0.02	31	0.369048
0.020833	32	0.380952
0.023208	33	0.392857
0.025	34	0.404762
0.025	35	0.416667
0.025641	36	0.428571
0.026667	37	0.440476
0.026667	38	0.452381
0.028571	39	0.464286
0.03125	40	0.47619
0.035417	41	0.488095
0.038124	42	0.5
0.03876	43	0.511905
0.040064	44	0.52381
0.0504	45	0.535714
0.054054	46	0.547619
0.060065	47	0.559524
0.071429	48	0.571429
0.077778	49	0.583333
0.1	50	0.595238
0.100128	51	0.607143
0.111702	52	0.619048
0.127226	53	0.630952
0.133333	54	0.642857
0.142857	55	0.654762
0.142857	56	0.666667
0.15	57	0.678571
0.16129	58	0.690476
0.166667	59	0.702381
0.175	60	0.714286
0.181818	61	0.72619
0.249997	62	0.738095
0.292887	63	0.75
0.333333	64	0.761905
0.3472	65	0.77381
0.499969	66	0.785714
0.5	67	0.797619
0.5	68	0.809524
0.532213	69	0.821429
0.6	70	0.833333
0.933333	71	0.845238
0.941176	72	0.857143
0.97619	73	0.869048
1	74	0.880952
1	75	0.892857
1	76	0.904762
1	77	0.916667
1	78	0.928571
1	79	0.940476
1	80	0.952381
1	81	0.964286
1	82	0.97619
1	83	0.988095
1	84	1

fraction of less than or equal to 2.85E-5 occurring as a result of damage to a pressurized cylinder containing hazardous waste is 1/84 ≈ 1.19%. This probability may serve as an estimate to the population cumulative probability distribution (of release fraction of maximum physical capacity) function at 2.85E-5.

Similarly, approximately 86.9% of the release fractions sampled were less than or equal to 0.976. Therefore, it is estimated that 0.869 is the probability that less than or equal to 97.6% of the maximum capacity of a shipment of cylinders will be released.

One problem with the data in table E.1 is that often, a certain release fraction may be repeated in the table. For example the 74-th and 84-th entries in the table, and all other entries between these two (75, 76, ..., 83), show a release fraction of 100% of the maximum physical capacity. In order to determine how to interpret this, the definition of cumulative probability must be reviewed.

Suppose X is a random variable, and Z is a value which this variable may take on. Then the probability that $X \leq Z$ is, by definition, the value of the cumulative probability distribution function evaluated at Z. Therefore, in the above example, there are actually 84 incidents (not 74, 75, ..., or 83) which have a release fraction of maximum physical capacity of less than <u>or equal to</u> 1. Therefore, 84/84 = 1 will serve as the estimated value of the population cumulative probability distribution function at 1. This situation can be generalized by approximating the value of the population cumulative probability distribution function at a certain value by the largest probability given when the sample contains multiple instances of the same release fraction. Doing so to the data in Table E.1, results in the numerical representation of the pressurized cylinder release fraction cumulative probability distribution given in Table E.2

The data in Table E.2 is given graphically in Figure 3.1. Note that, to obtain cumulative probabilities for a release fraction not explicitly given in Table E.2, a linear interpolation is required between the nearest two release fractions. The graph of the cumulative probability distribution has been drawn by connecting straight lines between points given in the Table E.2. This is equivalent to linearly interpolating intermediate values.

Table E.2 Cumulative Probability Distribution Function of Fraction of Maximum Capacity Released from Package Freight Pressurized Cylinders.

Release Fraction	Cumulative Probability	Release Fraction	Cumulative Probability	Release Fraction	Cumulative Probability	Release Fraction	Cumulative Probability
2.80E-05	1.19E-02	1.43E-01	6.67E-01	3.13E-02	4.76E-01	1.61E-01	6.90E-01
2.20E-04	2.38E-02	8.08E-03	2.38E-01	3.54E-02	4.88E-01	1.67E-01	7.02E-01
5.00E-04	3.57E-02	8.26E-03	2.50E-01	3.81E-02	5.00E-01	1.75E-01	7.14E-01
5.39E-04	4.76E-02	1.00E-02	2.62E-01	3.88E-02	5.12E-01	1.82E-01	7.26E-01
6.67E-04	5.95E-02	1.07E-02	2.74E-01	4.01E-02	5.24E-01	2.50E-01	7.38E-01
7.00E-04	7.14E-02	1.10E-02	2.86E-01	5.04E-02	5.36E-01	2.93E-01	7.50E-01
8.33E-04	9.52E-02	1.43E-02	3.10E-01	5.41E-02	5.48E-01	3.33E-01	7.62E-01
1.24E-03	1.07E-01	1.50E-02	3.21E-01	6.01E-02	5.60E-01	3.47E-01	7.74E-01
1.25E-03	1.19E-01	1.67E-02	3.45E-01	7.14E-02	5.71E-01	5.00E-01	7.86E-01
1.42E-03	1.31E-01	2.00E-02	3.69E-01	7.78E-02	5.83E-01	5.00E-01	8.10E-01
1.46E-03	1.43E-01	2.08E-02	3.81E-01	1.00E-01	5.95E-01	5.32E-01	8.21E-01
1.48E-03	1.55E-01	2.32E-02	3.93E-01	1.00E-01	6.07E-01	6.00E-01	8.33E-01
2.86E-03	1.67E-01	2.50E-02	4.17E-01	1.12E-01	6.19E-01	9.33E-01	8.45E-01
5.00E-03	1.90E-01	2.56E-02	4.29E-01	1.27E-01	6.31E-01	9.41E-01	8.57E-01
6.67E-03	2.02E-01	2.67E-02	4.52E-01	1.33E-01	6.43E-01	9.76E-01	8.69E-01
7.14E-03	2.14E-01	2.86E-02	4.64E-01	1.50E-01	6.79E-01	1.00E+00	1.00E+00
7.58E-03	2.26E-01						

E.2 Uncertainty in Analyzing Release Fractions of DOE Shipments

The release fraction cumulative probability distributions are delineated by container type, where the container categories recognized include small and large drums, pressurized cylinders, bulk pressurized containers and bulk non-pressurized containers (see Table 3.5 for a description of these categories). This delineation has been made by container category because it is believed to be the most dominant factor affecting the behavior of the release fraction random variable. However, it must be noted that not all drums are packaged the same, not all cylinders are packaged the same, and most certainly, there is a range of quality of construction within each of the container categories. For example, paint related materials and fuming sulfuric acid can both be packaged in 55 gallon drums. Because of the hazard presented by fuming sulfuric acid, thick absorbent overpacks may be placed around the drum. Furthermore, the drum containing the fuming sulfuric acid may have all welded seams whereas the drum used to package the paint related materials may be constructed with a plastic receptacle. The likelihood of a damaged receptacle resulting in a release should be much higher than the likelihood of a puncture to the drum with all welded seems. Many of the incidents used to construct these distributions concern releases of chemicals presenting a low level of hazard which have been generated by an agency not affiliated with DOE. The packagings used may not perform in an accident as well as the DOE packagings due to the requirements for packaging the DOE hazardous wastes which have the potential to cause more severe human health and environmental damages. As a result, the cumulative probability distributions of release fractions may be conservative in that cumulative probabilities may be overestimated.

Tables E.3 show the ten most frequent chemicals used in the construction of the pressurized cylinder release fraction cumulative probability distribution. Notice that one of the most frequent hazardous wastes represented in the table includes compressed oxygen, which probably does not pose either a great human health hazard or environmental hazard. Furthermore, the packaging requirements for compressed oxygen are less stringent than for any of the DOE generated hazardous wastes listed in Appendix A. As a result, the cylinders used to package the compressed oxygen may have plastic receptacles instead of all welded seams or less protective overpacks than those used by the DOE to contain their cylinder packagings. Subsequently, the cumulative probability distribution of release fractions from pressurized cylinders may be conservative in that probabilities are overestimated.

Similar tables have also been provided for each of the other four cumulative probability distributions shown in Figures 3.1 and 3.2 (small drums, large drums, bulk pressurized and bulk non-pressurized). In each of those tables (Tables E.4 thru E.7) there are chemicals which present a lower level of hazard to human health and potential environmental damage than does the DOE generated hazardous wastes.

Table E.3 10 Most Frequent Hazardous Liquid or Gas Chemicals Released from Pressurized Cylinders as a Result of a Truck Accident (Based upon the records of the HMIRS Database)

Chemical Name	Frequency	Chemical Name	Frequency
Acetylene dissolved	6	Fire extinguishers	5
Aerosol product	6	Hydrochloric acid anhydr	5
Nitrogen refrigerated liq	6	Liquefied petroleum gas	5
Oxygen compressed	6	Helium compressed	4
Boron trichloride	5	Oxygen refrigerated liq	4

Table E.4 10 Most Frequent Hazardous Liquid or Gas Chemicals Released from Large Drums (> 20 Gallons in Capacity) as a Result of a Truck Accident (Based upon the records of the HMIRS Database)

Chemical Name	Frequency	Chemical Name	Frequency
Stain	794	Alkaline liquid n.o.s.	212
Flammable liquids n.o.s.	550	Paint related material	180
Corrosive liquids n.o.s.	549	Adhesives	131
Resin solution	537	Ink printers flammable	122
Compound cleaning liquid	390	Poisonous liquids n.o.s.	106

Table E.5 10 Most Frequent Hazardous Liquid or Gas Chemicals Released from Small Drums (≤ 20 Gallons in Capacity) as a Result of a Truck Accident (Based upon the records of the HMIRS Database)

Chemical Name	Frequency	Chemical Name	Frequency
Compound cleaning liquid	151	Ink printers flammable	81
Flammable liquids n.o.s.	128	Liquid Cement	68
Adhesives	124	Coating solution	45
Corrosive liquids n.o.s.	120	Spirits of salt	43
Resin solution	105	Alkaline liquid n.o.s.	39

Table E.6 10 Most Frequent Hazardous Liquid or Gas Chemicals Released from Bulk Pressurized Containers as a Result of a Truck Accident (Based upon the records of the HMIRS Database)

Chemical Name	Frequency	Chemical Name	Frequency
Hydrogen refrigerated liq	23	Chlorine	1
Hydrogen compressed	5	Helium refrigerated liq	1
Hydrochloric acid anhydr	2	Hydrogen sulfide	1
Hydrogen chloride ref liq	2	Nitrogen refrigerated liq	1
Aerosol product	1	Resin solution	1

Table E.7 10 Most Frequent Hazardous Liquid or Gas Chemicals Released from Non-Pressurized Bulk Containers as a Result of a Truck Accident (Based upon the records of the HMIRS Database)

Chemical Name	Frequency	Chemical Name	Frequency
Case oil	424	Corrosive liquids n.o.s.	92
Diesel fuel	278	Hydrogen sulfate	82
Flammable liquids n.o.s.	114	Spirits of salt	67
Combustible liquid n.o.s.	109	Caustic soda solution	65
Petroleum crude oil	106	Petroleum naphtha	47

E.3 Risks Associated with Fire or Water Immersion Resulting from a Release

The basic concept behind the deterministic risk model presented in Chapter 4 is to compute risk as the sum of the products of the probabilities of an outcome multiplied by the corresponding outcome for each potential outcome. For the application presented in this thesis, the deterministic model was used to calculate shipment risks, which were then summed to determine the annual risks. The shipment risks, were computed by summing the products of the probability of a release at any one mile multiplied by the consequence (number of potentially life-threatening health effects) of that release. Future extensions of this work will include analysis of risks imposed by fire and chemical reactions occurring as a result of water immersion of the hazardous wastes released.

In order to implement these extensions using the deterministic model, the risk formula given in Equation 4.1 would be adapted to the following -

$$RISK = \sum_{S}\sum_{P}\underbrace{\left(AR_P \times PR_S \times PC\right)}_{\left\{\begin{array}{c}\text{Probability of a}\\ \text{water immersion or}\\ \text{fire, given a release}\end{array}\right\}} \times \underbrace{\left(EA_S \times PD_P\right)}_{\left\{\text{Consequence}\right\}} \qquad \textit{(Equation E.1)}$$

The four terms AR_P (probability of an accident), PR_S (probability of a release given an accident), EA_S (exposed area - mile^2) and PD_P (population density - people/mile^2) are the same as they are given in Equation 4.1. However, there is an additional term, *PC*. *PC* is the probability of the additional consequence under consideration given a release.

If interested in computing the risks resulting from fire than *PC* should be filled by the probability of a fire given that a release occurs. Furthermore, a model other than CASRAM (see section 4.4) would have to be used to determine the exposed area as CASRAM does not account for fires.

In computing the risk resulting from the hazardous waste being submersed in water, *PC* represents the probability that an immersion of the waste occurs given that a release occurs. Furthermore, either a model other than CASRAM would have to be used or to compute the exposed areas, as CASRAM does not account for reactivity with water, or the stoicheometry can be done by hand, determining what reactives to use as input to CASRAM.

In either case, risks associated with fire or water immersion resulting from the release of hazardous waste due to a truck accident, the probability of a fire given a release and the probability of a water immersion given a release need to be determined. These values can be approximated by taking the fraction of releases resulting in fire (or water immersion) divided by the total number of releases. These values are given below in Table E.8.

Numbers in Table E.8 are based upon 1989 to 1992 records of the HMIRS database. During the years of 1985 to 1988 the fire and water immersion fields are often left blank. It could be assumed when left blank, neither happened. However, the 1989 to 1992 records are also marked as true or false with regard to the fire and water immersion fields. As a result, this data is believed to be more accurate by leaving out the 1985 to 1988 data.

Table E.8 Probabilities and Accident Counts Involving Fire and Water Immersion

Consequence of Release	Number of Incidents	Probability of consequence given a release occurs
Fire	154	0.0173
Hazardous Waste Immersed in H_20	90	0.0101
Other (possibly no consequence)	8652	0.9726
Total	8,896	1.000

APPENDIX F

This appendix contains the results of the deterministic calculations. The route summary, exposed area and risk associated with each of the 63 potentially life-threatening shipments of DOE generated hazardous waste listed in Appendix A, is given below. Following these individual shipment data, the total annual risk is given (the sum of the shipment risks).

It is worth noting that for 32 of the 63 shipments (approximately 1/2), there is zero risk. This is a result of the assumption that there are no human inhabitants within 100 feet of the road. Therefore, those 32 zero risk shipments all had an assoicated exposed area of less than or equal to 100 feet.

Therefore less than half the shipments account for all the risk 1.74E-4). Furthermore, the top seven risk producing shipments (3, 8, 12, 23, 26, 46, 50) account for approximately 86% of the total annual risk (1.189E-4), and the top 2 (12, 23) account for approximately 68% of the total annual risk (1.49E-4).

Shipment 1
Route 1

	Miles	People /Mi.2
Rural	1.76E+03	1.17E+01
Suburban	1.57E+02	9.48E+02
Urban	1.89E+01	5.66E+03
Area (km^2)	0.00E+00	
Risk	0.00E+00	

Shipment 2
Route 1

	Miles	People /Mi.2
Rural	1.76E+03	1.17E+01
Suburban	1.57E+02	9.48E+02
Urban	1.89E+01	5.66E+03
Area (km^2)	0.00E+00	
Risk	0.00E+00	

Shipment 33
Route 19

	Miles	People / Mi.2
Rural	7.65E+02	1.33E+01
Suburban	1.45E+02	1.09E+03
Urban	1.66E+01	5.44E+03
Area (km^2)	0.00E+00	
Risk	0.00E+00	

Shipment 34
Route 19

	Miles	People / Mi.2
Rural	7.65E+02	1.33E+01
Suburban	1.45E+02	1.09E+03
Urban	1.66E+01	5.44E+03
Area (km^2)	0.00E+00	
Risk	0.00E+00	

Shipment 3
Route 2

	Miles	People / Mi.2
Rural	2.83E+01	2.76E+01
Suburban	1.79E+01	1.21E+03
Urban	1.83E+01	7.40E+03
Area (km^2)	6.24E-04	
Risk	8.18E-06	

Shipment 4
Route 2

	Miles	People / Mi.2
Rural	2.83E+01	2.76E+01
Suburban	1.79E+01	1.21E+03
Urban	1.83E+01	7.40E+03
Area (km^2)	2.14E-04	
Risk	2.81E-06	

Shipment 5
Route 2

	Miles	People / Mi.2
Rural	2.83E+01	2.76E+01
Suburban	1.79E+01	1.21E+03
Urban	1.83E+01	7.40E+03
Area (km^2)	0.00E+00	
Risk	0.00E+00	

Shipment 6
Route 2

	Miles	People / Mi.2
Rural	2.83E+01	2.76E+01
Suburban	1.79E+01	1.21E+03
Urban	1.83E+01	7.40E+03
Area (km^2)	0.00E+00	
Risk	0.00E+00	

Shipment 7
Route 2

	Miles	People / Mi.2
Rural	2.83E+01	2.76E+01
Suburban	1.79E+01	1.21E+03
Urban	1.83E+01	7.40E+03
Area (km^2)	0.00E+00	
Risk	0.00E+00	

Shipment 35
Route 19

	Miles	People / Mi.2
Rural	7.65E+02	1.33E+01
Suburban	1.45E+02	1.09E+03
Urban	1.66E+01	5.44E+03
Area (km^2)	4.95E-05	
Risk	9.61E-07	

Shipment 36
Route 19

	Miles	People / Mi.2
Rural	7.65E+02	1.33E+01
Suburban	1.45E+02	1.09E+03
Urban	1.66E+01	5.44E+03
Area (km^2)	7.20E-07	
Risk	1.40E-08	

Shipment 37
Route 19

	Miles	People / Mi.2
Rural	7.65E+02	1.33E+01
Suburban	1.45E+02	1.09E+03
Urban	1.66E+01	5.44E+03
Area (km^2)	1.03E-06	
Risk	2.00E-08	

Shipment 38
Route 19

	Miles	People / Mi.2
Rural	7.65E+02	1.33E+01
Suburban	1.45E+02	1.09E+03
Urban	1.66E+01	5.44E+03
Area (km^2)	9.35E-06	
Risk	1.81E-07	

Shipment 39
Route 19

	Miles	People / Mi.2
Rural	7.65E+02	1.33E+01
Suburban	1.45E+02	1.09E+03
Urban	1.66E+01	5.44E+03
Area (km^2)	3.18E-05	
Risk	6.17E-07	

Shipment 8
Route 4

	Miles	People / Mi.2
Rural	2.05E+03	1.51E+01
Suburban	2.16E+02	8.85E+02
Urban	2.98E+01	5.64E+03
Area (km^2)	1.67E-04	
Risk	4.93E-06	

Shipment 9
Route 4

	Miles	People / Mi.2
Rural	2.05E+03	1.51E+01
Suburban	2.16E+02	8.85E+02
Urban	2.98E+01	5.64E+03
Area (km^2)	0.00E+00	
Risk	0.00E+00	

Shipment 10
Route 5

	Miles	People / Mi.2
Rural	1.62E+03	1.16E+01
Suburban	1.94E+02	1.22E+03
Urban	8.66E+01	6.57E+03
Area (km^2)	0.00E+00	
Risk	0.00E+00	

Shipment 11
Route 5

	Miles	People / Mi.2
Rural	1.62E+03	1.16E+01
Suburban	1.94E+02	1.22E+03
Urban	8.66E+01	6.57E+03
Area (km^2)	5.53E-06	
Risk	3.67E-07	

Shipment 12
Route 5

	Miles	People / Mi.2
Rural	1.62E+03	1.16E+01
Suburban	1.94E+02	1.22E+03
Urban	8.66E+01	6.57E+03
Area (km^2)	5.48E-04	
Risk	3.63E-05	

Shipment 40
Route 19

	Miles	People / Mi.2
Rural	7.65E+02	1.33E+01
Suburban	1.45E+02	1.09E+03
Urban	1.66E+01	5.44E+03
Area (km^2)	2.06E-06	
Risk	4.00E-08	

Shipment 41
Route 19

	Miles	People / Mi.2
Rural	7.65E+02	1.33E+01
Suburban	1.45E+02	1.09E+03
Urban	1.66E+01	5.44E+03
Area (km^2)	4.26E-05	
Risk	8.27E-07	

Shipment 42
Route 21

	Miles	People / Mi.2
Rural	7.64E+02	1.36E+01
Suburban	1.08E+02	1.00E+03
Urban	1.02E+01	5.85E+03
Area (km^2)	0.00E+00	
Risk	0.00E+00	

Shipment 43
Route 21

	Miles	People / Mi.2
Rural	7.64E+02	1.36E+01
Suburban	1.08E+02	1.00E+03
Urban	1.02E+01	5.85E+03
Area (km^2)	0.00E+00	
Risk	0.00E+00	

Shipment 44
Route 22

	Miles	People / Mi.2
Rural	1.01E+03	1.06E+01
Suburban	5.21E+01	8.61E+02
Urban	1.04E+01	5.55E+03
Area (km^2)	4.02E-04	
Risk	3.49E-06	

Shipment 13
Route 5

	Miles	People / Mi.2
Rural	1.62E+03	1.16E+01
Suburban	1.94E+02	1.22E+03
Urban	8.66E+01	6.57E+03
Area (km^2)	9.29E-08	
Risk	6.16E-09	

Shipment 45
Route 23

	Miles	People / Mi.2
Rural	9.04E+02	1.78E+01
Suburban	1.31E+02	9.83E+02
Urban	2.86E+01	5.50E+03
Area (km^2)	0.00E+00	
Risk	0.00E+00	

Shipment 14
Route 8

	Miles	People / Mi.2
Rural	1.68E+03	1.81E+01
Suburban	2.92E+02	7.79E+02
Urban	4.19E+01	5.70E+03
Area (km^2)	7.76E-06	
Risk	2.95E-07	

Shipment 46
Route 23

	Miles	People / Mi.2
Rural	9.04E+02	1.78E+01
Suburban	1.31E+02	9.83E+02
Urban	2.86E+01	5.50E+03
Area (km^2)	3.06E-04	
Risk	7.16E-06	

Shipment 15
Route 8

	Miles	People / Mi.2
Rural	1.68E+03	1.81E+01
Suburban	2.92E+02	7.79E+02
Urban	4.19E+01	5.70E+03
Area (km^2)	0.00E+00	
Risk	0.00E+00	

Shipment 47
Route 23

	Miles	People / Mi.2
Rural	9.04E+02	1.78E+01
Suburban	1.31E+02	9.83E+02
Urban	2.86E+01	5.50E+03
Area (km^2)	0.00E+00	
Risk	0.00E+00	

Shipment 16
Route 7

	Miles	People / Mi.2
Rural	1.51E+03	1.35E+01
Suburban	1.57E+02	8.23E+02
Urban	1.50E+01	5.22E+03
Area (km^2)	0.00E+00	
Risk	0.00E+00	

Shipment 48
Route 23

	Miles	People / Mi.2
Rural	9.04E+02	1.78E+01
Suburban	1.31E+02	9.83E+02
Urban	2.86E+01	5.50E+03
Area (km^2)	0.00E+00	
Risk	0.00E+00	

Shipment 17
Route 7

	Miles	People / Mi.2
Rural	1.51E+03	1.35E+01
Suburban	1.57E+02	8.23E+02
Urban	1.50E+01	5.22E+03
Area (km^2)	4.29E-05	
Risk	7.27E-07	

Shipment 49
Route 23

	Miles	People / Mi.2
Rural	9.04E+02	1.78E+01
Suburban	1.31E+02	9.83E+02
Urban	2.86E+01	5.50E+03
Area (km^2)	1.07E-04	
Risk	2.51E-06	

Shipment 18
Route 8

	Miles	People / Mi.2
Rural	1.68E+03	1.81E+01
Suburban	2.92E+02	7.79E+02
Urban	4.19E+01	5.70E+03
Area (km^2)	8.37E-05	
Risk	3.19E-06	

Shipment 50
Route 24

	Miles	People / Mi.2
Rural	1.40E+03	2.74E+01
Suburban	3.51E+02	7.88E+02
Urban	5.20E+01	6.04E+03
Area (km^2)	8.83E-05	
Risk	4.27E-06	

Shipment 19
Route 9

	Miles	People / Mi.2
Rural	6.56E+02	2.16E+01
Suburban	9.05E+01	8.36E+02
Urban	1.01E+01	6.28E+03
Area (km^2)	0.00E+00	
Risk	0.00E+00	

Shipment 51
Route 25

	Miles	People / Mi.2
Rural	7.37E+02	1.30E+01
Suburban	1.40E+02	1.12E+03
Urban	2.12E+01	5.79E+03
Area (km^2)	0.00E+00	
Risk	0.00E+00	

Shipment 20
Route 11

	Miles	People / Mi.2
Rural	3.31E+02	4.87E+01
Suburban	1.92E+02	8.43E+02
Urban	3.50E+01	5.92E+03
Area (km^2)	0.00E+00	
Risk	0.00E+00	

Shipment 52
Route 25

	Rural	Suburban
Miles	7.37E+02	1.40E+02
People / Mi.2	1.30E+01	1.12E+03
Area (km^2)	1.67E-05	
Risk	3.70E-07	

Shipment 21
Route 11

	Miles	People / Mi.2
Rural	3.31E+02	4.87E+01
Suburban	1.92E+02	8.43E+02
Urban	3.50E+01	5.92E+03
Area (km^2)	0.00E+00	
Risk	0.00E+00	

Shipment 53
Route 25

	Rural	Suburban
Miles	7.37E+02	1.40E+02
People / Mi.2	1.30E+01	1.12E+03
Area (km^2)	7.60E-05	
Risk	1.68E-06	

Shipment 22
Route 11

	Miles	People / Mi.2
Rural	3.31E+02	4.87E+01
Suburban	1.92E+02	8.43E+02
Urban	3.50E+01	5.92E+03
Area (km^2)	0.00E+00	
Risk	0.00E+00	

Shipment 54
Route 25

	Rural	Suburban
Miles	7.37E+02	1.40E+02
People / Mi.2	1.30E+01	1.12E+03
Area (km^2)	1.48E-04	
Risk	3.27E-06	

Shipment 23
Route 11

	Miles	People / Mi.2
Rural	3.31E+02	4.87E+01
Suburban	1.92E+02	8.43E+02
Urban	3.50E+01	5.92E+03
Area (km^2)	2.76E-03	
Risk	8.26E-05	

Shipment 24
Route 14

	Miles	People / Mi.2
Rural	9.01E+02	2.43E+01
Suburban	1.76E+02	8.68E+02
Urban	1.96E+01	5.76E+03
Area (km^2)	5.73E-05	
Risk	1.24E-06	

Shipment 25
Route 16

	Miles	People / Mi.2
Rural	5.52E+02	2.33E+01
Suburban	1.45E+02	1.11E+03
Urban	3.42E+01	5.55E+03
Area (km^2)	7.52E-06	
Risk	2.13E-07	

Shipment 26
Route 16

	Miles	People / Mi.2
Rural	5.52E+02	2.33E+01
Suburban	1.45E+02	1.11E+03
Urban	3.42E+01	5.55E+03
Area (km^2)	1.96E-04	
Risk	5.55E-06	

Shipment 27
Route 18

	Miles	People / Mi.2
Rural	9.32E+02	1.79E+01
Suburban	1.35E+02	9.58E+02
Urban	2.40E+01	5.20E+03
Area (km^2)	0.00E+00	
Risk	0.00E+00	

Shipment 55
Route 25

	Rural	Suburban
Miles	7.37E+02	1.40E+02
People / Mi.2	1.30E+01	1.12E+03
Area (km^2)	2.61E-05	
Risk	5.78E-07	

Shipment 56
Route 25

	Rural	Suburban
Miles	7.37E+02	1.40E+02
People / Mi.2	1.30E+01	1.12E+03
Area (km^2)	2.36E-05	
Risk	5.22E-07	

Shipment 57
Route 34

	Miles	People / Mi.2
Rural	6.28E+02	2.39E+01
Suburban	1.17E+02	8.17E+02
Urban	2.10E+01	6.27E+03
Area (km^2)	0.00E+00	
Risk	0.00E+00	

Shipment 58
Route 35

	Miles	People / Mi.2
Rural	5.40E+02	2.06E+01
Suburban	1.18E+02	1.08E+03
Urban	2.23E+01	5.19E+03
Area (km^2)	0.00E+00	
Risk	0.00E+00	

Shipment 59
Route 36

	Miles	People / Mi.2
Rural	1.95E+03	1.41E+01
Suburban	2.14E+02	8.67E+02
Urban	2.12E+01	5.33E+03
Area (km^2)	1.82E-05	
Risk	4.41E-07	

Shipment 28
Route 18

	Miles	People / Mi.2
Rural	9.32E+02	1.79E+01
Suburban	1.35E+02	9.58E+02
Urban	2.40E+01	5.20E+03
Area (km^2)	0.00E+00	
Risk	0.00E+00	

Shipment 29
Route 18

	Miles	People / Mi.2
Rural	9.32E+02	1.79E+01
Suburban	1.35E+02	9.58E+02
Urban	2.40E+01	5.20E+03
Area (km^2)	1.25E-05	
Risk	2.58E-07	

Shipment 30
Route 18

	Miles	People / Mi.2
Rural	9.32E+02	1.79E+01
Suburban	1.35E+02	9.58E+02
Urban	2.40E+01	5.20E+03
Area (km^2)	0.00E+00	
Risk	0.00E+00	

Shipment 31
Route 18

	Miles	People / Mi.2
Rural	9.32E+02	1.79E+01
Suburban	1.35E+02	9.58E+02
Urban	2.40E+01	5.20E+03
Area (km^2)	0.00E+00	
Risk	0.00E+00	

Shipment 32
Route 18

	Miles	People / Mi.2
Rural	9.32E+02	1.79E+01
Suburban	1.35E+02	9.58E+02
Urban	2.40E+01	5.20E+03
Area (km^2)	0.00E+00	
Risk	0.00E+00	

Shipment 60
Route 36

	Miles	People / Mi.2
Rural	1.95E+03	1.41E+01
Suburban	2.14E+02	8.67E+02
Urban	2.12E+01	5.33E+03
Area (km^2)	0.00E+00	
Risk	0.00E+00	

Shipment 61
Route 36

	Miles	People / Mi.2
Rural	1.95E+03	1.41E+01
Suburban	2.14E+02	8.67E+02
Urban	2.12E+01	5.33E+03
Area (km^2)	0.00E+00	
Risk	0.00E+00	

Shipment 62
Route 36

	Miles	People / Mi.2
Rural	1.95E+03	1.41E+01
Suburban	2.14E+02	8.67E+02
Urban	2.12E+01	5.33E+03
Area (km^2)	0.00E+00	
Risk	0.00E+00	

Shipment 63
Route 36

	Miles	People / Mi.2
Rural	1.95E+03	1.41E+01
Suburban	2.14E+02	8.67E+02
Urban	2.12E+01	5.33E+03
Area (km^2)	0.00E+00	
Risk	0.00E+00	

TOTAL ANNUAL RISK = 1.74E-4

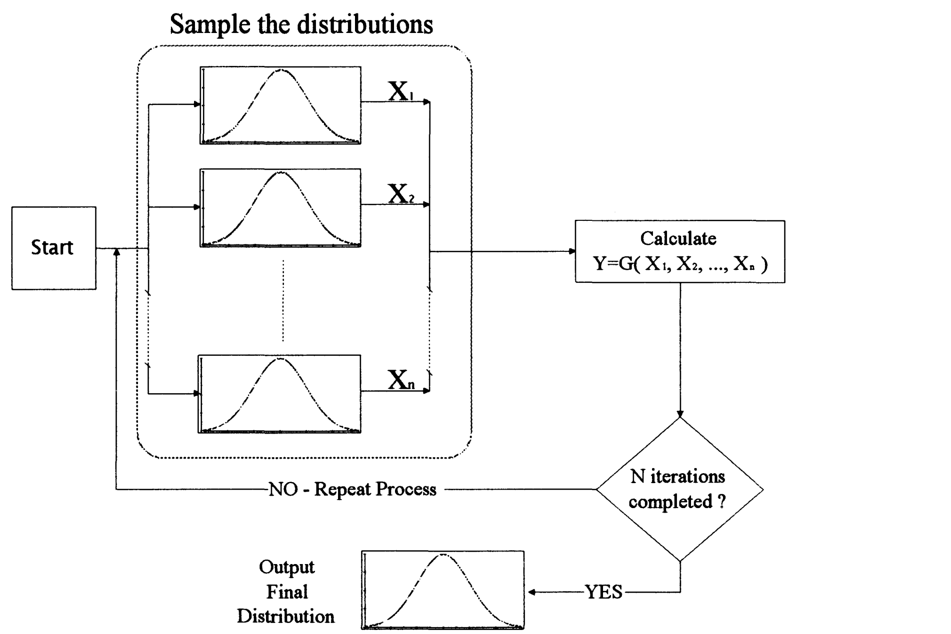
APPENDIX G

Monte Carlo methods have applications in both integration and simulation. This appendix will provide the reader with some general background information on Monte Carlo methods of simulation along with some additional details on the application of Monte Carlo methods in this thesis.

G.1. Monte Carlo Simulation

Suppose $Y = G(X_1, X_2, ..., X_n)$, where all of the X_i are mutually and stochastically independent random variables whose probability density functions are known. Then Y is also a random variable. Traditionally, analytical methods such as the change-of-variable or moment-generating-function technique are employed to determine the probability density function of Y. Often, the function G is very complex making it very difficult to apply traditional analytical techniques or even impossible. Using Monte Carlo simulation, a numerical alternative to analytic techniques is possible. The basic algorithm is illustrated in Figure G.1.

Figure G.1 Monte Carlo Simulation Methods



The Monte Carlo simulation method involves sampling a value from each of the mutually and stochastically independent random variables which risk is a function of, calculating the value of Y, and repeating this process until N iterations have been executed, where N is a user selected number (usually several hundred or even several thousand repetitions are required to obtain a smooth distribution).

G.1.1. Sampling Techniques

Generally, sampling is done by first sampling a uniformly distributed random variable with a random number generator. This random variable may be of the discrete type or of the continuous type. Commonly computer random number generators are based upon the linear congruential method defined by the following recursion:

$$y_{n+1} \equiv ay_n + c \bmod M \quad \text{for} \quad n = 0,1,2,\ldots \qquad \textbf{\textit{(Equation G.1)}}$$

where

M is a large positive integer (usually 2^{32}-1 or 7FFF in hexadecimal);

a is an integer in $[1,M)$ and gcd(a,M)=1;

c is an integer in the set $\{0, 1, 2, \ldots, M\text{-}1\}$;

Equation G.2 defines a recursion that can be used to generate a discrete uniformly distributed random integer. Often a real random number is needed in the interval [0,1]. Such a random variable may be approximated by dividing the random integer generated by the value of M. There is a great deal of literature on computer algorithms used for the generation of uniformly distributed random numbers. The reader is referred to *Random Number Generation and Quasi-Monte Carlo Methods* **[9]** for additional information on the subject.

Once the ability to generate uniformly distributed random numbers of the discrete or continuous type has been established, it is often a simple task to generate random numbers that are distributed non-uniformly. For example, if Y_1 and Y_2 are uniformly distributed over the interval (0,1], then the random variables X_1 and X_2 defined in

Equations G.2 and G.3 respectively (Equations G.2 and G.3 define the scheme suggested by Box and Muller **[5]** for randomly generating values of a standard normal random variable), are stochastically independent random variables, both distributed normally with mean 0 and variance 1. Given these transformations and the ability to generate values of a uniformly distributed (on (0,1]) random variable, randomly generating numbers from a standard normal distribution can easily be done.

$$X_1 = (-2 \cdot \ln Y_1)^{1/2} \cdot \cos(2\Pi Y_2) \qquad \textit{(Equation G.2)}$$

$$X_2 = (-2 \cdot \ln Y_1)^{1/2} \cdot \sin(2\Pi Y_2) \qquad \textit{(Equation G.3)}$$

Using the above transformation, samples of size 50, 100, 1,000 and 10,000 have been randomly generated and plotted against the standard normal cumulative probability function in Figures G.2, G.3 G.4 and G.5. As expected, the curve produced from a sample of size 10,000 shows that the random generation of values well simulates sampling from a standard normal population. Transformation techniques provide a simple method of non-uniform random number generation, however, analytic transformation are not always available. Another common technique used is called Latin hypercubes sampling (LHS).

To implement LHS, the range of the random variable must first be truncated to a closed interval (if the range is not already a closed interval). For example, if a sample from a standard normal population is desired, and if it is acceptable to neglect 0.1% of the distribution in the left and right tails, then the standard normal distribution can be truncated to the range [-3,3]. Once truncated, the LHS process continues by splitting the recognized range of the variable into N non-overlapping intervals on the basis of equal probability. Figure G.6 shows an example of truncating and partitioning the standard normal distribution into 5 equal probability (20%) intervals. To complete the process, random numbers are generated uniformly from within each of the partitions such that the same number of samples is drawn from each partition. For example, if a sample of size 100 is desired, then 20 items will be sampled from within each of the 5 partitions. Clearly, the more partitions selected, the better the simulation will be. In fact, the limiting distribution as the number of partitions approaches infinity is exactly the distribution under consideration.

Another approach that can be taken is using an actual sample based upon field data when available. For example, sampling from the release fraction, temporal (time of day and day of year), and meteorological conditions distributions does not require any sampling algorithm. Actual data was available from the HMIRS database and the National Climatic Data Center leading to actual samples ranging in size from 68 values to 27,000. When sufficient data is available, using real samples leads to the least amount of uncertainty.

For additional information on Monte Carlo simulation and methods of random number generation for Monte Carlo simulation and integration, the reader is referred to *Random Number Generation and Quasi-Monte Carlo Methods* **[9]** and *An Approach to Sensitivity Analysis of Computer Models* **[10]**.

Figure G.2 Sample Size of 50

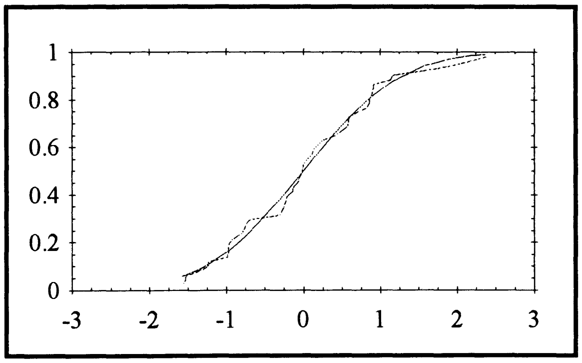


Figure G.3 Sample Size of 100

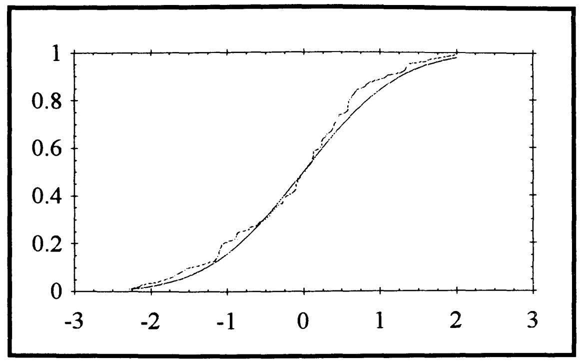


Figure G.4 Sample Size of 1000

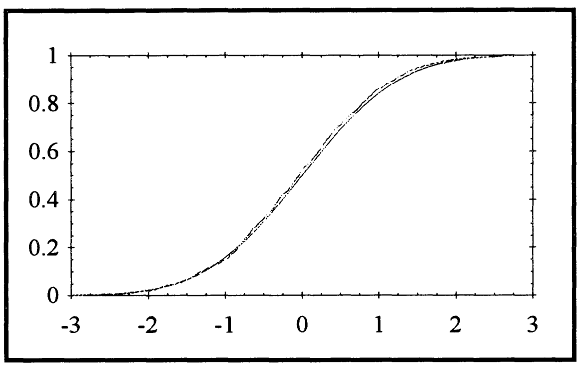


Figure G.5 Sample Size 10,000

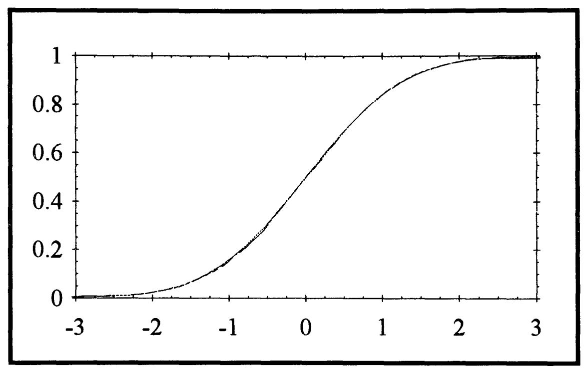


Figure G.6 Standard Normal Probability Density Function Truncated and Partitioned into 20% Non-overlapping Intervals