Release and Fire Incident Rates for Trucks Carrying Dangerous Goods

by

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ABSTRACT

The transport of dangerous goods (DG) results in risk. A release of the DG may cause harm to property, the environment or the public. Authorities need to understand the risk associated with the transport of DG, to make informed decisions regarding transport modes and routes. This thesis predicts rates of releases and fires for trucks in transit carrying DG loads. It is intended that others will use the DG incident rates in assessing the risks of using specific truck routes for transporting DG. The research produces a probabilistic model that predicts the release and fire incident rates using five databases from Canada, the USA and France.

This research provides a methodology for estimating DG release and fire incident rates that is better than previous methodologies. First, it examines and compares each of the potentially significant factors available in the data that may affect the input variables. Previous research has not adequately provided an overall analysis comparing potentially significant factors affecting release and fire incident rates. The model combines the input variables to produce release and fire incident rates. The research uses statistical analysis to identify significant factors affecting the input variables. This reduces the uncertainty in whether or not there is an effect that should be incorporated in the estimates of the input variables. The research uses further statistical analysis to define the uncertainty associated with the input variables.

Second, the research extends the treatment of uncertainty beyond that of previous research on the risk of transporting DG, which has included sensitivity analysis, low, best and high estimates, and confidence intervals. The analysis of uncertainty uses Monte Carlo simulations to propagate the uncertainty in the input variables through to the resulting release and fire incident rates. The analysis represents the uncertainty through probability distributions for the incident rates. Statistics on the distributions include mean, median, standard deviation, skewness, kurtosis, coefficient of variation, and percentiles. The distributions help to put the incident rates in context and allow for appropriate use of the rates in future quantitative risk assessment.

For accident-induced incidents, the thesis predicts the probabilities of release and fire, given a truck carrying DG and involved in an accident. For non-accident incidents, such as leaking valves, the thesis predicts the rates of non-accident releases and fires per billion vehicle kilometres (Bvkm). The thesis illustrates how we can combine accident and non-accident information to provide total expected releases and fires per Bvkm for trucks carrying DG loads.

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CHAPTER 1

INTRODUCTION

Chapter 1 contains the following sections:

1.1 Background
1.2 Summary of Research Approach
1.3 Research Scope
1.4 Research Problem
1.5 Research Objectives
1.6 Thesis Organisation

Chapter 1 defines the research problem in terms of the risk and uncertainty associated with the transport of dangerous goods (DG) by truck, and summarises the research objectives.

1.1 BACKGROUND

Transport Canada indicates that, each year in Canada, trucks carrying DG loads travel over 10 billion road vehicle-kilometres. The Canadian Dangerous Goods Accident Information System (DGAIS) indicates that this truck travel results in approximately 180 DG incidents per year. These include approximately 60 large releases (greater than 1,000 litres) per year, of which approximately eight per year include fires and/or explosions. The DG incidents can result in damage to property or the environment, and injury or death to exposed population.

Examples of such DG incidents from DGAIS include:

- A tractor tank trailer with pup carrying 58,000 litres of gasoline overturned on the highway and burst into flames, fatally injuring the driver and burning the trailer load.

- A tractor trailer with pup carrying 64,000 litres of propane collided head-on with another tractor trailer which was empty. The pup separated from the trailer and burned on a river shore, releasing 33,000 litres of product.

- The driver of a B-train tanker transporting 57,000 litres of gasoline lost control of the unit, colliding with a bus. The tanker then flipped on its side and caught fire. The driver of the tanker was fatally injured.

- The driver of a tanker truck transporting 50,000 litres of gasoline lost control of the unit, resulting in an overturn. The unit then went through the railings and exploded as it dropped down a mountain. The entire contents of the shipment were lost.

- During transit, a tractor tank trailer carrying 40,000 litres of petroleum crude oil overturned on the highway when the driver swerved to avoid a deer. The entire contents were burned. The driver was injured in the accident.

- The driver of a tractor tank trailer transporting 39,000 litres of propane lost control. The truck ran off the road and overturned. The tank ruptured and subsequently caught fire. The driver was seriously injured.

- A tractor tank trailer with one pup transporting 37,000 litres of gasoline rolled over on the highway and was destroyed by fire. Two people were killed and damage to property was extensive.

- While in transit, a truck and trailer carrying acid-filled batteries caught fire. Half of the load was lost. The local fire department extinguished the fire and the trailer was rehitched to the truck and sent to the final destination.

In order to choose between transport modes and routes, authorities need to know the risk associated with the transport of DG. A given truck route may pose a higher risk because trucks are more likely to have a DG release or fire on that route compared to alternate routes. Different types of trucks may have different propensities to have DG releases and fires.

This thesis predicts the expected rates of DG releases and fires for different types of roads and trucks, based on characteristics of roads and trucks that significantly affect the DG incident rates. The rates cannot be predicted exactly, and the thesis uses probability distributions to quantify the uncertainty associated with the predictions.

1.2 SUMMARY OF RESEARCH APPROACH

The following thesis predicts the probabilities of releases, fires and explosions for trucks in transit carrying DG loads. The analysis of DG incident rates was undertaken with the intention that others will use the rates in assessing the risks of using specific truck routes for transporting DG loads. The research produces a probabilistic model of release and fire incident rates using five databases from government agencies from Canada, the USA and France. Information from the different databases is combined to produce a model for use in locations with road and truck characteristics similar to North America or Europe. The research extracts from the various databases the significant factors that lead to release or fire, and information on the uncertainty associated with the input variables. Monte Carlo simulations propagate the uncertainty from the input variables to the resulting release and fire incident rates.

For accident-induced incidents, the thesis predicts the probabilities of release and fire, given a truck carrying DG and involved in an accident. For non-accident incidents, such as leaking valves, the thesis predicts the rates of non-accident releases and fires per billion vehicle kilometres (Bvkm). The thesis illustrates how we can combine accident and non-accident information to provide total expected releases and fires per Bvkm for trucks carrying DG loads.

1.3 RESEARCH SCOPE

In essence, every truck carries DG, in its fuel tank. However, this thesis specifically addresses trucks carrying DG loads in addition to their fuel tank. This analysis defines a "release" as a release of the DG load. Therefore there is a "release" if any of the DG load leaks or spills or is consumed by fire. There is no "release" if the only spill or leak is from the vehicle fuel tank.

According to DGAIS, in Canada there are approximately 150 releases per year of DG loads from trucks in transit. On the other hand, fires and/or explosions on trucks in transit carrying DG loads are relatively rare. DGAIS reports an average of 13 incidents of fire and/or explosion per year in Canada, of which 3 include explosions. The French DG incidents database reports an average of 9 incidents of fire and/or explosion per year, and does not distinguish between fires and explosions. Due to the scarcity of fire and explosion data, this thesis combines fire and explosions under a category called simply "fires".

Releases and fires can result from both accidents and non-accident incidents. A non-accident incident could include a release that occurs, for example, if a hatch or valve is not properly closed, if a corroded weld fails, if a package falls off the truck, or if a fire starts from a brake or tire overheating during transport. Accident-induced releases are more likely to be large compared with non-accident releases, but both accident and non-accident incidents can result in fires and can be catastrophic. The thesis addresses the probability of both accident and non-accident releases and fires from trucks in transit carrying DG loads.

This analysis focuses on trucks in transit. Therefore the incident rates given exclude incidents that occur while the truck is loading, unloading or in storage. While loading and unloading incidents are part of the overall risk of transporting DG loads, the focus of this analysis is on incidents along routes. We assume that DG incidents at the terminal or in storage do not affect the risk along the route.

1.4 RESEARCH PROBLEM

The research problem contains two components. The first component is the need to estimate release and fire incident rates as input to risk assessment for trucks carrying DG loads along specific routes. The second component is the quantification of the uncertainty associated with these incident rates. The sections below discuss these two components.

1.4.1 Risk

The Concise Oxford Dictionary (1991) defines risk as a chance or possibility of danger, loss, injury, or other adverse consequences. The transport of DG loads by truck results in risk. A release of the DG load may cause damage to property or to the environment, such as groundwater contamination. Populations exposed to a release may suffer injury or fatality.

The issue of transporting DG by truck (or any other mode, including pipeline, rail, ship or air) is of concern to authorities because the public is averse to the resulting risk. For road transport in particular, the road system is extensive, so that the opportunity for releases and fires is widespread. This gives rise to public apprehension, particularly when trucks carry DG substances through towns and cities. According to the factors that Shortreed (1984) quotes as affecting the perception of risk relative to actual risk, the public is averse to the risk of transporting DG because it is:

- potentially catastrophic.
- unknown rather than familiar.

- involuntary rather than voluntary (especially on the part of residents adjacent to DG truck routes).
- man-made rather than natural.
- of unclear benefit (for example, the general public may not be aware of the benefits of transporting pressure-liquefied chlorine).

Quantitative risk assessment (QRA) can identify the comparative risks of different modes (truck, pipeline, rail, ship or air) and different routes. Authorities need QRA for the transport of DG loads, in order that they may understand the actual risk (compared with the perceived risk) when making decisions regarding modes and routes. When a truck route is one of the alternatives for the transport of DG, then release and fire incident rates for trucks carrying DG loads are among the required inputs to the QRA. Other required inputs include the expected type and quantity of release, because the risk may be greater with a large spill than with a small leak. The QRA uses these inputs along with other factors, such as the nature of the DG, the terrain and the prevailing wind conditions, to determine the resulting damage area and the consequences of the DG release. A QRA must forecast the following:

- How often will a vehicle carrying a particular type of DG load on a particular route have an accident resulting in a release or fire? How often will a release or fire occur without an accident?

- What are the expected type and quantity of the release?

- What is the resulting damage area? What are the individual and societal consequences of the DG incident (number of people killed or injured, property or environment damage)?

In estimating release and fire incident rates, we want to control for predictive factors that significantly affect the probabilities of release and fire. For example, if there is an accident, there is a much higher probability of release of the DG load if the accident involves an overturn. "Overturn" is a significant factor in predicting the probability of a release given an accident.

Therefore the first component of the research problem is the need for estimates of release and fire incident rates for trucks carrying DG loads, that incorporate significant predictive factors. The incident rates should include the expected type and quantity of release. Analysts need the rates for use in QRA to assess DG truck routes, allowing comparison with other modes and routes for the transport of DG loads.

1.4.2 Uncertainty

We do not understand and cannot predict the world precisely. Yet analysts have often developed QRA models on the basis of a single value or "point estimate" for each input variable, ignoring the amount of uncertainty associated with those estimates. Often the point estimate is the mean value of the sample data for the input variable. If the analyst gives only one value, then all further calculations use that value, even though a range of values undoubtedly exists in the mind of the analyst. The range of values for the input variable represents uncertainty, which may arise because the value is changeable (for example, because it may fluctuate from year to year) or because the value is not known precisely.

Uncertainty may be great enough that significant discrepancies in predicted risk can arise. The discrepancies can be great enough to influence decisions regarding modes and routes for the transport of DG loads. For example, using point estimates of the input variables we can calculate a point estimate of the DG incident rate for a route. On the other hand, if we incorporate the uncertainty in the input variables in the analysis, we can estimate a probability distribution for the DG incident rate for the same route. The mean of the probability distribution may be higher or lower than the point estimate of the DG incident rate. This apparent paradox is explained in Chapter 9, and depends on the model equations and the probability distributions of the input variables. The probability distribution may lead us to different conclusions than those indicated by the point estimate.

Saccomanno et al. (1994) note that uncertainty in the quantification of risk can take several forms:

- measurement error, which is the failure to ascertain a quantity exactly. We can quantify measurement error by stating the range within which we know a parameter lies with a given level of confidence. Better data result in a narrower range.

- uncertainty in the modelling process. A more rigorous model more closely approximates the causes and effects in the real world. The more rigorous the model, the smaller is the uncertainty in the modelling process.

- uncertainty as to whether there is an effect that we should incorporate in an estimate. For example, there is uncertainty in the assumption that the proportion of releases with fires does not vary by province, by road conditions, etc.

- omission of possible causes of risk. This uncertainty is a function of the limits of the data.

It is particularly important to quantify the uncertainty when predicting low probability and potentially high consequence (catastrophic) events. For release and fire incident rates, we need the estimated size and character of uncertainty to:

- indicate the range and probability of possible values for the incident rates and put the predicted rates in context.

- describe the limitations of what we know about the incident rates and determine the implications of having limited knowledge.

- anticipate the unexpected and plan for contingencies which fall within the expected range of values. Quantifying the uncertainty may result in better solutions as it forces decision-makers to think in broader terms about the problem.

- identify important sources of uncertainty out of the many inputs to the model, and determine which factors are the most and least important in predicting the incident rates. This aids in building the model by showing which components need more attention.

- help us to decide whether we believe the incident rates or not. This is important if there are conflicting results from other models. If researchers clearly define the uncertainty associated with the models, we can be much clearer about the sources of disagreement and whether there really is a disagreement.

- identify means of possibly reducing the uncertainty.

- determine whether additional information to further reduce the uncertainty warrants the cost and effort to collect it. Generally, the greater the uncertainty, the greater is the expected value of additional information.

- allow for appropriate use of and improvements to the model in the future.

Therefore the second component of the research problem is the need for estimates of the uncertainty associated with predicted release and fire incident rates for trucks carrying DG loads.

1.5 RESEARCH OBJECTIVES

This research had three main objectives:

1. to determine significant factors that impact the probabilities of releases and fires, as well as the type and size of release, from trucks in transit carrying DG loads.

2. to identify accident and non-accident scenarios for trucks in transit carrying DG loads, based on the significant factors, and determine the expected release and fire incident rates for each scenario.

3. to create a probabilistic model that quantifies the uncertainty in the predicted release and fire incident rates, based on the uncertainty in the input variables.

Researchers will be able to use the predicted incident rates, along with their estimated uncertainty, in QRA analysis for the transport of DG on specific truck routes.

1.6 THESIS ORGANISATION

This thesis contains the following chapters:

Chapter 1: Introduction defines the research problem in terms of the risk and uncertainty associated with the transport of DG loads by truck, and summarises the research objectives.

Chapter 2: Literature Review provides an overview of approaches used by other researchers to quantify risk and uncertainty for the transport of DG loads. Chapter 2 demonstrates the need for further research.

Chapter 3: Research Methodology outlines the research tasks undertaken to generate a probabilistic model to predict release and fire incident rates for trucks carrying DG loads. Chapter 3 also discusses the application of logistic regression to determine significant factors, and the use of Monte Carlo simulations to quantify uncertainty in the output. A summary is provided of the model produced by this research.

Chapter 4: DG Release and Fire Characteristics documents the sources of data, the classification of DG incident outcomes, and the classification of possible factors that may potentially impact incident outcomes.

Chapter 5: Accident and Non-Accident Scenarios identifies factors that significantly affect DG incident outcomes and summarises the input variables for the model. Chapter 5 defines the accident and non-accident scenarios that arise from the combination of the significant factors.

Chapter 6: Point Estimates of Input and Output Values provides point estimates for the input variables, based on the mean values of the sample data. This chapter also provides point estimates of the output values that arise if we use the point estimates of the input values in the model and ignore uncertainty. The model output includes point estimates of outcome probabilities for accident scenarios and incidents per Bvkm for non-accident scenarios.

Chapter 7: Comparison of Model Output to Data compares point estimates from the model for accident and non-accident scenarios to DGAIS release data.

Chapter 8: Uncertainty in Input Values documents the probability distributions assigned to the input variables. These distributions reflect the uncertainty with respect to the values of the input variables.

Chapter 9: Uncertainty in Output Values documents the results of the Monte Carlo simulations to propagate the uncertainty in the input variables through to the uncertainty in the output variables. Each outcome probability or incident rate has a probability distribution, indicating the uncertainty about the output values. The analysis provides statistics that define each output distribution. The chapter summarises the mean values of the distributions for the outcome probabilities for accident scenarios and incidents per Bvkm for non-accident scenarios.

Chapter 10: Application of Research Results provides an application of the probabilistic model to two sample roads. The model application generates both point estimates and probability distributions for the expected rates of accident and non-accident incidents per Bvkm.

Chapter 11: Conclusions and Recommendations provides the final conclusions and recommendations.

CHAPTER 2

LITERATURE REVIEW

Chapter 2 contains the following sections:

2.1 Approach by Other Researchers
2.2 Need for New Research

Chapter 2 provides an overview of approaches used by other researchers to quantify risk and uncertainty for the transport of DG loads. Chapter 2 demonstrates the need for the research undertaken for this thesis.

2.1 APPROACH BY OTHER RESEARCHERS

To date, other researchers have generally used "most likely" point estimates of input variables for QRA for the transport of DG. They have not quantified uncertainty. Examples of this approach are numerous and include:

- a study in the Netherlands to judge risks on their acceptability for individuals and society, including the risks of transporting dangerous substances over water, rail and road (Vrijling et al., 1996). The study does not mention uncertainty.

- a description of quantitative approaches for hazardous materials transportation risk analysis for truck and train by Rhyne (1994). Rhyne notes that the data and the analysis models currently available may introduce large uncertainty, up to several orders of magnitude. However, Rhyne also questions whether incorporating the full complexity of relationships in the analysis is worthwhile, and whether it is practical when uncertainties are not well understood. Rhyne discusses factors that affect, for example, release rates given a truck carrying hazardous materials, but does not analyse the statistical significance of these factors.

- a study of the use of probabilistic risk assessment in the liquefied natural gas industry in the USA, including processing, transportation and storage (Pelto, 1984). Pelto notes that there are uncertainties in his model, but feels that the model results are still useful for comparative analysis.

- a case study comparing the risks of transporting chemicals by highway and rail in the USA using QRA (Kornhauser et al., 1994). The study does not address uncertainty, but does note that it is important to use quality (precise) data in order to identify the "best" route for the user.

- a study of a knowledge-based classification scheme for regulating the flow of hazardous materials through tunnels and on bridges in the USA (Hobeika et al., 1988). The study notes that QRA is a useful aid for decision-making and also notes that there is a scarcity of data. The authors suggest that we can use subjective estimation to augment the limitations of risk assessment techniques, using expert knowledge. The study does not address the quantification of uncertainty.

- a study of benchmark estimates of release accident rates in hazardous materials transportation by rail and truck in the USA (Glickman, 1988). The study notes that consistent, reliable estimates of release accident rates are essential when using risk assessment to compare the safety of rail and truck for a given shipment of hazardous materials. The study further notes that estimates that appear in the literature have shortcomings or inconsistencies that make it difficult, if not impossible, to perform such a comparison. However, the study implies that if the data were properly collected and classified, the data would be "accurate" and these inconsistencies would disappear. There is no mention of uncertainty in the accident rates. The study notes that release accident rates vary by vehicle type and track or road type and other factors, but the study does not analyse the statistical significance of these factors.

- a study examining the feasibility of rerouting and/or relocating the rail flow of dangerous commodities in the Toronto Area, and the ways and means of reducing risk and of improving public safety impacted by this method of transportation (IBI Group, 1988). Factors in assessing risk included number of road switches and road crossings, number of tracks, train speed, human susceptibility, quantity and mix of DG along the route, and meteorological conditions such as wind velocity and direction. The study notes that the cost estimates used in the study are preliminary, but are considered sufficiently reliable to provide a valid comparison of the alternatives. The study does not address the quantification of uncertainty.

- a report on major hazard aspects of the transport of dangerous substances in England (Health and Safety Commission, 1991). The study analyses risk from the transport of dangerous substances and assesses the relative risks by rail as compared with road. The report acknowledges that the risks estimated by QRA are subject to some uncertainty, but judges that QRA provides the best estimates of the risks involved and provides valuable insights. The study does not address the quantification of uncertainty.

- a description of guidelines for chemical transportation risk analysis (American Institute of Chemical Engineers, 1995). This book describes methods of transportation risk analysis which we can use to identify and evaluate risk reduction strategies such as changing the mode of transportation, shipment size, route, container, etc. The book lists sources of uncertainty in transportation risk analysis. The book notes that uncertainties can significantly influence results, but simply refers the reader to other guidelines published by the American Institute of Chemical Engineers for approaches to identifying and estimating uncertainty and sensitivity. The book uses point estimates in calculating risk.

- a report analysing routes in the USA for the transportation of hazardous materials including radioactive waste and spent nuclear fuel by use of effective risk estimation (Olekszyk, 1993). The report does not mention uncertainty.

- a report addressing multiobjective policy analysis of hazardous materials routing in the USA (Turnquist et al., 1993). The report does not mention uncertainty.

- a report addressing a framework for hazardous materials transport risk assessment for routes in Alberta (Erkut et al., 1995). The report presents a basic model for transportation risk assessment. One component in the model is the probability of a release given an accident, but the report does not discuss factors that may affect this probability. The report mentions sources of inaccuracy in the data used, but does not attempt to quantify uncertainty.

- a report documenting a risk-based procedure for evaluating policies for the transport of DG (Stewart, 1990). Stewart indicates that there is a statistically significant difference in release sizes for truck accidents with and without overturns. An accident with an overturn is more likely to have a large release. The report notes the difficulties associated with estimating average probabilities for rare events, but does not attempt to quantify the uncertainty.

None of the above studies and reports attempted to quantify uncertainty. The only studies found in the literature review that addressed uncertainty associated with the risk of transporting DG were by Van Aerde et al. (1987), Abkowitz et al. (1989), Leeming et al. (1993 and 1994), Saccomanno (1993), Saccomanno, Leeming and Stewart (1993), Saccomanno, Stewart and Shortreed (1993), Saccomanno, Yu and Shortreed (1993), Saccomanno et al. (1994), and Shortreed et al. (1994). For example, Leeming et al. (1993) provide upper, best and lower risk estimates comparing rail and road delivery of chlorine. Saccomanno, Yu and Shortreed (1993) provide 95% confidence intervals for accident rates, release probabilities and societal risk. Shortreed et al. (1994) document a transportation risk assessment for the Alberta Special Waste Management. The report notes that there is a high level of uncertainty in the estimates (typically +100% and -50% of the best estimate) and gives low, best and high risk estimates.

The literature review did not reveal any examples of Monte Carlo analysis for the risk of transporting DG. Abkowitz et al. (1989) discuss simulation modelling which would combine probability distributions of input parameters to estimate the risks of transporting DG, as in Monte Carlo analysis. However, with the state of computers in 1989, Abkowitz et al. dismiss the method as cost-prohibitive due to the computational time and expense involved in executing a single run, and the need to conduct multiple simulations to accumulate a basis for risk assessment.

The literature review did indicate that analysts have used Monte Carlo analysis to assess the risks of nuclear reactors. The US Nuclear Regulatory Commission performed the NUREG-1150 probabilistic risk assessments, completed in 1990, to provide a reassessment of the risk from commercial nuclear reactors determined in the Reactor Safety Study approximately 15 years earlier. The risk assessments involved analyses for five nuclear power plants and provided an assessment of the uncertainty in their results, using Monte Carlo analysis. The study group developed subjective probability distributions for each quantity under consideration using input from panels of experts (Helton, 1994).

The literature review revealed analysis of significant factors affecting certain aspects of the risk of DG releases and fires. For example, Leeming et al. (1993) indicate that factors significantly affecting road accident rates for trucks include road type, traffic pattern, traffic volume, truck type, load status, model year, hour of day, and driver age. Saccomanno et al. (1989) indicate that releases are affected by the operating speed and the size of the vehicle. Stewart (1990) indicates that the factor of overturn/no overturn affects release size for accident-induced releases. However, the literature review did not reveal an overall analysis comparing potentially significant factors affecting release and fire incident rates, as well as release type and size, for trucks in transit carrying DG loads.

2.2 NEED FOR NEW RESEARCH

The need for the analysis of risk uncertainty was confirmed in 1992 at an International Consensus Conference on the Risks of Transporting Dangerous Goods in Toronto (Saccomanno et al., 1994). The Conference addressed uncertainty in risk estimation by considering unexplained variations in a sample of estimates reported by various independent sources studying a common transport problem. Participants in the conference carried out a hypothetical corridor benchmark exercise involving the transport of DG loads by road and rail over two designated routes. Despite attempts to control for major sources of uncertainty, the participating groups reported widely different risk estimates. Recommendations from the Conference included:

> Uncertainty must be fully accounted for in the reporting of risk estimates. Risk and its components must be accompanied by confidence limits. The sensitivity of output to various assumptions regarding parameter values and inputs must be accounted for in the reporting of risks.

The research in this thesis provides a methodology for estimating DG release and fire incident rates that is better than previous methodologies. First, it examines and compares each of the potentially significant factors available in the data that may affect the input variables. Previous research has not adequately provided an overall analysis comparing potentially significant factors affecting release and fire incident rates. The model combines the input variables to produce release and fire incident rates. The research uses statistical analysis to identify significant factors affecting the input variables. The identification of significant factors reduces the uncertainty in whether or not there is an effect that we should incorporate in the estimates of the input variables. The research then uses further statistical analysis to define the uncertainty associated with the input variables.

Second, the research extends the treatment of uncertainty beyond that of previous research on the risk of transporting DG, which has included sensitivity analysis, low, best and high estimates, and confidence intervals. The analysis of uncertainty uses Monte Carlo simulations to propagate the uncertainty in the input variables through to the resulting release and fire incident rates. The analysis represents the uncertainty through probability distributions for the incident rates. Statistics on the distributions include mean, median, standard deviation, skewness, kurtosis, coefficient of variation, and percentiles. The distributions help to put the incident rates in context and allow for appropriate use of the rates in future QRA.

CHAPTER 3

RESEARCH METHODOLOGY

Chapter 3 contains the following sections:

3.1 Research Tasks
3.2 Logistic Regression
3.3 Monte Carlo Simulation
3.4 Summary of Model

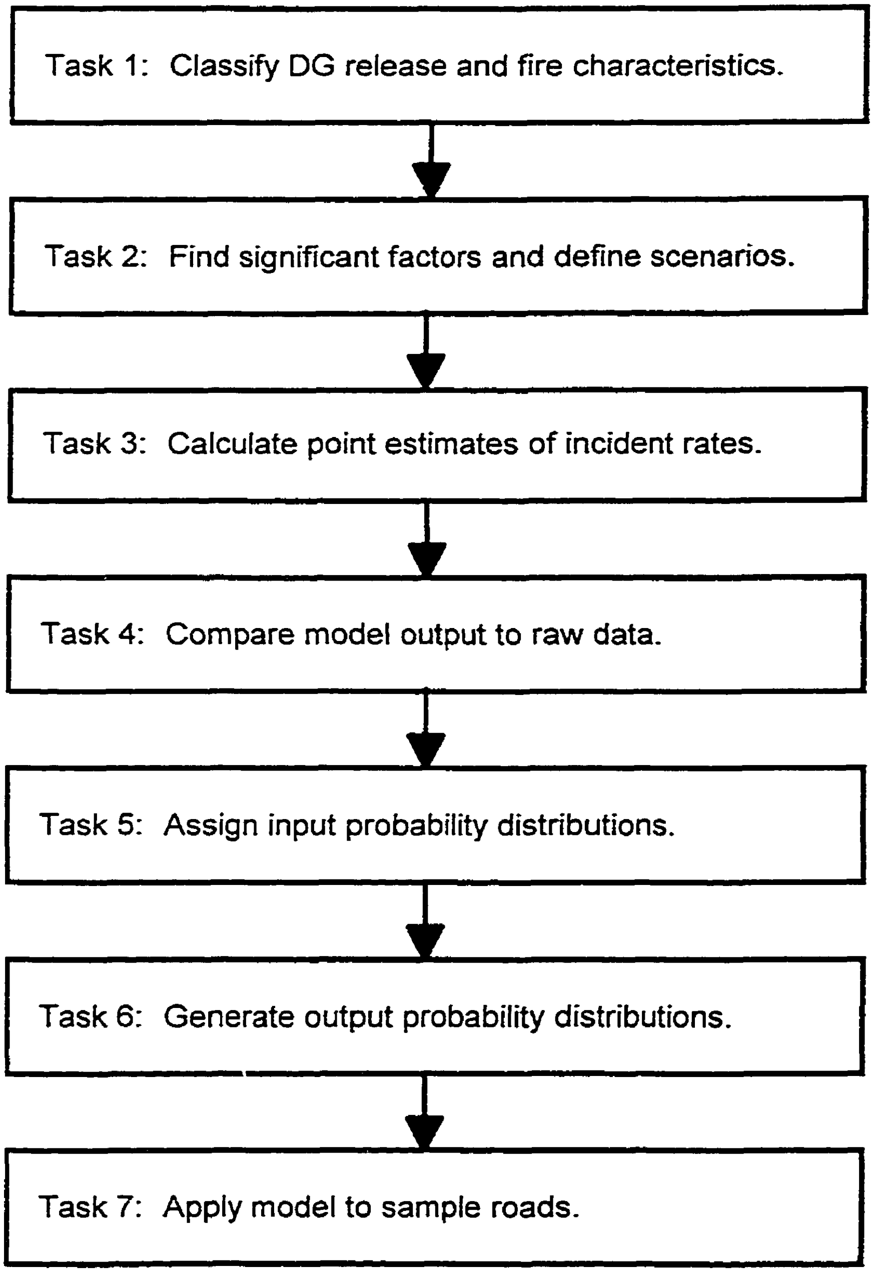
Chapter 3 outlines the research tasks undertaken to generate a probabilistic model to predict release and fire incident rates for trucks carrying DG loads. Chapter 3 also discusses the application of logistic regression to determine significant factors, and the use of Monte Carlo simulations to quantify uncertainty in the output. A summary is provided of the model produced by this research.

3.1 RESEARCH TASKS

Figure 3.1 summarises the seven tasks that formed the research methodology for this thesis. The tasks include:

Task 1: Classify DG release and fire characteristics from the available data into useful and manageable categories. Chapter 4 documents the sources of data, the classification of DG incident outcomes, and the classification of possible factors with the potential to impact incident outcomes.

Figure 3.1: Research Tasks



Task 2: Using stepwise logistic regression, identify factors that significantly affect DG incident outcomes. Identify the input variables for the model. Define the model in terms of accident and non-accident scenarios that arise from the combination of the selected factors. Section 3.2 below discusses the use of logistic regression to identify significant factors. Chapter 5 describes the significant factors and the resulting model.

Task 3: To illustrate the structure of the model, assign point estimates to the values of the input variables using the mean values of the sample data. Calculate point estimates of accident outcome probabilities and non-accident incident rates per Bvkm, using the point estimates of the input values in the model and ignoring uncertainty. Chapter 6 contains the point estimates for the model output.

Task 4: Compare the point estimates for the model output to DGAIS release data for accident and non-accident scenarios. Chapter 7 shows the comparison.

Task 5: Assign probability distributions to each input variable. These distributions reflect the uncertainty with respect to the values of the input variables. Chapter 8 documents the alternative distributions considered and the selected distributions for the input variables.

Task 6: Generate probability distributions for the output variables (accident outcome probabilities and non-accident incident rates), using Monte Carlo simulations. The Monte Carlo simulations propagate the uncertainty in the input variables through to the uncertainty in the output variables. Each output variable has a probability distribution that indicates the uncertainty about that variable. Section 3.3 below discusses the use of Monte Carlo simulations. Chapter 9 describes the output distributions resulting from the Monte Carlo simulations.

Task 7: Apply the probabilistic model to two sample roads, to generate point estimates and probability distributions for the expected rates of accident and non-accident incidents per Bvkm. Chapter 10 documents how to apply the model and the results of the sample application.

3.2 LOGISTIC REGRESSION

In this thesis, we use stepwise logistic regression to empirically identify predictive factors that significantly affect DG incident outcomes. Compared with the other available factors, these significant factors tend to have the most impact on the input variables. By using the significant factors in building the model, the model better explains variations in incident outcomes.

Logistic regression is useful for predicting the presence or absence of a characteristic or outcome based on the values of a set of explanatory factors. Logistic regression is suited to situations where the dependent variable is dichotomous. The dependent variable has the value 1 with the probability p and the value 0 with the probability $(1 - p)$. In dealing with probabilities, it is often convenient to use the log-odds (logistic transformation of the odds), which is $\log (p/(1 - p))$. This has the range $-\infty$ to $+\infty$, rather than 0 to 1. We may postulate a linear relationship between the log-odds and the explanatory factors as follows:

$$\log (p/(1 - p)) = U \tag{3.1}$$

where $U = \text{constant} + \beta_1 \times \text{factor}_1 + \beta_2 \times \text{factor}_2 + \ldots$

Solving for p gives:

$$p = \frac{\exp(U)}{1+\exp(U)} \tag{3.2}$$

The logistic transformation produces an equation that describes the expected value of p as a logistic function of U. The analyst chooses which predictor factors to include in U. The logistic regression estimates the corresponding values of the constant and the β coefficients that best fit the data. An example equation U for the conditional probability of a fire given that an accident has occurred, P(fire | accident), is as follows:

$$U = -1.25 - 1.44 \times \text{collision} - .92 \times \text{release} \tag{3.3}$$

where the factor "collision" equals 0 if there is a collision and 1 if there is no collision, and the factor "release" equals 0 if there is a release of the DG load and 1 if there is no release. If there is an accident that involves both a collision and a release of the DG load, then:

$$\begin{aligned} U &= -1.25 - 1.44 \times 0 - .92 \times 0 \\ &= -1.25 \end{aligned} \tag{3.4}$$

and:

$$\begin{aligned} &P(\text{fire} \mid \text{accident with collision and release}) \\ &= \frac{\exp(-1.25)}{1 + \exp(-1.25)} \\ &= .22 \end{aligned} \tag{3.5}$$

In our situation, each of our model input variables represents characteristics of an incident outcome and is dichotomous. For example, accident and non-accident incident outcomes can include a release or no release, and a fire or no fire. If there is a release, it can be a spill or a leak, and large or small. Thus *p* could represent the different model input variables, for example, the probability of a release, P(release), the probability of a fire, P(fire), etc. We treat each input variable separately, because we do not have enough data to cross-tabulate by every outcome characteristic (release, fire, release type and size) even without considering any significant factors (for example, collision, overturn, load size, etc.). A cross-tabulation of the data by all outcome characteristics contains empty cells.

To begin the selection of significant factors for each input variable, we propose an initial set of factors to include in U. As noted above, the expected value of p is described as a logistic function of U. We then use logistic regression through the software SPSS ® to fit the equation to the DGAIS data. Out of the three DG incident databases used for this analysis, the DGAIS database is the only one that includes all of the potential factors.

We use a "tear down" rather than a "build up" approach to determine significant factors. For each input variable, we begin by fitting an equation that includes all of the available factors that might potentially influence it. We then examine the significance of the factors as variables in an equation to predict the input variable. We drop the factor with the poorest significance. In the next step, the equation is then fitted to the data using the remaining factors. We again examine the significance of the factors and drop the factor with the poorest significance. We repeat this process in a stepwise fashion until all of the remaining factors are significant at the 5% level as variables in an equation to predict the input variable.

If a factor is not found significant and it is not strongly correlated to another factor, then it is not an important factor in the model compared to the other available factors. Section 5.1.2 later indicates that none of the accident or non-accident factors are strongly correlated. Therefore in the tear-down process, we do not consider a factor for re-entry in the equation once it has been dropped.

There is not a unique set of significant factors for each input variable. For example, if we chose to stop the tear-down process when all of the factors are significant at the 10% level, then we would identify more factors as significant. The scarcity of data, however, constrains the number of factors that we can include in the model. Chapter 5 notes for which input variables there is insufficient data to cross-tabulate by each of the factors significant at the 5% level, without resulting in empty cells in the cross-tabulation. Where empty cells occur, we reduce the number of factors included in the model for that input variable.

We do not directly use the equations resulting from the logistic regression in our model to predict release and fire incident rates. The equations are useful for indicating which factors are significant in predicting the input variables in our model. However, the equations only provide an approximation of the values for the input variables as indicated by the DGAIS data. For the model, we use the actual values for the input variables indicated by DGAIS and other available data.

We cross-tabulate the available data by the selected significant factors to obtain the probabilities of release and fire for different types of incidents. For example, collision is a significant factor in predicting accident-induced fires. Therefore we cross-tabulate the accident records into the categories of collisions with fires, collisions without fires, non-collision accidents with fires, and non-collision accidents without fires. These categories allow us to calculate the conditional probability of a fire given a collision accident, P(fire | collision accident), and the conditional probability of a fire given a non-collision accident, P(fire | non-collision accident).

Section 5.1 describes the results of the stepwise logistic regression in selecting significant factors for the input variables of P(release), P(fire), P(spill) and P(large release) for accident and non-accident scenarios.

3.3 MONTE CARLO SIMULATION

A Monte Carlo simulation forecasts a range of results possible for a situation under conditions of uncertainty. The simulation propagates the uncertainty in the input variables through to the uncertainty in the output variables.

The advantage of Monte Carlo simulation over sensitivity analysis is the output probability distributions. A sensitivity analysis results in single-point estimates that do not indicate the probability of any particular outcome. A sensitivity analysis can indicate what is possible, but not what is probable. On the other hand, a Monte Carlo simulation indicates what outcomes are probable by generating probability distributions for each output variable. The simulation shows the probability of each possible result.

Monte Carlo simulation works well compared to earlier simulation techniques which used exact and approximate algebraic solutions to propagate error through the model (Hoffman et al., 1995). Exact and approximate analytical methods to propagate uncertainty are usually feasible only for models of limited complexity. Monte Carlo simulation can handle very complex models and, given sufficient iterations, the output approaches exact solutions.

For the Monte Carlo simulations, we used the software package "Crystal Ball" ® which is produced by Decisioneering, Inc. The Monte Carlo simulation through Crystal Ball ® uses values and equations from a Microsoft Excel ® spreadsheet file. The software assists in assigning selected distributions to the input variables, running the simulation, and providing frequency counts, statistics and percentiles for the results of the simulation.

In general, the steps in a Monte Carlo simulation are as follows:

1. The analyst sets up a model, with input and output variables, and equations that relate the two.

   Our model is set up in an Excel ® spreadsheet. The input variables include, for example, P(fire | collision). The output variables are, for accidents, the probabilities of accident outcomes and, for non-accident incidents, the expected number of incidents per Bvkm. The equations are similar to those that we would use to calculate point estimates of the output variables from the point estimates of the input variables. Chapters 4 and 5 describe the accident and non-accident scenarios and the equations that make up our model.

2. The analyst assigns a probability distribution to each input variable, representing the uncertainty in the input variables. Chapter 8 describes the selection of the probability distributions for the input variables.

3. Using a computer program such as Crystal Ball ®, the analyst runs many iterations of the model. For each iteration, the computer program generates an independent random number for each input variable. The random number for an input variable is mathematically selected to conform to the probability distribution for that input variable.

4. For each iteration, the model uses the randomly selected input values to calculate a set of values for the output variables. The software stores the results of the iteration, and then begins the next iteration by generating a new random number for each input variable.

5. The results of the iterations are similar to a sample of experimental observations. The results may be combined statistically to produce frequency histograms of the overall results for each output variable. The analyst can then convert these frequency histograms to estimates of the corresponding probability distributions by setting the scale so that the total probability is 1. If desired, the analyst can fit a curve to each output probability distribution and test the fit of the curve using statistical measures such as Chi-square.

Chapter 9 summarises the output from our Monte Carlo simulations.

3.4 SUMMARY OF MODEL

3.4.1 Approach Rationale

This section summarises the rationale for the approach for the model. The following chapters provide further details on how and why the model took this form.

The model predicts release and fire incident rates for trucks carrying DG loads. The analysis of DG incident rates was undertaken with the intention that others will use the rates in assessing the risks of using specific truck routes for transporting DG loads. The risk assessment could be used to choose between alternative routes or modes, for issuing permits for trucks to use specific routes, for emergency response planning, etc.

The model was developed using five databases from Canada, the USA and France, including three DG incident databases and two road accident databases. Therefore, for some input variables, there are two data sources.

Where there are two sources of data for an input variable, the two sources give different estimates of the value of the input variable. The two sources could be viewed as representing two different populations. This would be true if the estimates vary between sources because of location-specific differences, for example, in roads or vehicles. On the other hand, the two estimates could vary simply because of differences, for example, in the methods of reporting and recording incidents. If we could control for differences in reporting and recording incidents, the estimates of the input variables from the two sources might be quite similar.

We have no information that allows us to discriminate regarding the reasons for the differences between estimates from different sources, nor do we have information that allows us to select one data source as being more reliable than another. We want to build a model for use in locations with road and truck characteristics similar to North America and Europe, and we want to incorporate all of the available information. Therefore we assume that where we have two sources, then we have two different samples from the same population, and the best estimate is a combination of the estimates from the two sources. Section 8.1 provides examples of the combining of data sources.

To be useful for risk assessment, the model needs to provide release and fire incident rates that include the expected type and quantity of release. Therefore we use four outcome characteristics to classify the types of DG incidents:

- release or no release.
- fire or no fire.
- release type (spill or leak).
- release size. A spill can be large or small, and a leak can be large or small.

Section 4.2 further discusses the classification of DG incident outcomes. The possible types of DG incidents include, for example, a large spill with fire, a small leak with no fire, a fire with no release, etc.

It is not possible to use the data as a model, because we do not have enough data to cross-tabulate by every outcome characteristic. Even without considering any significant factors (for example, collision, overturn, load size, etc.), a cross-tabulation of the data by all outcome characteristics contains empty cells. For example, we have no records of truck carrying a DG load and having a large non-accident leak with a fire. However, we believe that the probability is greater than 0 that a large leak with a fire will occur given a truck carrying a DG load. The model provides an estimate of that probability by treating the probability of each outcome characteristic as a separate input variable. The model combines the conditional probabilities of each of the four outcome characteristics to provide the probability of each type of DG incident.

For example, for a truck carrying a DG load and involved in an accident, a simplified equation for the probability of a large spill with fire is:

$$\begin{gathered}\text{P(large spill with fire} \mid \text{accident)} \\ = \text{P(release} \mid \text{accident)} \times \text{P(fire} \mid \text{accident)} \times \text{P(spill} \mid \text{release)} \times \text{P(large release} \mid \text{release)}\end{gathered} \tag{3.6}$$

As shown later, the final model equations are modified to include significant factors and the relationships between variables. For example, P(large release | release) is affected by whether the release is a spill or leak, and this relationship is included in the final model equations.

The model is based on statistical relationships rather than on cause-effect relationships. Our data do not provide information on the sequence of events or cause-effect relationships. For example, if there is a DG incident in one of our databases with a release and a fire, we do not know whether the fire started with say the vehicle fuel tank and then propagated to the DG load, or whether the fire started with the DG load and then spread to the rest of the vehicle. We only know that both a release and fire occurred.

Section 5.1 indicates significant factors for each outcome characteristic. The research uses logistic regression to empirically identify significant factors which affect the probabilities of outcome characteristics, including P(release), P(fire), P(spill) and P(large release). The factors are different for accident and non-accident scenarios. By using the factors in the model, the model better explains variations in incident outcomes. These factors, along with truck accident rates, are built into the model as required input from the model user. The factors include:

- type of DG load, which relates to P(release). The types of DG loads include DG1: toxic pressure-liquefied gases (PLG), DG2: flammable PLG, DG3: flammable liquid (the most common type of DG load for trucks), or DG4: toxic liquid.
- the proportion of accidents with overturns, which relates to P(release | accident).
- the proportion of accidents with collisions, which relates to P(fire | accident).

- whether the load size is large or small, which relates to P(spill) and P(large release) for an accident-induced release.
- whether the road is urban or rural, which relates to P(fire) and P(large release) for a non-accident release.
- whether the truck is a tanker or non-tanker, which relates to P(large release) for a non-accident release.

The significant factors for P(release) for an accident include the type of DG load and whether the accident involved an overturn. However, we cannot estimate P(release) for an accident directly from DGAIS, because DGAIS does not include records of all non-release accidents. DGAIS only includes records of non-release accidents if the accident involved a death or injury or damage to the means of containment due to impact stress or fatigue. We do have data that we assume provides unbiased estimates of P(overturn | type of DG load) and P(type of DG load) for accident-induced releases, P(release) and P(overturn) for trucks involved in accidents, and P(type of DG load) for trucks carrying DG loads. We use Bayes' Theorem to combine this information to estimate P(release) for a truck carrying a DG load and involved in an accident, as follows:

$$\text{P(release | overturn, type of DG load)} = \frac{\text{P(overturn | release, type of DG load) x P(type of DG load | release) x P(release)}}{\text{P(overturn) x P(type of DG load)}} \tag{3.7}$$

Section 5.1.3 contains details on the development of this equation and data sources for the five variables in the equation.

The research extracts information on the uncertainty associated with the input variables. Sources of uncertainty include fluctuations in the number of incidents over time, and differences between data sources. We assign a probability distribution to each input variable that incorporates the range of possible values over time and from alternate data sources. Where there are larger differences over time or between data sources, the probability distributions are wider and have larger standard deviations. For the input variables that are rates, such as the rate of non-accident releases per Bvkm, we fit lognormal distributions. For the input variables that are probabilities, such as P(fire | collision), we fit beta distributions and use the Gibbs sampler to determine the distribution parameters.

Monte Carlo simulations propagate the uncertainty from the input variables to the resulting release and fire incident rates. The Monte Carlo simulations provide probability distributions for each of the output variables. The probability distributions help to put the incident rates in context and allow for appropriate use of the rates in future risk assessment. Section 10.3 illustrates how an examination of the probability distributions can affect decisions regarding alternative routes and modes for transporting DG.

3.4.2 Model Components

The model predicts release and fire incident rates for trucks in transit carrying DG loads. The model consists of the accident and non-accident scenarios, the possible incident outcomes, the model equations, and the values of the input variables. The scenarios result from the combinations of significant factors that affect the values of the input variables. The model equations calculate the release and fire incident rates from the input variables.

3.4.3 Scenarios

The model includes 32 accident scenarios and 16 non-accident scenarios, for a total of 48 scenarios. The 32 accident scenarios are based on the following four significant factors:

1. type of DG load (DG1: toxic PLG, DG2: flammable PLG, DG3: flammable liquid, or DG4: toxic PLG).
2. load size (large load, LL, or small load, SL).
3. whether the accident involved an overturn, OT, or not.
4. whether the accident involved a collision, CO, or no collision, NCO.

The resulting 32 accident scenarios include:

Scenario 1: a truck carrying a large load of DG1: toxic PLG and involved in an accident with an overturn and a collision.
Scenario 2: a truck carrying a large load of DG2: flammable PLG and involved in an accident with an overturn and a collision.
Scenario 3: a truck carrying a large load of DG3: flammable liquid and involved in an accident with an overturn and a collision.
and so on to
Scenario 32: a truck carrying a small load of DG4: toxic liquid and involved in an accident with no overturn and no collision.

The 16 non-accident scenarios are based on the following three significant factors:

1. type of DG load (DG1: toxic PLG, DG2: flammable PLG, DG3: flammable liquid, and DG4: toxic PLG).
2. whether the truck is a tanker, TA, or non-tanker, NTA.
3. whether the truck is travelling on a rural road, RU, or urban road, UR.

The resulting 16 non-accident scenarios include:

Scenario 33: a tanker truck carrying DG1: toxic PLG on a rural road.
Scenario 34: a tanker truck carrying DG2: flammable PLG on a rural road.
Scenario 35: a tanker truck carrying DG3: flammable liquid on a rural road.
and so on to
Scenario 48: a non-tanker truck carrying DG4: toxic liquid on an urban road.

3.4.4 Incident Outcomes

For each accident scenario, there are 10 possible outcomes:

1. large spill with fire.
2. small spill with fire.
3. large leak with fire.
4. small leak with fire.
5. large spill no fire.
6. small spill no fire.
7. large leak no fire.
8. small leak no fire.
9. fire with no release.
10. no fire and no release.

For the non-accident scenarios, the possible outcomes are the same as the accident outcomes with the exception of Outcomes 9 and 10. For Outcome 9, fires without releases, there are not enough non-accident data to determine any significant factors. As discussed in Section 5.1.1, we assume that the mean and standard deviation for the rate of non-accident non-release fires are both .22 incidents per Bvkm, and do not analyse this incident rate further. For non-accident incidents with no release and no fire (Outcome 10), the incidents are not recorded in any of the databases and are not of interest to this analysis. Therefore, the model includes only the first eight possible outcomes for non-accident scenarios for further analysis.

To summarise, the model includes 10 possible outcomes for each of the 32 accident scenarios, and eight possible outcomes for each of the 16 non-accident scenarios, resulting in 448 combinations of scenarios and outcomes, or 448 output variables.

3.4.5 Model Equations

For each of the 448 scenario and outcome combinations, there is a different model equation. For the accident scenarios, the model equations calculate the probability of each accident outcome. For each accident scenario, the sum of the outcome probabilities is equal to 1. For the non-accident scenarios, the model equations calculate the rates of non-accident releases and fires per Bvkm.

For accident scenarios, there are 10 input variables in the model equations. The values of the input variables vary according to the accident scenario. The input variables for the accident scenarios include:

V1: P(overturn | release) for each type of DG or P(OT|RE, DG1), P(OT|RE,DG2), ...
V2: P(type of DG | release) or P(DG1|RE), P(DG2|RE), ...
V3: P(release) or P(RE)
V4: P(overturn) or P(OT)
V5: P(type of DG load) or P(DG1), P(DG2), ...
V6: P(fire | release) by collision/no collision or P(FI|RE,CO), P(FI|RE,NCO)
V7: P(fire | no release) by collision/no collision or P(FI|NRE,CO), P(FI|NRE,NCO)
V8: P(spill | release) by load size or P(SP|RE,LL), P(SP|RE,SL)
V9: P(large release | spill) by load size or P(LRE|SP,LL), P(LRE|SP,SL)
V10: P(large release | leak) by load size or P(LRE|LK,LL), P(LRE|LK,SL)

Accident Scenario 1 is a truck carrying a large load of DG1: toxic PLG and involved in an accident with a collision and an overturn. The model equations for the probabilities of the 10 possible outcomes for Accident Scenario 1 include:

$$P(\text{large spill with fire}) = \frac{P(OT|RE,DG1) \times P(DG1|RE) \times P(RE) \times P(FI|RE,CO) \times P(SP|RE,LL) \times P(LRE|SP,LL)}{P(OT) \times P(DG1)} \tag{3.8}$$

$$P(\text{sm sp with fire}) = \frac{P(OT|RE,DG1) \times P(DG1|RE) \times P(RE) \times P(FI|RE,CO) \times P(SP|RE,LL) \times [1-P(LRE|SP,LL)]}{P(OT) \times P(DG1)}$$

$$P(\text{lg leak with fire}) = \frac{P(OT|RE,DG1) \times P(DG1|RE) \times P(RE) \times P(FI|RE,CO) \times [1-P(SP|RE,LL)] \times P(LRE|LK,LL)}{P(OT) \times P(DG1)}$$

$$P(\text{sm lk w/fire}) = \frac{P(OT|RE,DG1) \times P(DG1|RE) \times P(RE) \times P(FI|RE,CO) \times [1-P(SP|RE,LL)] \times [1-P(LRE|LK,LL)]}{P(OT) \times P(DG1)}$$

$$P(\text{lg spill no fire}) = \frac{P(OT|RE,DG1) \times P(DG1|RE) \times P(RE) \times [1-P(FI|RE,CO)] \times P(SP|RE,LL) \times P(LRE|SP,LL)}{P(OT) \times P(DG1)}$$

$$P(\text{sm sp no fire}) = \frac{P(OT|RE,DG1) \times P(DG1|RE) \times P(RE) \times [1-P(FI|RE,CO)] \times P(SP|RE,LL) \times [1-P(LRE|SP,LL)]}{P(OT) \times P(DG1)}$$

$$P(\text{lg leak no fire}) = \frac{P(OT|RE,DG1) \times P(DG1|RE) \times P(RE) \times [1-P(FI|RE,CO)] \times [1-P(SP|RE,LL)] \times P(LRE|LK,LL)}{P(OT) \times P(DG1)}$$

$$P(\text{sm lk no fire}) = \frac{P(OT|RE,DG1) \times P(DG1|RE) \times P(RE) \times [1-P(FI|RE,CO)] \times [1-P(SP|RE,LL)] \times [1-P(LRE|LK,LL)]}{P(OT) \times P(DG1)}$$

$$P(\text{fire no release}) = \left[1-\frac{P(OT|RE,DG1) \times P(DG1|RE) \times P(RE)}{P(OT) \times P(DG1)}\right] \times P(FI|NRE,CO)$$

$$P(\text{no fire no release}) = \left[1-\frac{P(OT|RE,DG1) \times P(DG1|RE) \times P(RE)}{P(OT) \times P(DG1)}\right] \times [1-P(FI|NRE,CO)]$$

Accident Scenario 2 is a truck carrying a large load of DG2: flammable PLG and involved in an accident with a collision and an overturn. The model equations for the probabilities of the 10 possible outcomes for Accident Scenario 2 include:

(3.9)

$$P(\text{large spill with fire}) = \frac{P(OT|RE,DG2) \times P(DG2|RE) \times P(RE) \times P(FI|RE,CO) \times P(SP|RE,LL) \times P(LRE|SP,\ LL)}{P(OT) \times P(DG2)}$$

$$P(\text{sm sp with fire}) = \frac{P(OT|RE,DG2) \times P(DG2|RE) \times P(RE) \times P(FI|RE,CO) \times P(SP|RE,LL) \times [1-P(LRE|SP,LL)]}{P(OT) \times P(DG2)}$$

$$P(\text{lg leak with fire}) = \frac{P(OT|RE,DG2) \times P(DG2|RE) \times P(RE) \times P(FI|RE,CO) \times [1-P(SP|RE,LL)] \times P(LRE|LK,LL)}{P(OT) \times P(DG2)}$$

$$P(\text{sm lk w/fire}) = \frac{P(OT|RE,DG2) \times P(DG2|RE) \times P(RE) \times P(FI|RE,CO) \times [1-P(SP|RE,LL)] \times [1-P(LRE|LK,LL)]}{P(OT) \times P(DG2)}$$

$$P(\text{lg spill no fire}) = \frac{P(OT|RE,DG2) \times P(DG2|RE) \times P(RE) \times [1-P(FI|RE,CO)] \times P(SP|RE,LL) \times P(LRE|SP,LL)}{P(OT) \times P(DG2)}$$

$$P(\text{sm sp no fire}) = \frac{P(OT|RE,DG2) \times P(DG2|RE) \times P(RE) \times [1-P(FI|RE,CO)] \times P(SP|RE,LL) \times [1-P(LRE|SP,LL)]}{P(OT) \times P(DG2)}$$

$$P(\text{lg lk no fire}) = \frac{P(OT|RE,DG2) \times P(DG2|RE) \times P(RE) \times [1-P(FI|RE,CO)] \times [1-P(SP|RE,LL)] \times P(LRE|LK,LL)}{P(OT) \times P(DG2)}$$

$$P(\text{sm lk no fire}) = \frac{P(OT|RE,DG2) \times P(DG2|RE) \times P(RE) \times [1-P(FI|RE,CO)] \times [1-P(SP|RE,LL)] \times [1-P(LRE|LK,LL)]}{P(OT) \times P(DG2)}$$

$$P(\text{fire no release}) = \left[1-\frac{P(OT|RE,DG2) \times P(DG2|RE) \times P(RE)}{P(OT) \times P(DG2)}\right] \times P(FI|NRE,CO)$$

$$P(\text{no fire no release}) = \left[1-\frac{P(OT|RE,DG2) \times P(DG2|RE) \times P(RE)}{P(OT) \times P(DG2)}\right] \times [1-P(FI|NRE,CO)]$$

Each accident scenario has a different set of model equations, up to Accident Scenario 32, which includes a truck carrying a small load of DG4: toxic liquid and involved in an accident with no collision and no overturn. The model equations for the probabilities of the 10 possible outcomes for Accident Scenario 32 include:

(3.10)

$$P(\text{lg sp with fire}) = \frac{[1-P(OT|RE,DG4)] \times P(DG4|RE) \times P(RE) \times P(FI|RE,NCO) \times P(SP|RE,SL) \times P(LRE|SP,SL)}{[1-P(OT)] \times P(DG4)}$$

$$P(\text{sm sp w/fire}) = \frac{[1-P(OT|RE,DG4)] \times P(DG4|RE) \times P(RE) \times P(FI|RE,NCO) \times P(SP|RE,SL) \times [1-P(LRE|SP,SL)]}{[1-P(OT)] \times P(DG4)}$$

$$P(\text{lg lk w/fire}) = \frac{[1-P(OT|RE,DG4)] \times P(DG4|RE) \times P(RE) \times P(FI|RE,NCO) \times [1-P(SP|RE,SL)] \times P(LRE|LK,SL)}{[1-P(OT)] \times P(DG4)}$$

$$P(\text{sm lk w/fire}) = \frac{[1-P(OT|RE,DG4)] \times P(DG4|RE) \times P(RE) \times P(FI|RE,NCO) \times [1-P(SP|RE,SL)] \times [1-P(LRE|LK,SL)]}{[1-P(OT)] \times P(DG4)}$$

$$P(\text{lg sp no fire}) = \frac{[1-P(OT|RE,DG4)] \times P(DG4|RE) \times P(RE) \times [1-P(FI|RE,NCO)] \times P(SP|RE,SL) \times P(LRE|SP,SL)}{[1-P(OT)] \times P(DG4)}$$

$$P(\text{sm sp no fire}) = \frac{[1-P(OT|RE,DG4)] \times P(DG4|RE) \times P(RE) \times [1-P(FI|RE,NCO)] \times P(SP|RE,SL) \times [1-P(LRE|SP,SL)]}{[1-P(OT)] \times P(DG4)}$$

$$P(\text{lg lk no fire}) = \frac{[1-P(OT|RE,DG4)] \times P(DG4|RE) \times P(RE) \times [1-P(FI|RE,NCO)] \times [1-P(SP|RE,SL)] \times P(LRE|LK,SL)}{[1-P(OT)] \times P(DG4)}$$

$$P(\text{sm lk nofire}) = \frac{[1-P(OT|RE,DG4)] \times P(DG4|RE) \times P(RE) \times [1-P(FI|RE,NCO)] \times [1-P(SP|RE,SL)] \times [1-(LRE|LK,SL)]}{[1-P(OT)] \times P(DG4)}$$

$$P(\text{fire no release}) = \{1-\frac{[1-P(OT|RE,DG4)] \times P(DG4|RE) \times P(RE)\}}{[1-P(OT)] \times P(DG4)} \times P(FI|NRE,NCO)$$

$$P(\text{no fire no release}) = \{1-[1-\frac{P(OT|RE,DG4)] \times P(DG4|RE) \times P(RE)\}}{[1-P(OT)] \times P(DG4)} \times [1-P(FI|NRE,NCO)]$$

For non-accident scenarios, there are five input variables in the model equations. The values of the input variables vary according to the non-accident scenario. The input variables for the non-accident scenarios include:

V1: releases per Bvkm by type of DG load or (releases per Bvkm|DG1), ...
V2: P(fire | release) by rural or urban road or P(FI|RE,RU), P(FI|RE,UR)
V3: P(spill | release) or P(SP|RE)
V4: P(large release | spill)
by rural or urban road
and tanker or non-tanker truck or P(LRE|SP,RU,TA), P(LRE|SP,RU,NTA), ...
V5: P(large release | leak)
by rural or urban road
and tanker or non-tanker truck or P(LRE|LK,RU,TA), P(LRE|LK,RU,NTA), ...

Non-Accident Scenario 33 is a tanker truck carrying DG1: toxic PLG on a rural road. The model equations for the incident rates for the eight possible outcomes for Non-Accident Scenario 33 include:

(3.11)

large spills with fire per Bvkm = (releases per Bvkm|DG1) x P(FI|RE,RU) x P(SP|RE) x P(LR|SP,RU,TA)

small spills with fire per Bvkm = (releases per Bvkm|DG1) x P(FI|RE,RU) x P(SP|RE) x [1-P(LR|SP,RU,TA)]

large leaks with fire per Bvkm = (releases per Bvkm|DG1) x P(FI|RE,RU) x [1-P(SP|RE)] x P(LR|LK,RU,TA)

sm leaks with fire per Bvkm = (releases per Bvkm|DG1) x P(FI|RE,RU) x [1-P(SP|RE)] x [1-P(LR|LK,RU,TA)]

large spills no fire per Bvkm = (releases per Bvkm|DG1) x [1-P(FI|RE,RU)] x P(SP|RE) x P(LR|SP,RU,TA)

small spills no fire per Bvkm = (releases per Bvkm|DG1) x [1-P(FI|RE,RU)] x P(SP|RE) x [1-P(LR|SP,RU,TA)]

large leaks no fire per Bvkm = (releases per Bvkm|DG1) x [1-P(FI|RE,RU)] x [1-P(SP|RE)] x P(LR|LK,RU,TA)

sm lks no fire per Bvkm = (releases per Bvkm|DG1) x [1-P(FI|RE,RU)] x [1-P(SP|RE)] x [1-P(LR|LK,RU,TA)]

Non-Accident Scenario 34 is a tanker truck carrying DG2: flammable PLG on a rural road. The model equations for the incident rates for the eight possible outcomes for Non-Accident Scenario 34 include:

(3.12)

large spills with fire per Bvkm = (releases per Bvkm|DG2) x P(FI|RE,RU) x P(SP|RE) x P(LR|SP,RU,TA)

small spills with fire per Bvkm = (releases per Bvkm|DG2) x P(FI|RE,RU) x P(SP|RE) x [1-P(LR|SP,RU,TA)]

large leaks with fire per Bvkm = (releases per Bvkm|DG2) x P(FI|RE,RU) x [1-P(SP|RE)] x P(LR|LK,RU,TA)

sm leaks with fire per Bvkm = (releases per Bvkm|DG2) x P(FI|RE,RU) x [1-P(SP|RE)] x [1-P(LR|LK,RU,TA)]

large spills no fire per Bvkm = (releases per Bvkm|DG2) x [1-P(FI|RE,RU)] x P(SP|RE) x P(LR|SP,RU,TA)

small spills no fire per Bvkm = (releases per Bvkm|DG2) x [1-P(FI|RE,RU)] x P(SP|RE) x [1-P(LR|SP,RU,TA)]

large leaks no fire per Bvkm = (releases per Bvkm|DG2) x [1-P(FI|RE,RU)] x [1-P(SP|RE)] x P(LR|LK,RU,TA)

sm lks no fire per Bvkm = (releases per Bvkm|DG2) x [1-P(FI|RE,RU)] x [1-P(SP|RE)] x [1-P(LR|LK,RU,TA)]

Each non-accident scenario has a different set of model equations, up to Non-Accident Scenario 48, which is a non-tanker truck carrying DG4: toxic liquid on an urban road. The model equations for the incident rates for the eight possible outcomes for Non-Accident Scenario 48 include:

(3.13)

large spills with fire per Bvkm = (releases per Bvkm|DG4) x P(FI|RE,UR) x P(SP|RE) x P(LR|SP,UR,NTA)

small spills with fire per Bvkm = (releases per Bvkm|DG4) x P(FI|RE,UR) x P(SP|RE) x [1-P(LR|SP,UR,NTA)]

large leaks with fire per Bvkm = (releases per Bvkm|DG4) x P(FI|RE,UR) x [1-P(SP|RE)] x P(LR|LK,UR,NTA)

sm lks with fire per Bvkm = (releases per Bvkm|DG4) x P(FI|RE,UR) x [1-P(SP|RE)] x [1-P(LR|LK,UR,NTA)]

large spills no fire per Bvkm = (releases per Bvkm|DG4) x [1-P(FI|RE,UR)] x P(SP|RE) x P(LR|SP,UR,NTA)

sm spills no fire per Bvkm = (releases per Bvkm|DG4) x [1-P(FI|RE,UR)] x P(SP|RE) x [1-P(LR|SP,UR,NTA)]

lg leaks no fire per Bvkm = (releases per Bvkm|DG4) x [1-P(FI|RE,UR)] x [1-P(SP|RE)] x P(LR|LK,UR,NTA)

sm lks no fire per Bvkm = (releases per Bvkm|DG4)x[1-P(FI|RE,UR)] x [1-P(SP|RE)] x [1-P(LR|LK,UR,NTA)]

Chapter 4 documents the sources of data, the classification of the DG incident outcomes, and the classification of possible factors that may potentially impact incident outcomes. Chapter 5 identifies factors that significantly affect DG incident outcomes and summarises the input variables for the model. Chapter 5 defines the accident and non-accident scenarios that arise from the combination of the significant factors. Chapter 6 provides point estimates for the input and output variables, to illustrate the structure of the model.

CHAPTER 4

DG RELEASE AND FIRE CHARACTERISTICS

Chapter 4 contains the following sections:

4.1 Data Sources
4.2 Classification of Incident Outcomes
4.3 Potential Factors

Chapter 4 documents the sources of data, the classification of DG incident outcomes, and the classification of possible factors that may potentially impact incident outcomes.

4.1 DATA SOURCES

Government agencies from Canada, the USA and France kindly provided databases for use in this research. Figure 4.1 illustrates the available databases and the relevant data fields in each database. There are three DG incident databases and two road accident databases. Section 4.1.2 describes the DG incident data and Section 4.1.3 describes the accident data.

The variety of databases allows a comparison of release and fire incident characteristics from different sources. We assume that each source provides an estimate of the value of the input variable, such as P(fire | collision). This assumption is discussed further in Chapter 8. Plots of the data indicate that the values for input variables from different sources are generally similar. The estimates of the value for an input variable may vary between data sources because of a variety of causes of uncertainty. For example, differences in the methods of reporting and recording incidents may result in differences in measurement error. Where

Figure 4.1: Databases

DG Incident Data

Database:	DGAIS	ORIS	MTMD
Source:	Transport Canada	MOE	France
Area:	Canada	Ontario	France
Years:	1988 to 1995	1988 to 1997	1987 to 1992
Relevant Data Fields:	year accident on road truck type type of DG load load release release size overturn collision fire spill tanker truck load size urban/rural	year accident on road truck type of DG load load release release size overturn	year accident on road truck DG load load release release size overturn collision fire

Accident Data

Database:	ADS	MARS
Source:	MTO	WSDOT
Area:	Ontario	Washington State
Years:	1988 to 1995	1990 to 1996
Relevant Data Fields:	year accident on road truck type load release overturn collision fire truck loaded tanker truck	year accident on road truck load release overturn collision fire

there are few records for a certain type of incident, one incident more or less can result in a noticeably different value for the input variable. Fluctuations in the number of incidents from year to year may result in varying values. Factors that are unavailable in the DG incident databases, such as differences in speed limits or other road and vehicle characteristics, may result in uncertainty. The range of values aids in quantifying uncertainty for a model to predict release and fire incident rates for trucks carrying DG loads, for use in locations with road and truck characteristics similar to North America and Europe.

None of the available databases contain information about the sequence of events in an incident. For example, if there is an incident with a release and fire, we do not know whether the fire started with say the vehicle fuel tank and then propagated to the DG load, or whether the fire started with the DG load and then spread to the rest of the vehicle. We only know that both a release and fire occurred. In addition, none of the databases have information on the size of fires. We can infer that a fire with a large release is probably a large fire, but we do not have the data to confirm this.

4.1.1 Data of Interest

As mentioned in Section 1.1 of the introduction to this thesis, the thesis addresses the probability of accident-induced and non-accident releases, fires and explosions for trucks in transit carrying DG loads. A "release" is defined as a release of the DG load, excluding any spill or leak from the vehicle fuel tank. The thesis combines fire and explosions under a category called simply "fires". The analysis focuses exclusively on trucks in transit, moving along their routes, and excludes incidents that occur while the truck is loading, unloading or in storage.

We further qualify the data used in terms of the type of trucks, where this information is available. The research focuses on the types of trucks that carry loads classified as dangerous by the 1996 North American Emergency Response Guideline (NAERG, 1996). This excludes other types of vehicles that typically do not carry DG loads. Examples of excluded vehicles include cars, pick-up trucks, recreational vehicles, livestock carriers and car carriers.

The research focuses on trucks that are carrying partial or full loads. This excludes unloaded trucks. Trucks that are partially loaded with DG may pose a greater risk than fully loaded trucks. Partially loaded trucks carrying liquid tend to have more stability problems because the liquid can slosh back and forth when the truck accelerates, decelerates or turns. This may affect an accident outcome. Some types of DG can only ignite if they are in a gaseous state, and a partial load of pressure-liquefied gas can result in some of the load in a gaseous state.

4.1.2 DG Incident Data

Data from Transport Canada

The Dangerous Goods Accident Information System (DGAIS) database comes from The Transport Dangerous Goods Directorate, an arm of Transport Canada. This database provides information on reportable DG incidents in Canada, over the eight years from 1988 to 1995. DGAIS is the most detailed of the three available DG incident databases, and has the most records. As shown in Figure 4.1, relevant DGAIS data fields include:

- the year of the incident.
- whether it was an accident or non-accident incident.
- whether the incident occurred in transit on a road, or elsewhere, such as in storage or while unloading.
- the type of truck.
- the type of DG load.
- whether there was a release of the DG load or not. We classify a DG incident with a leak or spill from the vehicle fuel tank only as a non-release incident.
- the size of the release.
- if the incident involved an accident, whether there was an overturn or not.

- if the incident involved an accident, whether there was a collision or not. DGAIS and the other databases define a "collision" as an accident that involves an impact with either a fixed or a moveable object.
- whether the incident involved a fire or not (with or without a release).
- if there was a release, whether it was a leak or spill.
- whether the truck was a tanker or non-tanker. A non-tanker truck could include, for example, a box van or flat bed truck carrying DG in cylinders or barrels.
- the size of the load.
- whether the incident occurred on an urban or rural road.

The DGAIS documentation notes that reports must be filed with Transport Canada for any reportable accident deemed to be of significance that involves the transport of DG in Canada. Transport Canada enters these reports in DGAIS. Transport Canada broadly defines significant as an amount of produce released from containment that was beyond a threshold and that presented a danger to the public. As well, when DG are involved, accidents involving a death or injury or damage to the means of containment due to impact stress or fatigue must be reported. Therefore DGAIS also contains a number of non-release DG incidents.

This analysis uses DGAIS incident records for trucks in transit. We did not use the available DGAIS incident records for other types of vehicles such as trains, ships or airplanes. We also excluded DGAIS incident records for trucks that are loading, unloading or in storage. The database includes approximately 1,430 relevant DG incident records: 850 accidents and 580 non-accident incidents, of which approximately 240 are non-release incidents.

For trucks carrying DG, the Transport Dangerous Goods Directorate also has provided estimates of the percentage of vehicle-kilometres by type of DG load. The estimates are provided by province and by year from 1986 to 1990. The Directorate generated these estimates of vehicle-kilometres for each type of DG by combining information from:

- Statistic Canada's annual Motor Carrier Freight Survey of commercial road carriers (trucking companies).
- Statistic Canada's quarterly For-Hire Trucking (Commodity Origin and Destination) Survey.
- the Ontario Commercial Vehicle Surveys.

Data from the Ministry of Environment of Ontario

The Occurrence Report Information System (ORIS) Version 4.0 database comes from the Spills Action Centre of the Ministry of Environment of Ontario (MOE). This database provides information on releases of DG in the Province of Ontario, from 1988 to 1997.

The analysis uses the ORIS records for load releases from trucks on roads in transit. This excludes DG release records for:

- other types of vehicles such as trains, ships or airplanes.
- other sources such as pipelines, sewers, storage facilities, etc.
- trucks that are loading, unloading or in storage.
- spills or leaks from truck fuel tanks as opposed to releases of the truck pay-load.

The database includes approximately 540 relevant DG release records. As shown in Figure 4.1, relevant ORIS data fields include:

- the year of the incident.
- whether it was an accident or non-accident incident.

- whether the incident occurred on-road or off-road.
- whether the vehicle was a truck or not.
- the type of DG load.
- whether there was a release of the DG load or not (as opposed to a release from the fuel tank only).
- the size of release.
- if the incident involved an accident, whether there was an overturn or not.

In theory, each of the records in the ORIS database for Ontario from 1988 to 1995 should also be in the DGAIS database for Canada. However, neither database contains records of every DG release that should have been reported. For specific types of DG incidents, for some years DGAIS contains more records for Ontario and for some years ORIS contains more records. The two databases provide two different samples of DG incidents and two sources for estimates of the values of input variables. The uncertainty arising from the differences between the two databases is discussed further in Chapter 8.

Data from France

The Mission Transport des Matières Dangereuses (MTMD) database contains records of releases of DG from trucks in France, from 1987 to 1992. The database includes approximately 1,100 DG relevant release records. As shown in Figure 4.1, relevant MTMD data fields include:

- the year of the incident.
- whether it was an accident or non-accident incident.
- whether the incident occurred on-road or off-road.
- whether the vehicle was a truck or not.
- whether the load was a DG load or not.
- whether there was a release of the DG load or not.
- the size of release.

- if the incident involved an accident, whether there was an overturn or not.
- if the incident involved an accident, whether there was a collision or not.
- whether the incident involved a fire or not.

4.1.3 Accident Data

Data from the Ministry of Transportation of Ontario

The Accident Data System (ADS) database comes from the Ministry of Transportation of Ontario (MTO). This database provides information on all reportable road accidents taking place on Provincial highways in the Province of Ontario, from 1988 to 1995. As defined in ADS for the years from 1988 to 1995, a "reportable" road accident either resulted in injury or death or exceeded $700 in total property damage.

The analysis uses the ADS accident records for loaded trucks, excluding unloaded trucks and excluding car carriers, livestock carriers and recreational vehicles. The database contains approximately 24,870 relevant truck accident records. The actual type of load (dangerous or not) in these truck accidents is unknown, but it is assumed that truck accident characteristics are similar, regardless of whether the load is dangerous or not. As shown in Figure 4.1, relevant ADS data fields include:

- the year of the accident.
- whether the accident included a collision, an overturn, and/or the vehicle running off the road. An ADS record could include an incident where none of these events occur, such as when a load falls off a truck and causes damage, or if a fire starts from a brake or tire overheating during transport.
- whether the accident occurred on-road or off-road.
- the type of truck.
- whether there was a load release or not.
- whether there was a fire or not.

- whether the truck was loaded or unloaded.
- whether the truck was a tanker or non-tanker.

In theory, each of the records of accident-induced releases or fires in Ontario from 1988 to 1995 in the DGAIS and ORIS databases has a matching truck accident record in ADS. It may be possible to find the matching records through descriptions of accident time, location, etc., but this is not of interest for this analysis. We use the ADS database to provide general truck accident characteristics.

Data from Washington State

The Master Accident Record System (MARS) database comes from the Washington State Department of Transportation (WSDOT). This database provides information on all reportable accidents taking place on all roads in Washington State, USA from 1990 to 1996.

The analysis uses the MARS accident records where at least one of the vehicles involved was a heavy truck, in transit on a road. This excludes, for example, cars, pick-up trucks, farm equipment, buses and motorcycles and off-road accidents. The database contains approximately 11,370 relevant truck accident records.

As shown in Figure 4.1, relevant MARS data fields include:

- the year of the accident.
- whether the accident included a collision, an overturn, and/or the vehicle running off the road.
- whether the accident occurred on-road or off-road.
- whether the vehicle was a truck or not.
- whether there was a load release or not.
- whether there was a fire or not.

4.2 CLASSIFICATION OF INCIDENT OUTCOMES

As discussed earlier in Section 1.2, for QRA analysis the DG incident rates must indicate:

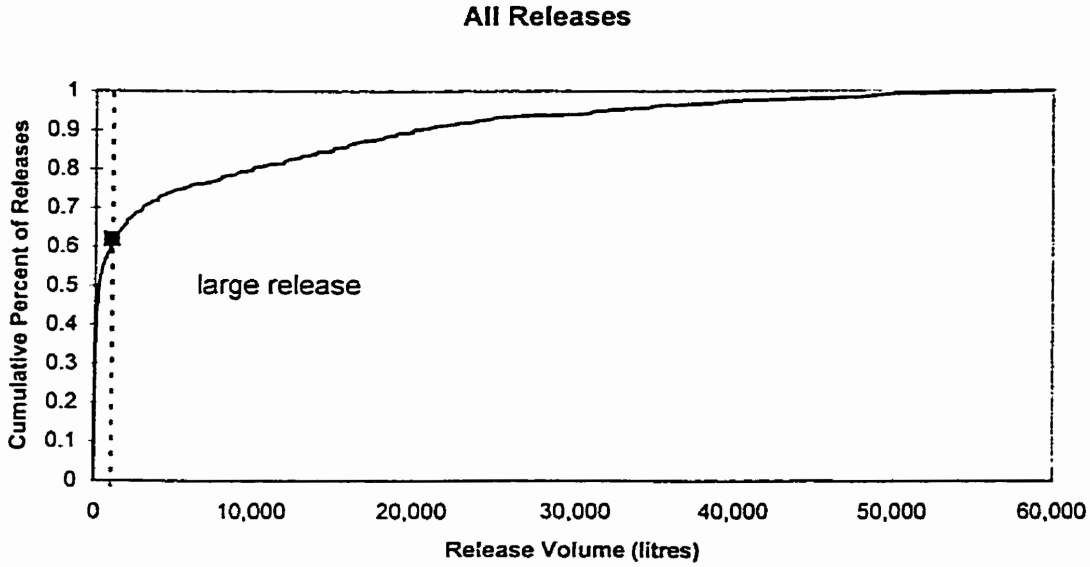
- whether or not there is a release of the DG load. In this analysis the term "release" applies to a release of the DG load, and not to a leak or spill from a fuel tank.
- whether or not there is a fire.
- the rate and quantity of the release.

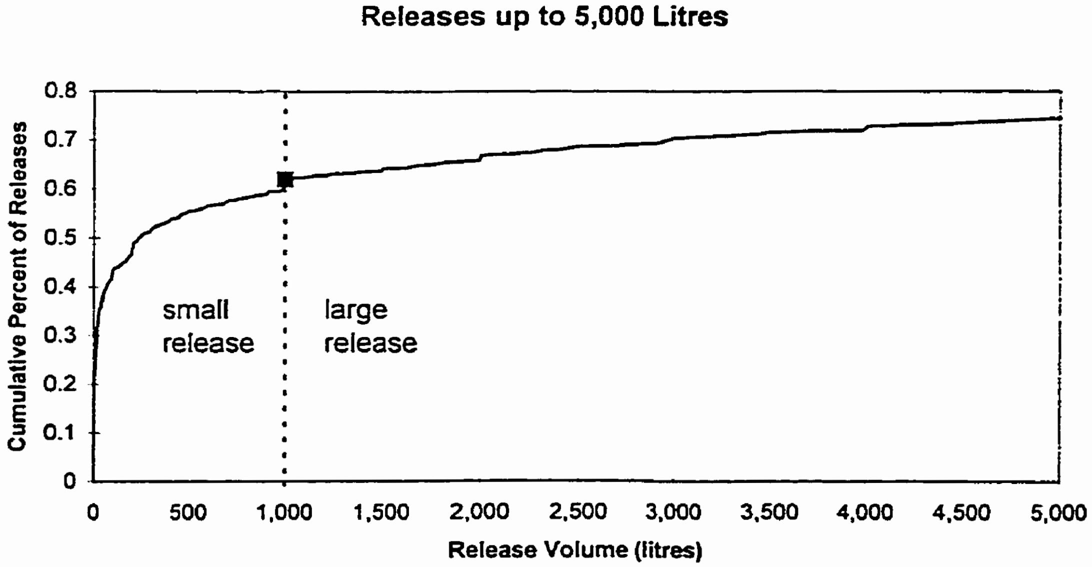
The term "fire" applies to both fires and/or explosions. Approximately 7% of DGAIS incidents and 5% of MTMD incidents include fires, for a combined mean of 6% of DG incidents with fires. A fire may occur with or without a release of the DG load. For fires without releases, the fire may destroy the vehicle fuel and possibly part of the vehicle, but does not affect the DG load. For fires with releases, the incident may destroy some or all of the DG load and possibly the vehicle fuel and vehicle. Either the DG load initiates the fire or the fire propagates to include the DG load. If a flammable DG load is involved, the fire can produce a much higher heat intensity than if only the vehicle fuel burns.

In DGAIS, a release is either a "spill" or a "leak". The rate of release generally defines the difference between spills and leaks. DGAIS notes that the major distinction between a spill and a leak relates to the time that elapses following the initial release of product. DGAIS defines a spill as an immediate or continuous release of product from containment. Typically, a release of product in a spill is of a short duration. A leak, on the other hand, is a small, sporadic release. The release of a DG in a leak is usually of a long duration. From DGAIS, approximately 31% of releases from trucks in transit are leaks and 69% are spills. Both spills and leaks can be large or small, but a spill is more likely to be large than a leak.

DGAIS, ORIS and MTMD records contain the actual size of the release. Figure 4.2 shows the distribution of releases by volume reported by DGAIS. To avoid empty cells in cross-tabulations of the DG incident data by incident characteristics, we need to combine the data

Figure 4.2: Graphs of Release Volumes





Note: small release = release less than 1,000 litres
large release = release 1,000 litres or greater

Source of release volumes: DGAIS

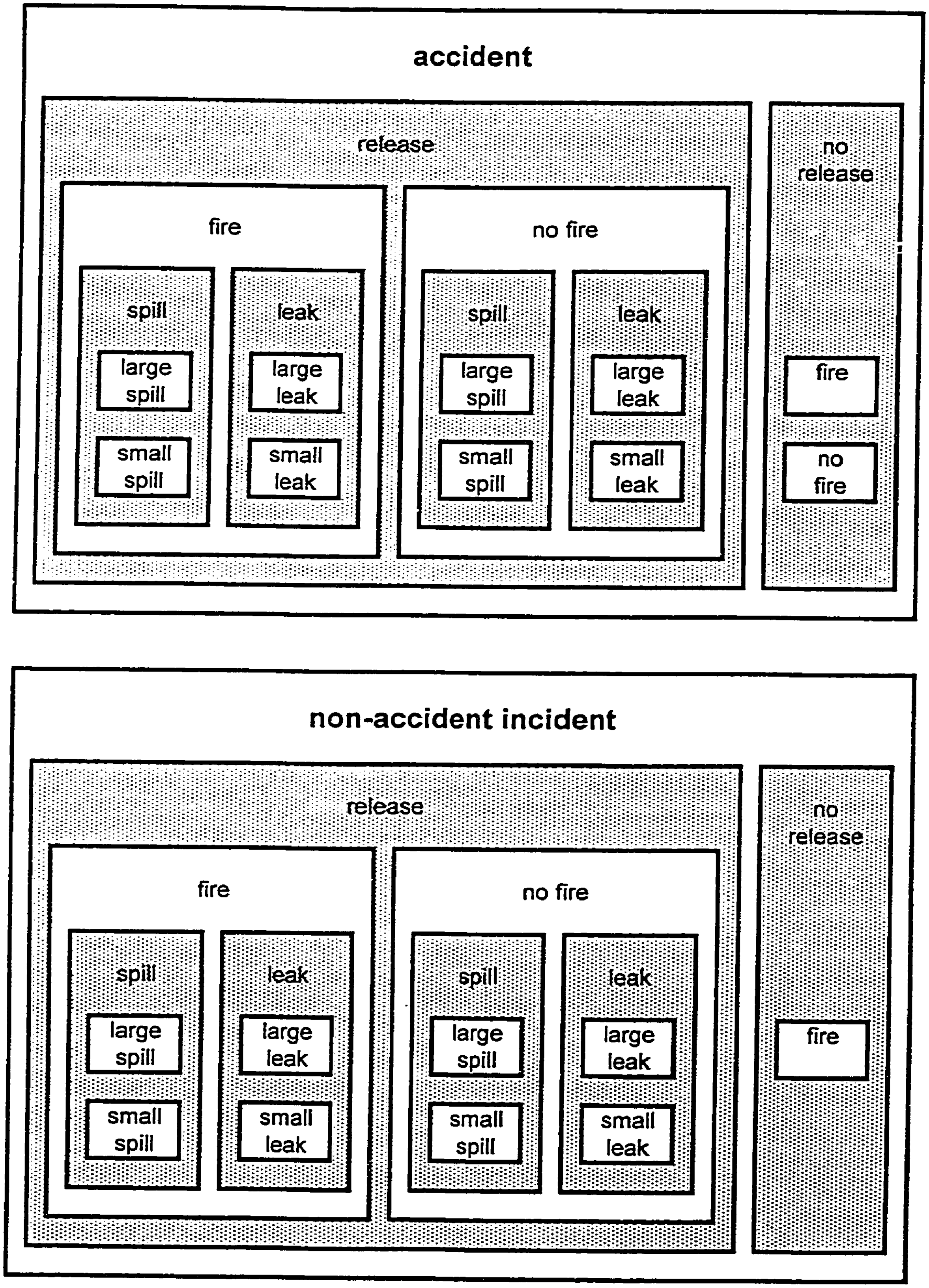
into logical, broader classifications. Therefore we classify the size of a release as either "large" (1,000 litres or greater) or "small" (less than 1,000 litres). Approximately 60% of DGAIS, 77% of ORIS releases and 41% of MTMD releases are smaller than 1,000 litres, for a combined mean of 60% small releases. The size of large releases varies widely, from 1,000 to over 60,000 litres, with an average of approximately 14,000 litres.

The four characteristics of release/no release, fire/no fire, spill/leak, and large release/small can be combined to describe all possible DG incident outcomes and ultimately to provide useful input for QRA analysis. However, we also need to define the DG incident as an accident or non-accident incident, in order to determine the incident rates per Bvkm. We define accidents as events involving one or a combination of a collision, an overturn or the truck running off the road, where these events cause enough damage or injury for the police to report them. If the event does not include any of a collision, overturn or running off the road, we classify the event as a non-accident. A non-accident incident could include a release that occurs if a valve is not properly closed, if a corroded weld fails, or if a fire starts from a brake or tire overheating during transport.

Figure 4.3 shows the resulting outcome classification scheme for DG incidents. Figure 4.3 groups DG incidents as either accident or non-accident. Both accidents and non-accident incidents can result in a release or no release. If there is a release, there are a further eight sub-classifications including:

- large spill with fire.
- small spill with fire.
- large leak with fire.
- small leak with fire.
- large spill no fire.
- small spill no fire.
- large leak no fire.
- small leak no fire.

Figure 4.3: Outcome Classification Scheme



For accidents with no release, there can still be a fire or no fire. For non-accident incidents with no release, there must be a fire for the incident to be recorded. If there is an incident with no accident, no release and no fire, then it is not recorded in any of the databases and is not of interest to this analysis.

We cannot estimate the incident rates for each of the possible outcomes shown in Figure 4.3 directly from the raw data. There are not enough records in any of the DG incident databases to cross-tabulate by each of the possible outcomes without ending up with empty cells. However, we can calculate the incident rates for each of the possible outcomes using simple equations. Figure 4.4 summarises these model equations, with the exception of the incident rates for non-accident non-release fires, which are discussed later in Section 5.1.

For accident scenarios, the input variables in the model equations include:

- accident rate. This is the number of accidents per Bvkm.
- P(release | accident). An accident can result in a release or no release
- P(fire | accident). An accident can result in a fire, whether there is a release or not.
- P(spill | release). If there is an accident-induced release, it is either a spill or leak.
- P(large release | release). If there is an accident-induced release, it is either large or small.

For non-accident scenarios, the input variables in the model equations include:

- release rate. This is the number of non-accident releases per Bvkm. For non-accident incidents, the equations are for releases only. Non-accident non-release fires are discussed later in Section 5.1.1.
- P(fire | release). For non-accident incidents, we consider only releases. The release can be combined with a fire or no fire.
- P(spill | release). If there is a non-accident release, it is either a spill or leak.
- P(large release | release). If there is a non-accident release, it is either large or small.

Figure 4.4: Model Equations

General Equations for Accident Scenarios

rate of incidents with large spill & fire = accident rate x P(release | accident) x P(fire | accident)
x P(spill | release) x P(large release | release)

rate of incidents with small spill & fire = accident rate x P(release | accident) x P(fire | accident)
x P(spill | release) x (1-P(large release | release))

rate of incidents with large leak & fire = accident rate x P(release | accident) x P(fire | accident)
x (1-P(spill | release)) x P(large release | release)

rate of incidents with small leak & fire = accident rate x P(release | accident) x P(fire | accident)
x (1-P(spill | release)) x (1-P(large release | release))

rate of incidents with large spill no fire = accident rate x P(release | accident) x (1-P(fire | accident))
x P(spill | release) x P(large release | release)

rate of incidents with small spill no fire = accident rate x P(release | accident) x (1-P(fire | accident))
x P(spill | release) x (1-P(large release | release))

rate of incidents with large leak no fire = accident rate x P(release | accident) x (1-P(fire | accident))
x (1-P(spill | release)) x P(large release | release)

rate of incidents with small leak no fire = accident rate x P(release | accident) x (1-P(fire | accident))
x (1-P(spill | release)) x (1-P(large release | release))

rate of incidents with fire no release = accident rate x (1-P(release | accident)) x P(fire | accident)

rate of incidents with no fire no release = accident rate x (1-P(release | accident)) x (1-P(fire | accident))

General Equations for Non-Accident Scenarios

rate of incidents with large spill & fire = release rate x P(fire | release)
x P(spill | release) x P(large release | release)

rate of incidents with small spill & fire = release rate x P(fire | release)
x P(spill | release) x (1-P(large release | release))

rate of incidents with large leak & fire = release rate x P(fire | release)
x (1-P(spill | release)) x P(large release | release)

rate of incidents with small leak & fire = release rate x P(fire | release)
x (1-P(spill | release)) x (1-P(large release | release))

rate of incidents with large spill no fire = release rate x (1-P(fire | release))
x P(spill | release) x P(large release | release)

rate of incidents with small spill no fire = release rate x (1-P(fire | release))
x P(spill | release) x (1-P(large release | release))

rate of incidents with large leak no fire = release rate x (1-P(fire | release))
x (1-P(spill | release)) x P(large release | release)

rate of incidents with small leak no fire = release rate x (1-P(fire | release))
x (1-P(spill | release)) x (1-P(large release | release))

For example, we can consider a hypothetical scenario as follows:

- a truck accident rate of 1400 accidents per Bvkm.

- a non-accident DG incident rate of 5 incidents per Bvkm.

- a sample of 1000 accidents involving trucks carrying DG loads which includes:
    - 30 releases
    - 40 fires (with or without a release)
    - 27 spills (with or without a fire)
    - 26 large releases (with or without a fire or spill).

- a sample of 100 non-accident releases from trucks carrying DG loads which includes:
    - 2 fires
    - 50 spills (with or without a fire)
    - 25 large releases (with or without a fire or spill).

Using the equations in Figure 4.4, we can calculate the combined rate of accident and non-accident incidents with large spills and fires per Bvkm for the hypothetical scenario as follows:

$$\begin{aligned}
&\text{number of incidents with large spills and fires per Bvkm} \\
&= \text{number of accidents with large spills and fires per Bvkm} \\
&\quad + \\
&\quad \text{number of non-accident incidents with large spills and fires per Bvkm} \\
&= (\text{accident rate per Bvkm}) \times P(\text{release} \mid \text{accident}) \\
&\quad \times P(\text{fire} \mid \text{accident}) \times P(\text{spill} \mid \text{release}) \times P(\text{large release} \mid \text{release}) \\
&\quad + \\
&\quad (\text{number of non-accident releases per Bvkm}) \\
&\quad \times P(\text{fire} \mid \text{release}) \times P(\text{spill} \mid \text{release}) \times P(\text{large release} \mid \text{release}) \\
&= 1400 \times 30/1000 \times 40/1000 \times 27/30 \times 26/30 + 5 \times 2/100 \times 50/100 \times 25/100 \\
&= 1.3104 + .0125 \\
&= 1.3229 \text{ incidents with large spill and fire per Bvkm}
\end{aligned} \tag{4.1}$$

The equations in Figure 4.4 assume that all of the input variables are statistically independent. The equations indicate that, for example:

$$P(\text{release and fire} \mid \text{accident}) = P(\text{release} \mid \text{accident}) \times P(\text{fire} \mid \text{accident}) \tag{4.2}$$

The analysis of significant factors later in Chapter 5 checks this assumption. If the variables are not independent, then the equation is modified to include the relationship. For example, Chapter 5 shows that release is a significant factor in predicting fire. The equation is modified as follows:

$$P(\text{release and fire} \mid \text{accident}) = P(\text{release} \mid \text{accident}) \times P(\text{fire} \mid \text{accident-induced release}) \quad (4.3)$$

4.3 POTENTIAL FACTORS

To explain variations in incident rates, we need to determine which factors available in the data have a significant impact on incident outcomes. For accidents, two of the potential factors to predict the characteristics of DG incidents include:

- whether the accident included an overturn or not.
- whether the accident included a collision or not.

An accident can have:

- both an overturn and a collision.
- an overturn with no collision.
- a collision with no overturn.
- no overturn and no collision.

From ADS for Ontario highways, approximately 2% of truck accidents involve overturns and collisions, 5% involve overturns with no collision, 82% involve collisions with no overturn, and 11% involve no overturn and no collision. An accident that has no overturn and no collision typically involves a vehicle sliding or running off the road into the ditch.

For both accident and non-accident incidents, additional potential factors available in the data include:

- type of DG load, discussed further in Section 4.3.1.
- small or large load size, discussed further in Section 4.3.2.
- truck type, discussed further in Section 4.3.3.
- whether the truck is a tanker or non-tanker.
- whether the truck is travelling on an urban or rural road.
- for fires, whether there is a release of the DG load or not.
- for spills and leaks, whether there is a fire or not.
- for release size, whether there is a fire or not and whether the release is a leak or spill.

The above is not an exhaustive list of potential factors affecting fire and release incident rates. The list is restricted to potential factors about which there is information in one or more of the five databases used for this analysis. There may be other factors that we do not include in our model because of lack of data. For example, the report by Saccomanno, Leeming and Stewart (1993) comparing risk estimates for a benchmark corridor exercise suggests that the speed limit affects release probabilities given an accident. A higher speed limit is related to a higher probability of release. However, we do not have information on the speed limit for releases in the available data, and so this factor is not included in our model.

4.3.1 Types of DG Loads

Trucks transport many types of DG loads by road. These DG may be corrosive, flammable, explosive, radioactive, poisonous, infectious or carcinogenic. They may be liquid (pressurised or unpressurised), gaseous or solid. The 1996 North American Emergency Response Guide Book (NAERG, 1996) details nine major classes of DG, 22 sub-classes and hundreds of specific DG products. The major classes and sub-classes of DG include:

Class 1: explosives
  11: capable of producing a mass explosion
  12: a projection hazard but not a mass explosion hazard
  13: a fire hazard with minor projection and/or minor blast hazard
  14: a minor hazard, effects confined largely to package
  15: insensitive explosive substances

Class 2: gases
  21: inflammable gases
  22: gases not poisonous or flammable
  23: poisonous gases
  24: corrosive

Class 3: flammable and combustible liquids
  31: having flashpoint below -18° Celsius
  32: having flashpoint greater than or equal to -18° and less than 23° Celsius
  33: having flashpoint greater than or equal to 23° and
  less than or equal to 61° Celsius

Class 4: flammable solids
  41: combustible through friction or heat retained from processing
  42: liable to spontaneous heating in contact with air
  43: emit flammable gases or spontaneously combustible
  with water or water vapour

Class 5: oxidising substances and organic substances
  51: oxidising substances which increase risk or intensity of fire
  52: organic peroxides either combustible or oxidisers

Class 6: poisonous (toxic) and infectious substances

61: poisonous by inhalation, ingestion, skin contact
62: infectious substance

Class 7: radioactive materials

Class 8: corrosives causing severe damage to living tissue or freight

Class 9: miscellaneous

91: miscellaneous dangerous goods
92: environmental hazard
93: dangerous waste products

We do not have enough data to examine each of these classes of DG. To limit the classes of DG to a manageable number, we have focused our analysis on four types of DG loads:

DG1: PLG that are toxic and/or corrosive and non-combustible, for example, pressure-liquefied chlorine gas.
DG2: PLG that are flammable, for example, liquefied petroleum gas or propane.
DG3: liquids that are flammable, for example, gasoline or fuel oil.
DG4: liquids that are toxic and/or corrosive and non-combustible, for example, pesticides.

To simplify the terminology, the remainder of the report refers to these classes of DG as:

DG1: toxic PLG
DG2: flammable PLG
DG3: flammable liquid
DG4: toxic liquid

In this analysis, we have not classified some miscellaneous types of DG, such as solids, and have not analysed these further. Unclassified DG represent approximately 7% of all DG transported by road and approximately 6% of all DG releases by trucks in transit carrying DG loads.

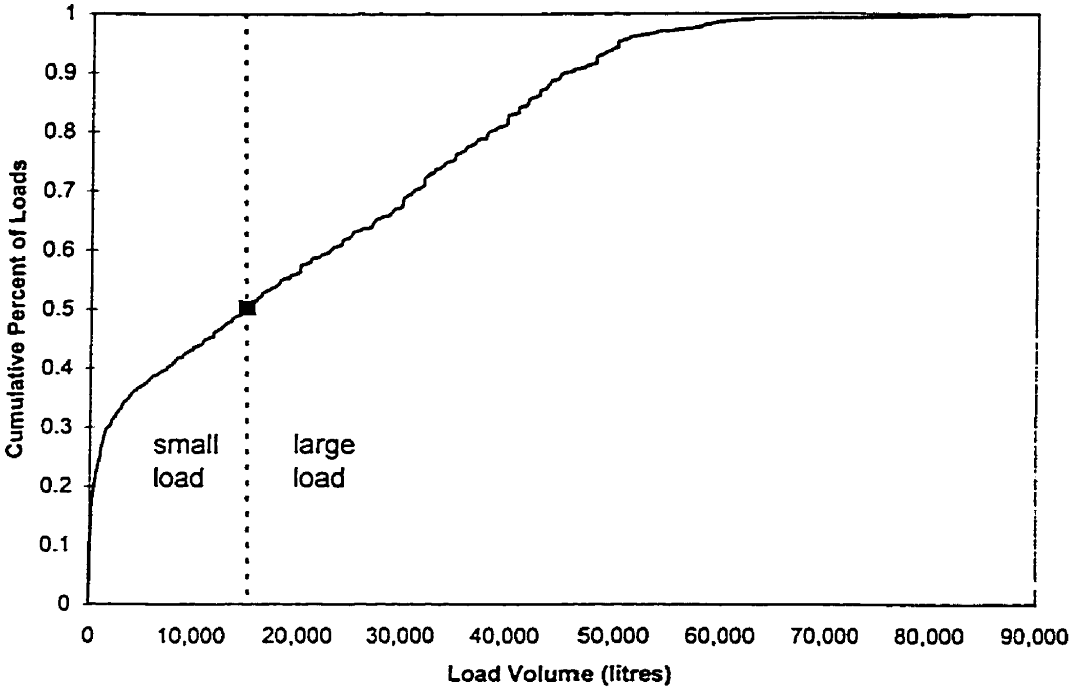
From Statistics Canada, the road kilometres by trucks carrying the above classes of DG loads may be grouped by the type of load: approximately 65% flammable liquid, 24% toxic liquid, 6% flammable PLG and 5% toxic PLG. Flammable liquids are the most common type of DG load. From DGAIS, approximately 60% of DG incidents occur on rural roads (in agricultural or uninhabited areas) and 40% on urban roads (in commercial, industrial or residential areas).

We use the type of DG load to reflect different types of truck configurations and their propensity to release given an accident or a non-accident incident. For example, from DGAIS, tanker trucks transport approximately 70% of DG1: toxic PLG, DG2: flammable PLG and DG3: flammable liquid. On the other hand, tanker trucks transport only approximately 35% of DG4: toxic liquid. If not in a tanker truck, DG1: toxic PLG and DG2: flammable PLG are most commonly transported in cylinders while DG3: flammable liquid and DG4: toxic liquid are most commonly transported in drums or pails. Tanker trucks that carry DG1: toxic PLG and DG2: flammable PLG, liquids with appreciable vapour pressures, are typically "thick walled". Tanker trucks that carry DG3: flammable liquid and DG4: toxic liquid, liquids at atmospheric pressure, are typically "thin walled" (Marshall, 1991).

4.3.2 Load Size

We classify a small load as a load smaller than 15,000 litres and a large load as a load of 15,000 litres or greater. Figure 4.5 shows the distribution of load sizes by volume reported by DGAIS. ORIS and MTMD do not report load size. From DGAIS, for trucks carrying DG loads, approximately 52% of the loads are smaller than 15,000 litres. A truck could be carrying a small load because the truck is small, or because it is a large truck is carrying only a partial load.

Figure 4.5: Graph of Load Volumes



Note: small load = load less than 15,000 litres
large load = load 15,000 litres or greater

Source of load sizes: DGAIS

4.3.3 Types of Trucks

There is a variety of information available about truck types in both the DGAIS and the ADS databases. We know the power unit may be either a straight truck or a tractor. A straight truck may be open, closed, a tanker or a dump truck, and may tow a full trailer. A tractor may tow a semi-trailer or double trailers. The trailer type could be van, flat bed, tanker or dump. For this thesis, we use the following classification scheme:

- straight truck.
- straight truck with full trailer.
- tractor with semi-trailer.
- tractor with double trailers.

From ADS, general truck accidents include approximately 66% tractors with semi-trailers, 23% straight trucks, 7% tractors with double trailers, and 3% straight trucks with full trailers. From DGAIS, incidents involving trucks carrying DG loads include approximately 54% tractors with semi-trailers, 26% straight trucks, 18% tractors with double trailers, and 2% straight trucks with full trailers. There is an over-representation of tractors with double trailers in the DGAIS data. This could be because DG loads are more commonly carried in tractors with double trailers than other types of goods.

We also consider a separate factor describing the type of truck: tanker or non-tanker. We can combine this factor with any of the four truck types to provide a more detailed truck description, for example, straight tanker truck, tractor with non-tanker semi-trailer, etc. From ADS, general truck accidents include approximately 6% tanker trucks. From DGAIS, approximately 62% of the DG incidents involve tanker trucks. There is an over-representation of tanker trucks in the DGAIS data, likely because liquid DG loads are commonly carried in tanker trucks.

CHAPTER 5

ACCIDENT AND NON-ACCIDENT SCENARIOS

Chapter 5 contains the following sections:

5.1 Significant Factors
5.2 Definition of Scenarios and Model

Chapter 5 identifies factors that significantly affect DG incident outcomes and summarises the input variables for the model. Chapter 5 defines the accident and non-accident scenarios that arise from the combination of the significant factors.

5.1 SIGNIFICANT FACTORS

In this thesis, we use stepwise logistic regression to identify predictive factors that significantly affect DG incident outcomes. Compared with the other available factors, these significant factors tend to have the most impact on the input variables. By using significant factors in building the model, the model better explains variations in incident outcomes.

Earlier, Section 3.2 described the method of selecting significant factors through stepwise logistic regression. The input variables for our model were used as dependent variables in the logistic regression. Only factors significant at the 5% level as variables in an equation to predict the dependent variable were considered for the model. If the logistic regression did not indicate a significance at the 5% level, then the factors were rejected one by one, in a stepwise fashion. None of the accident or non-accident factors are strongly correlated. Therefore we did not consider a factor for re-entry in the equation once it had been dropped.

5.1.1 Dependent Variables for the Logistic Regression

Our dependent variables for the logistic regression include each of the input variables in the model equations to predict incident outcomes. From Section 4.2, the ten input variables include:

- accident rate per Bvkm
- P(release | accident)
- P(fire | accident)
- P(spill | accident-induced release)
- P(large release | accident-induced release)

- non-accident release rate per Bvkm
- P(fire | non-accident release)
- P(spill | non-accident release)
- P(large release | non-accident release)

- non-accident non-release fire rate per Bvkm.

We did not undertake logistic regression for the input variables that are rates per Bvkm, including accident rate, non-accident release rate, and non-accident non-release fire rate, for the following reasons:

- In this thesis, we do not analyse accident rates nor the factors affecting accident rates. Other researchers have identified factors influencing accident rates. For example, Leeming et al. (1993) indicates that factors significantly affecting road accident rates for trucks include road type, traffic pattern, traffic volume, truck type, load status, model year, hour of day, and driver age. A further analysis of accident rates and their factors is beyond the scope of this research. We assume that future users of our model will supply accident rates that are appropriate to the specific sections of road they are analysing.

- We calculate the incident rate of non-accident releases as follows:

$$\frac{\text{number of incidents of non-accident releases}}{\text{number of vehicle kilometres travelled}} \tag{5.1}$$

  From Transport Canada, we have the vehicle-kilometres of trucks carrying DG loads, by type of DG load, by year and by province. No further details are available regarding the number of kilometres travelled. According to Transport Canada staff, variations by province are more likely due to differences in reporting than differences in incidents. Therefore we do not consider "province" as a factor in the model. We use the years to provide separate data points. Therefore, we use the type of DG load as the only factor in predicting the incident rate of non-accident releases. No logistic regression is undertaken for the incident rate of non-accident releases because of the data limitations.

- For incident rates for non-accident fires without releases, there is only a small amount of data available. From the MTMD data for trucks carrying DG loads, there were only 4 incidents of non-accident non-release fires from 1987 to 1992 in France. From DGAIS, there were only 7 incidents of non-accident fires without releases from 1988 to 1990 in Canada. From Statistics Canada information, the estimated road vehicle kilometres for trucks carrying DG loads from 1988 to 1990 in Canada was 31.6 Bvkm. Therefore the incident rate of non-accident non-release fires is approximately .22 incidents per Bvkm. We do not attempt to find further factors to explain this incident rate, because of the scarcity of data.

For the remaining seven input variables, we undertook stepwise logistic regression to identify significant factors. We used the DGAIS database for the logistic regression because it is the only available DG incident database that includes all of the potential factors. DGAIS also has the most incident records.

5.1.2 Collinearity Between Factors

Logistic regression may fail to indicate that a factor is significant in predicting the dependent variable, either because the factor has a minor effect on the dependent variable, or because the factor is collinear with another factor in the equation. Omission of collinear factors that are important in explaining the dependent variable is undesirable.

We checked for collinearity between factors by using SPSS ® to calculate the Spearman's correlation coefficient, *r*, for bivariate data. Most of the available factors are bivariate, for example, large load/small load, with the exception of type of DG load and truck type. These two factors have four possible categories each. For this test, we replaced the categorical factors for type of DG load and truck type each with four bivariate dummy factors: DG1, DG2, DG3 and DG4, and Truck1, Truck2, Truck3 and Truck4. For example, the dummy factor DG1 equals 1 if the DG load is toxic PLG and equals 0 if the load is another type of DG. The factors DG1, DG2, DG3 and DG4 are mutually exclusive. If DG1 equals 1 then DG2, DG3 and DG4 must equal 0.

Tables 5.1 and 5.2 show Spearman's correlation coefficient for each pair of factors for accident and non-accident DG incidents. The tables do not show the correlation between pairs of dummy factors that are mutually exclusive.

Correlations measure how the factors are related. The correlation coefficient quantifies the strength of the linear relationship between two factors. Correlation coefficients range in value from -1 to +1. A value of 0 indicates no linear relationship between two variables. A value of +1 indicates a perfect positive relationship. A value of -1 indicates a perfect negative relationship. Generally, a correlation coefficient greater than approximately .5 indicates some substantial relationship between factors. It is generally accepted that a correlation coefficient greater than approximately .9 indicates that factors are strongly related, such that one factor nearly explains the other, and collinearity may be a problem. Rawlings

Table 5.1: Spearman's Correlation Coefficients for Factors for Accident Scenarios

	collision/no collision	DG1: toxic PLG/not DG1	DG2: flammable PLG/not DG2	DG3: flammable liquid/not DG3	DG4: toxic liquid/not DG4	fire/no fire	large/small release	leak/spill	large/small load	overturn/no overturn	release/no release	tanker/non-tanker truck	truck1: straight truck/not truck1	truck2: straight truck with trailer/not truck2	truck3: tractor with semi-trailer/not truck3	truck4: tractor with double trailers/not truck4	urban/rural
collision/no collision	1.000	-.002	.002	-.046	.064	.198	.008	.010	-.076	-.531	-.090	-.069	.008	-.024	.064	-.072	.150
DG1: toxic PLG/not DG1	-.002	1.000				-.016	-.046	-.179	-.111	-.033	-.230	-.098	.058	.022	.017	-.086	.031
DG2: flammable PLG/not DG2	.002		1.000			.012	-.087	-.279	.036	-.016	-.405	.002	.067	-.050	.005	-.052	.049
DG3: flammable liquid/not DG3	-.046			1.000		.025	.223	.308	.128	.094	.430	.255	-.059	.073	-.113	.159	-.080
DG4: toxic liquid/not DG4	.064				1.000	-.034	-.191	-.088	-.133	-.090	-.010	-.282	-.031	-.069	.140	-.102	.039
fire/no fire	.198	-.016	.012	.025	-.034	1.000	.109	.016	.043	-.126	.077	-.007	-.052	-.031	.039	.019	-.001
large/small release	.008	-.046	-.087	.223	-.191	.109	1.000	.339	.456	.026	.000	.304	-.272	.041	.075	.159	-.141
leak/spill	.010	-.179	-.279	.308	-.088	.016	.339	1.000	.147	.039	.000	.155	-.120	.012	.051	.052	-.069
large/small load	-.076	-.111	.036	.128	-.133	.043	.456	.147	1.000	.140	.085	.406	-.333	-.014	.073	.235	-.034
overturn/no overturn	-.531	-.033	-.016	.094	-.090	-.126	.026	.039	.140	1.000	.195	.176	-.017	.004	-.116	.148	-.119
release/no release	-.090	-.230	-.405	.430	-.010	.077	.000	.000	.085	.195	1.000	.112	-.036	.042	-.065	.093	-.094
tanker/non-tanker truck	-.069	-.098	.002	.255	-.282	-.007	.304	.155	.406	.176	.112	1.000	-.034	.006	-.128	.177	-.069
truck1: straight truck/not truck1	.008	.058	.067	-.059	-.031	-.052	-.272	-.120	-.333	-.017	-.036	-.034	1.000				.119
truck2: straight truck with trailer/not truck2	-.024	.022	-.050	.073	-.069	-.031	.041	.012	-.014	.004	.042	.006		1.000			-.061
truck3: tractor with semi-trailer/not truck3	.064	.017	.005	-.113	.140	.039	.075	.051	.073	-.116	-.065	-.128			1.000		-.160
truck4: tractor with double trailers/not truck4	-.072	-.086	-.052	.159	-.102	.019	.159	.052	.235	.148	.093	.177				1.000	-.076
urban/rural	.150	.031	.049	-.080	.039	-.001	-.141	-.069	-.034	-.119	-.094	-.069	.119	-.061	-.016	-.076	1.000

Table 5.2: Spearman's Correlation Coefficients for Factors for Non-Accident Scenarios

	DG1: toxic PLG/not DG1	DG2: flammable PLG/not DG2	DG3: flammable liquid/not DG3	DG4: toxic liquid/not DG4	fire/no fire	large/small release	leak/spill	large/small load	tanker/non-tanker truck	truck1: straight truck/not truck1	truck2: straight truck with trailer/not truck2	truck3: tractor with semi-trailer/not truck3	truck4: tractor with double trailers/not truck4	urban/rural
DG1: toxic PLG/not DG1	1.000				.069	.095	-.117	-.013	.073	.085	.082	-.091	-.004	-.039
DG2: flammable PLG/not DG2		1.000			.101	.053	-.058	-.067	.016	.123	-.016	-.087	-.054	.036
DG3: flammable liquid/not DG3			1.000		.034	.111	.011	.109	.112	-.002	-.068	-.065	.155	-.056
DG4: toxic liquid/not DG4				1.000	-.110	-.180	.071	-.077	-.155	-.090	.035	.146	-.131	.060
fire/no fire	.069	.101	.034	-.110	1.000	.137	.034	.089	.085	.073	-.014	-.123	.112	-.111
large/small release	.095	.053	.111	-.180	.137	1.000	.104	.347	.344	.005	.061	-.103	.176	-.235
leak/spill	-.117	-.058	.011	.071	.034	.104	1.000	-.049	-.031	.025	-.026	-.009	-.021	-.026
large/small load	-.013	-.067	.109	-.077	.089	.347	-.049	1.000	**.683**	-.006	.041	-.138	.250	-.239
tanker/non-tanker truck	.073	.016	.112	-.155	.085	.344	-.031	**.683**	1.000	.169	.059	-.300	.260	-.262
truck1: straight truck/not truck1	.085	.123	-.002	-.090	.073	.005	.025	-.006	.169	1.000				-.013
truck2: straight truck with trailer/not truck2	.082	-.016	-.068	.035	-.014	.061	-.026	.041	.059		1.000			-.001
truck3: tractor with semi-trailer/not truck3	-.091	-.087	-.065	.146	-.123	-.103	-.009	-.138	-.300			1.000		.083
truck4: tractor with double trailers/not truck4	-.004	-.054	.155	-.131	.112	.176	-.021	.250	.260				1.000	-.140
urban/rural	-.039	.036	-.056	.060	-.111	-.235	-.026	-.239	-.262	-.013	-.001	.083	-.140	1.000

(1988) states that, for serious collinearity, the variation inflation factor, equal to $1/(1 - r^2)$, must be greater than 10. Therefore, for serious collinearity, the correlation coefficient, r, must be greater than approximately .95.

None of the correlation coefficients in Tables 5.1 and 5.2 are greater than .7, indicating that there is no serious collinearity problem with the accident or non-accident factors.

In Table 5.1, there is one pair of factors for accident scenarios with a correlation coefficient greater than .5. The factors of "collision/no collision" and "overturn/no overturn" have a correlation coefficient of -.531, indicating that accidents tend to be reported as involving collisions or overturns but not both. This corresponds with the ADS data from MTO, which indicates that only approximately 3% of truck accidents involve both collisions and overturns.

In Table 5.2, there is one pair of factors for non-accident scenarios with a correlation coefficient greater than .5. The factors of "tanker/non-tanker truck" and "large load/small load" have a correlation coefficient of .683. This correlation arises because tanker trucks tend to have large loads and non-tanker trucks tend to have small loads.

5.1.3 Significant Factors for P(release | accident)

Appendix A contains the details of the stepwise logistic regression for each dependent variable, including the significance of the tested and selected factors, the fitted logistic equation to predict the dependent variable using the selected factors, the Chi-square for the logistic equation and its significance, and the equation R^2. Table 5.3 summarises the results, showing the significant factors and the rejected factors for each dependent variable. As shown in Table 5.3, significant factors in predicting P(release | accident) include:

1. whether the accident involves an overturn of the truck or not, and
2. the type of DG load.

Table 5.3: Summary of Results of Logistic Regression

Dependent Variable	Factors Significant at the 5% Level	Rejected Factors *
P(release | accident)	overturn type of DG load	load size collision truck type urban/rural tanker truck
P(fire | accident)	collision release	urban/rural load size tanker truck type of DG load overturn truck type
P(spill | accident-induced release)	load size	type of DG load fire collision urban/rural overturn truck type tanker truck
P(large release | accident-induced release)	load size spill fire urban/rural	tanker truck collision type of DG load overturn truck type
P(fire | non-accident release)	urban/rural	type of DG load load size tanker truck truck type
P(spill | non-accident release		fire type of DG load urban/rural tanker truck truck type load size
P(large release | non-accident release)	tanker truck spill type of DG load load size urban/rural	fire truck type

* Note: Rejected factors are listed in order from last rejected to first rejected.

From the ADS database, Ontario police report that approximately 7% of general truck accidents include overturns. From the MARS database, approximately 2% of truck accidents in Washington State include overturns, for a combined mean of 5% overturns. However, the DGAIS database indicates that approximately 84% of truck accidents with DG releases include overturns. The ORIS database for Ontario indicates 58% and the MTMD database for France indicates 48% of truck accidents with DG releases involve overturns, for a combined mean of approximately 69% accident-induced DG releases with overturns. For comparison, Harwood et al. (1989) found that 41% of DG releases result from single-vehicle overturning accidents. Overturns are greatly over-represented in accident-induced DG releases, indicating that a DG release is more likely if the accident includes an overturn.

We cannot estimate P(release | accident) for trucks carrying DG loads directly from the DGAIS database, because DGAIS does not include records of all non-release accidents. DGAIS only has records of non-release accidents if the accident involved a death or injury or damage to the means of containment due to impact stress or fatigue. However, we can use Bayes' Theorem to estimate P(release) for trucks carrying DG loads and involved in accidents, by type of accident and type of DG load, as follows:

$$P(\text{release} \mid \text{overturn, type of DG load}) \tag{5.2}$$

$$= \frac{P(\text{overturn} \mid \text{release, type of DG load}) \times P(\text{release} \mid \text{type of DG load})}{P(\text{overturn} \mid \text{type of DG load})}$$

and:

$$P(\text{release} \mid \text{type of DG load}) \tag{5.3}$$

$$= \frac{P(\text{type of DG load} \mid \text{release}) \times P(\text{release})}{P(\text{type of DG load})}$$

If we assume that P(overturn) does not vary by the type of DG load, such that P(overturn | type of DG load) equals P(overturn), then we can combine the above equations as follows:

$$\begin{aligned} &P(\text{release} \mid \text{overturn, type of DG load}) \\ &= \frac{P(\text{overturn} \mid \text{release, type of DG load}) \times P(\text{type of DG load} \mid \text{release}) \times P(\text{release})}{P(\text{overturn}) \times P(\text{type of DG load})} \end{aligned} \tag{5.4}$$

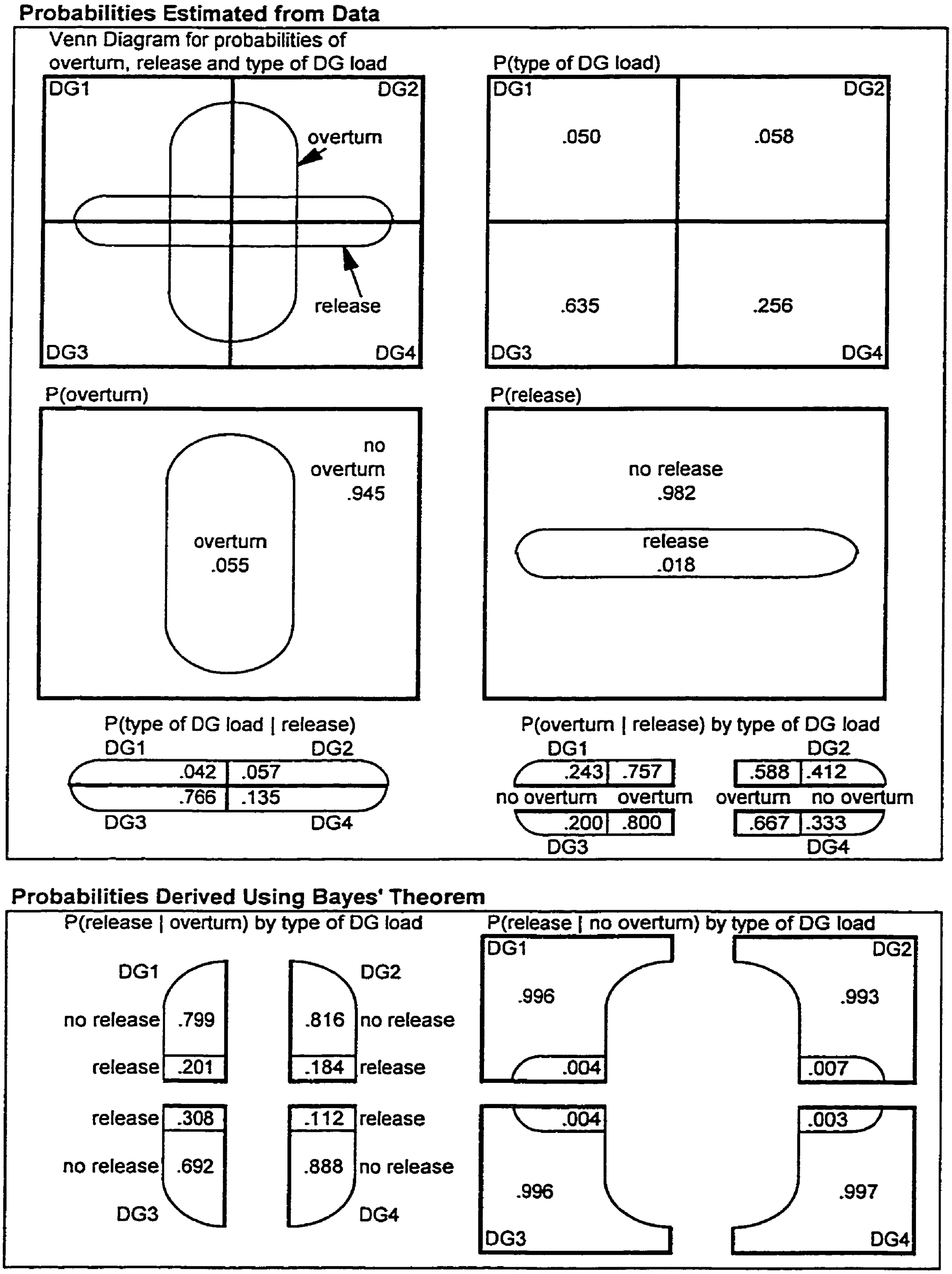
This provides the first five input variables for the accident model, as follows:

V1: P(overturn | release) by type of DG load
V2: P(type of DG load | release)
V3: P(release)
V4: P(overturn)
V5: P(type of DG load)

Figure 5.1 contains Venn diagrams which illustrate these five input variables, as well as P(release | overturn) and P(release | no overturn) by type of DG load.

The DGAIS and ORIS databases provide estimates for P(overturn | release) and P(type of DG | release) for trucks carrying DG loads and involved in accidents. We could not use the MTMD DG incident database from France as a data source for these input variables because it does not define the type of DG load. The ADS and MARS accident databases provide estimates for P(release) and P(overturn) for loaded trucks involved in accidents. Information from Transport Canada provides estimates for the P(type of DG load) for trucks carrying DG loads. Chapter 6 provides and discusses point estimates of the values of the input variables, based on the mean values of the sample data.

Figure 5.1: Venn Diagrams for Probabilities of Overturn, Release and Type of DG Load for a Truck Carrying a DG Load and Involved in an Accident



5.1.4 Significant Factors for P(fire | accident)

As shown in Table 5.3, significant factors in predicting P(fire | accident) include:

1. whether the accident involves a collision or not, and
2. whether the accident involves a release of the DG load or not.

This provides the next two input variables for the accident model, as follows:

V6: P(fire | release) by collision or not
V7: P(fire | no release) by collision or not

It is interesting that the type of DG load does not appear as a variable that is significant at the 5% level in an equation to predict P(fire | accident). This could be because the model predicts the probability of a fire starting, not the size of the fire. The probability of a fire starting could be quite similar for trucks carrying flammable or non-flammable DG loads, even though the consequences if the fire includes the DG load are drastically different.

The DGAIS and MTMD databases provide estimates for P(fire | release) and P(fire | no release) for trucks carrying DG loads and involved in accidents. We could not use the ORIS database from MOE as a source for these input variables because it contains only releases and does not indicate whether there was a fire or not.

5.1.5 Significant Factors for P(spill | accident-induced release)

As shown in Table 5.3, the significant factor in predicting P(spill | accident-induced release) is whether the load size is large or small. This provides the next input variable for the accident model, as follows:

V8: P(spill | release) by load size

The DGAIS database provides estimates for P(spill | release) for trucks carrying DG loads and involved in accidents. We could not use the ORIS and MTMD databases as data sources for this input variable because they do not define releases as spills or leaks.

5.1.6 Significant Factors for P(large release | accident-induced release)

As shown in Table 5.3, significant factors in predicting P(large release | accident-induced release) include:

1. whether the load size is large or small.
2. whether the release is a spill or leak.
3. whether there is a fire or not.
4. whether it is a rural or urban road.

However, cross-tabulation of the DGAIS accident-induced releases by release size and all four significant factors results in empty cells in the cross-tabulation. Scarcity of data limits the cross-tabulation for release size to the two most significant factors:

1. whether the load size is large or small, and
2. whether the release is a spill or leak.

This provides the final two input variables for the accident model, as follows:

V9: P(large release | spill) by load size
V10: P(large release | leak) by load size

The DGAIS database provides estimates for P(large release | spill) and P(large release | leak) for trucks carrying DG loads and involved in accidents. We could not use the ORIS and MTMD databases as data sources for these input variables because they do not define releases as spills or leaks.

5.1.7 Significant Factors for Non-Accident Release Rates

As discussed earlier, no logistic regression is undertaken for the incident rate of non-accident releases because of the data limitations. Therefore the first input variable for the non-accident model is:

V1: rate of non-accident releases per Bvkm by type of DG load

Estimates for the rate of non-accident releases per Bvkm come from a combination of information from the DGAIS database and from Transport Canada.

5.1.8 Significant Factors for P(fire | non-accident release)

As shown in Table 5.3, the significant factor in predicting P(fire | non-accident release) is whether the truck is travelling on a rural or urban road. This provides the second input variable for the non-accident model, as follows:

V2: P(fire | release) for rural or urban roads

Information for P(fire | release) comes from the DGAIS database for trucks carrying DG loads with non-accident releases. We could not use the ORIS and MTMD databases as data sources for the second input variable. The ORIS database does not include information about fires and the MTMD database does not define the roads as rural or urban.

5.1.9 Significant Factors for P(spill | non-accident release)

As shown in Table 5.3, none of the available factors were identified as significant in predicting P(spill | non-accident release). Therefore the third input variable for the non-accident model is simply:

V3: P(spill | release)

The DGAIS database provides estimates for P(spill | release) for trucks carrying DG loads with non-accident releases. We could not use the ORIS and MTMD databases as data sources for this input variable because they do not define releases as spills or leaks.

5.1.10 Significant Factors for P(large release | non-accident release)

As shown in Table 5.3, significant factors in predicting P(large release | non-accident release) include:

1. whether the truck is a tanker or non-tanker.
2. whether it is a rural or urban road.
3. whether the release is a spill or leak.
4. the type of DG load.
5. the load size.

However, cross-tabulation of the DGAIS non-accident releases by release size and all five significant factors results in empty cells in the cross-tabulation. Scarcity of data limits the cross-tabulation for release size to the following three factors:

1. whether the truck is a tanker or non-tanker.
2. whether it is a rural or urban road.
3. whether the release is a spill or leak.

This provides the final two input variables for the non-accident model, as follows:

V4: P(large release | spill) by load size
by rural or urban road and by tanker or non-tanker truck.

V5: P(large release | leak) by load size
by rural or urban road and by tanker or non-tanker truck.

The DGAIS database provides estimates for P(large release | spill) and P(large release | leak) for trucks carrying DG loads with non-accident releases. We could not use the ORIS and MTMD databases as data sources for these input variables because they do not define releases as spills or leaks.

5.1.11 Summary of Factors and Input Variables

Table 5.4 lists the ten input variables for accident scenarios. Table 5.5 lists the five input variables for the non-accident scenarios. The tables also identify the available data sources for the estimated values of the input variables and the factors for each input variable. Table 5.6 summarises the data sources and data fields used for all of the factors and input variables selected for use in the accident and non-accident models. For each data field, Table 5.6 also indicates the categorical data coding and the definition of the coding. Chapter 6 provides and discusses point estimates of the values of the input variables, based on the mean values of the sample data.

Table 5.4: List of Input Variables - Accident Scenarios

Input Variable	Selected Records	Source	Factors
V1 P(overturn | release)	trucks in transit carrying DG loads involved in accidents	DGAIS ORIS	toxic PLG flammable PLG flammable liquid toxic liquid
V2 P(type of DG load | release)	trucks in transit carrying DG loads involved in accidents	DGAIS ORIS	toxic PLG flammable PLG flammable liquid toxic liquid
V3 P(release)	loaded trucks in transit involved in accidents	ADS MARS	
V4 P(overturn)	loaded trucks in transit involved in accidents	ADS MARS	
V5 P(type of DG load)	trucks in transit carrying DG loads	Transport Canada	toxic PLG flammable PLG flammable liquid toxic liquid
V6 P(fire | release)	trucks in transit carrying DG loads involved in accidents	DGAIS MTMD	collision no collision
V7 P(fire | no release)	trucks in transit carrying DG loads involved in accidents	DGAIS MTMD	collision no collision
V8 P(spill | release)	trucks in transit carrying DG loads involved in accidents	DGAIS	large load small load
V9 P(large release | spill)	trucks in transit carrying DG loads involved in accidents	DGAIS	large load small load
V10 P(large release | leak)	trucks in transit carrying DG loads involved in accidents	DGAIS	large load small load

Table 5.5: List of Input Variables - Non-Accident Scenarios

<table>
<tr><th>Input Variable</th><th>Selected Records</th><th>Source</th><th colspan="2">Factors</th></tr>
<tr><td>V1
releases per Bvkm</td><td>non-accident releases from trucks in transit carrying DG loads</td><td>DGAIS
&
Transport Canada</td><td colspan="2">toxic gas
flammable gas
flammable liquid
toxic liquid</td></tr>
<tr><td>V2
P(fire | release)</td><td>non-accident releases from trucks in transit carrying DG loads</td><td>DGAIS</td><td colspan="2">rural
urban</td></tr>
<tr><td>V3
P(spill | release)</td><td>non-accident releases from trucks in transit carrying DG loads</td><td>DGAIS</td><td colspan="2"></td></tr>
<tr><td rowspan="2">V4
P(large release | spill)</td><td rowspan="2">non-accident releases from trucks in transit carrying DG loads</td><td rowspan="2">DGAIS</td><td>rural</td><td>tanker truck
non-tanker truck</td></tr>
<tr><td>urban</td><td>tanker truck
non-tanker truck</td></tr>
<tr><td rowspan="2">V5
P(large release | leak)</td><td rowspan="2">non-accident releases from trucks in transit carrying DG loads</td><td rowspan="2">DGAIS</td><td>rural</td><td>tanker truck
non-tanker truck</td></tr>
<tr><td>urban</td><td>tanker truck
non-tanker truck</td></tr>
</table>

Table 5.6: Summary of Data Used for Factors and Input Variables

Source	Data Field	Coding	Definition of Coding
Transport Canada DGAIS	year	88 to 95	1988 to 1995
	accident	1	accident, including overturns, collisions and running off the road
		0	non-accident, including, for example, releases due to unclosed valves or poor packaging of load
	type of DG load	1	toxic PLG: DG load is PLG which is toxic and/or corrosive and non-combustible
		2	flammable PLG: DG load is flammable PLG
		3	flammable liquid: DG load is flammable liquid
		4	toxic liquid: DG load is liquid which is toxic and/or corrosive and non-combustible
	release	1,0	release / no release of the DG load
	fire	1,0	fire and/or explosion / no fire and no explosion
	spill	1	spill: typically an immediate or continuous release, usually of a short duration
		0	leak: typically a small, sporadic release, usually of a long duration
	release size	0	small release, less than 1,000 litres
		1	large release, 1,000 litres or greater
	overturn	1,0	overturn / no overturn
	collision	1,0	collision / no collision
	truck type	1	straight truck
		2	straight truck with full trailer
		3	tractor with semi-trailer
		4	tractor with double trailers
	tanker truck	0	non-tanker truck, such as van, flat bed or dump truck
		1	tanker truck
	load size	0	small DG load, less than 15,000 litres
		1	large DG load, 15,000 litres or greater
	urban	1,0	urban / rural
MOE ORIS	year	88 to 97	1988 to 1997
	DG	1,2,3,4	variable values similar to DGAIS
	overturn	1,0	overturn / no overturn
France MTMD	year	87 to 92	1987 to 1992
	release	1,0	release / no release of the DG load
	collision	1,0	collision / no collision
	fire	1,0	fire and/or explosion / no fire and no explosion
MTO ADS	year	88 to 95	1988 to 1995
	release	1,0	release / no release of load
	overturn	1,0	overturn / no overturn
WSDOT MARS	year	90 to 96	1990 to 1996
	release	1,0	release / no release of load
	overturn	1,0	overturn / no overturn
Transport Canada	year	86 to 90	1986 to 1990
	DG	1,2,3,4	variable values similar to type of DG load for DGAIS

Records Selected from Each Data Source:

DGAIS:	trucks in transit carrying DG loads, in Canada
ORIS:	trucks in transit carrying DG loads and involved in accidents with releases, in Ontario
MTMD:	trucks in transit carrying DG loads and involved in accidents, in France
ADS:	loaded trucks in transit involved in accidents, in Ontario
MARS:	loaded trucks in transit involved in accidents, in the State of Washington
Transp Can:	maximum estimated road vehicle kilometres for trucks carrying DG loads, in Canada

5.2 DEFINITION OF SCENARIOS AND MODEL

For accident scenarios, the significant factors selected in Section 5.1 to build the model include:

- whether the accident involves an overturn or not.
- whether the accident involves a collision or not.
- the load size.
- the type of DG load.

These four factors result in 32 different accident scenarios, as shown in Table 5.7. These factors are used to update the general model equations for accident scenarios given earlier in Figure 4.4. For example, for Accident Scenario 1, the general equation from Figure 4.4 to calculate the rate of incidents with large spills and fire is:

(5.5)

rate of incidents with large spills and fire

= accident rate x P(release | accident) x P(fire | accident) x P(spill | release) x P(large release |release)

As noted earlier in Section 5.1,we do not analyse accident rates in this thesis. We assume that future users of our model will supply appropriate accident rates. Therefore our general model equation becomes:

(5.6)

P(large spill with fire | accident)

= P(release | accident) x P(fire | accident) x P(spill | release) x P(large release | release)

Table 5.7: Definition of Accident Scenarios

Scenario	Overturn	Collision	Load Size	Type of DG Load
1	overturn	collision	large load	toxic PLG
2				flammable PLG
3				flammable liquid
4				toxic liquid
5			small load	toxic PLG
6				flammable PLG
7				flammable liquid
8				toxic liquid
9		no collision	large load	toxic PLG
10				flammable PLG
11				flammable liquid
12				toxic liquid
13			small load	toxic PLG
14				flammable PLG
15				flammable liquid
16				toxic liquid
17	no overturn	collision	large load	toxic PLG
18				flammable PLG
19				flammable liquid
20				toxic liquid
21			small load	toxic PLG
22				flammable PLG
23				flammable liquid
24				toxic liquid
25		no collision	large load	toxic PLG
26				flammable PLG
27				flammable liquid
28				toxic liquid
29			small load	toxic PLG
30				flammable PLG
31				flammable liquid
32				toxic liquid

Using the significant factors identified earlier in this chapter, the model equation becomes:

$$\begin{aligned}
&P(\text{large spill with fire} \mid \text{Scenario 1 accident}) \\
&= P(\text{large spill with fire} \mid \text{truck carrying large load of DG1 with collision and overturn}) \\
&= P(\text{release} \mid \text{overturn, DG1}) \times P(\text{fire} \mid \text{release, collision}) \times P(\text{spill} \mid \text{release, large load}) \\
&\quad \times P(\text{large release} \mid \text{spill, large load})
\end{aligned} \tag{5.7}$$

Substituting Equation 5.4 for P(release | overturn, DG1) provides the model equation specific to Accident Scenario 1:

$$\begin{aligned}
&P(\text{large spill with fire} \mid \text{Scenario 1 accident}) \\
&= \frac{P(\text{overturn} \mid \text{release, DG1}) \times P(\text{DG1} \mid \text{release}) \times P(\text{release})}{P(\text{overturn}) \times P(\text{DG1})} \\
&\times P(\text{fire} \mid \text{release, collision}) \times P(\text{spill} \mid \text{release, large load}) \times P(\text{large release} \mid \text{spill, large load})
\end{aligned} \tag{5.8}$$

For non-accident scenarios, the significant factors selected in Section 5.1 to build the model include:

- whether the road is rural or urban.
- whether the truck is a tanker or non-tanker.
- the type of DG load.

These three factors result in 16 different non-accident scenarios, as shown in Table 5.8. These factors are used to update the general model equations for non-accident scenarios given earlier in Figure 4.4. For example, for Non-Accident Scenario 33, the general equation from Figure 4.4 to calculate the rate of incidents with large spills and fire is:

(5.9)

rate of incidents with large spills and fire

= release rate x P(fire | release) x P(spill | release) x P(large release |release)

Using the significant factors identified earlier in this chapter, the model equation specific to Non-Accident Scenario 33 becomes:

(5.10)

rate of incidents with large spills and fire for Non-Accident Scenario 33

= rate of incidents with large spills and fire for tanker trucks carrying DG1 on rural roads

= (releases per Bvkm | DG1) x P(fire | release, rural road)

x P(spill | release) x P(large release | spill, rural road, tanker truck)

The 32 accident scenarios and 16 non-accident scenarios make up a total of 48 scenarios. These 48 accident and non-accident scenarios, combined with the model equations, make up our probabilistic model. We can use the model to determine the expected release and fire incident rates for trucks in transit carrying DG loads, for each scenario. The values of the input variables for the model equations vary by scenario.

Table 5.8: Definition of Non-Accident Scenarios

Scenario	Urban/Rural	Tanker Truck	Type of DG Load
33	rural	tanker truck	toxic PLG
34			flammable PLG
35			flammable liquid
36			toxic liquid
37		non-tanker truck	toxic PLG
38			flammable PLG
39			flammable liquid
40			toxic liquid
41	urban	tanker truck	toxic PLG
42			flammable PLG
43			flammable liquid
44			toxic liquid
45		non-tanker truck	toxic PLG
46			flammable PLG
47			flammable liquid
48			toxic liquid

CHAPTER 6

POINT ESTIMATES OF INPUT AND OUTPUT VALUES

Chapter 6 contains the following sections:

6.1 Point Estimates of Input Variables
6.2 Point Estimates of Output Variables

Chapter 6 provides point estimates for the input variables, based on the mean values of the sample data. This chapter also provides point estimates of the output values that arise if we use the point estimates for the input variables in the model and ignore uncertainty. The model output includes point estimates of outcome probabilities for accident scenarios and incidents per Bvkm for non-accident scenarios.

6.1 POINT ESTIMATES OF INPUT VARIABLES

We examine point estimates of the input variables, not because we recommend using these values in predicting release and fire incident rates, but to illustrate the structure of the model. As discussed later in Chapters 8 and 9, we prefer to use probability distributions rather than point estimates in describing the expected values of the input and output variables because the distributions take into account all of the information available, including the data and the assumed shapes of the distributions.

Appendix B contains the sample data from the different sources (DGAIS, ORIS, etc.) and the calculated mean values of the sample data for the input variables, for the accident and non-accident scenarios. The mean values of the sample data are taken as point estimates of the input variables.

Appendix B shows the number of incidents, including the number of incidents by time interval from each data source and the overall total. The number of incidents fluctuate by time interval, resulting in a range of possible values for each input variable. The uncertainty associated with the range of values for each input variable is further discussed in Chapter 8. For the point estimates, we consider only the overall total number of incidents.

The input variables may have one or two sources of data. For example, Variable 8: P(spill | release) has one source of data, Transport Canada's DGAIS. We calculate the mean value of P(spill | release) for a truck carrying a small load and involved in an accident as follows:

$$\begin{aligned} &\text{mean for } P(\text{spill} \mid \text{release}) \\ &= (\text{number of spills}) / (\text{number of releases}) \\ &= 127 / 164 \\ &= .774 \end{aligned} \tag{6.1}$$

Where there are two sources of data, we combine the two data sources with the assumption that both sources of data provide estimates of the same value. This assumption is discussed further in Chapter 8. The estimates of the value may vary between sources because of differences in the methods of reporting and recording incidents, fluctuations in the number of incidents from year to year, or other sources of uncertainty.

For example, we can consider V1: P(overturn | release) for a truck carrying toxic PLG and involved in an accident. V1: P(overturn | release) has two sources of data, DGAIS from Transport Canada and ORIS from the Ontario MOE. DGAIS has 28 observations of accidents with releases of toxic PLG and ORIS has 9. We calculate the mean value of P(overturn | release) for a truck carrying toxic PLG and involved in an accident as follows:

$$
\begin{aligned}
&\text{mean for P(overturn | release)} \\
&= \text{(total overturns from both sources) / (total releases from both sources)} \\
&= (24 + 4) / (28 + 9) \\
&= .757
\end{aligned}
\tag{6.2}
$$

This method of calculating the mean favours the data source with more observations. The sections below summarise and discuss the mean values of the sample data as point estimates of the input variables.

6.1.1 Point Estimates of Input Variables for Accident Scenarios

As described earlier in Table 5.4, there are ten input variables for each accident scenario, Accident V1 to V10. The first five variables combine to give P(release | accident).

Table 6.1 summarises the point estimates for Accident V1: P(overturn | release) by type of DG load.

Table 6.1 Accident V1: P(overturn | release)

Type of DG Load	Overturn	No Overturn
DG1: toxic PLG	.757	.243
DG2: flammable PLG	.588	.412
DG3: flammable liquid	.800	.200
DG4: toxic liquid	.667	.333

Most accident-induced releases are associated with overturns, especially for trucks carrying flammable liquids. We can infer either that an overturn indicates a more serious accident which is more likely to result in a release, or that overturns cause releases. For a tanker truck, the hatch or dome may not be well designed to prevent a release when the vehicle is on its side or upside down. In addition, there may be more chance of a puncture, overpressurisation, or a crease causing failure of the tanker liner if the vehicle overturns. From DGAIS, most releases associated with tanker overturns are from the dome or hatch or from damage to the containment liner. For a non-tanker truck, the containers (cylinders, drums, etc.) may have more chance of damage if the truck overturns. From DGAIS, most releases associated with non-tanker overturns are from damage to the packages containing the DG.

Table 6.2 summarises the point estimates for Accident V2: P(type of DG load | release). The most common type of DG given an accident-induced release is DG3: flammable liquid (77%), followed by DG4: toxic and/or corrosive liquid (14%). For comparison, Harwood et al. (1989) found that DG releases resulting from traffic accidents were 71% flammable liquids and 13% corrosive materials. These proportions are to be expected, since these are the most common types of DG loads on the highways. From DGAIS, the most common types of flammable liquids in DG incidents are gasoline, fuel oil and petroleum crude oil.

Table 6.2 Accident V2: P(type of DG load | release)

DG1: toxic PLG	.042
DG2: flammable PLG	.057
DG3: flammable liquid	.766
DG4: toxic liquid	.135
Total	1.000

The point estimate for Accident V3: P(release) is .018 and for Accident V4: P(overturn) is .055. Table 6.3 summarises the point estimates for Accident V5: P(type of DG load). The most common type of DG load on the highways is DG3: flammable liquid, followed by DG4: toxic liquid.

Table 6.3 Accident V5: P(type of DG load)

DG1: toxic PLG	.050
DG2: flammable PLG	.058
DG3: flammable liquid	.635
DG4: toxic liquid	.256
Total	1.000

Figure 6.1 contains a bar chart of the point estimates of Accident Variables 1 to 5. In Figure 6.1, V2: P(type of DG load | release) and V5: P(type of DG load) are juxtaposed to show that there is a higher probability of DG3: flammable liquid in accident-induced releases than in DG trucks travelling on the highways in general. This indicates that if a truck carrying flammable liquid is involved in an accident, it is more likely to have a release than trucks carrying other types of DG loads.

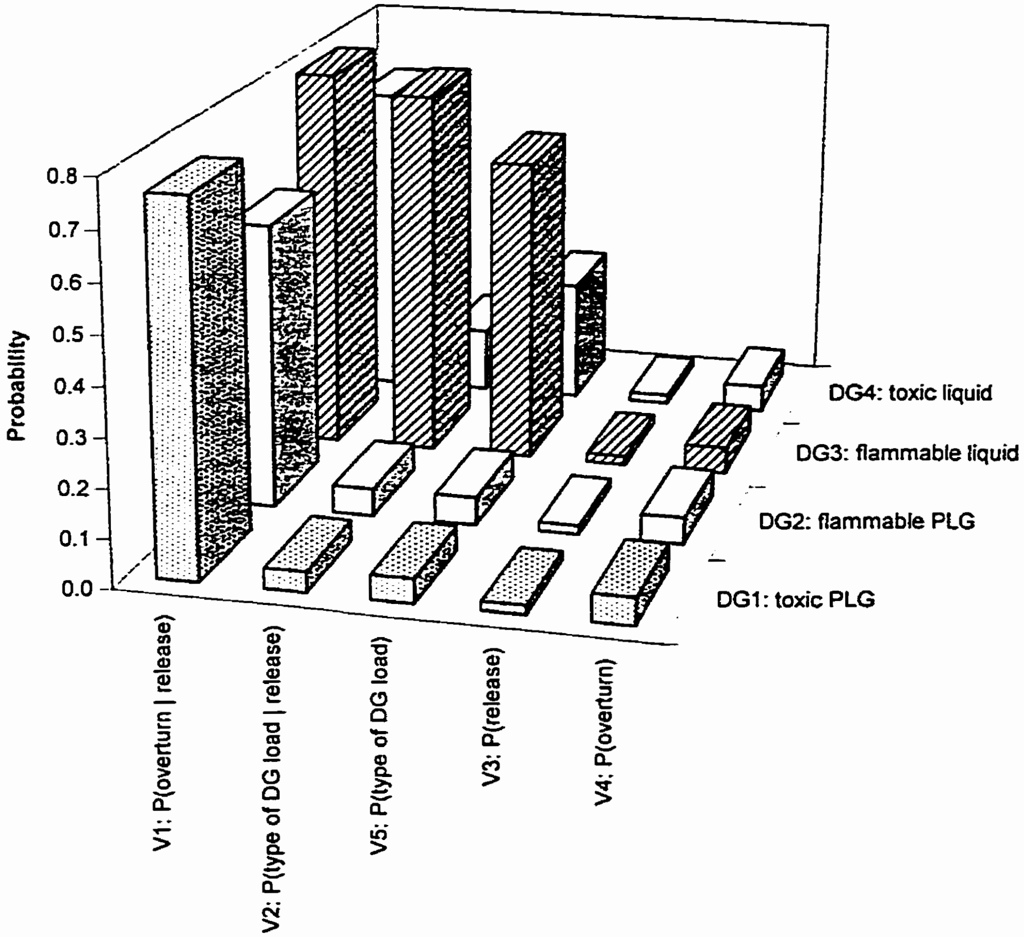
Table 6.4 summarises P(release | accident) by accident type and type of DG load. The equations from Section 5.1.3 combine the point estimates for Accident Variables 1 to 5 to produce P(release | accident). Table 6.4 shows that approximately 11% to 31% of overturns also have releases, compared with less than 1% of non-overturn accidents. For DG3: flammable liquid, the proportion of overturn accidents that have releases is higher than for the other types of DG loads. For DG4: toxic liquid, the proportion of overturn accidents with releases is less than for the other types of DG loads.

Table 6.4: P(release | accident)

	Type of DG Load	Release	No Release
Overturn	DG1: toxic PLG	.201	.799
	DG2: flammable PLG	.184	.816
	DG3: flammable liquid	.308	.692
	DG4: toxic liquid	.112	.888
No Overturn	DG1: toxic PLG	.004	.996
	DG2: flammable PLG	.007	.993
	DG3: flammable liquid	.004	.996
	DG4: toxic liquid	.003	.997

Saccomanno, Yu and Shortreed (1993) provide average values for the probability of a release given an accident of .025, .05 and .18 for tanker trucks carrying chlorine (DG1), liquefied petroleum gas (DG2) and gasoline (DG3) respectively. Harwood et al. (1989) estimate the probability of release for a truck carrying a DG load is .13 to .15 for all accidents, .08 if the truck is carrying gases in bulk, .19 if the truck is carrying liquids in bulk, and .38 if the truck overturns. These estimates support the above findings that accidents with overturns are more likely to have releases, especially if the truck is carrying flammable liquids.

Figure 6.1: Bar Chart of Input Variable Values Used to Calculate P(release | accident)



Compared with other types of DG loads, DG3: flammable liquid is more likely to be carried in tanker trucks while DG4: toxic liquid is more likely to be carried in non-tanker trucks (for example, in drums or pails). Tanker trucks carrying flammable liquids such as gasoline or fuel oil are typically "thin-walled" tankers, while PLG are carried in "thick-walled" tankers. A thick-walled tanker may have a tank within a tank, to control pressure and temperature, and so have a stronger construction. Trucks that carry propane are made of heavier material than trucks that carry gasoline. In addition, in a tanker truck carrying DG3: flammable liquid, the hatch or dome is the weakest point of the containment system. The hatch seals, but also has a vent that can leak if the truck is on its side. On the other hand, with a pressurised tank the valves function no matter which side is up. Therefore the thin-walled trucks are more likely to suffer a puncture or crease of the liner if the truck overturns, and more likely to leak or spill from the hatch.

Table 6.5 summarises the point estimates for Accident V6: P(fire | release) and V7: P(fire | no release) by type of accident.

Table 6.5: Accident V6 and V7: P(fire)

		Fire	**No Fire**
Release	**Collision**	.165	.835
	No Collision	.066	.934
No Release	**Collision**	.027	.973
	No Collision	.009	.991

Table 6.5 indicates that P(fire) is over 15 times greater if the accident includes a collision and a release, compared with an accident with neither a collision nor a release. A collision may contribute to a fire starting in several ways. If the collision damages the electrical system of the truck and the truck battery is still connected, sparks from the electrical system may start a fire. The diesel fuel carried in the truck fuel tank does not readily catch fire. However, if a truck collides with a car, the gasoline from the car may catch fire and the fire may spread to the truck. Some types of flammable DG loads can explode or catch fire if they are exposed to the air, depending on the flashpoint of the product. A combination of products may be explosive if mixed because of simultaneous releases.

The fact that a fire is more likely with a release may indicate a more severe accident, which is more likely to have a fire. On the other hand, the fact that there is a fire may make it more likely that a release of the DG load will occur. The data do not tell us which comes first, the release or the fire.

Table 6.6 summarises the point estimates for Accident V8: P(spill | release) by load size. An accident-induced release is more likely to be a spill rather than a leak if the truck is carrying a large load compared with a small load. It is to be expected that a large load is more likely to have a large release, because a large load has more to release. By definition, a large release is more likely to be a spill.

Table 6.6: Accident V8: P(spill | release)

Load Size	Spill	Leak
large load	.888	.112
small load	.774	.226

Table 6.7 summarises the point estimates for Accident V9: P(large release | spill) and Accident V10: P(large release | leak). The probability that an accident-induced release will be large rather than small is much greater if there is a spill from a large load, compared with a leak from a small load. Again, it is to be expected that a large load is more likely to have a large release, which by definition is more likely to be a spill.

Table 6.7: Accident V9 and V10: P(large release | release)

		Large Release	Small Release
Large Load	**Spill**	.880	.120
	Leak	.533	.467
Small Load	**Spill**	.449	.551
	Leak	.162	.838

Figure 6.2 contains bar charts of the point estimates for P(release | accident) and the remaining input variables for the accident scenarios. By scanning the tallest bars in these charts, we can see that a truck carrying a large load of DG3: flammable liquid and involved in an accident with an overturn and a collision is more likely to have a large spill with a fire than other accident scenarios.

Table 6.8 contains a summary of the point estimates of all of the input variables for each of the 32 accident scenarios. These combinations of input values will be used to calculate the point estimates of accident outcome probabilities.

6.1.2 Point Estimates of Input Variables for Non-Accident Scenarios

Table 6.9 summarises the point estimates for Non-Accident V1: Releases per Bvkm. For non-accident incidents, flammable DG have a lower release rate than toxic and/or corrosive (non-flammable) DG by a factor of about three.

Table 6.9: Non-Accident V1: Releases per Bvkm

Type of DG Load	Release Rate
DG1: toxic PLG	11.07
DG2: flammable PLG	4.03
DG3: flammable liquid	4.57
DG4: toxic liquid	13.94

To put these release rates in perspective, a single truck travelling 500 km every day for a year would travel approximately 182,500 vehicle-km. A fleet of 5,500 trucks travelling 500 km every day for a year would travel approximately 1 Bvkm. If every truck in this very large fleet were carrying a DG load, we would expect the fleet to experience between 4 and 14 non-accident releases per year.

Figure 6.2: Bar Charts of Input Variable Values for Accident Scenarios

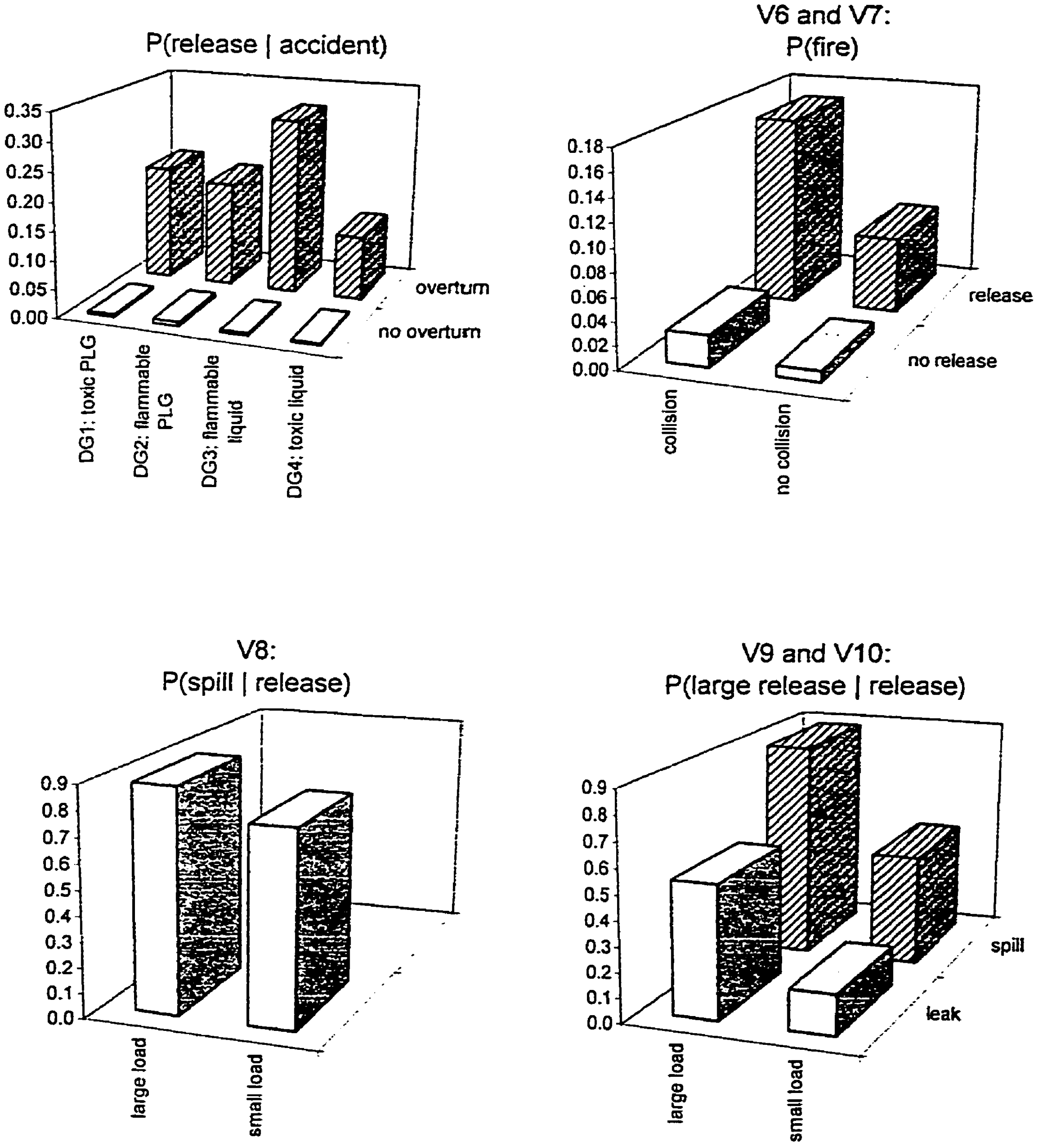


Table 6.8: Point Estimates of Input Variables by Accident Scenario

Scenario	Overturn	Collision	Large Load	Type of DG Load *	V1: P(overturn|release) or P(no overturn|release)	V2: P(type of DG | release)	V3: P(release)	V4: P(overturn) or P(no overturn)	V5: P(type of DG load)	V6: P(fire | release)	V7: P(fire | no release)	V8: P(spill | release)	V9: P(large release | spill)	V10: P(large release | leak)
1	y	y	y	1	.757	.042	.018	.055	.050	.165	.027	.888	.880	.533
2	y	y	y	2	.588	.057	.018	.055	.058	.165	.027	.888	.880	.533
3	y	y	y	3	.800	.766	.018	.055	.635	.165	.027	.888	.880	.533
4	y	y	y	4	.667	.135	.018	.055	.256	.165	.027	.888	.880	.533
5	y	y	n	1	.757	.042	.018	.055	.050	.165	.027	.774	.449	.162
6	y	y	n	2	.588	.057	.018	.055	.058	.165	.027	.774	.449	.162
7	y	y	n	3	.800	.766	.018	.055	.635	.165	.027	.774	.449	.162
8	y	y	n	4	.667	.135	.018	.055	.256	.165	.027	.774	.449	.162
9	y	n	y	1	.757	.042	.018	.055	.050	.066	.009	.888	.880	.533
10	y	n	y	2	.588	.057	.018	.055	.058	.066	.009	.888	.880	.533
11	y	n	y	3	.800	.766	.018	.055	.635	.066	.009	.888	.880	.533
12	y	n	y	4	.667	.135	.018	.055	.256	.066	.009	.888	.880	.533
13	y	n	n	1	.757	.042	.018	.055	.050	.066	.009	.774	.449	.162
14	y	n	n	2	.588	.057	.018	.055	.058	.066	.009	.774	.449	.162
15	y	n	n	3	.800	.766	.018	.055	.635	.066	.009	.774	.449	.162
16	y	n	n	4	.667	.135	.018	.055	.256	.066	.009	.774	.449	.162
17	n	y	y	1	.243	.042	.018	.945	.050	.165	.027	.888	.880	.533
18	n	y	y	2	.412	.057	.018	.945	.058	.165	.027	.888	.880	.533
19	n	y	y	3	.200	.766	.018	.945	.635	.165	.027	.888	.880	.533
20	n	y	y	4	.333	.135	.018	.945	.256	.165	.027	.888	.880	.533
21	n	y	n	1	.243	.042	.018	.945	.050	.165	.027	.774	.449	.162
22	n	y	n	2	.412	.057	.018	.945	.058	.165	.027	.774	.449	.162
23	n	y	n	3	.200	.766	.018	.945	.635	.165	.027	.774	.449	.162
24	n	y	n	4	.333	.135	.018	.945	.256	.165	.027	.774	.449	.162
25	n	n	y	1	.243	.042	.018	.945	.050	.066	.009	.888	.880	.533
26	n	n	y	2	.412	.057	.018	.945	.058	.066	.009	.888	.880	.533
27	n	n	y	3	.200	.766	.018	.945	.635	.066	.009	.888	.880	.533
28	n	n	y	4	.333	.135	.018	.945	.256	.066	.009	.888	.880	.533
29	n	n	n	1	.243	.042	.018	.945	.050	.066	.009	.774	.449	.162
30	n	n	n	2	.412	.057	.018	.945	.058	.066	.009	.774	.449	.162
31	n	n	n	3	.200	.766	.018	.945	.635	.066	.009	.774	.449	.162
32	n	n	n	4	.333	.135	.018	.945	.256	.066	.009	.774	.449	.162

* Type of DG Load
1 = toxic PLG
2 = flammable PLG
3 = flammable liquid
4 = toxic liquid

Table 6.10 summarises the point estimates for Non-Accident V2: P(fire | release).

Table 6.10: Non-Accident V2: P(fire | release)

	Fire	No Fire
Rural	.066	.934
Urban	.022	.978

For non-accident releases, the probability of fire is approximately three times higher in rural incidents than in urban incidents. Non-accident releases include releases that occur, for example, if a hatch or valve is not properly closed, if a weld fails due to corrosion, if a package falls off the truck, or if a fire starts from a brake or tire overheating during transport. It may be that rural roads are rougher than urban roads, and trucks generally travel faster on rural roads because of higher speed limits compared to urban areas. Higher rural speeds and rougher roads may cause more vibration of the vehicle. More vibration may cause a part of the truck that is about to fail or a load that is about to shift to do so. In addition, trucks travelling on rural roads may be on longer trips than trucks in urban areas, so that the vehicle travels farther between driver checks. On a rural road, the driver may not notice that a release is occurring or that a fire is about to start.

The point estimate for Non-Accident V3: P(spill | release) is 0.51. Table 6.11 summarises Non-Accident V4: P(large release | spill) and V5: P(large release | leak). A non-accident release is over 30 times more likely to be large rather than small if it is a spill from a tanker truck on a rural road, compared with a leak from a non-tanker truck on an urban road.

Table 6.11: Non-Accident V4 and V5: P(large release | release)

			Large Release	Small Release
Tanker Truck	**Rural**	**Spill**	.439	.561
		Leak	.222	.778
	Urban	**Spill**	.225	.775
		Leak	.100	.900
Non-Tanker Truck	**Rural**	**Spill**	.107	.893
		Leak	.024	.976
	Urban	**Spill**	.014	.986
		Leak	.014	.986

From DGAIS, the most common location of a non-accident release from a tanker truck is from a valve and from a non-tanker truck is from the package material. Tankers can carry a large quantity in one container. If a spill or leak begins, it is possible to lose the entire load. On the other hand, if the DG load is carried in cylinders or drums, one package may leak or spill while the others remain intact. Therefore, the release is more likely to be large with a tanker truck than a non-tanker truck. By definition, a spill is more likely to be large than a leak. A release is more likely to be large on rural roads. As discussed above, there may be more vibration due to road roughness and vehicle speed on rural roads, and the driver may travel farther between vehicle checks. A non-accident release on an rural road may go unnoticed while the vehicle travels some distance, allowing more of the DG load to escape.

Figure 6.3 contains bar charts of the point estimates for the five input variables for the non-accident scenarios. By scanning the tallest bars in these charts, we can see that a tanker truck carrying DG4: toxic liquid on a rural road is expected to have more large spills with fire per Bvkm than other non-accident scenarios.

Table 6.12 contains a summary of the point estimates of all of the input variables for each of the 16 non-accident scenarios. These combinations of input values will be used to calculate point estimates of non-accident incident rates per Bvkm.

Figure 6.3: Bar Charts of Input Variable Values for Non-Accident Scenarios

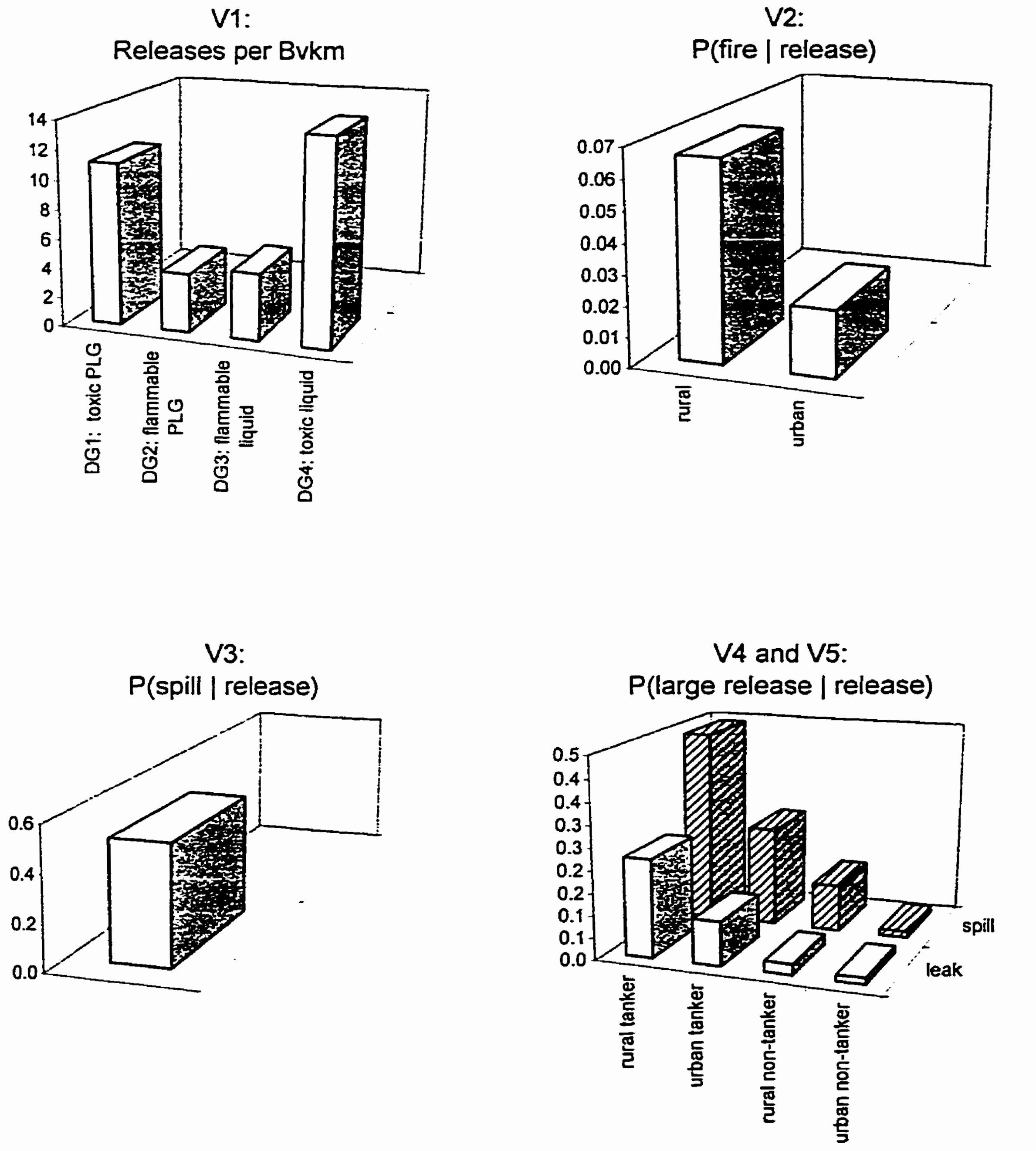


Table 6.12: Point Estimates of Input Variables by Non-Accident Scenario

Scenario	Urban / Rural	Tanker Truck	Type of DG Load	V1: Releases per Bvkm	V2: P(fire | release)	V3: P(spill | release)	V4: P(large release | spill)	V5: P(large release | leak)
33	rural	y	toxic PLG	11.07	.066	.512	.439	.222
34	rural	y	flammable PLG	4.03	.066	.512	.439	.222
35	rural	y	flammable liquid	4.57	.066	.512	.439	.222
36	rural	y	toxic liquid	13.94	.066	.512	.439	.222
37	rural	n	toxic PLG	11.07	.066	.512	.107	.024
38	rural	n	flammable PLG	4.03	.066	.512	.107	.024
39	rural	n	flammable liquid	4.57	.066	.512	.107	.024
40	rural	n	toxic liquid	13.94	.066	.512	.107	.024
41	urban	y	toxic PLG	11.07	.022	.512	.225	.100
42	urban	y	flammable PLG	4.03	.022	.512	.225	.100
43	urban	y	flammable liquid	4.57	.022	.512	.225	.100
44	urban	y	toxic liquid	13.94	.022	.512	.225	.100
45	urban	n	toxic PLG	11.07	.022	.512	.014	.014
46	urban	n	flammable PLG	4.03	.022	.512	.014	.014
47	urban	n	flammable liquid	4.57	.022	.512	.014	.014
48	urban	n	toxic liquid	13.94	.022	.512	.014	.014

6.2 POINT ESTIMATES OF OUTPUT VARIABLES

We calculate point estimates of the output variables by using the point estimates for the input variables in the accident and non-accident models. We do not recommend this method of estimating values for the output variables. The calculations are shown here to illustrate the application of the model equations, and to allow a comparison later in Chapter 9 of the point estimates for the output variables with the mean values of the probability distributions for the output variables that result from the Monte Carlo process.

Table 6.13 contains point estimates of outcome probabilities for each accident scenario. Table 6.14 contains the point estimates of the expected incidents per Bvkm for each non-accident scenario. Tables 6.13 and 6.14 provide sufficient decimal places for each value to allow a visual comparison between the largest and the smallest values.

Table 6.13: Point Estimates of Outcome Probabilities by Accident Scenario

Scenario	Overturn	Collision	Large Load	Type of DG Load *	Probability of Accident Outcome										
					release								no release		total
					fire				no fire				fire	no fire	
					spill		leak		spill		leak				
					large	small	large	small	large	small	large	small			
1	y	y	y	1	.02591	.00354	.00197	.00173	.13104	.01789	.00998	.00874	.02137	.77783	1.00
2	y	y	y	2	.02381	.00325	.00181	.00159	.12038	.01643	.00917	.00803	.02181	.79373	1.00
3	y	y	y	3	.03981	.00543	.00303	.00265	.20130	.02748	.01534	.01342	.01849	.67304	1.00
4	y	y	y	4	.01451	.00198	.00111	.00097	.07338	.01002	.00559	.00489	.02373	.86382	1.00
5	y	y	n	1	.01152	.01415	.00121	.00627	.05827	.07156	.00613	.03169	.02137	.77783	1.00
6	y	y	n	2	.01059	.01300	.00111	.00576	.05353	.06573	.00563	.02911	.02181	.79373	1.00
7	y	y	n	3	.01770	.02174	.00186	.00963	.08951	.10993	.00942	.04868	.01849	.67304	1.00
8	y	y	n	4	.00645	.00792	.00068	.00351	.03263	.04007	.00343	.01775	.02373	.86382	1.00
9	y	n	y	1	.01034	.00141	.00079	.00069	.14662	.02001	.01117	.00977	.00722	.79198	1.00
10	y	n	y	2	.00949	.00130	.00072	.00063	.13469	.01839	.01026	.00898	.00737	.80817	1.00
11	y	n	y	3	.01588	.00217	.00121	.00106	.22523	.03075	.01716	.01502	.00625	.68528	1.00
12	y	n	y	4	.00579	.00079	.00044	.00039	.08210	.01121	.00626	.00547	.00802	.87954	1.00
13	y	n	n	1	.00460	.00564	.00048	.00250	.06519	.08006	.00686	.03546	.00722	.79198	1.00
14	y	n	n	2	.00422	.00518	.00044	.00230	.05989	.07355	.00630	.03257	.00737	.80817	1.00
15	y	n	n	3	.00706	.00867	.00074	.00384	.10015	.12299	.01054	.05447	.00625	.68528	1.00
16	y	n	n	4	.00257	.00316	.00027	.00140	.03651	.04483	.00384	.01986	.00802	.87954	1.00
17	n	y	y	1	.00048	.00007	.00004	.00003	.00244	.00033	.00019	.00016	.02664	.96962	1.00
18	n	y	y	2	.00097	.00013	.00007	.00006	.00489	.00067	.00037	.00033	.02654	.96597	1.00
19	n	y	y	3	.00058	.00008	.00004	.00004	.00292	.00040	.00022	.00019	.02662	.96891	1.00
20	n	y	y	4	.00042	.00006	.00003	.00003	.00213	.00029	.00016	.00014	.02665	.97009	1.00
21	n	y	n	1	.00021	.00026	.00002	.00012	.00109	.00134	.00011	.00059	.02664	.96962	1.00
22	n	y	n	2	.00043	.00053	.00005	.00023	.00217	.00267	.00023	.00118	.02654	.96597	1.00
23	n	y	n	3	.00026	.00031	.00003	.00014	.00130	.00159	.00014	.00071	.02662	.96891	1.00
24	n	y	n	4	.00019	.00023	.00002	.00010	.00095	.00116	.00010	.00052	.02665	.97009	1.00
25	n	n	y	1	.00019	.00003	.00001	.00001	.00274	.00037	.00021	.00018	.00900	.98725	1.00
26	n	n	y	2	.00039	.00005	.00003	.00003	.00547	.00075	.00042	.00036	.00897	.98354	1.00
27	n	n	y	3	.00023	.00003	.00002	.00002	.00326	.00045	.00025	.00022	.00900	.98654	1.00
28	n	n	y	4	.00017	.00002	.00001	.00001	.00238	.00033	.00018	.00016	.00901	.98773	1.00
29	n	n	n	1	.00009	.00011	.00001	.00005	.00122	.00149	.00013	.00066	.00900	.98725	1.00
30	n	n	n	2	.00017	.00021	.00002	.00009	.00243	.00299	.00026	.00132	.00897	.98354	1.00
31	n	n	n	3	.00010	.00013	.00001	.00006	.00145	.00178	.00015	.00079	.00900	.98654	1.00
32	n	n	n	4	.00007	.00009	.00001	.00004	.00106	.00130	.00011	.00058	.00901	.98773	1.00

* Type of DG Load
1 = toxic PLG
2 = flammable PLG
3 = flammable liquid
4 = toxic liquid

Table 6.14: Point Estimates of Incidents per Bvkm by Non-Accident Scenario

Scenario	Urban / Rural	Tanker Truck	Type of DG Load *	Incidents per Bvkm								
				fire				no fire				total
				spill		leak		spill		leak		
				large	small	large	small	large	small	large	small	
33	r	y	1	.163	.208	.079	.276	2.325	2.971	1.123	3.930	11.07
34	r	y	2	.059	.076	.029	.100	.845	1.080	.408	1.429	4.03
35	r	y	3	.067	.086	.033	.114	.960	1.226	.464	1.623	4.57
36	r	y	4	.205	.262	.099	.347	2.926	3.739	1.413	4.946	13.94
37	r	n	1	.040	.332	.009	.346	.567	4.728	.123	4.930	11.07
38	r	n	2	.014	.121	.003	.126	.206	1.719	.045	1.793	4.03
39	r	n	3	.016	.137	.004	.143	.234	1.952	.051	2.035	4.57
40	r	n	4	.050	.418	.011	.435	.714	5.951	.155	6.204	13.94
41	u	y	1	.027	.094	.012	.105	1.248	4.297	.529	4.762	11.07
42	u	y	2	.010	.034	.004	.038	.454	1.563	.192	1.732	4.03
43	u	y	3	.011	.039	.005	.043	.515	1.774	.218	1.966	4.57
44	u	y	4	.035	.119	.015	.132	1.570	5.409	.666	5.994	13.94
45	u	n	1	.002	.120	.002	.115	.075	5.470	.073	5.218	11.07
46	u	n	2	.001	.044	.001	.042	.027	1.989	.027	1.898	4.03
47	u	n	3	.001	.050	.001	.047	.031	2.258	.030	2.154	4.57
48	u	n	4	.002	.151	.002	.144	.095	6.884	.092	6.568	13.94

- Type of DG Load
  1 = toxic PLG
  2 = flammable PLG
  3 = flammable liquid
  4 = toxic liquid

The estimates in Tables 6.13 are calculated using the model equations specific to each scenario. For example, the model equation to calculate P(release | accident) for Accident Scenario 1 (truck carrying a large load of DG1: toxic PLG and involved in an accident with an overturn and collision) is as follows:

$$\text{P(large spill with fire} \mid \text{Scenario 1 accident)} \tag{6.3}$$

$$= \frac{\text{P(overturn} \mid \text{release, DG1)} \times \text{P(DG1} \mid \text{release)} \times \text{P(release)}}{\text{P(overturn)} \times \text{P(DG1)}}$$

$$\times \text{ P(fire} \mid \text{release, collision)} \times \text{P(spill} \mid \text{release, large load)} \times \text{P(large release} \mid \text{spill, large load)}$$

$$= \frac{.757 \times .042 \times .018}{.055 \times .050} \times .165 \times .888 \times .880$$

$$= .026$$

The model equation to calculate, for example, the rate of incidents with large spills and fire for Non-Accident Scenario 33 (tanker truck carrying DG1: toxic PLG on a rural road) is:

$$\text{rate of incidents with large spills and fire for Non-Accident Scenario 33} \tag{6.4}$$

$$= \text{(releases per Bvkm} \mid \text{DG1)} \times \text{P(fire} \mid \text{release, rural road)}$$
$$\times \text{ P(spill} \mid \text{release)} \times \text{P(large release} \mid \text{spill, rural road, tanker truck)}$$

$$= 11.07 \times .066 \times .512 \times .439$$

$$= .163 \text{ large spills with fire per Bvkm}$$

Characteristics of accident outcome probabilities and non-accident incident rates are discussed later in this thesis, in Section 9.2.3.

CHAPTER 7

COMPARISON OF MODEL OUTPUT TO DATA

Chapter 7 contains the following sections:

7.1 Comparison of Model Output to Data for Accident Scenarios
7.2 Comparison of Model Output to Data for Non-Accident Scenarios
7.3 Conclusions Regarding Model

Chapter 7 compares point estimates from the model for accident and non-accident scenarios to DGAIS release data.

7.1 Comparison of Model Output to Data for Accident Scenarios

Our model to predict release and fire incident rates for trucks carrying DG loads consists of the model equations, the accident and non-accident scenarios, and the values of the input variables. The model equations calculate the release and fire incident rates from the input variables. Figure 4.4 and Section 5.1.3 provide the general model equations. The scenarios result from the combinations of significant factors that affect the values of the input variables. Tables 6.8 and 6.12 provide point estimates of the input variables for the model for each accident and non-accident scenario.

In comparing the model output for accident scenarios directly to release data, we can only compare the part of the model that predicts outcomes once a release has occurred. The other part of the model that calculates P(release | accident) uses a combination of data from both accident and DG incident databases, and is not directly comparable to either set of data.

The part of the model that predicts outcomes given an accident-induced release uses the factors of collision and load size. Table 7.1 shows the number of Canadian DG incidents recorded in DGAIS for the resulting accident scenarios, from 1988 to 1995.

Even with data from eight years, Table 7.1 contains several empty cells for fire incidents for different types of releases. These empty cells are why we use combinations of input variables to estimate the probability of accident outcomes rather than simply cross-tabulating the data. For example, we have no records of a truck carrying a large load and involved in a collision resulting in a small leak with a fire. However, we believe that the probability of this type of incident is greater than 0. The model provides an estimate of that probability. The probabilities of all possible outcomes sum to 1. Where the model provides a probability for an unobserved outcome, then the probabilities of the other outcomes are reduced accordingly.

Table 7.1 indicates that the majority of accident-induced releases are from trucks carrying large DG loads and involved in accidents without collisions (315 out of 567 incidents, or 56%). This agrees with our earlier findings, that releases are more likely to be related to overturns than collisions. For accident release scenarios, the most likely outcome is a spill or leak with no fire (508 out of 567 incidents, or 90%). Accident-induced releases from trucks with large loads are most likely to be large (339 out of 403 incidents, or 84%). Accident-induced releases from trucks with small loads are most likely to be small (101 out of 164 incidents, or 62%). Accident-induced fires with releases are most likely to be large spills (47 out of 59 incidents, or 80%).

Table 7.2 provides a comparison of the DGAIS release data with the model output by accident scenario. Figure 7.1 provides the same information in graphical form. For example, we can look at the first accident scenario, a truck carrying a large DG load and involved in an accident with a collision and a release. Directly from the DGAIS data, P(large spill with fire | accident-induced release) is 17/88, or .193. On the other hand, the model output is calculated using the point estimates of the input variables for the probabilities of fires, spills and release size from Table 6.8. Continuing with the same example scenario:

Table 7.1: DGAIS Release Data
by Accident Scenario

Collision	Large Load	Source	Number of Accidents with Releases								
			fire				no fire				total
			spill		leak		spill		leak		
			large	small	large	small	large	small	large	small	
y	y	DGAIS	17	1	2		60	3	2	3	88
y	n	DGAIS	3	4		1	12	16	1	7	44
n	y	DGAIS	23		2	1	215	39	18	17	315
n	n	DGAIS	4	1			38	49	5	23	120
total			47	6	4	2	325	107	26	50	567

Table 7.2: Comparison of DGAIS Release Data with Model Output
by Accident Scenario

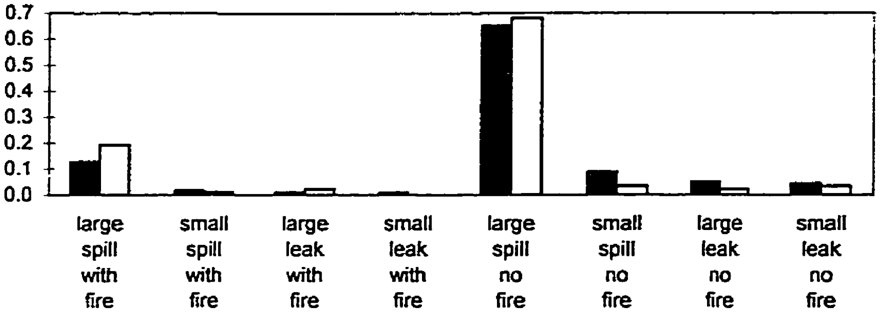
Collision	Large Load	Source	Probability of Release Outcome								
			fire				no fire				total
			spill		leak		spill		leak		
			large	small	large	small	large	small	large	small	
y	y	Model	.129	.018	.010	.009	.653	.089	.050	.044	1.000
		DGAIS	.193	.011	.023	.000	.682	.034	.023	.034	1.000
y	n	Model	.057	.070	.006	.031	.290	.356	.031	.158	1.000
		DGAIS	.068	.091	.000	.023	.273	.364	.023	.159	1.000
n	y	Model	.051	.007	.004	.003	.730	.100	.056	.049	1.000
		DGAIS	.073	.000	.006	.003	.683	.124	.057	.054	1.000
n	n	Model	.023	.028	.002	.012	.325	.399	.034	.177	1.000
		DGAIS	.033	.008	.000	.000	.317	.408	.042	.192	1.000

Figure 7.1: Histograms Comparing DGAIS Release Data with Model Output by Accident Scenario

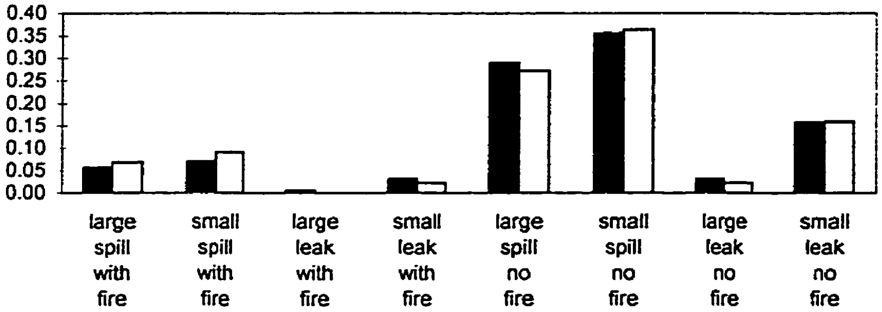
X-axis Units: release outcome Y-Axis Units: probability of release outcome

Legend:	black bar:	model output
	white bar:	estimate from DGAIS release data

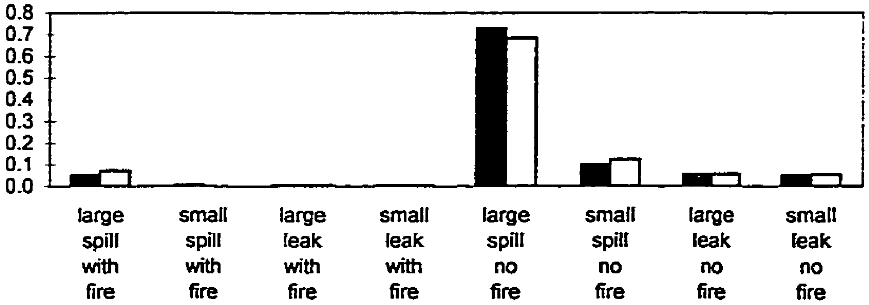
Accident Scenario: collision with release of large load



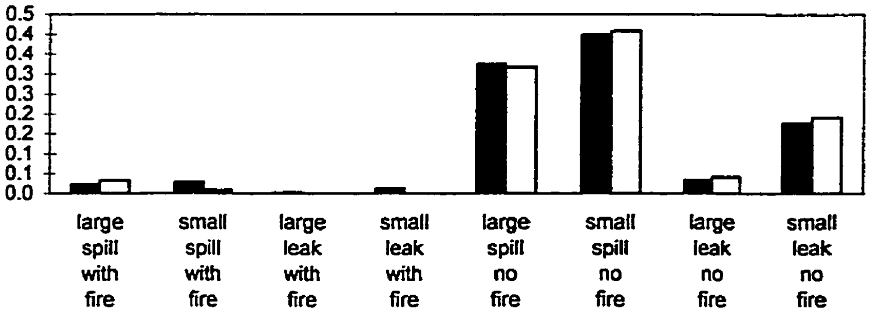
Accident Scenario: collision with release of small load



Accident Scenario: no collision with release of large load



Accident Scenario: no collision with release of small load



$$\begin{aligned}&P(\text{large spill with fire} \mid \text{release})\\&= P(\text{fire} \mid \text{release, collision}) \times P(\text{spill} \mid \text{release, large load}) \times P(\text{large release} \mid \text{spill, large load})\\&= .165 \times .888 \times .880\\&= .129\end{aligned} \tag{7.1}$$

Usually, the fit between two sets of data is measured by the Chi-Square statistic. In this case, the Chi-Square statistic is not valid because there are too many cells with few observations. Over half of the cells in the DGAIS cross-tabulation have fewer than five observations. From a visual inspection of Figure 7.1, there is a good match between the release data and the model. This is not surprising, because DGAIS is one of the two sources of information for the variable of P(fire | release) and the only source of information for the variables P(spill | release) and P(large release | spill). Discrepancies between the release data and the model generally occur as a result of empty cells in the release data table.

7.2 Comparison of Model Output to Data for Non-Accident Scenarios

Similar to the accident scenarios, for non-accident scenarios we can only compare output from part of the model to the release data. The comparable part is that which predicts outcomes once a release has occurred. The other part of the model that calculates the number of release incidents per Bvkm uses both DGAIS and other Transport Canada information, and is not directly comparable to either set of data.

The part of the model that predicts outcomes given a non-accident release uses the factors of urban/rural road and tanker/non-tanker truck. Table 7.3 shows the number of incidents recorded in DGAIS for the resulting non-accident scenarios. This table contains many empty cells for fire incidents for different types of releases.

Table 7.3 indicates that the majority of non-accident releases are from non-tanker trucks travelling on urban roads (292 out of 555 incidents, or 53%). Similar to accident scenarios, the most likely non-accident incident is a spill or leak with no fire (489 out of 555 incidents,

Table 7.3: DGAIS Release Data
by Non-Accident Scenario

Urban / Rural	Tanker Truck	Source	Number of Non-Accident Releases								
			fire				no fire				total
			spill		leak		spill		leak		
			large	small	large	small	large	small	large	small	
r	y	DGAIS	4			3	14	23	10	32	86
r	n	DGAIS	2	3			4	47	1	40	97
u	y	DGAIS		1		2	9	30	4	34	80
u	n	DGAIS		2		3	2	143	2	140	292
total			6	6	0	8	29	243	17	246	555

Table 7.4: Comparison of DGAIS Release Data with Model Output
by Non-Accident Scenario

Urban / Rural	Tanker Truck	Source	Probability of Release Outcome								
			fire				no fire				total
			spill		leak		spill		leak		
			large	small	large	small	large	small	large	small	
r	y	Model	.0147	.0188	.0071	.0249	.2099	.2682	.1014	.3549	1.0000
		DGAIS	.0465	.0000	.0000	.0349	.1628	.2674	.1163	.3721	1.0000
r	n	Model	.0036	.0300	.0008	.0312	.0512	.4269	.0111	.4451	1.0000
		DGAIS	.0206	.0309	.0000	.0000	.0412	.4845	.0103	.4124	1.0000
u	y	Model	.0025	.0085	.0011	.0095	.1127	.3880	.0478	.4300	1.0000
		DGAIS	.0000	.0125	.0000	.0250	.1125	.3750	.0500	.4250	1.0000
u	n	Model	.0001	.0109	.0001	.0104	.0068	.4939	.0066	.4712	1.0000
		DGAIS	.0000	.0068	.0000	.0103	.0068	.4897	.0068	.4795	1.0000

or 88%). Non-accident releases from tanker trucks are more likely to be large spills (27 out of 166 incidents, or 16%) compared with releases from non-tanker trucks (8 out of 389 incidents, or 2%).

Table 7.4 provides a comparison of the DGAIS release data with the model output by non-accident scenario. Figure 7.2 provides the same information in graphical form. For example, we can look at the first non-accident scenario, a tanker truck carrying a DG load on a rural road and experiencing a non-accident release. Directly from the DGAIS data, P(large spill with fire | non-accident release) is 4/86, or .0465. On the other hand, the model output is calculated using the point estimates of the input variables for the probabilities of fires, spills and release size from Table 6.12. Continuing with the same example scenario:

$$\begin{aligned} &\text{P(large spill with fire | release)} \\ &= \text{P(fire | release, rural)} \times \text{P(spill | release)} \times \text{P(large release | spill, rural, tanker)} \\ &= .066 \times .512 \times .439 \\ &= .0147 \end{aligned} \tag{7.2}$$

From a visual inspection of Figure 7.2, there is a good match between the non-accident release data and the model. Discrepancies generally occur as a result of empty cells in the release data table.

7.3 Conclusions Regarding Model

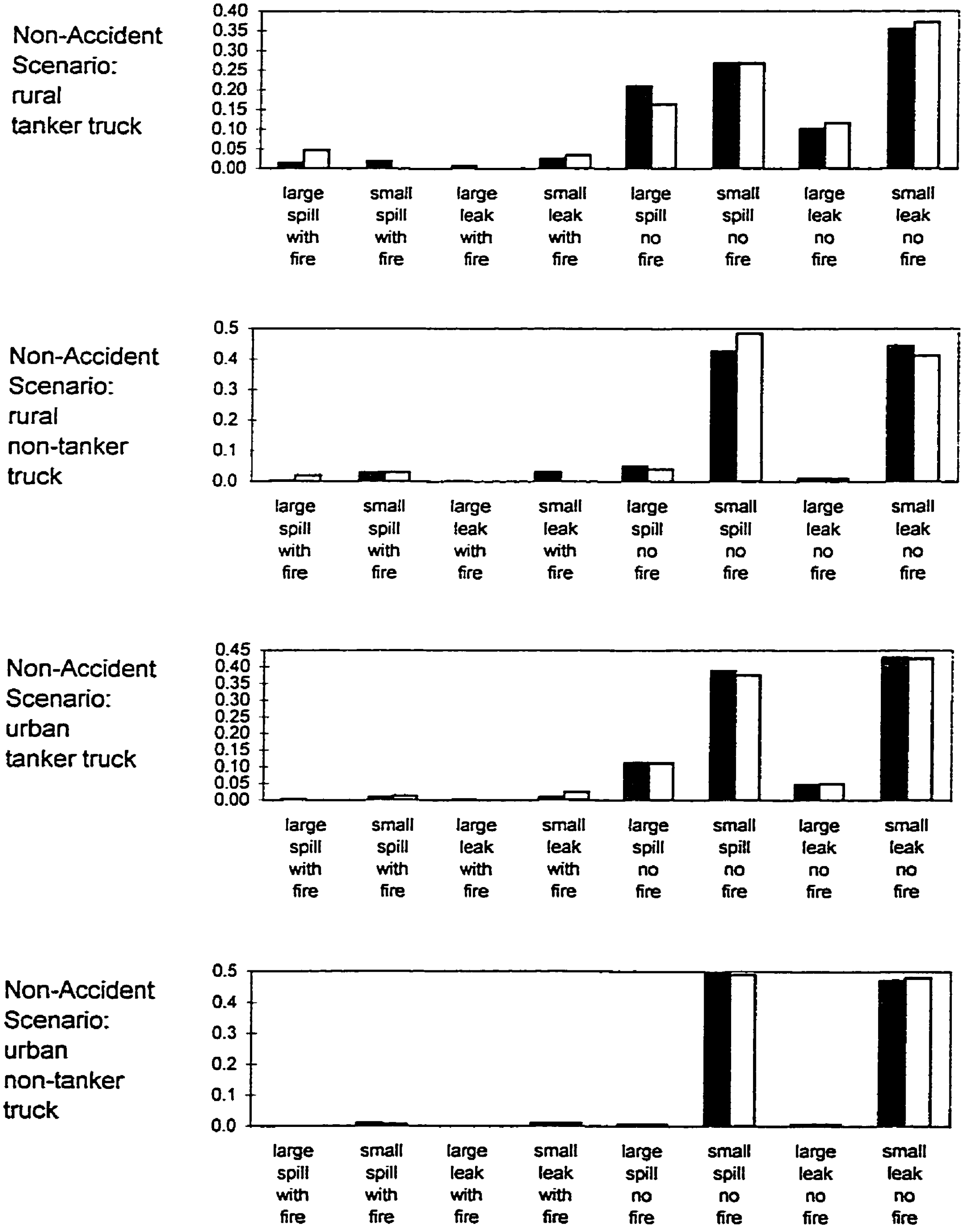
The model provides estimates of the probabilities of DG release outcomes similar to those obtained directly from the DGAIS data, for accident and non-accident scenarios. The model offers several advantages. The model allows us to:

- estimate probabilities for incidents for which the data sources have no records. For example, DGAIS has no records of small leaks with fire for the accident scenario of a truck carrying a large DG load and involved in an accident with a collision. By

Figure 7.2: Histograms Comparing DGAIS Release Data with Model Output by Non-Accident Scenario

X-axis Units: release outcome Y-Axis Units: probability of release outcome

Legend:	black bar:	model output
	white bar:	estimate from DGAIS release data



combining the input variables, the model provides an estimate of .009 for the probability of a small leak with fire for that accident scenario.

- incorporate the effects of significant factors. Figure 7.3 shows the probability of release outcomes for accident scenarios based on different factors. Figure 7.3 first shows the probability of release outcomes for accident scenarios including the significant factors of collision/no collision and large/small load. The probability of a large spill with fire ranges from .02 to .13 depending on whether the load is large or small and whether there is a collision or not. Figure 7.3 next shows the probability of release outcomes for accident scenarios including only the factor of collision/no collision. Now the probability of a large spill with fire has a narrower range of .04 to .11, depending on whether there is a collision or not. Finally Figure 7.3 shows the probability of release outcomes for all accidents combined. Without incorporating any factors, the probability of a large spill with fire is given as .06. This underestimates the probability of a large spill with fire for a truck with a large load involved in a collision, and overestimates it for a truck with a small load involved in a non-collision accident. Figure 7.3 illustrates the importance of including significant factors to explain variations in the probabilities of incident outcomes.

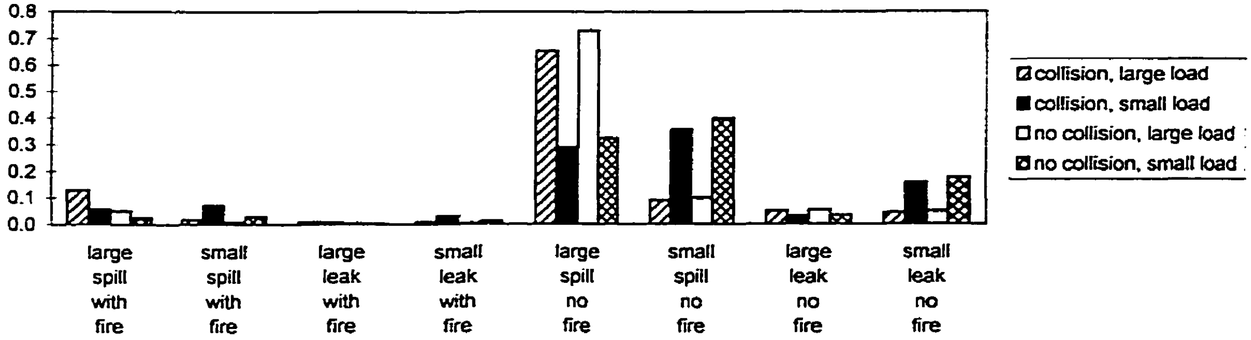
- combine information from different data sources to estimate probabilities that we cannot estimate from a single source. For example, we combine the number of non-accident releases by type of DG load from DGAIS with the road vehicle kilometres by type of DG load from Transport Canada to estimate the number of non-accident releases per Bvkm.

- combine information from different sources to estimate the values of input variables. For example, DGAIS from Transport Canada and MTMD from France both contain records of trucks carrying DG loads and involved in accidents. In both databases, the records indicate whether or not the accident involved a collision, and whether or not there was a fire. We can combine the information from both sources to estimate P(fire | accident) with and without a release and with and without a collision.

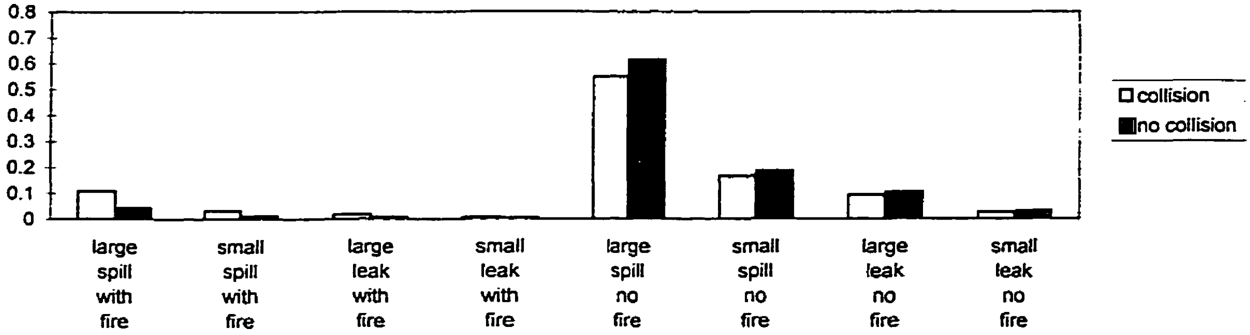
Figure 7.3: Histograms Comparing Model Output Using Different Factors for Accident Scenarios

X-axis Units: release outcome Y-Axis Units: probability of release outcome

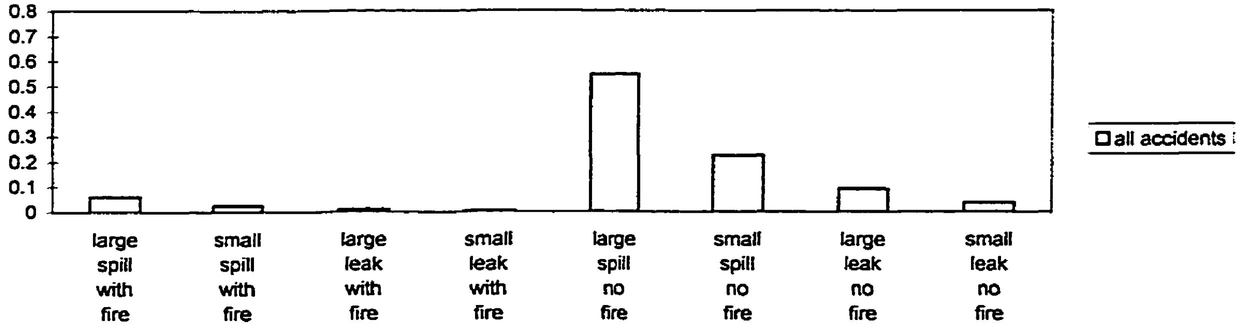
Factors for Accident Scenarios: collision/no collision, large/small load



Factors for Accident Scenarios: collision/no collision



Factors for Accident Scenarios: all accidents combined



CHAPTER 8

UNCERTAINTY IN INPUT VALUES

Chapter 8 contains the following sections:

8.1 Sources of Uncertainty in the Data
8.2 Form of Probability Distributions
8.3 Parameters for Beta Probability Distributions
8.4 Distributions for Input Variables

Chapter 8 documents the probability distributions assigned to the input variables. These distributions reflect the uncertainty with respect to the values of the input variables.

8.1 SOURCES OF UNCERTAINTY IN THE DATA

To estimate the uncertainty in the output variables, we need to define the uncertainty in the input variables. Therefore we assign a probability distribution to each input variable. The relative height of the probability distribution for a certain value indicates the probability of that value occurring in the future.

We assign the probability distributions based on a sample of possible values for each input variable. We use historical data to provide the sample of possible values. Appendix B contains the data for the input variables from the different sources (DGAIS, ORIS, etc.).

The estimates of the value of an input variable may vary because of fluctuations in the number of incidents over time. The data in Appendix B are cross-tabulated by yearly time intervals, by time intervals of two years or longer, and by the total time period of five to ten years for which the data are available. In estimating uncertainty, we do not use the cross-tabulation by the total time period, because that does not provide sufficient information on the variation between time periods. If there are sufficient data, we use the cross-tabulation by yearly time intervals. Where some years contain no records of certain types of incident outcomes, we use the cross-tabulation by time intervals of two years or longer, to avoid empty cells caused by scarcity of data. For example, we can consider accident input variable V1.1, P(overturn | release) for a truck carrying toxic PLG and involved in an accident. As shown in Appendix B, DGAIS contains data for V1.1 from 1988 to 1995. DGAIS provides estimates of V1.1 for the time intervals 1988-89, 1990-91, 1992-93 and 1994-95. The estimates range from .833 to .875. The range of values indicates the uncertainty caused by the fluctuations in the number of incidents. The probability distribution that we assign to the input variable reflects the uncertainty caused by fluctuations over time.

Accident input variables V1, V2, V3, V4, V6 and V7 have two sources of data. The remaining input variables have one source of data. For V1: P(overturn | release) and V2: P(type of DG load | release), there are data from both DGAIS (Canada) and ORIS (Ontario) in Canada. For V3: P(release) and V4: P(overturn), there are data from ADS (Ontario) and MARS (State of Washington). For V6: P(fire | release) and V7: P(fire | no release), there are data from DGAIS (Ontario) and MTMD (France).

Combining the data from different sources uses all of the information available. Where there are two sources of data for an input variable, the two sources give different estimates of the value of the input variable. The two sources of data could be viewed as two different populations. This would be true if the estimates vary between sources because of location-specific differences, for example, in roads or vehicles. On the other hand, the two estimates could vary simply because of differences, for example, in the methods of reporting and recording incidents. If we could control for differences in reporting and recording incidents, the estimates of the input variable from the two sources might be quite similar.

We have no information that allows us to discriminate regarding the reasons for the differences between estimates from different sources, nor do we have information that allows us to select one data source as being more reliable than another. We want to build a model for use in locations with road and truck characteristics similar to North America or Europe that incorporates all of the available information, while reflecting the uncertainty in the estimates. Therefore we assume that where we have estimates from two sources, then the estimates are from the same population and the best estimate is a combination of the estimates from the two sources.

For example, we may again consider accident input variable V1.1, P(overturn | release). From DGAIS, which includes data from across Canada from 1988 to 1995, we have estimates for V1.1 ranging from .833 to .875. From ORIS, which includes data from Ontario from 1988 to 1997, we have estimates for V1.1 ranging from .333 to .500. From Transport Canada data, Ontario accounts for approximately 40% of the Canadian road vehicle kilometres for trucks carrying DG loads. Therefore we would expect that the actual value of V1.1 should be quite similar for Ontario and for Canada. We can assume that, in this case, differences arise between the DGAIS and ORIS estimates because of differences in the methods of reporting and recording incidents. We further expect that if exactly the same reporting and recording methods were used for DGAIS and ORIS, their estimates of V1.1 would be quite similar.

It is difficult to say whether DGAIS or ORIS is the more reliable data source. Neither database contains records of every DG release that should have been reported. ORIS contains fewer records because it only covers Ontario, but it includes a more complete sample. The ORIS database includes records of approximately 540 releases from trucks in transit in Ontario over ten years. DGAIS contains more records overall because it covers all of Canada, but a smaller percent of all releases. For example, DGAIS includes approximately 1190 records of releases over eight years, but only 280 records of releases in Ontario. DGAIS may be biased towards the more dramatic releases that are more likely to be reported to the national DG incidents database.

We assume that each of the estimates from DGAIS and ORIS are possible values of V1.1. Similarly, where we have estimates from other pairs of sources, such as DGAIS and MTMD, or ADS and MARS, we assume that each of the estimates are possible values of the respective variable. Therefore we assign a probability distribution to each input variable that incorporates the range of possible values from both sources.

8.2 FORM OF PROBABILITY DISTRIBUTIONS

Henrion (1995) notes that, where there are not enough sample data to fit a probability distribution to an uncertain quantity using goodness-of-fit measures, there are four questions that we need to answer in selecting the most appropriate kind of distribution:

- Is it discrete or continuous? A continuous distribution assumes that there is an infinite number of values between any two points on the distribution.
- If it is continuous, is it bounded?
- Does it have one mode or more than one? The modes of an uncertain quantity are the values at the local maxima of the probability density function.
- Is it symmetric or skewed?

8.2.1 Probability Distributions for Input Variables Bounded by 0 and 1

Most of our input variables are probabilities, such as P(overturn | release), P(fire | collision), etc. The probability distribution for an input variable that is a probability is continuous and is bounded by 0 and 1. We would expect that the distribution would have one mode, and would be either positively or negatively skewed. The beta distribution fits these criteria.

The beta distribution is commonly used to represent the uncertainty in the probability of occurrence of an event, because its range is limited between 0 and 1. Lindley (1965) notes that the family of beta distributions has the important property that if p has a beta distribution, then $(1 - p)$ also has a beta distribution, but with the parameters α and β interchanged. This makes it particularly useful if p is the probability of success, for $(1 - p)$ is then the probability of failure and has a distribution of the same family. The beta distribution is also very flexible in terms of the wide variety of shapes it can assume, including positively or negatively skewed, depending on the values of its parameters. Therefore we assume that the input variables in our model that are probabilities have beta probability distributions. A beta distribution has the following probability density function:

$$P(p; \alpha,\beta) = \frac{\Gamma(\alpha + \beta)}{\Gamma(\alpha)\,\Gamma(\beta)}\; p^{(\alpha - 1)}\,(1 - p)^{(\beta - 1)} \tag{8.1}$$

where:

p = the value of the input variable (probability of incident outcome)

α and β = parameters of the equation, where: mean of $p = \alpha / (\alpha + \beta)$

For each input variable, we have several sample values for p including $p_1, p_2, \ldots, p_i$ from i different observations from different data sources and time intervals. We combine the information to produce the following overall joint probability density function for the parameters of the distribution:

$$P(\alpha, \beta\,; p_1, p_2, \ldots, p_i) \tag{8.2}$$

$$\propto \left[\frac{\Gamma(\alpha+\beta)}{\Gamma(\alpha)\,\Gamma(\beta)} p_1^{(\alpha-1)}\,(1-p_1)^{(\beta-1)}\right] \left[\frac{\Gamma(\alpha+\beta)}{\Gamma(\alpha)\,\Gamma(\beta)} p_2^{(\alpha-1)}\,(1-p_2)^{(\beta-1)}\right] [\ldots] \left[\frac{\Gamma(\alpha+\beta)}{\Gamma(\alpha)\,\Gamma(\beta)} p_i^{(\alpha-1)}\,(1-p_i)^{(\beta-1)}\right]$$

$$= \frac{[\Gamma(\alpha + \beta)]^i}{[\Gamma(\alpha)\,\Gamma(\beta)]^i}\; (p_1 p_2 \ldots p_i)^{(\alpha - 1)}\; [(1-p_1)(1-p_2)\ldots(1-p_i)]^{(\beta - 1)}$$

8.2.2 Probability Distributions for Sample Observations

The sample values for p_i are based on observations of a number of DG incidents, with or without a given characteristic, for given data sources and time intervals. In statistical terms, each value of p_i is based on a number of successes (number of relevant DG incidents with the characteristic) and a number of failures (number of relevant DG incidents without the characteristic). For example, we can again consider accident input variable V1.1, P(overturn | release) for a truck carrying toxic PLG and involved in an accident. For V1.1, the first time interval in DGAIS provides a sample observation of 7 incidents of a truck carrying a load of toxic PLG and involved in an accident with a release. Of these 7 incidents, 6 involved an overturn and 1 did not. This observation includes 7 trials with 6 successes and 1 failure. The mean value of p_i for this observation i is (number of successes)/(number of trials) or 6/7 or .857.

For observation i of successes and failures for a given data source and time interval, the probability of x successes has a binomial distribution as follows:

$$P(x\,;p_i\,,n) = \binom{n}{x} p_i^{\,x} (1-p_i)^{y} \tag{8.3}$$

where:

x = number of successes

y = number of failures

n = number of trials = $x + y$

p_i = probability of success on each trial

Therefore the likelihood is also binomial:

$$l(p_i\,;x,y) \propto p_i^{\,x} (1-p_i)^{y} \tag{8.4}$$

Lindley (1965) suggests that the family of beta distributions is the natural one to consider as prior distributions for the probability p_i of success, with the form $p_i^{\,a} (1-p_i)^{b}$. We want to chose values for a and b that provide a non-informative prior. Lindley (1965) notes that, since any observation always increases either a or b, it corresponds to the greatest possible ignorance to take a and b as small as possible. For the prior density to have a total integral 1 it is necessary and sufficient that both a and b exceed -1. Lindley (1965) therefore recommends that $a = b = -1$. Lindley's prior takes the form:

$$\mathrm{P}(p_i) \propto p_i^{-1} (1 - p_i)^{-1} \tag{8.5}$$

If we combine Lindley's prior with our likelihood function, then the posterior distribution is:

$$\mathrm{P}(p_i\,;x, y) \tag{8.6}$$

$$\propto [p_i^{-1} (1 - p_i)^{-1}]\,[p_i^{x} (1 - p_i)^{y}]$$

$$\propto p_i^{x-1} (1 - p_i)^{y-1}$$

Therefore for each observation i of successes and failures, we can draw a sample p_i from a posterior beta distribution with parameters x successes and y failures as follows:

$$\mathrm{P}(p_i\,; x, y) = \frac{\Gamma(x + y)\, p_i^{(x-1)} (1 - p_i)^{(y-1)}}{\Gamma(x)\,\Gamma(y)} \tag{8.7}$$

Equation 8.7 is a posterior beta distribution for p_i based on a binomial likelihood for each observation of successes and failures. We can only evaluate this distribution once we have observed at least one success and one failure; otherwise its integral does not converge. When the observation includes a large number of trials, the posterior beta distribution is narrow. Values selected at random from a very narrow distribution are nearly constant, and in an iterative procedure carry more weight. When the observation includes a small number of trials, the posterior beta distribution is wider. Values selected at random from a wide distribution are more likely to vary widely, and in an iterative procedure carry less weight.

We can again consider V1.1. As noted above, the sample observation for V1.1 from DGAIS for the first time interval includes 7 trials with 6 successes and 1 failure. Therefore $x = 6$ and $y = 1$. The mean value of p_i for the first time interval can be calculated from the sample data as (number of successes)/(number of trials) or 6/7 or .857. Similarly, the mean value of the posterior beta distribution for p_i for the first time interval is $x/(x+y)$ or 6/7 or .857.

We can use the posterior beta distributions for each observation of successes and failures to estimate the parameters for the overall beta distribution for the value p for the input variable. Figure 8.1 shows the beta distributions for example input variable V1.4, P(overturn | release) for a truck carrying toxic liquid and involved in an accident. Figure 8.1 shows the posterior beta distributions for each observation of successes and failures for V1.4 as well as the overall beta distribution for the value p. The method of solving for the overall equation parameters is discussed in Section 8.3.

8.2.3 Probability Distributions for Input Variables Bounded by 0

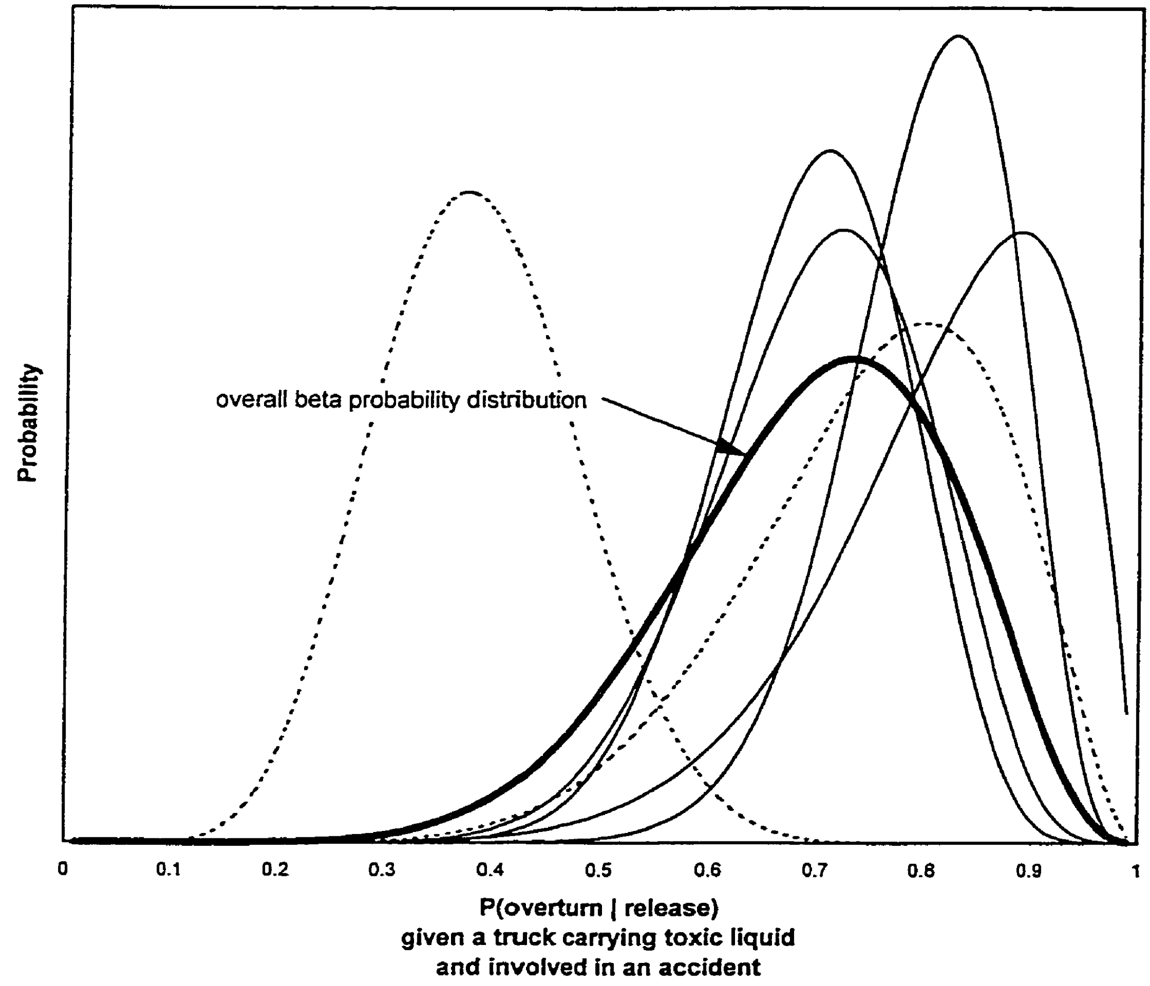
The first input variable for non-accident scenarios is the rate of releases per Bvkm. The probability distribution for the rate of releases is continuous and must be greater than 0, but has no upper limit. We know that the rate of release cannot be 0 because we have observations of releases occurring. We would further expect that the distribution would have one mode, and would be positively skewed, with most of the values near the lower limit, which corresponds with the observed values for the rate of releases per Bvkm.

Henrion (1995) notes that if there is a sharp lower bound of 0 for a quantity, but no sharp upper bound, a single mode, and right skew, then the lognormal or gamma distributions are good candidates for probability distributions, with the lognormal being used most widely. Therefore we assume that the input variables in our model that are rates of releases have lognormal probability distributions.

Figure 8.1: Beta Probability Distribution for Input Variable V1.4

Legend:

Input Variable V1.4:	P(overturn | release) for a truck carrying toxic liquid and involved in an accident
solid lines:	posterior beta probability distributions for observations from first data source
dashed lines:	posterior beta probability distributions for observations from second data source
heavy line:	overall beta probability distribution for input variable V1.4



A lognormal distribution has the following probability density function:

$$f(r\,;\mu,\sigma) = \frac{1}{r\,(2\pi)^{1/2}\,\sigma}\exp\left(-\left(\ln(r)-\mu\right)^2/2\,\sigma^2\right) \tag{8.8}$$

where:

r = value of the input variable (rate of releases per Bvkm)

μ = mean of the natural logarithm of the sample values

σ = standard deviation of the natural logarithm of the sample values.

8.3 PARAMETERS FOR BETA PROBABILITY DISTRIBUTIONS

Most of the input variables in the model are probabilities of incident outcomes, p. From Section 8.2.1, we know that we can express the uncertainty in p as a beta probability distribution, with parameters α and β. The beta probability distribution for each input variable is fit to the sample data to provide estimates of the unknown parameters α and β. The sample data include sample observations of successes and failures from different data sources and time intervals. The observations provide sample values p_1, p_2, ..., p_i, each of which themselves have uncertainty. From Section 8.2.2, we know that we can express the uncertainty in each sample p_i as a posterior beta probability distribution. Therefore we fit the overall beta probability distribution for the input variable not just to single sample values of p_1, p_2, ..., p_i, but to a set of i posterior beta probability distributions.

We used the Gibbs sampler to solve for the expected values of α and β for the overall beta probability density function for each input variable. Smith (1991) notes that the Gibbs sampler is a variant of a Markov chain simulation procedure. It uses an iterative procedure to find the distribution of a multivariate random variable, given the joint probability density function. In our case, the iterative procedure produces many samples of the values for α and β. After many iterations, the average values of the samples of α and β converge to the expected values.

The Gibbs sampler uses the joint probability density function for α and β, which is:

(8.9)

$$P(\alpha, \beta ; p_1, p_2, ..., p_i)$$

$$\propto \frac{[\Gamma(\alpha + \beta)]^i}{[\Gamma(\alpha)\,\Gamma(\beta)]^i} (p_1 p_2 \ldots p_i)^{(\alpha - 1)} [(1 - p_1)(1 - p_2) \ldots (1 - p_i)]^{(\beta - 1)}$$

If we hold β and p_i constant, the conditional probability density function for α is proportional to:

(8.10)

$$\frac{[\Gamma(\alpha + \beta)]^i}{\Gamma(\alpha)^i} (p_1 p_2 \ldots p_i)^{(\alpha - 1)} = \text{cdf}\alpha$$

If we hold α and p_i constant, the conditional probability density function for β is proportional to:

(8.11)

$$\frac{[\Gamma(\alpha + \beta)]^i}{\Gamma(\beta)^i} [(1 - p_1)(1 - p_2) \ldots (1 - p_i)]^{(\beta - 1)} = \text{cdf}\beta$$

Alternative methods of solving for the expected values of values of α and β for the overall beta probability density functions include analytical methods such as maximum likelihood or the method of moments. We do not use maximum likelihood estimates because it is not practical to find the derivative of equation 8.9, where each value of $p_1, p_2, ..., p_i$ comes from a separate beta distribution. We do not use the method of moments because, as Kendall et al. (1991) note, fitting a distribution to a sample of a population by the method of moments does not provide the most efficient estimators of the unknown parameters, unless the distribution is normal. We are fitting beta rather than normal distributions to the sample data. Therefore we use Gibbs sampler to solve for the expected values of values of α and β.

The steps in the Gibbs sampler procedure that we used to determine α and β for each input variable are as follows:

A. Assume starting values for α and β, say $\alpha = \beta = 5$.

B. Generate one value p_i for each observation of successes and failures, from the posterior beta distribution given in equation (8.7).

C. Generate the next value of α.

1. Generate 100 values of a random number R from a uniform distribution between 0 and 1 ($R_1, R_2, \dots , R_{100}$).
2. Evaluate cdfα where $\alpha =$ R for each value of R (cdfα_1, cdfα_2, ... , cdfα_{100}) while holding constant the current values of β and each p_i.
3. Calculate $F_1 = \text{cdf}\alpha_1$, $F_2 = \text{cdf}\alpha_1 + \text{cdf}\alpha_2$, ..., $F_{100} = \text{cdf}\alpha_1 + \text{cdf}\alpha_2 + \dots + \text{cdf}\alpha_{100}$.
4. Calculate $FN_1 = F_1/F_{100}$, $FN_2 = F_2/F_{100}$, ... , $FN_{100} = F_{100}/F_{100}$.
5. Generate one value V from a uniform distribution between 0 and 1.
6. Count the number C of FN values smaller than V.
7. Chose $\alpha = R_{C+1}$. This is now the current value of α.

D. Similarly, generate the next value of β.

1. Generate a new set of 100 values of a random number R from a uniform distribution between 0 and 1 ($R_1, R_2, \dots , R_{100}$).
2. Evaluate cdfβ where $\beta =$ R for each value of R (cdfβ_1, cdfβ_2, ... , cdfβ_{100}) while holding constant the current values of α and each p_i.
3. Calculate $F_1 = \text{cdf}\beta_1$, $F_2 = \text{cdf}\beta_1 + \text{cdf}\beta_2$, ..., $F_{100} = \text{cdf}\beta_1 + \text{cdf}\beta_2 + \dots + \text{cdf}\beta_{100}$.
4. Calculate $FN_1 = F_1/F_{100}$, $FN_2 = F_2/F_{100}$, ... , $FN_{100} = F_{100}/F_{100}$.
5. Generate one value V from a uniform distribution between 0 and 1.
6. Count the number C of FN values smaller than V.
7. Chose $\beta = R_{C+1}$. This is now the current value of β.

E. Record the values of α and β. Return to Step B. Continue for 50,000 iterations. Calculate the mean values of α and β from the 50,000 iterations.

As noted above, after many iterations, the mean values of α and β converge to their expected values. We used the mean values of α and β to generate the overall beta probability distributions for the input variables that are probabilities of incident outcomes.

8.4 DISTRIBUTIONS FOR INPUT VARIABLES

Appendix C contains graphs showing the resulting probability distributions for each input variable. For comparison, the graphs also show the data points from each data source for each input variable. As expected, a wide spread of data points results in a wide probability distribution, and a narrow spread of data points results in a narrow probability distribution.

Appendix D contains the values of the parameters that define the probability distributions for each input variable. For the beta distributions, the parameters include the values of α and β. Appendix D also provides the mean and standard deviation for the beta distributions. For the lognormal distributions, the parameters include the mean and standard deviation of the sample data for the input variable.

Table 8.1 compares the means of the beta distributions given in Appendix D with the point estimates of the input variables given earlier in Chapter 6 for accident and non-accident scenarios. The point estimates come from the means of the sample data, (total number of successes)/(total number of trials), for each input variable. It is interesting to note that the means of the beta distributions differ slightly from the means calculated directly from the sample data. Both are valid estimates of the expected values of the input variables. The differences arise from the fitting of the overall beta distribution to the distributions of the sample values. We prefer to use the beta distributions in describing the input variables because they take into account all of the information available, including the data and the assumed shapes of the distributions.

Table 8.1: Comparison of Means of Distributions to Point Estimates for Input Variables

	Input Variable	Mean of Distribution	Point Estimate
Accident	V1.1: P(overturn | release) for toxic PLG	.706	.757
	V1.2: P(overturn | release) for flammable PLG	.594	.588
	V1.3: P(overturn | release) for flammable liquid	.795	.800
	V1.4: P(overturn | release) for toxic liquid	.695	.667
	V2.1: P(toxic PLG | release)	.038	.042
	V2.2: P(flammable PLG | release)	.059	.057
	V2.3: P(flammable liquid | release)	.768	.766
	V2.4: P(toxic liquid | release)	.133	.135
	V3: P(release | accident)	.015	.018
	V4: P(overturn | accident)	.046	.055
	V5.1: P(toxic PLG)	.051	.050
	V5.2: P(flammable PLG)	.059	.058
	V5.3: P(flammable liquid)	.629	.635
	V5.4: P(toxic liquid)	.260	.256
	V6.1: P(fire | release, no collision)	.063	.066
	V6.2: P(fire | release, collision)	.171	.165
	V7.1: P(fire | no release, no collision)	.018	.009
	V7.2: P(fire | no release, collision)	.075	.027
	V8.1: P(spill | release, small load)	.773	.774
	V8.2: P(spill | release, large load)	.888	.888
	V9.1: P(large release | spill, small load)	.437	.449
	V9.2: P(large release | spill, large load)	.881	.880
	V10.1: P(large release | leak, small load)	.163	.162
	V10.2: P(large release | leak, large load)	.548	.533
Non-Accident	V1.1: Releases per Bvkm for toxic PLG	11.07	11.07
	V1.2: Releases per Bvkm for flammable PLG	4.03	4.03
	V1.3: Releases per Bvkm for flammable liquid	4.57	4.57
	V1.4: Releases per Bvkm for toxic liquid	13.94	13.94
	V2.1: P(fire | release, rural road)	.058	.066
	V2.2: P(fire | release, urban road)	.019	.022
	V3: P(spill | release)	.516	.512
	V4.1: P(large release | spill, rural non-tanker)	.123	.107
	V4.2: P(large release | spill, rural tanker)	.517	.439
	V4.3: P(large release | spill, urban non-tanker)	.018	.014
	V4.4: P(large release | spill, urban tanker)	.175	.225
	V5.1: P(large release | leak, rural non-tanker)	.029	.024
	V5.2: P(large release | leak, rural tanker)	.237	.222
	V5.3: P(large release | leak, urban non-tanker)	.016	.014
	V5.4: P(large release | leak, urban tanker)	.102	.100

CHAPTER 9

UNCERTAINTY IN OUTPUT VALUES

Chapter 9 contains the following sections:

9.1 Monte Carlo Simulations
9.2 Output Probability Distributions

Chapter 9 documents the results of the Monte Carlo simulations to propagate the uncertainty in the input variables through to the uncertainty in the output variables. Each outcome probability or incident rate has a distribution, indicating the uncertainty about the output values. The analysis provides statistics that define each output distribution. The chapter summarises the mean values of the output probability distributions for the accident outcome probabilities and non-accident incident rates.

9.1 MONTE CARLO SIMULATIONS

9.1.1 Input to Monte Carlo Simulations

The steps in the Monte Carlo simulation are discussed in Section 3.3. To run, the simulation requires information from the model as follows:

- input variables. Separate simulations were run for each possible outcome for each accident and non-accident scenario. Tables 5.4 and 5.5 list the input variables for the accident and non-accident scenarios respectively. The input variables include, for example, P(fire | release), P(spill | release), etc.

- output variables. For the accident model, the output variables are the probabilities of accident outcomes. Figure 4.3 shows that there are ten possible accident outcomes. For the accident model, the output variables include P(large spill with fire | accident), P(small leak no fire | accident), etc. For the non-accident model, the output variables are the number of incidents per Bvkm. Figure 4.3 shows that there are nine possible non-accident incident outcomes. The non-accident model includes eight of these outcomes. As discussed in Section 5.1.1, there are not enough data on the ninth outcome, non-accident non-release fires, to find significant factors that lead to such incidents. The incident rate of non-accident non-release fires is approximately .22 incidents per Bvkm. For the non-accident model, the output variables include the number of non-accident large spills with fire per Bvkm, the number of non-accident small leaks with fire per Bvkm, etc.

- equations that relate the input and output variables. The equations are the same as those used earlier to calculate point estimates of the output. The equations to calculate P(release | accident) are as discussed in Section 5.1.3. The general model equations to combine P(release | accident) and the remaining input variables are shown in Figure 4.4.

- probability distributions for each of the input variables. Appendix C shows the probability distributions fitted to the data for each input variable.

9.1.2 Number of Iterations

The number of iterations in the Monte Carlo simulation affects the output of the model. The simulation produces frequency histograms of possible values for each output variable. We can then convert these frequency histograms to probability distributions by setting the scale so that the total probability is 1. For a low number of iterations, the probability distributions are ragged and the statistics for the distributions (mean, standard deviation, etc.) fluctuate as more iterations are completed. For a high number of iterations, the probability distributions become smooth and the statistics of the distributions stabilise. However, a high number of iterations also consumes more computer time to run the simulation. We want to use enough iterations in the simulation to produce smooth probability distributions and stable statistics for the distributions, while minimising computer time.

Figure 9.1 contains probability distributions for a sample output, for simulations with varying numbers of iterations. The number of iterations ranges from 500 to 100,000. The sample output is P(large spill with fire | accident) for Accident Scenario 1, where a truck carrying a large load of toxic PLG is involved in an accident with an overturn and collision. Figure 9.1 shows that the probability distributions are quite ragged for 500 to 5,000 iterations. The probability distributions are quite smooth for 20,000 iterations or more.

Table 9.1 contains the statistics for the probability distribution for the same sample output used in Figure 9.1. Table 9.1 shows that the statistics for the mean of the distribution are stable to two significant digits after about 30,000 iterations.

We decided to run the simulations for the accident and non-accident models for 50,000 iterations, to provide both smooth probability distributions and stable distribution statistics for each output variable.

9.2 OUTPUT PROBABILITY DISTRIBUTIONS

9.2.1 Shape of Output Probability Distributions

For each output variable in our model, we have a data set of 50,000 values generated by the Monte Carlo process. We can generate a histogram summarising the 50,000 values and showing the probabilities of different values of the output variable. Alternatively, we can empirically assign a continuous probability distribution to the data set. We can then use the continuous probability distribution to calculate the probabilities of the different values of the output variable. It would be quite unwieldy to store the actual frequency counts for each output variable for future use, but quite simple to provide the parameters for the continuous

Figure 9.1: Output Probability Distributions for Various Numbers of Iterations

Accident Scenario 1: accident with overturn and collision, large load of toxic PLG

X-axis Units: P(large spill with fire | accident)
Y-axis Units: probability

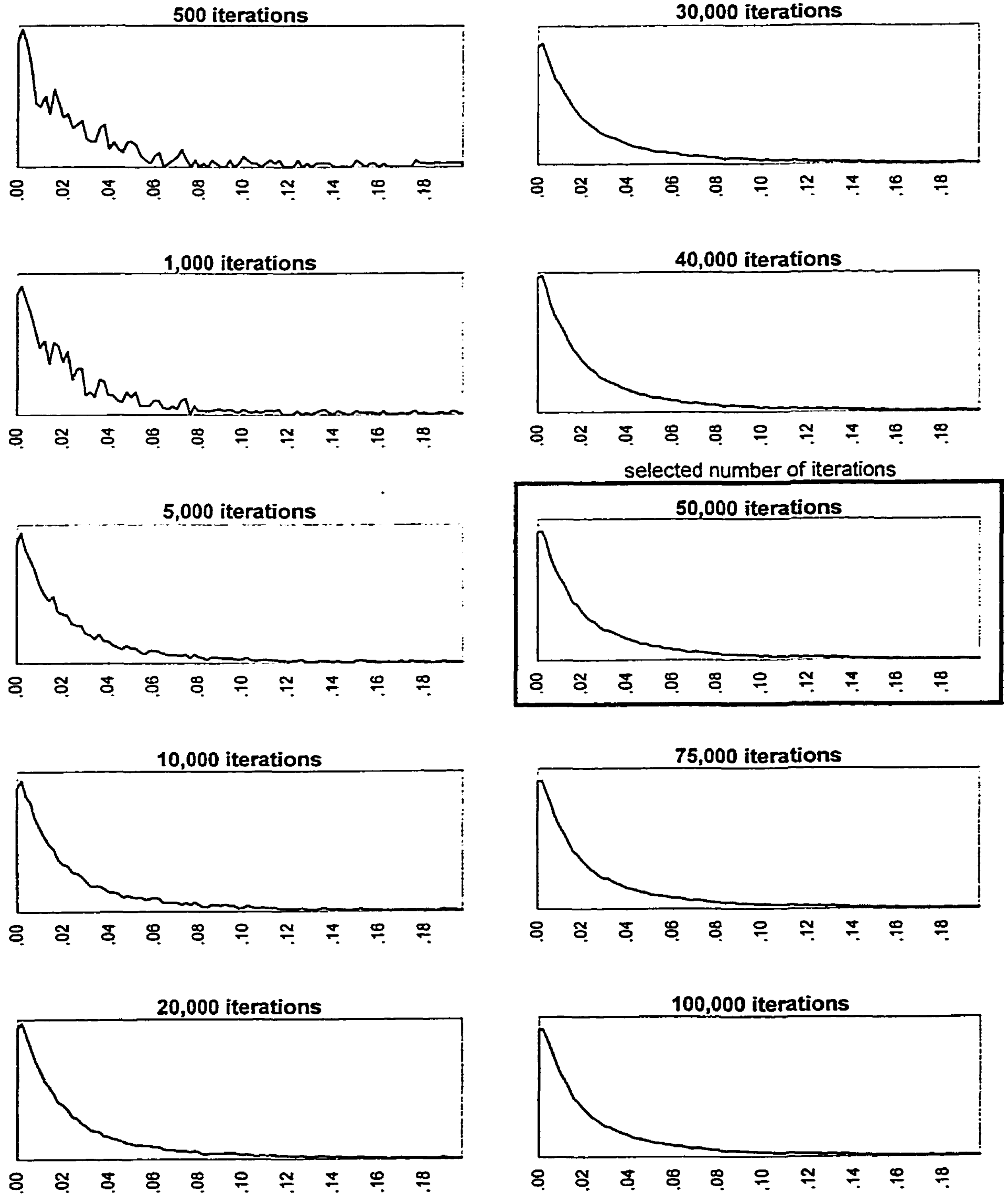


Table 9.1: Statistics for Output Probability Distributions for Various Numbers of Iterations

Output Variable: P(large spill with fire | accident)
for Accident Scenario 1
(overturn and collision, large load of toxic PLG)

Trials	Mean	Median	Standard Deviation	Skewness	Kurtosis	Coeff. of Variation
500	.03533	.01915	.05191	3.94	24.46	1.47
1,000	.03632	.01915	.05478	3.91	23.21	1.51
5,000	.03689	.01837	.06470	7.67	107.89	1.75
10,000	.03703	.01794	.06322	6.94	90.48	1.71
20,000	.03749	.01819	.06756	9.35	186.60	1.80
30,000	.03790	.01819	.07040	9.59	183.93	1.86
40,000	.03803	.01821	.07003	9.21	169.10	1.84
50,000	**.03802**	**.01810**	**.07194**	**9.94**	**197.17**	**1.89**
75,000	.03805	.01803	.07411	10.72	223.55	1.95
100,000	.03805	.01805	.07378	10.73	233.58	1.94

probability distribution, making the output much more useful for future QRA analysts. Therefore we assign a continuous probability distribution to each output variable.

We used the Crystal Ball ® software package in choosing the shape of the output probability distributions. Crystal Ball ® includes a distribution-fitting feature, which uses maximum likelihood estimators or other parameter estimation techniques to fit probability distributions to a data set, depending on the type of probability distribution. Alternative continuous probability distributions include normal, triangular, lognormal, uniform, exponential, Weibull, beta, gamma, logistic, pareto and extreme value. The software chooses values for the parameters of the distributions that maximise the probability of producing the data set. Crystal Ball also provides measures of the goodness-of-fit between each set of data and each continuous probability curve.

We used two scenarios to illustrate the output variable distributions. The first sample scenario is Accident Scenario 1, where a truck carrying a large load of toxic PLG is involved in an accident with an overturn and collision. The second sample scenario is Non-Accident Scenario 33, for a tanker truck carrying toxic PLG on a rural road. Each accident scenario in our model has ten output variables, including P(large spill with fire), P(small spill with fire), etc. Each non-accident scenario in our model has eight output variables, including number of incidents of large spill with fire per Bvkm, number of incidents of small spill with fire per Bvkm, etc. For the two samples, there is a total of 18 output variables.

The Chi-Square statistic measures goodness-of-fit, or how closely a set of observed frequencies corresponds to expected frequencies. In our case, the observed frequencies come from a 100-cell histogram summarising the 50,000 values generated for each output variable by the Monte Carlo process. A histogram with 100 cells provides a smooth distribution with greater than five observations in each cell. Unfortunately, the Chi-Square is too sensitive to use with a very high number of cells and observations such as we have in this case. Small deviations between the observed and expected frequencies result in a high Chi-Square. According to the Chi-Square test, none of the alternative continuous probability distributions fit the data well. The Chi-Square test does indicate that a lognormal distribution fits 17 out of the 18 accident and non-accident variables better (or less poorly) than the alternatives. For one of the 18 variables, the Chi-Square test indicates that a beta distribution fits better than the alternatives. For consistency, we assigned a lognormal distribution to every output variable. Based on the Central Limit Theorem, we would expect the output variables, which are the product of several random input variables, to have approximately lognormal distributions.

Figures 9.2 and 9.3 compare the output probability distributions to empirically assigned lognormal distributions for each output variable, for the sample accident and non-accident scenarios. The output probability distribution is generated from the 100-cell histogram of the 50,000 values generated for each output variable by the Monte Carlo process. The lognormal distribution is calculated from the mean and standard deviation of the 50,000 values. Each of the output variables for Scenarios 1 and 33 is positively skewed, with one exception. The last output variable for Scenario 1, P(no fire no release), is negatively skewed. We generated the lognormal distribution for this last variable by transforming the mean to (1 - mean). Based on a visual inspection of Figures 9.2 and 9.3, there is a close fit between the observed frequencies and the lognormal distributions.

Appendix E contains the statistics for the probability distributions for each of the output variables, for each accident and non-accident scenario. The statistics include:

- 2.5th percentile
- 97.5th percentile
- mean
- median
- standard deviation
- skewness
- kurtosis

Figure 9.2: Comparison of Output Probability Distributions to Lognormal Distributions for Sample Accident Scenario

Accident Scenario 1: accident with overturn and collision, large load of toxic PLG

X-axis Units: probability of accident outcome Y-axis Units: probability

Legend: solid lines: probability distribution plotted from observed Monte Carlo output
dashed lines: probability distribution plotted from expected lognormal distribution, using mean and standard deviation from Monte Carlo output

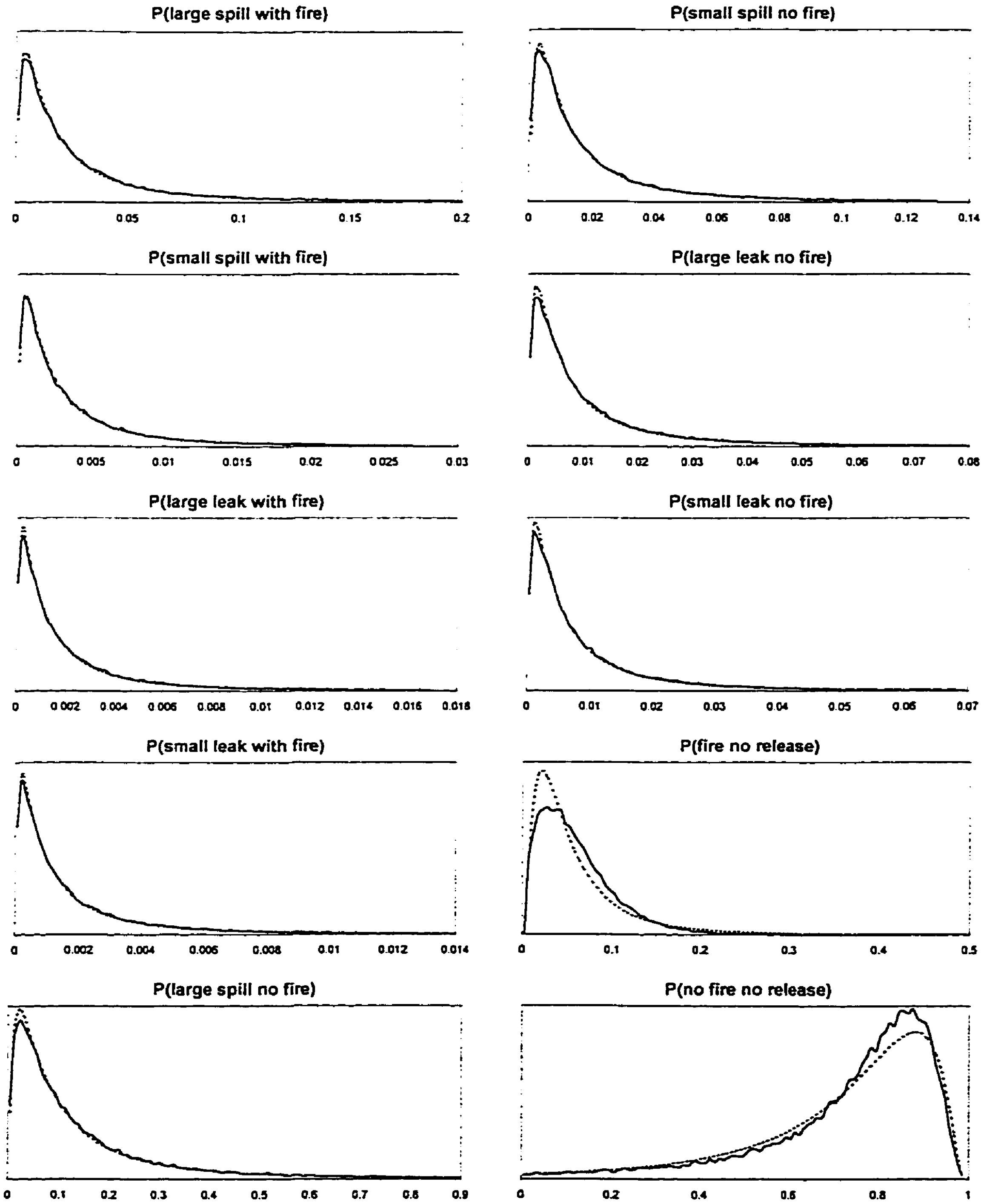


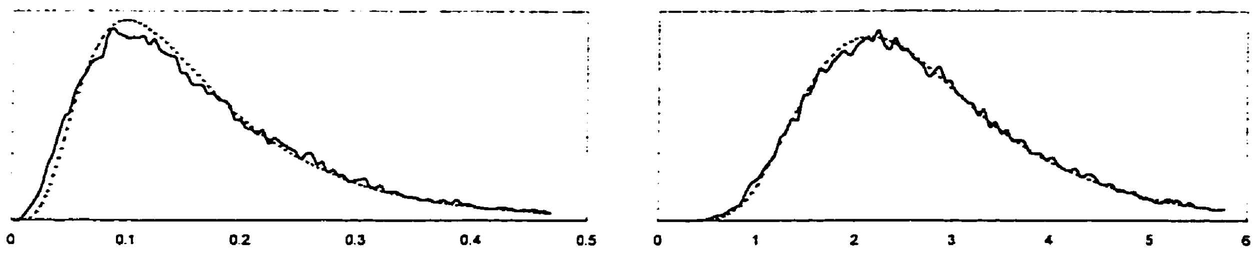
Figure 9.3: Comparison of Output Probability Distributions to Lognormal Distributions for Sample Non-Accident Scenario

Non-Accident Scenario 33: tanker truck carrying toxic PLG on rural road

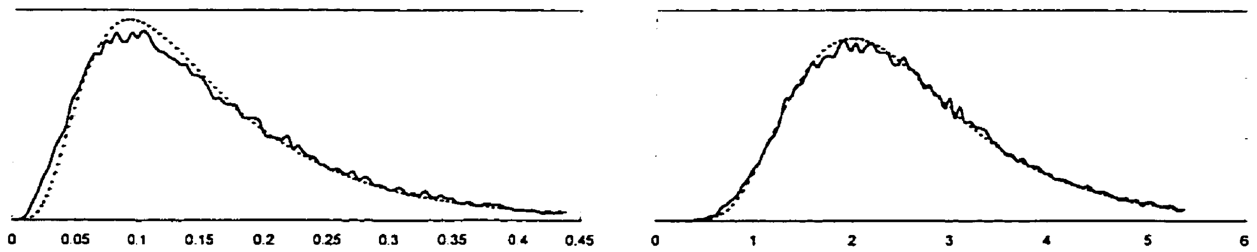
X-axis Units: incidents per Bvkm Y-axis Units: probability

Legend: solid lines: probability distribution plotted from observed Monte Carlo output
dashed lines: probability distribution plotted from expected lognormal distribution, using mean and standard deviation from Monte Carlo output

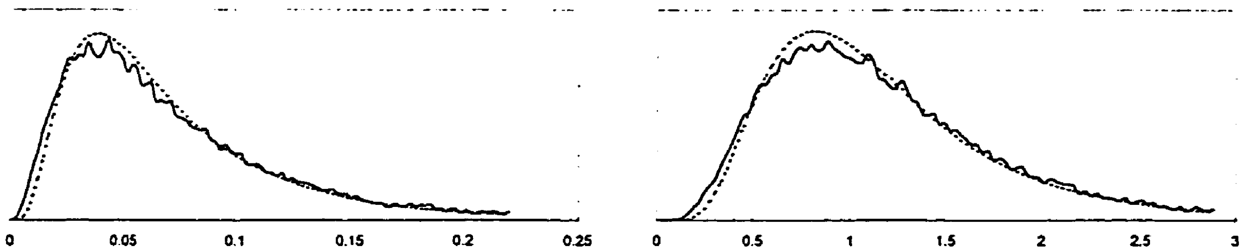
large spill with fire **large spill no fire**



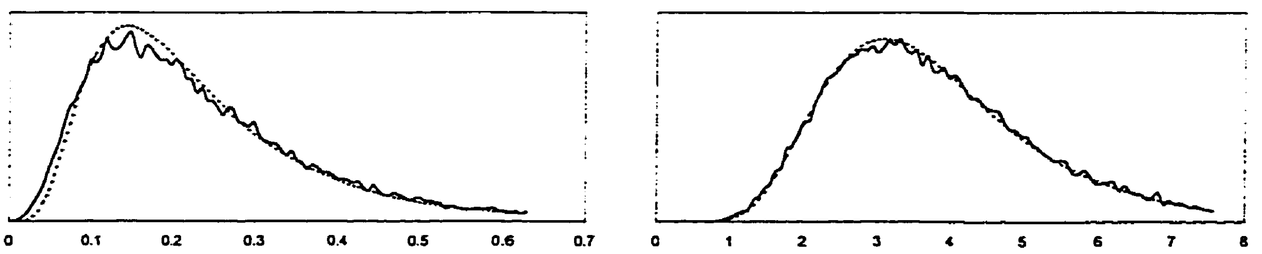
small spill with fire **small spill no fire**



large leak with fire **large leak no fire**



small leak with fire **small leak no fire**



9.2.2 Range of Output Probability Distributions

Figures 9.4 and 9.5 show the range of the output probability distributions in terms of the 95% probability intervals, for each of the accident and non-accident scenarios respectively. Figure 9.4 covers three pages and Figure 9.5 covers two pages. The probability intervals are shown vertically, as high-low bars. Each high-low bar represents a different accident or non-accident scenario. The high end of the bar represents the 97.5th percentile for the probability distribution. The low end of the bar represents the 2.5th percentile. The longer the bar, the greater is the uncertainty in the output variable.

Each high-low bar has a tick showing the mean value of the distribution. As we know from Section 9.2.1, the output probability distributions are generally lognormal in shape and usually positively skewed. Therefore the mean value within each probability interval tends to appear closer to the low end of the interval.

In Figure 9.4, the 95% probability intervals are graphed separately for Scenarios 1 to 16 (accidents with overturns) and for Scenarios 17 to 31 (accidents without overturns), because of the large difference in the scale of the output values for these two groups of scenarios. In comparing the scales we can see that, for the probability of an accident outcome with a release, the mean and 97.5th percentile of the distribution are generally 40 to 70 times larger with an overturn compared with no overturn.

Similarly in Figure 9.5, the 95% probability intervals are graphed separately for Scenarios 33 to 40 (rural non-accident scenarios) and for Scenarios 41 to 48 (urban non-accident scenarios), because of the difference in the scale of the output values. In comparing the scales we can see that, for non-accident incidents, the mean and 97.5th percentile of the distribution for incident rates of releases with fires are generally three to eight times higher in rural compared with urban areas. Large spills or leaks without fires are also more frequent in rural areas.

Figure 9.4: High-Low Graphs Showing Ranges of Output Probability Distributions by Accident Scenario

Legend:	x-axis:	Accident scenario number
	y-axis:	Probability of accident outcome
	bar:	Range of values from 2.5th to 97.5th percentile for probability of accident outcome
	tick:	Mean value for probability of accident outcome

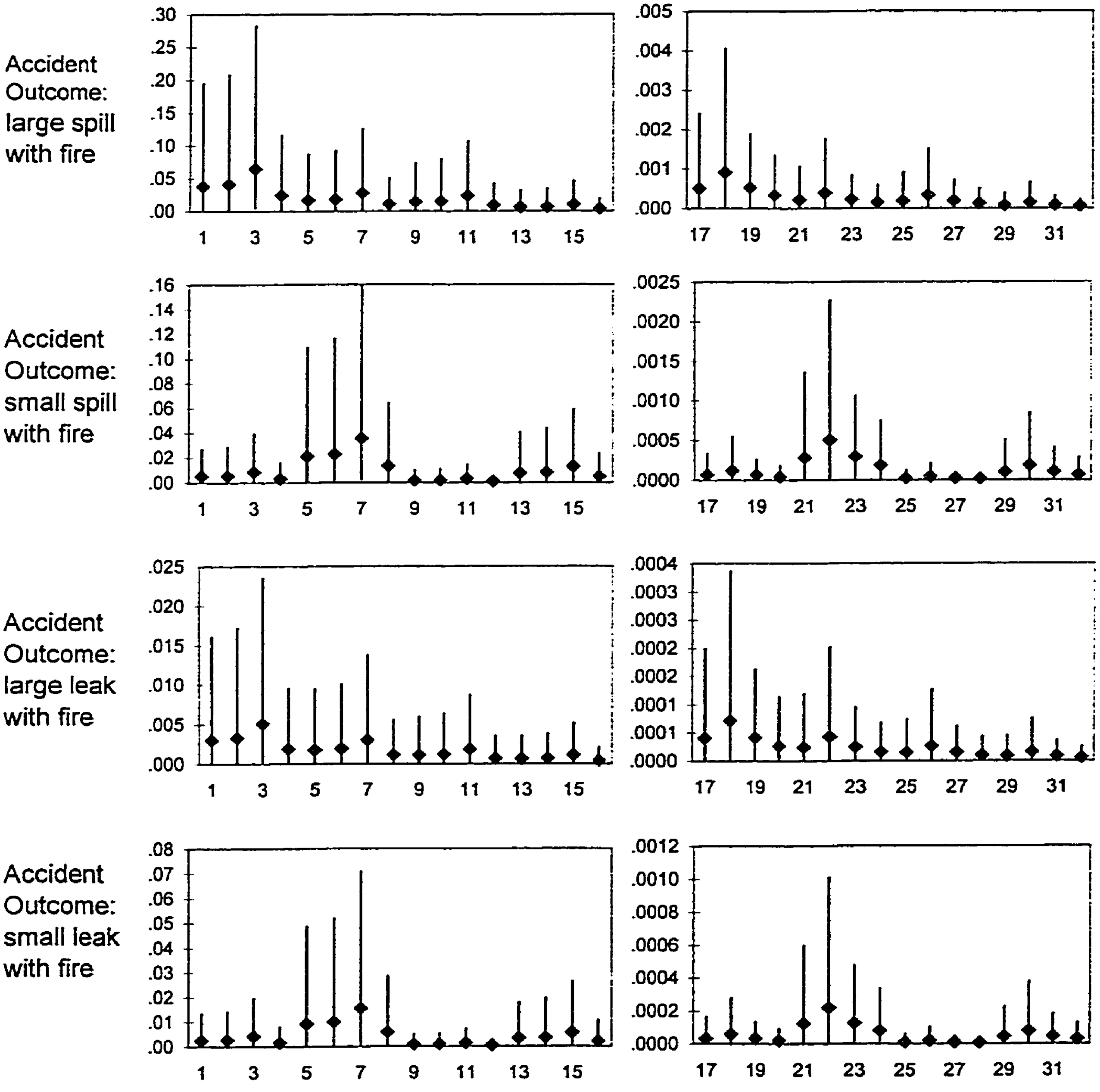


Figure 9.4: High-Low Graphs Showing Ranges of Output Probability Distributions by Accident Scenario (continued)

Legend: x-axis: Accident scenario number
y-axis: Probability of accident outcome
bar: Range of values from 2.5th to 97.5th percentile for probability of accident outcome
tick: Mean value for probability of accident outcome

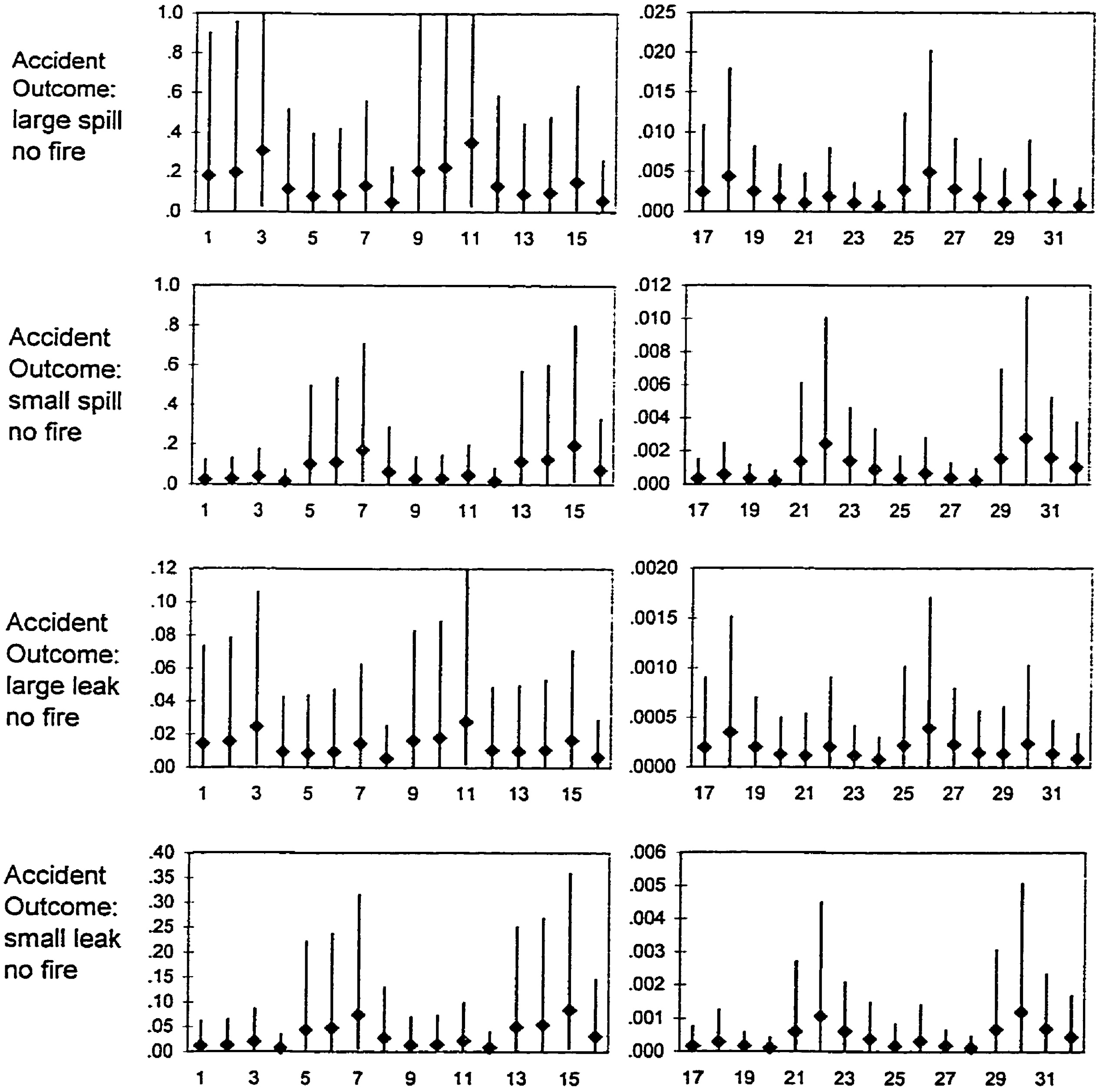


Figure 9.4: High-Low Graphs Showing Ranges of Output Probability Distributions by Accident Scenario (continued)

Legend:	x-axis:	Accident scenario number
	y-axis:	Probability of accident outcome
	bar:	Range of values from 2.5th to 97.5th percentile for probability of accident outcome
	tick:	Mean value for probability of accident outcome

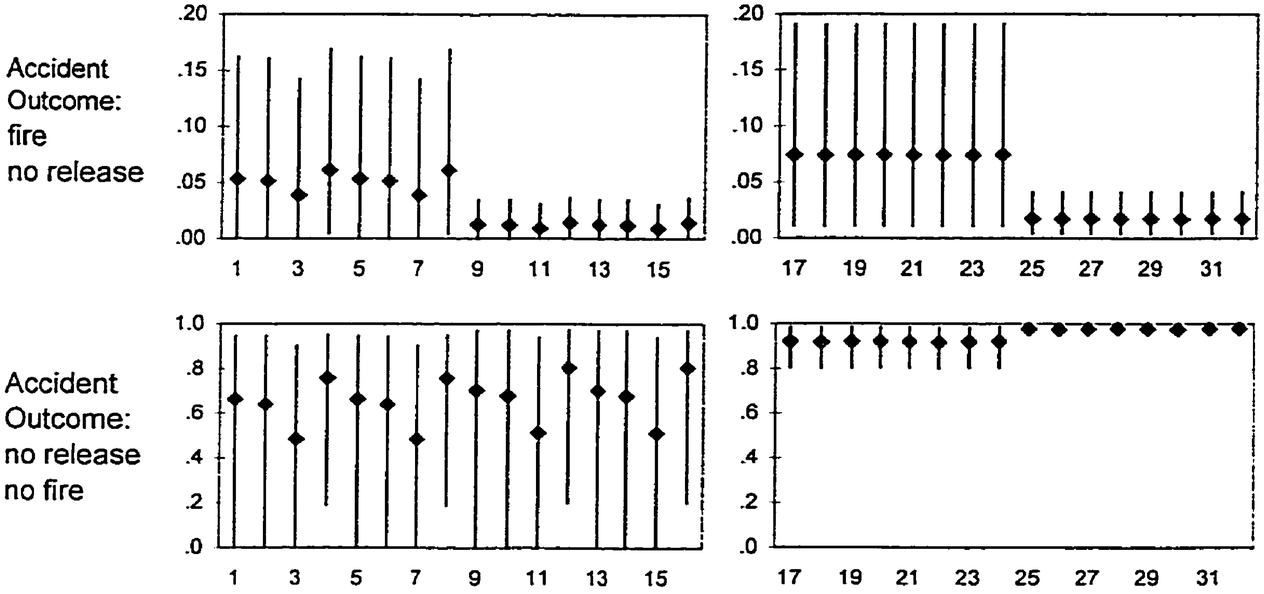


Figure 9.5: High-Low Graphs Showing Ranges of Output Probability Distributions by Non-Accident Scenario

Legend: x-axis: Non-accident scenario number
y-axis: Incidents per Bvkm
bar: Range of values from 2.5th to 97.5th percentile for incidents per Bvkm
tick: Mean value for incidents per Bvkm

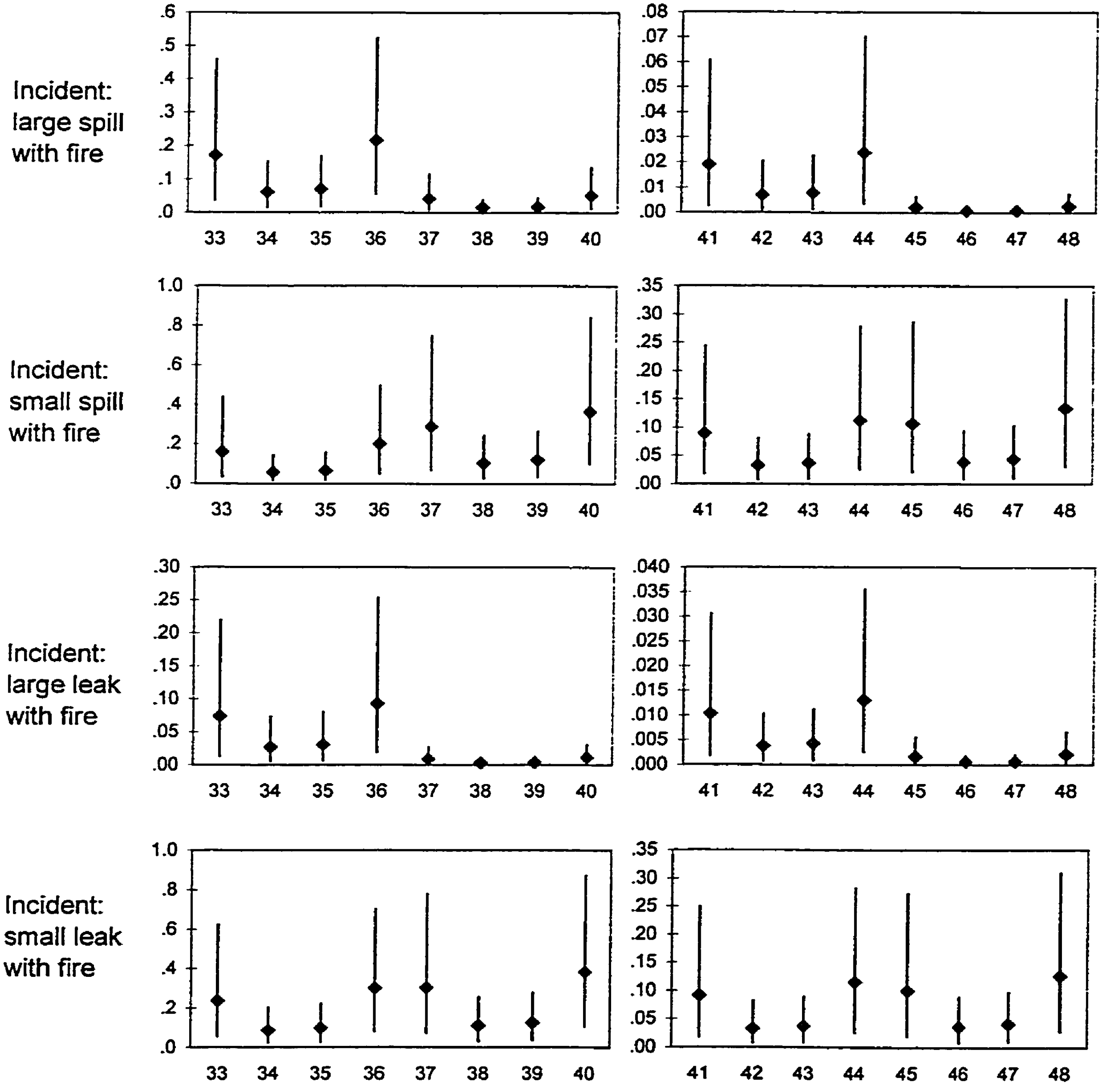
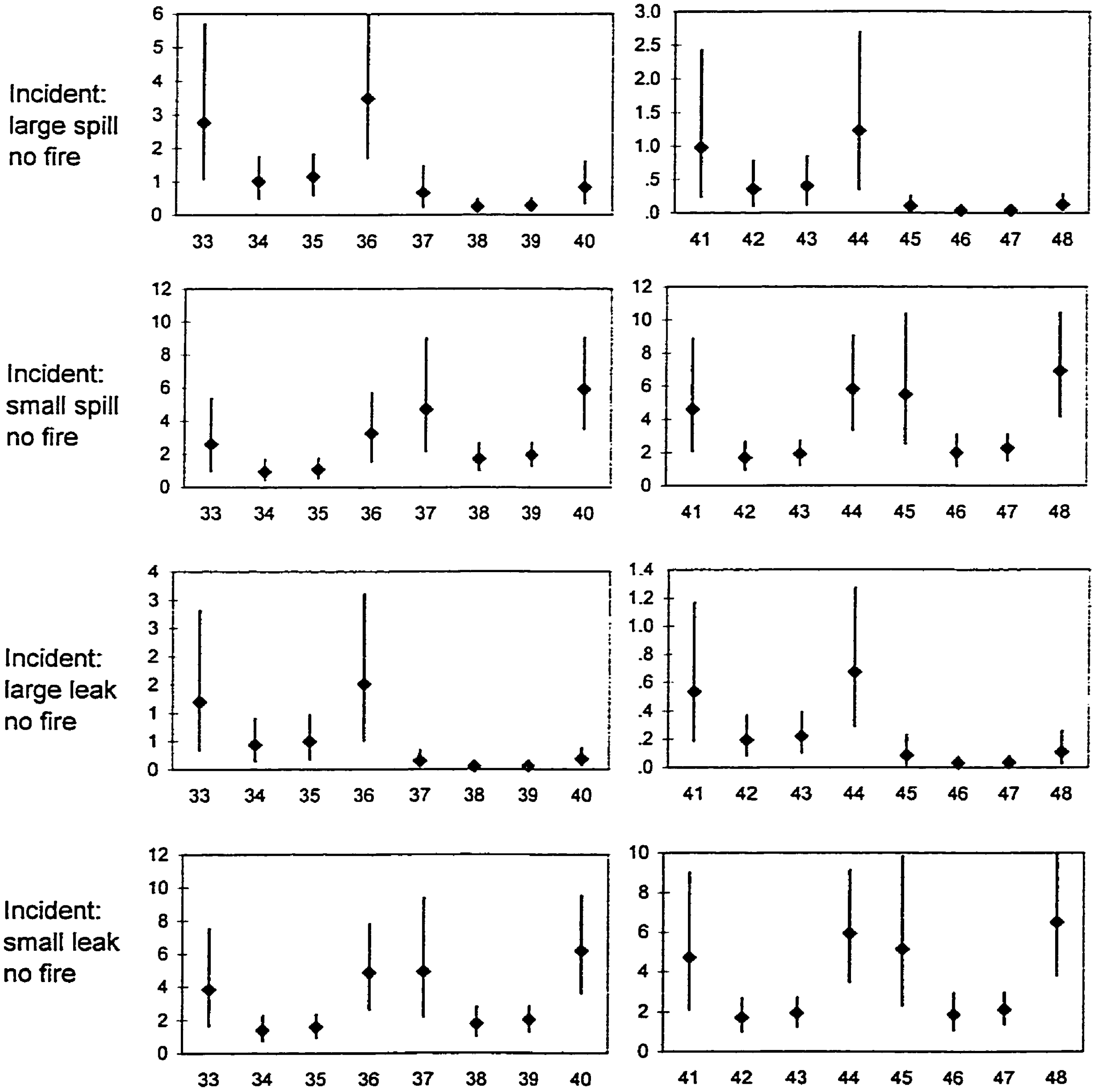


Figure 9.5: High-Low Graphs Showing Ranges of Output Probability Distributions by Non-Accident Scenario (continued)

Legend: x-axis: Non-accident scenario number
y-axis: Incidents per Bvkm
bar: Range of values from 2.5th to 97.5th percentile for incidents per Bvkm
tick: Mean value for incidents per Bvkm



Appendix E shows that the coefficient of variation is fairly consistent for each output variable. For example, depending on the accident scenario, the coefficient of variation ranges from 1.0 to 2.4 for the probability of a large spill with a fire. As a general result, the higher the probability of the outcome, the greater is the width of the 95% probability interval. The width of the 95% probability interval varies dramatically for different scenarios. From Figure 9.4, we can observe that the distributions for the following accident outcomes have higher mean probabilities and wider 95% probability intervals:

- fires and large spills or leaks, for trucks carrying large loads and involved in collisions (Scenarios 1 to 4 and 17 to 21).
- large spills or leaks but no fire, for trucks carrying large loads (Scenarios 1 to 4, 9 to 12, 17 to 20, and 25 to 28).
- small spills or leaks, with or without fires, for trucks carrying small loads (Scenarios 5 to 8, 13 to 16, 21 to 24, and 29 to 32).
- fires but no release, for collisions (Scenarios 1 to 8 and 17 to 24).

For accident outcomes with no fires and no releases, overturns (Scenarios 1 to 16) tend to have the widest probability intervals while accidents with no overturn and no collision (Scenarios 25 to 32) have the narrowest probability intervals and the highest means for the outcome probability.

From Figure 9.5, we can observe that the distributions for the following non-accident incidents have higher mean incident rates and wider 95% probability intervals:

- large spills or leaks, with or without fires, for tanker trucks carrying pressurised or unpressurised toxic liquids (Scenarios 33, 36, 41, and 44).

- small spills or leaks, with or without fires, for trucks carrying pressurised or unpressurised toxic liquids (Scenarios 33, 36, 37, 40, 41, 44, 45 and 48).

9.2.3 Mean Values of Output Probability Distributions

Table 9.2 summarises the mean values of the outcome probability distributions for accident scenarios. Table 9.3 summarises the mean values of the probability distributions for the expected number of incidents per Bvkm for non-accident scenarios.

We can compare the mean values of the distributions in Tables 9.2 and 9.3 with the earlier point estimates in Tables 6.13 and 6.14. It is interesting that there is a noticeable difference between the two sets of tables. For example, for a truck carrying a large load of toxic PLG and involved in an accident with an overturn and collision, the mean of the probability distribution for a large spill with fire is approximately .038 compared with the earlier point estimate of .026.

The differences between the mean values of the distributions and the point estimates for the output variables arise for two reasons. First, as discussed in Section 8.4, the mean values of the probability distributions for the input variables are different from the point estimates of the input variables. The Monte Carlo process used the probability distributions for the input variables to generate the output distributions, while the point estimates of the output variables were calculated using point estimates of the input variables.

Second, there is division in the equations which combine the input variables to calculate the output variables. This division affects the means of the output variables. For example, the equations to predict the probability of accident outcomes include the term:

$$\frac{V2 \times V3}{V5} = \frac{P(\text{type of DG load} \mid \text{release}) \times P(\text{release})}{P(\text{type of DG load})} \tag{9.1}$$

Table 9.2: Mean Values of Outcome Probability Distributions by Accident Scenario

Scenario	Overturn	Collision	Large Load	Type of DG Load *	Probability of Accident Outcome										
					release								no release		total
					fire				no fire				fire	no fire	
					spill		leak		spill		leak				
					large	small	large	small	large	small	large	small			
1	y	y	y	1	.03802	.00514	.00301	.00249	.18290	.02472	.01447	.01196	.05342	.66386	1.00
2	y	y	y	2	.04141	.00558	.00329	.00271	.19902	.02680	.01576	.01301	.05157	.64085	1.00
3	y	y	y	3	.06431	.00868	.00511	.00421	.30889	.04166	.02446	.02020	.03885	.48362	1.00
4	y	y	y	4	.02418	.00326	.00192	.00158	.11614	.01566	.00919	.0076C	.06126	.75922	1.00
5	y	y	n	1	.01649	.02117	.00179	.00922	.07931	.10180	.00860	.04434	.05342	.66386	1.00
6	y	y	n	2	.01801	.02299	.00195	.01005	.08648	.11049	.00937	.04826	.05157	.64085	1.00
7	y	y	n	3	.02794	.03573	.00303	.01561	.13419	.17155	.01456	.07493	.03885	.48362	1.00
8	y	y	n	4	.01051	.01343	.00114	.00586	.05045	.06450	.00548	.02816	.06126	.75922	1.00
9	y	n	y	1	.01391	.00188	.00110	.00091	.20702	.02798	.01638	.01355	.01267	.70460	1.00
10	y	n	y	2	.01512	.00203	.00120	.00099	.22531	.03034	.01786	.01474	.01223	.68018	1.00
11	y	n	y	3	.02342	.00315	.00186	.00153	.34978	.04719	.02771	.02289	.00922	.51325	1.00
12	y	n	y	4	.00882	.00119	.00070	.00058	.13150	.01773	.01041	.00860	.01450	.80598	1.00
13	y	n	n	1	.00602	.00774	.00065	.00337	.08978	.11523	.00974	.05018	.01267	.70460	1.00
14	y	n	n	2	.00656	.00839	.00071	.00367	.09792	.12508	.01061	.05463	.01223	.68018	1.00
15	y	n	n	3	.01017	.01300	.00111	.00569	.15196	.19428	.01649	.08484	.00922	.51325	1.00
16	y	n	n	4	.00383	.00490	.00042	.00214	.05713	.07303	.00620	.03188	.01450	.80598	1.00
17	n	y	y	1	.00051	.00007	.00004	.00003	.00248	.00033	.00020	.00016	.07438	.92180	1.00
18	n	y	y	2	.00092	.00012	.00007	.00006	.00442	.00060	.00035	.00029	.07416	.91902	1.00
19	n	y	y	3	.00053	.00007	.00004	.00003	.00256	.00035	.00020	.00017	.07437	.92168	1.00
20	n	y	y	4	.00034	.00005	.00003	.00002	.00164	.00022	.00013	.00011	.07448	.92300	1.00
21	n	y	n	1	.00022	.00029	.00002	.00012	.00107	.00138	.00012	.00060	.07438	.92180	1.00
22	n	y	n	2	.00040	.00051	.00004	.00022	.00192	.00245	.00021	.00107	.07416	.91902	1.00
23	n	y	n	3	.00023	.00029	.00002	.00013	.00111	.00142	.00012	.00062	.07437	.92168	1.00
24	n	y	n	4	.00015	.00019	.00002	.00008	.00071	.00091	.00008	.00040	.07448	.92300	1.00
25	n	n	y	1	.00019	.00003	.00001	.00001	.00280	.00038	.00022	.00018	.01760	.97857	1.00
26	n	n	y	2	.00033	.00005	.00003	.00002	.00500	.00068	.00039	.00033	.01755	.97563	1.00
27	n	n	y	3	.00019	.00003	.00002	.00001	.00290	.00039	.00023	.00019	.01760	.97845	1.00
28	n	n	y	4	.00012	.00002	.00001	.00001	.00185	.00025	.00015	.00012	.01763	.97985	1.00
29	n	n	n	1	.00008	.00010	.00001	.00005	.00122	.00156	.00013	.00068	.01760	.97857	1.00
30	n	n	n	2	.00014	.00019	.00002	.00008	.00217	.00278	.00024	.00121	.01755	.97563	1.00
31	n	n	n	3	.00008	.00011	.00001	.00005	.00126	.00161	.00014	.00070	.01760	.97845	1.00
32	n	n	n	4	.00005	.00007	.00001	.00003	.00080	.00103	.00009	.00045	.01763	.97985	1.00

- Type of DG Load
  1 = toxic PLG
  2 = flammable PLG
  3 = flammable liquid
  4 = toxic liquid

Table 9.3: Mean Values of Probability Distributions for Incidents per Bvkm by Non-Accident Scenario

Scenario	Urban / Rural	Tanker Truck	Type of DG Load *	Incidents per Bvkm								
				fire				no fire				total
				spill		leak		spill		leak		
				large	small	large	small	large	small	large	small	
33	r	y	1	.171	.160	.074	.238	2.772	2.594	1.199	3.851	11.06
34	r	y	2	.062	.058	.027	.087	1.010	.945	.437	1.402	4.03
35	r	y	3	.071	.066	.031	.098	1.147	1.073	.496	1.592	4.57
36	r	y	4	.216	.202	.093	.299	3.492	3.269	1.511	4.850	13.93
37	r	n	1	.041	.291	.009	.303	.661	4.705	.148	4.903	11.06
38	r	n	2	.015	.106	.003	.110	.241	1.714	.054	1.785	4.03
39	r	n	3	.017	.120	.004	.125	.274	1.946	.061	2.027	4.57
40	r	n	4	.052	.366	.011	.381	.834	5.927	.186	6.175	13.93
41	u	y	1	.019	.090	.010	.092	.977	4.612	.535	4.725	11.06
42	u	y	2	.007	.033	.004	.033	.356	1.680	.195	1.720	4.03
43	u	y	3	.008	.037	.004	.038	.404	1.908	.221	1.953	4.57
44	u	y	4	.024	.113	.013	.116	1.230	5.812	.675	5.950	13.93
45	u	n	1	.002	.107	.002	.101	.101	5.488	.086	5.174	11.06
46	u	n	2	.001	.039	.001	.037	.037	1.999	.031	1.884	4.03
47	u	n	3	.001	.044	.001	.042	.042	2.270	.036	2.139	4.57
48	u	n	4	.002	.134	.002	.127	.127	6.914	.109	6.516	13.93

- Type of DG Load
  1 = toxic PLG
  2 = flammable PLG
  3 = flammable liquid
  4 = toxic liquid

For this term, the variables V2 and V3 are independent. The expected value of V2 x V3 is equal to the expected value of V2 times the expected value of V3, such that:

$$E(V2) \times E(V3) = E(V2 \times V3) \tag{9.2}$$

However, the expected value of the term V2 x V3 / V5 is not equal to the expected value of V2 x V3 divided by the expected value of V5:

$$E(V2 \times V3) / E(V5) \neq E(V2 \times V3 / V5) \tag{9.3}$$

For example, say the term V2 x V3 has a lognormal distribution with mean .20 and standard deviation .02, and say the term V5 has a lognormal distribution with mean .50 and standard deviation .05. Then the mean of the distribution for the term V2 x V3 / V5 is approximately .40. However, if the standard deviation of the term V5 is increased to say .25, then the mean of the distribution for the term V2 x V3 / V5 is approximately .50. The expected value of the term is affected by the probability distributions of the input variables.

We prefer to use the probability distributions rather than the point estimates in describing the expected values of the output variables because the distributions take into account all of the information available, including the data and the assumed shapes of the distributions. Therefore we discuss the characteristics of accident outcome probabilities and non-accident incident rates in terms of the means of their probability distributions rather than their point estimates.

Figure 9.6 contains a 3-dimensional bar graph of the mean outcome probabilities for all accident scenarios. Figure 9.6 shows that fortunately, for accident scenarios, the most likely accident outcome is no release no fire. Depending on the accident category, the mean of the probability distribution for no release no fire is approximately:

- 48% to 81% with an overturn (Scenarios 1 to 16).
- 92% with collision no overturn (Scenarios 17 to 24).
- 98% with no overturn no collision (Scenarios 25 to 32).

If the accident involves an overturn, the next most likely outcome is generally a large spill with no fire (approximately 5% to 35%). If there is no overturn, the next most likely outcome is a fire with no release of the DG load (approximately 7% with and 2% without a collision). If there is no overturn, the mean of the probability distribution for a release is less than 1%.

Figure 9.7 contains a 3-dimensional bar graph of the outcome probabilities for accident fire scenarios only. By focusing on these outcomes only, we can better compare the means of the probability distributions for the different accident scenarios. Figure 9.7 shows that, for Scenarios 1 to 16 (which include overturns), the mean probabilities of spills and leaks with fire are higher than for Scenarios 17 to 33 (which do not include overturns).

The highest bar on the graph in Figure 9.7 is the mean probability for a large spill with a fire for Accident Scenario 3 collision (approximately 6% large spills with fire). Scenario 3 includes a truck carrying a large load of flammable liquids and involved in an accident with an overturn and collision. The least likely accident outcomes include a release with a fire if there is no overturn and no collision (approximately .02% to .04% releases with fires for Scenarios 25 to 32). The mean probability of a large spill with fire is in the range of 300 to 800 times greater (depending on the type of DG load) for a truck carrying a large load with an overturn and collision (Scenarios 1 to 4), compared with a truck carrying a small load that simply runs off the road (Scenarios 29 to 32).

Figure 9.6: 3-D Graph of Mean Outcome Probabilities for All Accident Scenarios

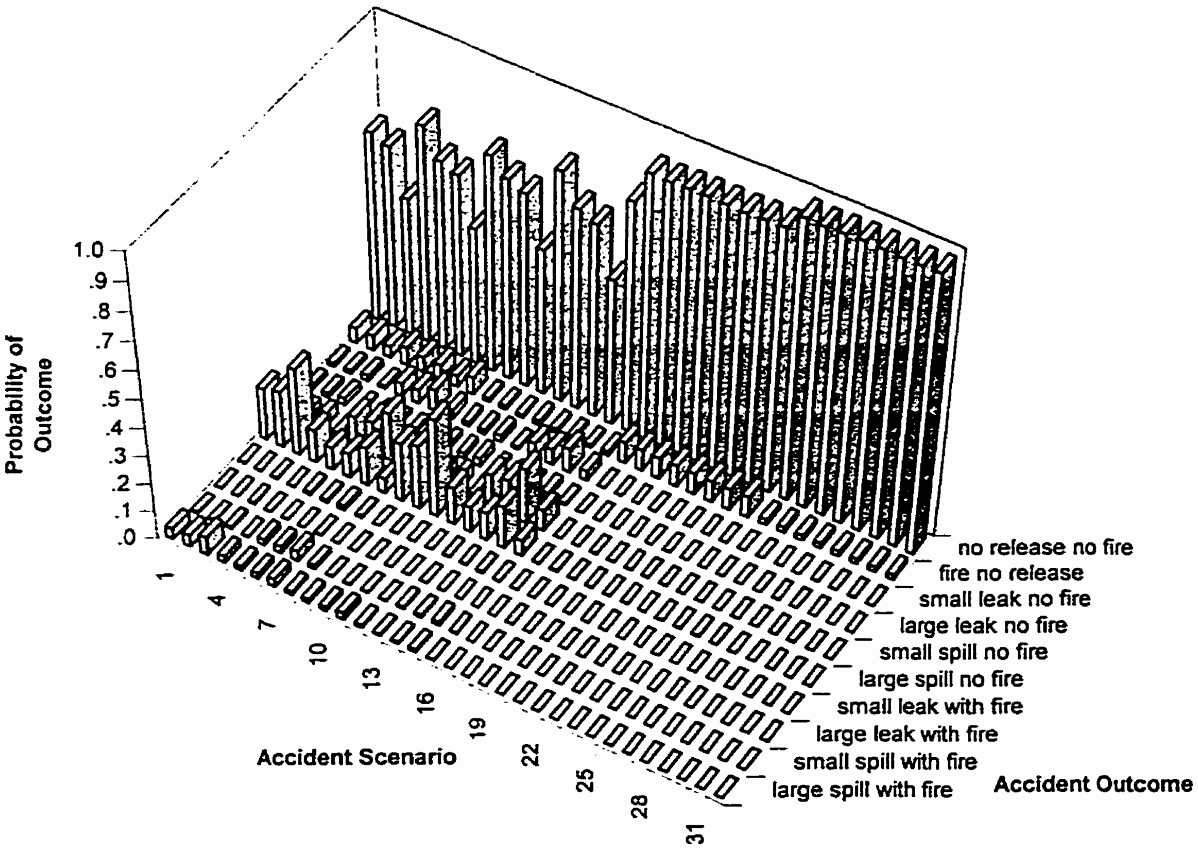


Figure 9.7: 3-D Graph of Mean Outcome Probabilities for Accident Fire Scenarios

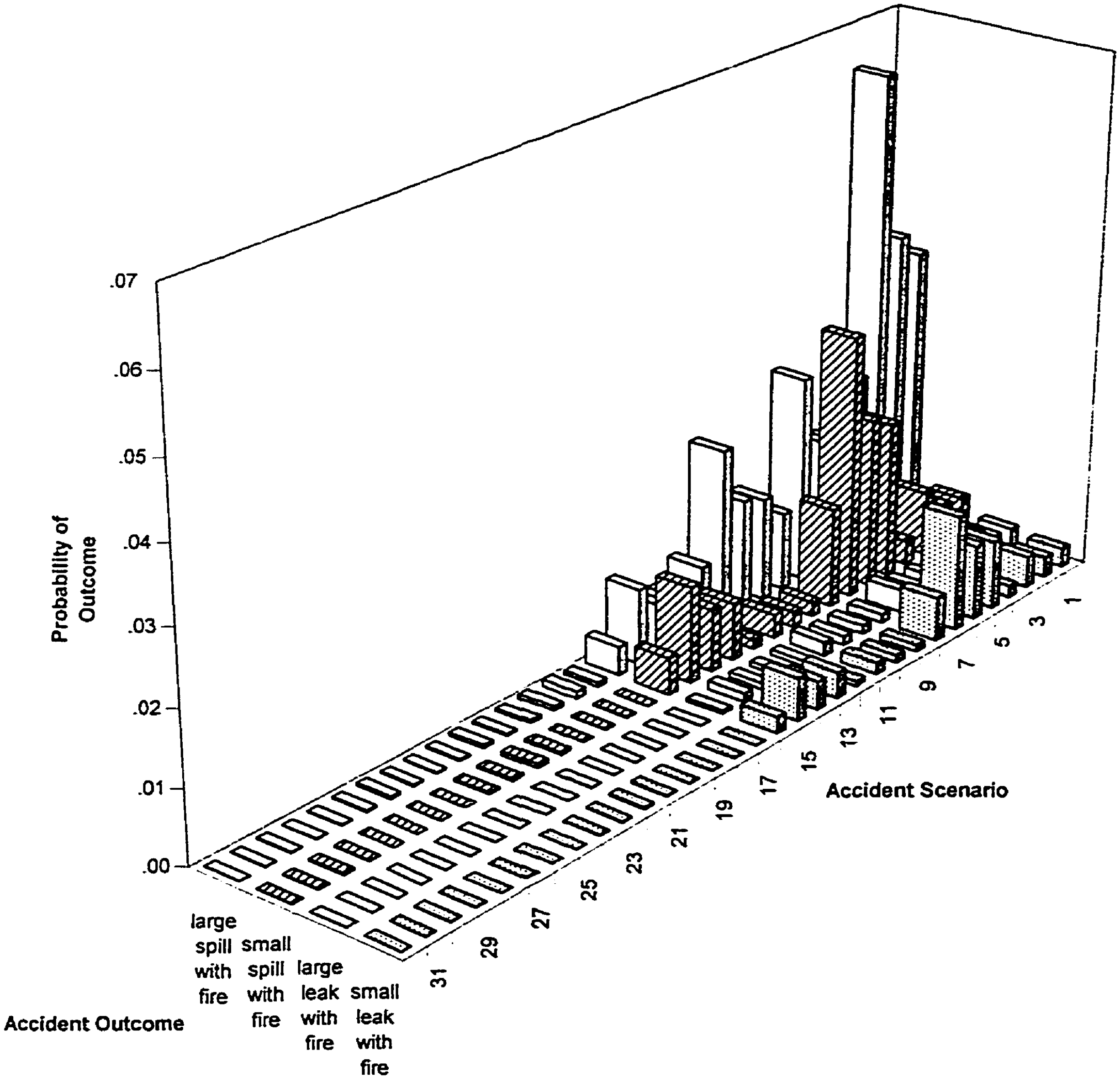


Figure 9.8 contains a 3-dimensional bar graph of the mean incident rates for all non-accident scenarios. Figure 9.8 shows that, for non-accident release scenarios, the highest mean incident rate is for small spills or leaks with no fire. We can expect a mean of between approximately 1.4 and 6.5 small leaks with no fire per Bvkm, depending on the non-accident scenario.

For non-accident scenarios, the mean incident rate for large spills with fire is over 80 times greater for a tanker truck in a rural area (approximately .07 to .22 large spills with fire per Bvkm for Scenarios 33 to 36), compared with a non-tanker truck in an urban area (approximately .001 to .002 large spills with fire per Bvkm for Scenarios 45 to 48). These mean incident rates vary with the type of DG load.

Figure 9.9 contains a 3-dimensional bar graph that focuses on the mean incident rates for non-accident fire scenarios only. Figure 9.9 shows that, for each non-accident fire scenario, the mean incident rates for small leaks and spills with fires are higher (approximately .07 to .75 small releases with fire per Bvkm) than those for large leaks or spills with fires (approximately .001 to .31 large releases with fire per Bvkm). In addition, the mean fire incident rate for all types of releases combined tends to be higher for rural roads (approximately .23 to .81 fires per Bvkm for Scenarios 33 to 40) than urban roads (approximately .08 to .27 fires per Bvkm for Scenarios 41 to 48). The non-accident scenario with the highest mean incident rate of large spills with fire is Scenario 36, which includes a tanker truck carrying toxic liquid on a rural road (approximately .22 large spills with fire per Bvkm).

Figure 9.8: 3-D Graph of Mean Incident Rates for All Non-Accident Scenarios

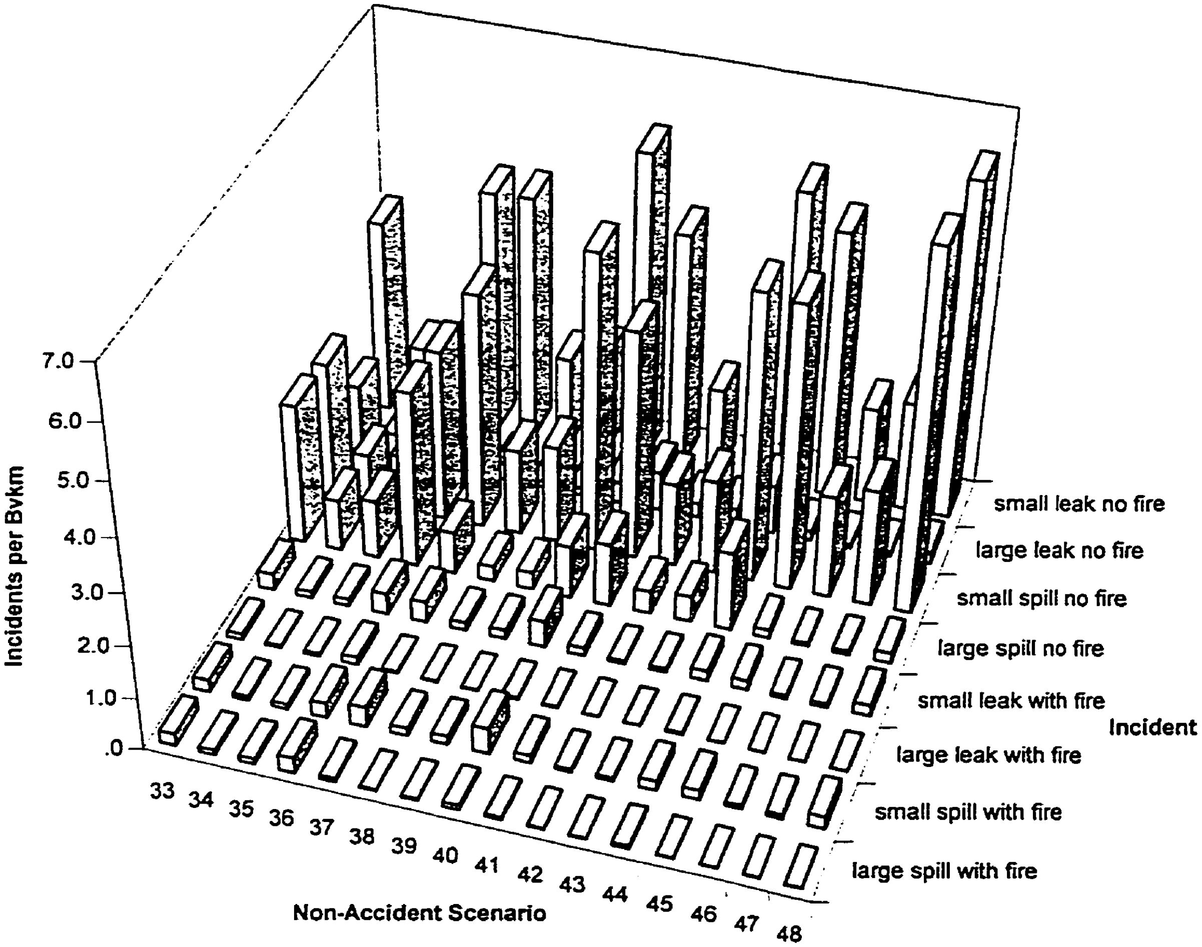
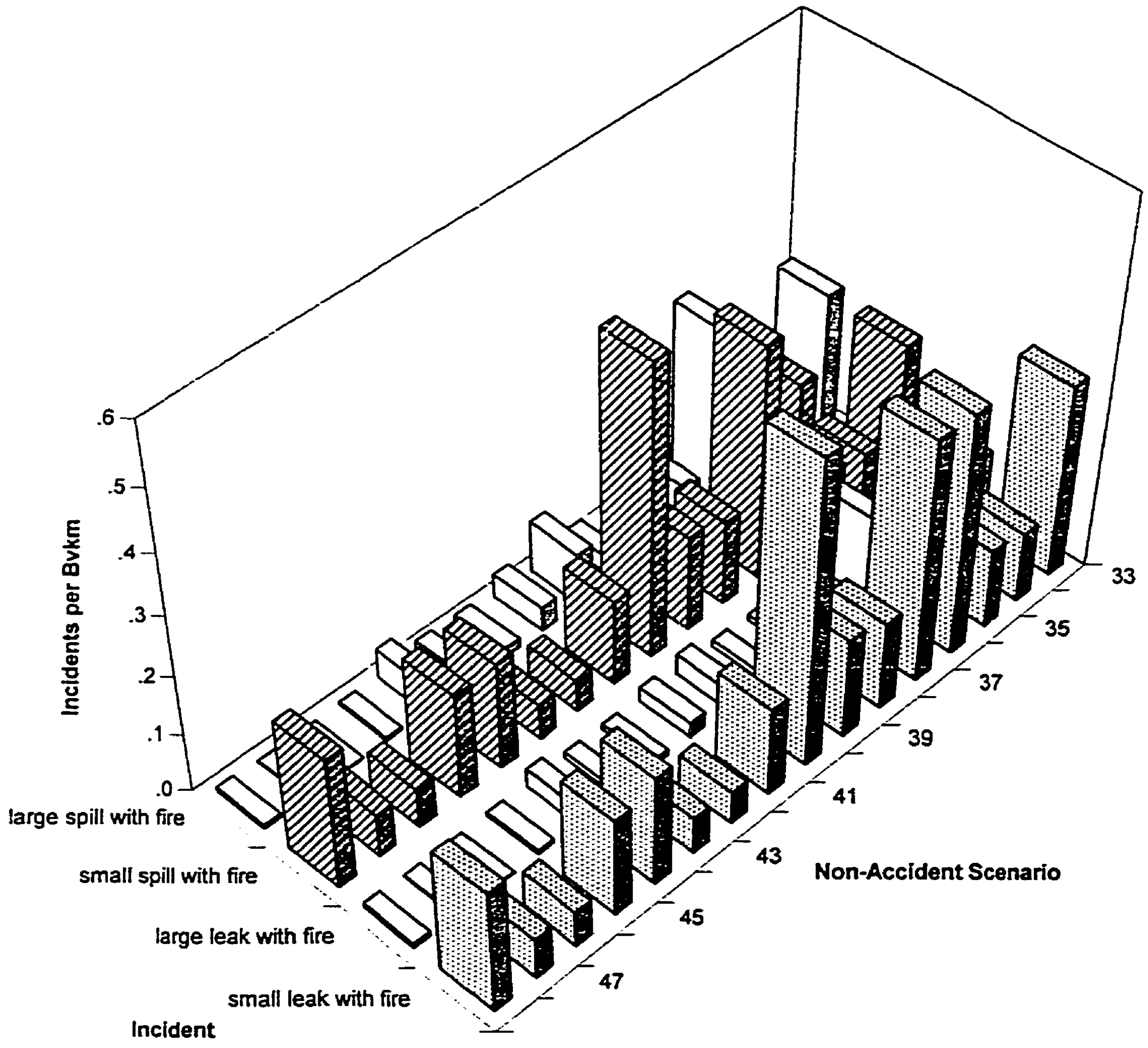


Figure 9.9: 3-D Graph of Mean Incident Rates for Non-Accident Fire Scenarios



CHAPTER 10

SAMPLE APPLICATION OF RESEARCH RESULTS

Chapter 10 contains the following sections:

10.1 Sample Roads
10.2 Point Estimates of Output Values for Sample Application
10.3 Uncertainty in Output Values for Sample Application

Chapter 10 provides an application of the model to two sample roads. The model application generates both point estimates and probability distributions for the expected rates of accident and non-accident incidents per Bvkm.

10.1 SAMPLE ROADS

To use our model to predict release and fire incident rates, we need to know the following information about the vehicle:

- the type of DG load.
- whether the truck is a tanker or non-tanker.
- the load size.

For this sample application of the model, we assume that the vehicle is a tanker truck carrying a large load of flammable liquid.

In an actual application of the model to a route, the user would divide the route into segments that are fairly homogeneous in terms of three factors:

- the proportion of truck accidents with overturns and/or collisions.
- whether the road is urban or rural.
- the truck accident rate.

Table 10.1 contains the proportion of accidents with overturns and/or collisions by Ontario highway. The ADS database supplies this information for loaded trucks involved in accidents on Ontario highways from 1988 to 1995. Table 10.1 sorts the highways by proportion of accidents with overturns, from high to low. The proportion of accidents with overturns varies widely, from .022 for Highway 5 to .133 for Highway 101. It is likely that the proportion of accidents with overturns and/or collisions varies widely along a given highway. For all Ontario truck accidents combined, approximately 2% involve overturns and collisions, 5% involve overturns with no collision, 82% involve collisions with no overturn, and 11% involve no overturn and no collision.

A detailed analysis of accidents to determine which factors lead to overturns and/or collisions is beyond the scope of this thesis. Preliminary analysis of the Ontario ADS using logistic regression indicates that overturns are more likely for accidents on ramps, compared with other sections of road. From ADS, approximately 20% of truck accidents on ramps involve overturns, compared with only 4% on other road sections. Collisions are more likely for accidents at intersections. Tractors with double trailers are more likely to overturn in an accident than other truck types. The proportion of accidents with overturns and collisions may also vary by road geometry, travel speed, road surface conditions, driver training, etc.

To show a range of results, we roughly base our two sample roads on Highways 7 and 17. We assume that the proportions of accidents with overturns and collisions on the sample roads are the same as the proportions given for Highways 7 and 17 in Table 10.1. Highway 7 runs through southern Ontario from Sarnia to Ottawa, through many urban areas. Highway

Table 10.1: Proportion of Truck Accidents with Overturn and/or Collision by Ontario Highway

	Number of Accidents					Proportion of Accidents						
Overturn:	y	y	n	n	total	y	y	n	n	total	y	
Collision:	y	n	y	n		y	n	y	n			y
Hwy 101	5	14	101	23	143	.035	.098	.706	.161	1.000	.133	.741
Hwy 144	7	13	119	27	166	.042	.078	.717	.163	1.000	.120	.759
Hwy 403	18	33	415	73	539	.033	.061	.770	.135	1.000	.095	.803
Hwy 17	**81**	**117**	**1,682**	**267**	**2,147**	**.038**	**.054**	**.783**	**.124**	**1.000**	**.092**	**.821**
Hwy 402	6	13	159	36	214	.028	.061	.743	.168	1.000	.089	.771
Hwy 9	9	5	127	24	165	.055	.030	.770	.145	1.000	.085	.824
Hwy 11	64	115	1,766	247	2,192	.029	.052	.806	.113	1.000	.082	.835
Hwy 69	7	22	310	66	405	.017	.054	.765	.163	1.000	.072	.783
Hwy 3	3	17	240	29	289	.010	.059	.830	.100	1.000	.069	.841
Hwy 86	2	4	77	17	100	.020	.040	.770	.170	1.000	.060	.790
Hwy 401	160	324	7,114	899	8,497	.019	.038	.837	.106	1.000	.057	.856
Hwy 6	5	12	302	21	340	.015	.035	.888	.062	1.000	.050	.903
Hwy 400	18	24	695	107	844	.021	.028	.823	.127	1.000	.050	.845
Hwy 27	2	5	128	8	143	.014	.035	.895	.056	1.000	.049	.909
Hwy 417	9	13	391	41	454	.020	.029	.861	.090	1.000	.048	.881
Hwy 427	8	9	299	37	353	.023	.025	.847	.105	1.000	.048	.870
Hwy 2	5	14	350	29	398	.013	.035	.879	.073	1.000	.048	.892
Hwy 24	3	2	96	9	110	.027	.018	.873	.082	1.000	.045	.900
Hwy 1	43	43	1,686	176	1,948	.022	.022	.866	.090	1.000	.044	.888
Hwy 10	1	4	110	4	119	.008	.034	.924	.034	1.000	.042	.933
Hwy 7	**15**	**21**	**1,027**	**70**	**1,133**	**.013**	**.019**	**.906**	**.062**	**1.000**	**.032**	**.920**
Hwy 8	1	2	87	10	100	.010	.020	.870	.100	1.000	.030	.880
Hwy 404	5	1	197	28	231	.022	.004	.853	.121	1.000	.026	.874
Hwy 5	1	2	124	7	134	.007	.015	.925	.052	1.000	.022	.933
All Highways	596	1,089	19,861	2,637	24,183	.025	.045	.821	.109	1.000	.070	.846

17 runs through northern Ontario between Ottawa and Thunder Bay, typically through rural areas with few urban areas. Neither highway has any interchanges and therefore neither highways has any ramps. For this example, we classify our Highway 7 sample road as "urban" and our Highway 17 sample road as "rural".

Table 10.2 below summarises the expected proportion of accidents with overturns and/or collisions for our sample roads.

Table 10.2: Proportion of Truck Accidents with Overturn and/or Collision for Sample Roads

	Highway 7	Highway 17
overturn and collision	.013	.038
overturn no collision	.019	.054
collision no overturn	.906	.783
no overturn no collision	.062	.124
total	1.000	1.000

The MTO report *Provincial Highways Traffic Volumes 1992* provides estimates of accident rates for all vehicle types combined for each Provincial highway in Ontario. Generally, trucks have lower accident rates than cars. For the purposes of this example, we assume that the truck accident rates on our sample roads are the same as the accident rates provided for the combined vehicle types on Highways 7 and 17 in the MTO report. The accident rate for Highway 7 varies between 200 and 6,900 accidents per Bvkm, depending on the section of highway. The mean accident rate for Highway 7 is 1,330 accidents per Bvkm. The accident rate for Highway 17 varies between 200 and 6,500 accidents per Bvkm, depending on the section of highway. The mean accident rate for Highway 17 is 1,200 accidents per Bvkm.

To summarise, our sample road which we call Highway 7 has a higher accident rate but a lower proportion of accidents with overturns. Our sample road which we call Highway 17 has a lower accident rate but the accidents are more likely to involve overturns.

10.2 POINT ESTIMATES OF OUTPUT VALUES FOR SAMPLE APPLICATION

We use the information regarding the type of DG load, load size, whether the truck is a tanker or non-tanker truck, and whether the road is urban or rural to select the relevant model scenarios for our sample application. Tables 5.7 and 5.8 earlier described the model scenarios. For a tanker truck carrying a large load of flammable liquid, the relevant Accident Scenarios are 3, 11, 19 and 27. The relevant Non-Accident Scenarios for the same truck are 35 if the truck is on a rural road and 43 if the truck is on an urban road.

Table 10.3 contains a spreadsheet that combines the required information from the model and from the sample roads to calculate the point estimates of incidents per Bvkm for the sample roads. Table 10.3 shows both the input information and the calculated output results. The required information to apply the model includes:

- from the model, the point estimates of the probabilities of accident outcomes by accident type (overturn and/or collision). Table 6.13 provides the estimates relevant to our sample roads for Scenarios 3, 11, 19 and 27.

- also from the model, the point estimates of the non-accident incidents per Bvkm for Scenarios 35 and 43. Table 6.14 provides these estimates.

- an estimate of the incident rate of non-accident non-release fires. From Section 5.1.1, the incident rate is approximately .22 incidents per Bvkm.

- for the sample roads, the probabilities of the types of accident (overturn and/or collision), given that an accident has occurred. Table 10.2 provides these probabilities.

- the accident rates for the sample roads. From Section 10.1, the mean accident rates are 1,330 accidents per Bvkm for Highway 7 and 1,200 accidents per Bvkm for Highway 17.

Table 10.3: Spreadsheet to Calculate Point Estimates of Incidents per Bvkm for Sample Roads

	Incident Outcome											Probability of Type of Accident	
	release								no release		total		
	fire				no fire				fire	no fire			
	spill		leak		spill		leak						
	large	small	large	small	large	small	large	small					
	Probability of Accident Outcome by Accident Type *											**Hwy 7**	**Hwy 17**
a	.03981	.00543	.00303	.00265	.20130	.02748	.01534	.01342	.01849	.67304	1.00	.013	.038
b	.01588	.00217	.00121	.00106	.22523	.03075	.01716	.01502	.00625	.68528	1.00	.019	.054
c	.00058	.00008	.00004	.00004	.00292	.00040	.00022	.00019	.02662	.96891	1.00	.906	.783
d	.00023	.00003	.00002	.00002	.00326	.00045	.00025	.00022	.00900	.98654	1.00	.062	.124
												Acc Rate per Bvkm	
Hwy	**Probability of Accident Outcome by Sample Highway**											**Hwy 7**	**Hwy 17**
7	.0014	.0002	.0001	.0001	.0097	.0013	.0007	.0006	.0250	.9608	1.00	1330	
17	.0028	.0004	.0002	.0002	.0226	.0031	.0017	.0015	.0230	.9445	1.00		1200
Hwy	**Accidents per Bvkm**												
7	1.8	.2	.1	.1	12.9	1.8	1.0	.9	33.3	1277.9	1330		
17	3.4	.5	.3	.2	27.1	3.7	2.1	1.8	27.6	1133.4	1200		
Hwy	**Non-Accident Incidents per Bvkm ****												
7	.011	.039	.005	.043	.515	1.774	.218	1.966	.220		4.79		
17	.067	.086	.033	.114	.960	1.226	.464	1.623	.220		4.79		
Hwy	**Total Accident and Non-Accident Incidents per Bvkm**												
7	1.8	.3	.1	.2	13.4	3.5	1.2	2.8	33.5	1277.9	1335		
17	3.5	.6	.3	.3	28.0	4.9	2.5	3.4	27.8	1133.4	1205		

Notes:

* Accident Type a = Scenario 3 (overturn and collision)
Accident Type b = Scenario 11 (overturn no collision)
Accident Type c = Scenario 19 (collision no overturn)
Accident Type d = Scenario 27 (no overturn no collision)

** Non-Accident Incidents for Highway 7 = Scenario 43 (urban)
Non-Accident Incidents for Highway 17 = Scenario 35 (rural)

Legend:

input values

calculated values

As an example of the equations used in the spreadsheet in Table 10.3, we can calculate the point estimate of the total number of large spills with fires per Bvkm for Highway 7 as follows:

(10.1)

total number of large spills with fire per Bvkm

= number of non-accident large spills with fire per Bvkm
+ number of accident-induced large spills with fire per Bvkm

= number of non-accident large spills with fire per Bvkm
+ {accident rate
x [P(large spill with fire | overturn & collision) x P(overturn & collision | accident)
+ P(large spill with fire | overturn no collision) x P(overturn no collision | accident)
+ P(large spill with fire | collision no overturn) x P(collision no overturn | accident)
+ P(large spill with fire | no overturn no collision) x P(no overturn no collision | accident)]}

= .011 + {1,330 x [.03981 x .013 + .01588 x .019 + .00058 x .906 + .00023 x .062]}

= 1.8 large spills with fire per Bvkm

The model predicts that small releases will be approximately 60% non-accident for the urban road (Highway 7) and 30% non-accident for the rural road (Highway 17). Only about 5% of the large releases are expected to be non-accident for both highways. For comparison, Kornhauser et al. (1994) note that, in the USA, 1/3 of DG releases are accident-related and 2/3 are non-accident.

10.3 UNCERTAINTY IN OUTPUT VALUES FOR SAMPLE APPLICATION

10.3.1 Uncertainty in Accident Rates, Type of Accident and Incident Outcomes

To quantify the uncertainty in the output values for our sample application, we need to know the uncertainty in all of the input variables. There is uncertainty in the estimates of the accident rates and of the probabilities of the type of accident for our sample roads. To quantify the uncertainty for the probabilities of the type of accident, we used annual data from the Ontario ADS for the sample roads. We grouped the data by two-year intervals to provide four sets of data points for each accident type, for each sample road, and fit lognormal curves to the data points. To quantify the uncertainty for the accident rates, we took as data points the accident rates given in the MTO *Provincial Highways Traffic Volumes 1992* for the different sections of each highway. We fit lognormal curves to the accident rate data points, for each sample road, to represent their probability distributions.

From our model, Appendix E provides the mean and standard deviation for the probability distribution for each incident outcome, for each relevant accident and non-accident scenario. Table 10.4 summarises this information. We use the means and standard deviations to re-create lognormal probability distributions. We do not have a probability distribution from the model for the number of non-accident non-release fires per Bvkm, and assume that the mean and standard deviation for this rate are both .22 incidents per Bvkm.

We then combine these uncertain inputs using a spreadsheet and equations similar to those used in Table 10.3, and Monte Carlo simulations. These simulations provide probability distributions for the incidents per Bvkm for each type of incident outcome, and for each sample road.

Table 10.4: Mean and Standard Deviation for Probability Distributions for Model Variables Relevant to Sample Roads

		Scenario					
		3	11	19	27	35	43
large spill with fire	mean	.06431	.02342	.00053	.00019	.07082	.00785
	std dev	.10164	.03924	.00050	.00020	.03876	.00574
small spill with fire	mean	.00868	.00315	.00007	.00003	.06633	.03713
	std dev	.01331	.00495	.00007	.00003	.03677	.02094
large leak with fire	mean	.00511	.00186	.00004	.00002	.03062	.00431
	std dev	.00996	.00393	.00004	.00002	.01970	.00276
small leak with fire	mean	.00421	.00153	.00003	.00001	.09825	.03802
	std dev	.00772	.00294	.00004	.00001	.05056	.02124
large spill no fire	mean	.30889	.34978	.00256	.00290	1.14663	.40416
	std dev	.42808	.48551	.00211	.00237	.31615	.18984
small spill no fire	mean	.04166	.04719	.00035	.00039	1.07308	1.90771
	std dev	.05673	.06434	.00030	.00034	.30724	.38547
large leak no fire	mean	.02446	.02771	.00020	.00023	.49581	.22134
	std dev	.04062	.04630	.00019	.00021	.20502	.07463
small leak no fire	mean	.02020	.02289	.00017	.00019	1.59195	1.95297
	std dev	.03200	.03648	.00015	.00017	.35593	.37551
fire no release	mean	.03885	.00922	.07437	.01760	.22	.22
	std dev	.06370	.01389	.04766	.00974	.22	.22
no fire no release	mean	.48362	.51325	.92168	.97845		
	std dev	.61583	.65446	.04778	.01024		

10.3.2 Mean Incident Rates

The incident rates are the output from the sample model application. Table 10.5 summarises the means from the probability distributions for incident rates for a tanker truck carrying a large load of flammable liquid on the sample roads, Highways 7 and 17. The mean expected number of releases is 61.5 per Bvkm for Highway 17 and 31.2 per Bvkm for Highway 7. For comparison, Kornhauser et al. (1994) estimate a release rate of approximately 28.0 releases per Bvkm for tanker trucks carrying anhydrous ammonia (a non-flammable toxic gas).

It is interesting that although Highway 7 has the higher accident rate, Highway 17 is expected to have more releases per Bvkm, with and without fires. The higher release rate is related to the higher proportion of overturn accidents on Highway 17. For both highways, spills are expected to be more common than leaks, and large releases more common than small, with and without fires.

Figure 10.1 provides bar charts of the means from the probability distributions for incident rates for the sample roads. Figure 10.1 first shows a bar chart of the mean incident rates for all possible accident outcomes. For both highways, by far the most frequent type of incident for a tanker truck carrying a large load of flammable liquid is expected to be no release no fire. The mean expected number of incidents with no release no fire is 1,217 per Bvkm for Highway 7 and 1,071 per Bvkm for Highway 17.

Figure 10.1 then shows a bar chart, which focuses on mean release incident rates. For a tanker truck carrying a large load of flammable liquid, Highway 17 is expected to have a higher mean incident rate than Highway 7 for all types of releases. The most apparent difference in the mean incident rates between the two highways is for large spills no fire. For this type of release, the mean incident rate is expected to be 40.6 per Bvkm for Highway 17 and 18.6 per Bvkm for Highway 7. Again, this difference in incident rates relates to the higher proportion of overturn accidents on Highway 17, even though the accident rate is higher on Highway 7.

Table 10.5: Summary of Means of Probability Distributions for Incidents per Bvkm for Sample Roads

		Highway 7		
		fire	no fire	total
spill	large	2.6	18.6	21.2
	small	.4	4.4	4.8
leak	large	.2	1.7	1.9
	small	.2	3.1	3.3
no release		91.9	1217.1	1309.0
total		95.2	1244.9	1340.1

release	3.3	27.8	31.2
no release	91.9	1217.1	1309.0
total	95.2	1244.9	1340.1

spill	2.9	23.0	26.0
leak	.4	4.8	5.2
total	3.3	27.8	31.2

large	2.8	20.3	23.1
small	.6	7.5	8.1
total	3.3	27.8	31.2

		Highway 17		
		fire	no fire	total
spill	large	5.1	40.6	45.7
	small	.7	6.4	7.2
leak	large	.4	3.7	4.1
	small	.4	4.2	4.6
no release		74.9	1071.2	1146.0
total		81.5	1126.0	1207.5

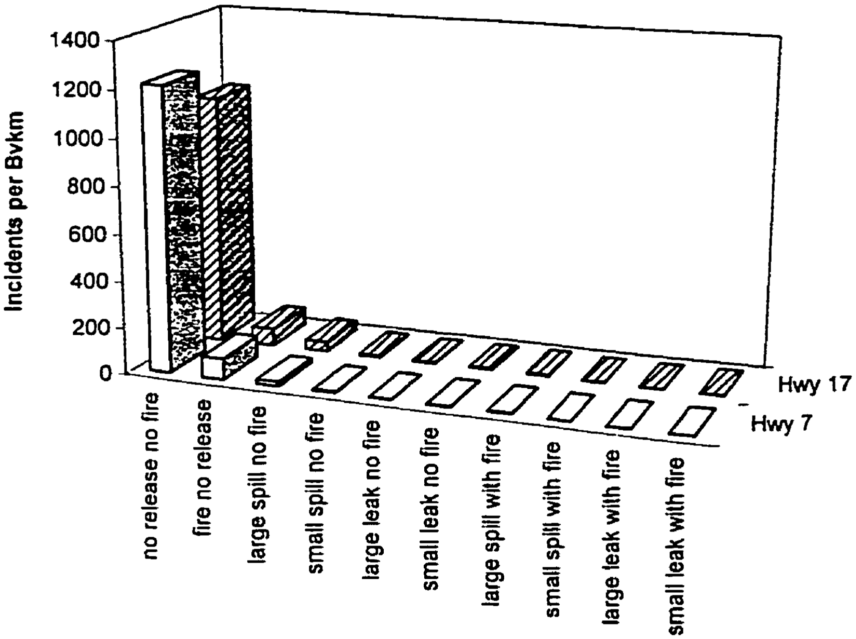
release	6.6	54.9	61.5
no release	74.9	1071.2	1146.0
total	81.5	1126.0	1207.5

spill	5.8	47.0	52.8
leak	.8	7.8	8.7
total	6.6	54.9	61.5

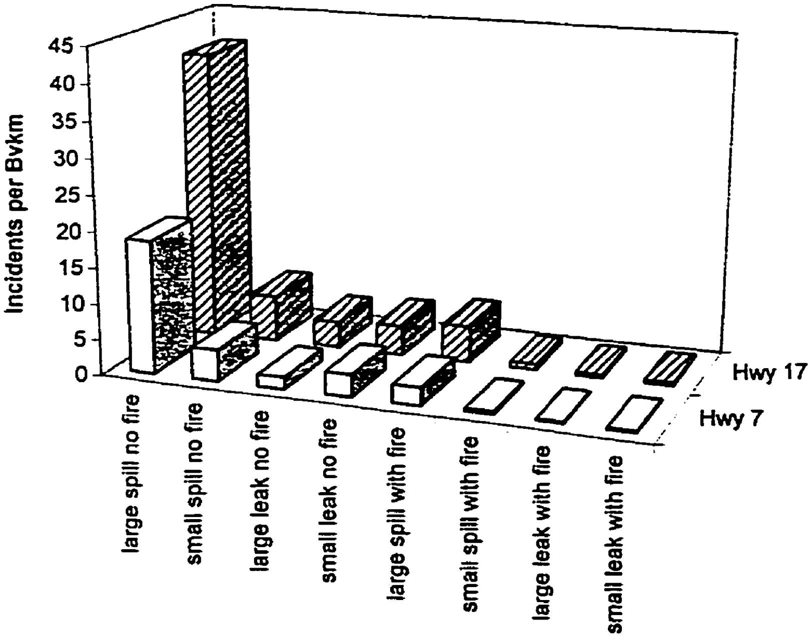
large	5.5	44.3	49.8
small	1.2	10.6	11.7
total	6.6	54.9	61.5

Figure 10.1: Bar Chart of Means of Probability Distributions for Incidents per Bvkm for Sample Roads

Incident Rates for All Possible Incident Outcomes



Release Incident Rates



10.3.3 Uncertainty in Incident Rates

Table 10.6 summarises the statistics for the probability distributions for the incident rates. Each of the probability distributions is positively skewed, as is compatible with a lognormal distribution.

Table 10.6 shows that the kurtosis is generally lower for the release incident rates for Highway 17 compared with Highway 7. A lower kurtosis indicates a flatter probability curve. This is confirmed in Figure 10.2, which contains graphs comparing the probability distributions for each type of incident per Bvkm for the sample roads. Generally, the probability distributions for the release rates for Highway 17 are flatter and extend further than for Highway 7.

The coefficient of variation is generally higher for the incident rates for Highway 7 compared with Highway 17. This indicates that, as a proportion of the mean, there is more uncertainty in the expected incident rates for Highway 7, even though Highway 17 has wider 95% probability intervals.

Table 10.6 shows the 2.5th and 97.5th percentiles for the probability distributions for the incidents per Bvkm for the sample roads. For each type of incident, the 97th percentile is two to five times greater than the mean value for the probability distribution. This indicates the high level of uncertainty associated with these estimates. Analysts should not ignore this uncertainty in applying these results to further risk analysis. There is further uncertainty in the impacts of the incidents to the environment and to the public. The combined uncertainty in the incident rates and incident impacts could result in a significant amount of uncertainty in the predicted risks of transporting DG loads by truck.

Table 10.6: Statistics for Probability Distributions for Incidents per Bvkm for Sample Roads

Highway	Incident Outcome	2.5th percentile	97.5th percentile	Mean	Median	Standard Deviation	Skewness	Kurtosis	Coeff. of Variation
Highway 7	large spill with fire	.21	11.98	2.56	1.37	4.85	14.67	463.35	1.90
	small spill with fire	.06	1.61	.38	.22	.62	15.92	758.79	1.63
	large leak with fire	.02	1.00	.20	.10	.38	10.17	191.65	1.89
	small leak with fire	.04	.81	.20	.12	.34	17.63	610.04	1.73
	large spill no fire	2.00	83.28	18.62	10.78	28.68	9.80	206.17	1.54
	small spill no fire	1.85	13.08	4.39	3.39	4.21	16.71	790.75	.96
	large leak no fire	.31	7.16	1.67	1.00	2.44	8.78	150.86	1.46
	small leak no fire	1.68	7.50	3.15	2.68	2.04	10.08	225.26	.65
	fire no release	11.20	347.18	91.87	62.47	100.22	4.71	51.62	1.09
	no release no fire	256.54	3632.17	1217.09	965.57	937.23	2.94	21.93	.77
Highway 17	large spill with fire	.55	22.22	5.06	2.98	7.63	13.51	565.66	1.51
	small spill with fire	.12	3.00	.74	.47	.97	8.05	141.39	1.32
	large leak with fire	.06	1.96	.42	.24	.66	13.10	486.88	1.57
	small leak with fire	.09	1.60	.42	.28	.49	6.96	99.13	1.19
	large spill no fire	5.29	169.64	40.62	25.42	53.54	8.06	166.25	1.32
	small spill no fire	1.53	23.83	6.43	4.43	6.86	5.40	55.85	1.07
	large leak no fire	.69	14.92	3.66	2.29	5.20	11.44	288.49	1.42
	small leak no fire	1.60	13.12	4.16	3.14	3.65	6.48	89.99	.88
	fire no release	10.83	271.66	74.87	53.09	73.02	3.45	25.11	.98
	no release no fire	261.32	3001.42	1071.16	878.80	736.72	2.30	12.72	.69

This uncertainty is also shown in Figure 10.2. The probability distributions for the expected incident rates for Highways 7 and 17 all overlap. Even though Highway 17 has a higher mean incident rate for all types of releases, there is a still a chance that Highway 7 could have higher incident rates.

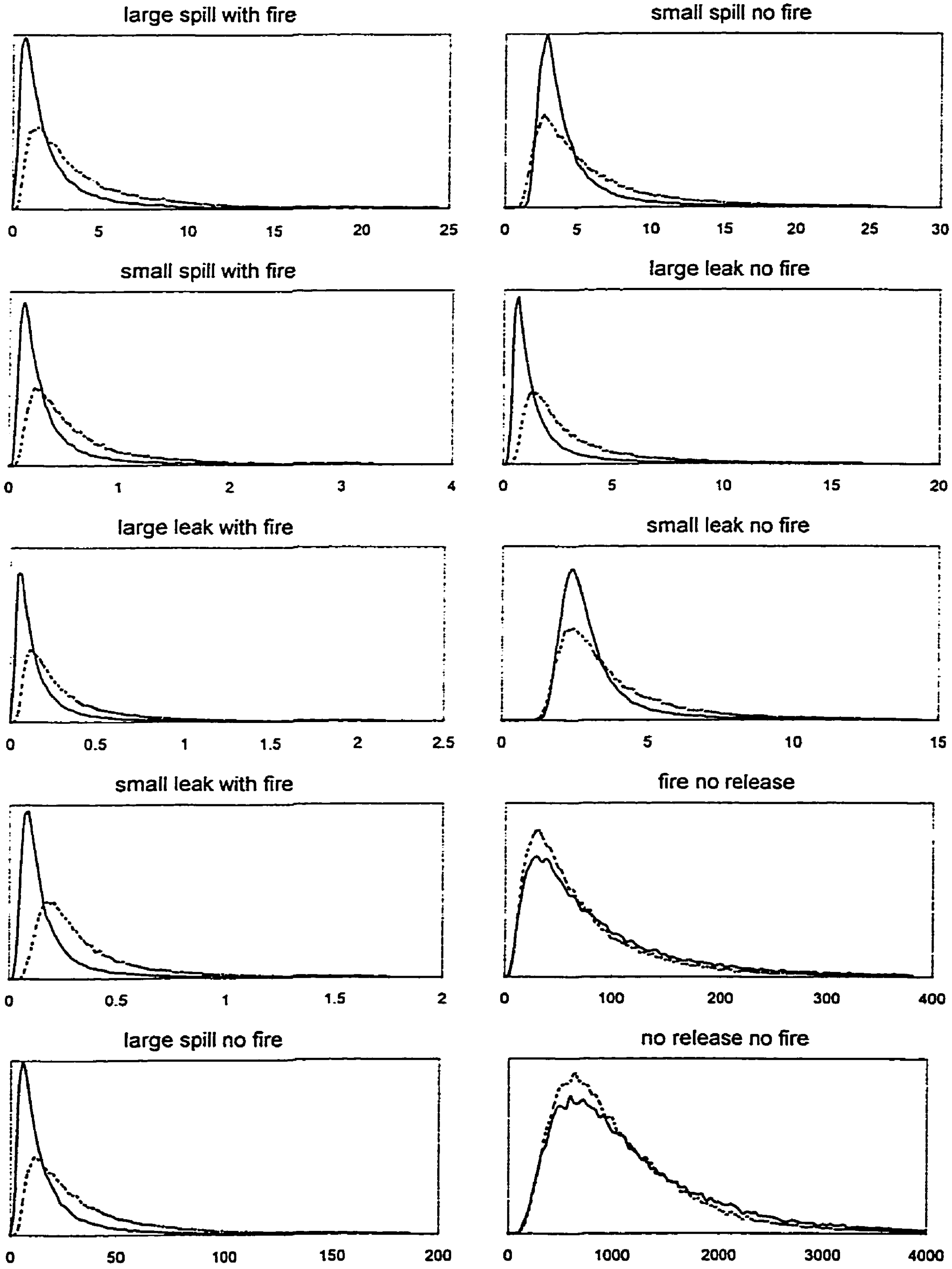
For example, we can consider the incident rates for large spills with fire for the two highways. The mean incident rate is 5.1 incidents per Bvkm for Highway 17 and 2.6 incidents per Bvkm for Highway 7. In comparing the means, it seems clear that there is more risk of large spills with fires for tankers carrying flammable liquid on Highway 17 compared to Highway 7. We can also compare the 50,000 observations of the incident rates generated at random by the Monte Carlo process for Highways 7 and 17 and used to produce the probability distributions in Figure 10.2. A pairwise comparison of the random observations indicates that there is probability of approximately 23% that the opposite will be true, that there will be a higher incident rate on Highway 7 compared to Highway 17.

If there were even more overlap between the distributions for the two highways, say because of a lower accident rate on Highway 17, the probability of a higher incident rate on Highway 7 compared to Highway 17 would be higher. For example, if the mean accident rate for Highway 17 were only 700 rather than 1,200 accidents per Bvkm, then the mean incident rate for large spills with fire on Highway 17 would be 3.0 incidents per Bvkm compared to 2.6 incidents per Bvkm on Highway 7. In this case, the means indicate that there is still more risk of large spills with fires for tankers carrying flammable liquid on Highway 17 compared to Highway 7. However, a pairwise comparison of the random observations indicates that there is probability of approximately 40% that the opposite will be true, that there will be a higher incident rate on Highway 7 compared to Highway 17.

Figure 10.2: Comparison of Probability Distributions for Incidents per Bvkm for Sample Roads

Legend: solid line: Highway 7
dashed line: Highway 17

X-axis Units: Incidents per Bvkm
Y-axis Units: probability



large spill with fire

small spill no fire

small spill with fire

large leak no fire

large leak with fire

small leak no fire

small leak with fire

fire no release

large spill no fire

no release no fire

10.3.4 Importance of Comparing Distributions

Table 10.7 provides a comparison of the mean values from the probability distributions to the point estimates of incidents per Bvkm for the sample roads. Table 10.7 shows that, for all types of releases for both highways, with and without fires, the mean value from the output probability distribution is in the range of 10% to 50% higher than the point estimate. The reasons for the differences between the means and the point estimates are as discussed earlier in Section 9.2.3. We prefer to use the probability distributions to describe the incident rates, because they take into account all of the information available, including the data and the assumed shapes of the distributions.

For the two sample highways, Highways 7 and 17, a comparison of the point estimates indicates the same conclusion as a comparison of the distributions: Highway 17 is more likely to have higher release and fire incident rates. However, if we were comparing one of the highways to an alternate mode of transport, it would be important to compare the probability distributions of the incident rates for the two modes.

To illustrate, we can compare Highway 17 to a hypothetical other mode of transporting DG loads. For Highway 17, the incident rate for large spills with fire has a lognormal distribution with a mean of 5.1 and a standard deviation of 7.6 incidents per Bvkm. We can assume that, for the hypothetical other mode, the incident rate for large spills with fire also has a lognormal distribution with a mean of say 4.5 and a standard deviation of say 3 incidents per Bvkm.

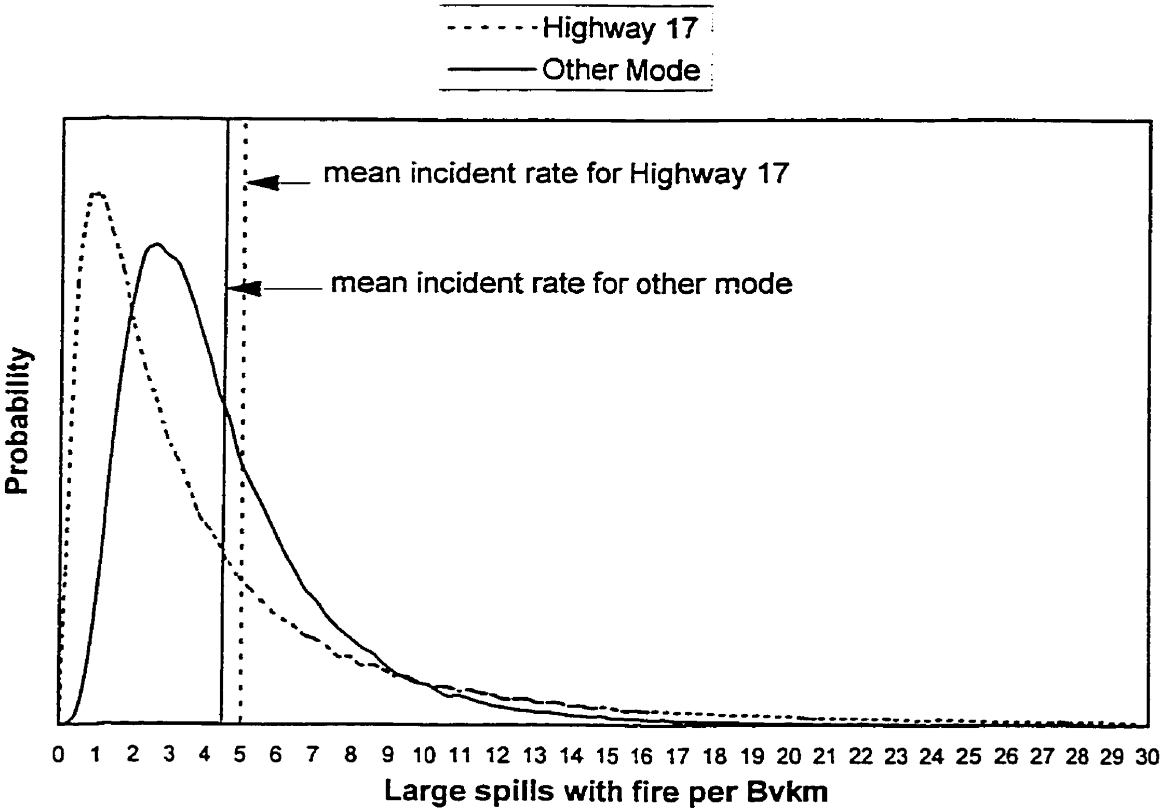
Table 10.7: Comparison of Mean Value from Probability Distribution to Point Estimates for Incidents per Bvkm for Sample Roads

Highway	Incident Outcome	Incidents per Bvkm	
		Point Estimate	Mean from Probability Distribution
Highway 7	large spill with fire	1.82	2.56
	small spill with fire	0.29	.38
	large leak with fire	0.14	.20
	small leak with fire	0.16	.20
	large spill no fire	13.40	18.62
	small spill no fire	3.53	4.39
	large leak no fire	1.20	1.67
	small leak no fire	2.82	3.15
	fire no release	33.53	91.87
	no release no fire	1277.90	1217.09
	total	1334.79	1340.12
	total releases	23.36	31.16
	total releases with fire	2.41	3.33
Highway 17	large spill with fire	3.48	5.06
	small spill with fire	0.55	.74
	large leak with fire	0.29	.42
	small leak with fire	0.34	.42
	large spill no fire	28.03	40.62
	small spill no fire	4.92	6.43
	large leak no fire	2.53	3.66
	small leak no fire	3.43	4.16
	fire no release	27.83	74.87
	no release no fire	1133.38	1071.16
	total	1204.79	1207.53
	total releases	43.58	61.50
	total releases with fire	4.67	6.64

Figure 10.3 shows the probability distributions and the means for the incident rates of large spills with fire for the Highway 17 and the hypothetical other mode. If we simply compare the means of the distributions, there appears to be less risk of large spills with fire with the other mode compared to Highway 17. Based on the means, the other mode is preferred. However, if we compare the distributions, there is probability of approximately 59% that the opposite will be true, that there will be a higher incident rate on the other mode compared to Highway 17. Based on a comparison of the distributions, Highway 17 is preferred.

Another method of comparison is to set a tolerance limit. For example, we could have a tolerance limit of 10 large spills with fire per Bvkm. From an inspection of the probability distributions in Figure 10.3, we can see that the probability is greater for Highway 17 than the hypothetical other mode that the incident rate for large spills with fire will be greater than 10 per Bvkm. The probability that the incident rate for large spills with fire will be greater than 10 per Bvkm is approximately 12% for Highway 17 and 5% for the other mode. Based on this method of comparison, the other mode is preferred. Therefore the method of comparison can affect decisions as well.

Figure 10.3: Comparison of Incident Rates for Large Spills with Fire For Highway 17 and Hypothetical Other Mode



CHAPTER 11

CONCLUSIONS AND RECOMMENDATIONS

Chapter 11 contains the following sections:

11.1 Observations and Conclusions

11.2 Recommendations

Chapter 11 summarises the thesis observations and conclusions and provides recommendations regarding future analysis and research.

The objectives of the research were:

1. to determine significant factors that impact the probabilities of releases and fires, as well as the type and size of release, from trucks in transit carrying DG loads.

2. to identify accident and non-accident scenarios for trucks in transit carrying DG loads, based on the significant factors, and determine the expected release and fire incident rates for each scenario.

3. to create a probabilistic model that quantifies the uncertainty in the predicted release and fire incident rates, based on the uncertainty in the input variables.

For accidents, the thesis predicts the probabilities of release and fire, given that an accident has occurred. For non-accident incidents, the thesis predicts the rates of non-accident releases and fires per billion vehicle kilometres (Bvkm). The thesis illustrates how we can accident information to provide total expected releases and fires per Bvkm for trucks carrying DG loads. Researchers can use the expected incident rates, along with their estimated uncertainty, in QRA analysis for the transport of DG on specific truck routes.

11.1 OBSERVATIONS AND CONCLUSIONS

11.1.1 DG Release and Fire Characteristics

The following observations and conclusions are drawn from cross-tabulations combining data from the three available DG incident databases and the two road accident databases.

1. Approximately 6% of DG incidents include fires.

2. Approximately 31% of releases from DG loads from trucks in transit are leaks and 69% are spills.

3. Approximately 60% of releases from DG loads are small (less than 1,000 litres). The size of large releases varies widely, from 1,000 to over 60,000 litres.

4. For trucks carrying DG loads, approximately 50% of the loads are small (less than 15,000 litres). There could be a small load because the truck is small, or because a large truck is only carrying a partial load.

5. The road kilometres by trucks in Canada carrying DG loads may be grouped by the type of load: approximately 65% flammable liquid, 24% toxic liquid, 6% flammable PLG and 5% toxic PLG. Flammable liquids are the most common type of DG load on the highways.

6. In Canada, approximately 60% of DG incidents occur on rural roads (in agricultural or uninhabited areas) and 40% on urban roads (in commercial, industrial or residential areas).

7. In Ontario, general truck accidents include approximately 66% tractors with semi-trailers, 23% straight trucks, 7% tractors with double trailers, and 3% straight trucks with full trailers. In Canada, incidents involving trucks carrying DG loads include approximately 54% tractors with semi-trailers, 26% straight trucks, 18% tractors with double trailers, and 2% straight trucks with full trailers. There is an over-representation of tractors with double trailers in the DGAIS data. This could be because DG loads are more commonly carried in tractors with double trailers than other types of goods.

8. In Ontario, general truck accidents include approximately 6% tanker trucks. In Canada, approximately 62% of the DG incidents involve tanker trucks. There is an over-representation of tanker trucks in the DG incidents, likely because liquid DG loads are commonly carried in tanker trucks.

9. For Ontario highways, approximately 2% of truck accidents involve overturns and collisions, 5% involve overturns no collision, 82% involve collisions no overturn, and 11% involve no overturn no collision. An accident that has no overturn and no collision typically involves a vehicle sliding or running off the road into the ditch. From combined Ontario and Washington sources, approximately 5% of truck accidents have overturns. However, approximately 69% of truck accidents with releases include overturns. Overturns are over-represented in truck accidents with releases, compared with general truck accidents.

10. The incident rate of non-accident non-release fires is approximately .22 incidents per Bvkm.

11.1.2 Significant Factors for Predicting Incident Outcomes

The following observations and conclusions are drawn from analysis of the data using logistic regression, and cross-tabulation of the data by the selected significant factors.

Accident Scenarios

1. Significant factors in predicting P(release | accident) include whether the accident includes an overturn or not, and the type of DG load. Most accident-induced releases are associated with overturns, especially for flammable liquids. Approximately 59% to 80% of releases involve overturns, depending on the type of DG load. Most releases associated with overturns are from the dome or hatch or from damage to the containment liner.

   For general truck accidents, approximately 2% include releases of their loads. In comparison, for trucks carrying DG loads and involved in accidents with overturns, approximately 11% to 31% have releases, depending on the type of DG load. If there is no overturn, less than 1% have releases.

   The most common type of DG load on the highways and in accident-induced releases is DG3: flammable liquid, followed by DG4: toxic liquid. The most common types of flammable liquid loads in DG incidents are gasoline, fuel oil and petroleum crude oil. For DG3: flammable liquid the proportion of overturn accidents with releases is the highest (approximately 31%) and for DG4: toxic liquid, the proportion of overturn accidents with releases is the lowest (approximately 11%).

2. Significant factors in predicting P(fire | accident) include whether the accident includes a collision or not, and whether there is a release of the DG load or not. P(fire) is over five times greater if the accident includes a collision and a release (approximately 17% fires), compared with an accident with neither a collision nor a release (approximately 1% fires).

It is interesting that the type of DG load does not appear as a variable that is significant in predicting P(fire | accident). This could be because the model predicts the probability of a fire starting, not the size of the fire. The probability of a fire starting could be quite similar for trucks carrying flammable or non-flammable DG loads, even though the consequences if the fire includes the DG load are drastically different.

3. Load size is a significant factor in predicting P(spill | accident-induced release). An accident-induced release is more likely to be a spill rather than a leak if the truck is carrying a large load (approximately 89% spills) compared with a small load (approximately 77% spills).

4. Significant factors in predicting P(large release | accident-induced release) include the load size, whether the release of the DG load is a spill or leak, whether there is a fire or not, and whether the truck is on an urban or rural road. Scarcity of data limits the model to using the two most significant factors: whether the load size is large or small, and whether the release is a spill or leak. The probability that an accident-induced release will be large rather than small is much greater if there is a spill from a large load (approximately 88% large), compared with a leak from a small load (approximately 16% large).

5. For accident scenarios, the four significant factors selected to build the model include whether the accident involves an overturn or not, whether the accident involves a collision or not, the load size, and the type of DG load.

Non-Accident Scenarios

1. For non-accident incidents, flammable DG have a lower release rate (approximately 4 to 5 releases per Bvkm) than toxic and/or corrosive (non-flammable) DG (approximately 11 to 14 releases per Bvkm) by a factor of about three.

2. A significant factor in predicting P(fire | non-accident release) is whether the truck is on an urban or rural road. The probability of fire is about three times higher in rural incidents (approximately 7% fires) than in urban incidents (approximately 2% fires).

3. Approximately 51% of non-accident releases are spills rather than leaks.

4. Significant factors in predicting P(large release | non-accident release) include whether the truck is a tanker or non-tanker, whether the release of the DG load is a spill or leak, the type of DG load, the load size, and whether the truck is on an urban or rural road. Scarcity of data limits the model to using the following three factors: whether the truck is a tanker or non-tanker, whether it is a rural or urban road, and whether the release is a spill or leak. A non-accident release is over 30 times more likely to be large rather than small if it is a spill from a tanker truck on a rural road (approximately 44% large), compared with a leak from a non-tanker truck on an urban road (less than 2% large).

5. For non-accident scenarios, the three significant factors selected to build the model include whether the road is urban or rural, whether the truck is a tanker or non-tanker, and the type of DG load.

11.1.3 Comparison of Model Output to Data

The following observations and conclusions are drawn from a comparison of the model output to release data.

Accident Scenarios

1. From the release data, the majority (56%) of accident-induced releases are from trucks carrying large DG loads and involved in accidents without collisions.

2. For accident scenarios, most (90%) releases are spills or leaks with no fire.

3. Most (84%) accident-induced releases from trucks with large loads are large spills. Most (62%) accident-induced releases from trucks with small loads are small spills.

4. Most (80%) releases with accident-induced fires are large spills.

5. Generally, there is a good match between the model and release data for accident scenarios. Discrepancies generally occur as a result of empty cells in the accident-induced release data table.

Non-Accident Scenarios

1. The majority (53%) of non-accident releases are from non-tanker trucks travelling on urban roads.

2. For non-accident release scenarios, most (88%) of releases are spills or leaks with no fire.

3. Non-accident releases from tanker trucks are more likely to be large spills (16% large spills) compared with releases from non-tanker trucks (2% large spills).

4. Generally, there is a good match between the model and release data for non-accident scenarios. Discrepancies generally occur as a result of empty cells in the non-accident release data table.

11.1.4 Uncertainty in Input Values

Our input variables are either rates or probabilities. For the variables that are rates, such as the rate of non-accident releases per Bvkm, we fit lognormal distributions. These distributions have values greater than 0 but with no upper limit. The lognormal distributions are positively skewed, with most of the values near the lower limit.

For the variables that are probabilities, such as P(fire | collision), we fit beta distributions. We used the Gibbs sampler to determine the distribution parameters. The beta distributions range between 0 and 1, and are either positively or negatively skewed.

11.1.5 Uncertainty in Output Values

The probability distributions for the model output variables are generally lognormal in shape. Therefore we can replicate the probability distribution for each output variable by simply generating a lognormal distribution based on the mean and standard deviation of the output variable. For the one output variable, P(no fire no release), which is negatively skewed, we can generate a lognormal distribution by transforming the mean to (1 - mean).

The range of the 95% probability interval varies dramatically for different scenarios. Generally, the higher the probability of the outcome, the greater is the width of the 95% probability interval. The following observations and conclusions are drawn from the probability distributions for the output variables.

Accident Scenarios

1. For the probability of an accident outcome with a release, the mean and 97.5th percentile of the probability distribution are generally 40 to 70 times larger with an overturn compared with no overturn.

2. The following accident outcomes have probability distributions with higher means and wider 95% probability intervals:

   - fires and large spills or leaks, for trucks carrying large loads and involved in collisions.

   - large spills or leaks but no fire, for trucks carrying large loads.

   - small spills or leaks, with or without fires, for trucks carrying small loads.

   - fires but no release, for collisions.

3. For accident outcomes with no fires and no releases, scenarios with overturns tend to have the widest 95% probability intervals, while scenarios with no overturn and no collision have the narrowest 95% probability intervals and the highest means for the outcome probability .

Non-Accident Scenarios

1. For non-accident incidents, the mean and 97.5th percentile of the probability distribution for the incident rates of large spills with fires are generally three to eight times higher in rural compared with urban areas. Large spills or leaks are also more frequent in rural areas.

2. The following non-accident incidents have probability distributions with higher mean incident rates and wider 95% probability intervals:

   - large spills or leaks, with or without fires, for tanker trucks carrying pressurised or unpressurised toxic liquids.

   - small spills or leaks, with or without fires, for trucks carrying pressurised or unpressurised toxic liquids.

11.1.6 Mean Values of Output Probability Distributions

The following observations and conclusions comparing scenarios (accident and non-accident) are drawn from the mean values of the output probability distributions from the model.

Accident Scenarios

For accident scenarios, the model output is the probability of accident outcomes for the different accident scenarios.

1. For accident scenarios, the most likely accident outcome is no release no fire. Depending on the accident category, the probability of no release no fire is approximately 48% to 81% with an overturn, 92% with collision no overturn, and 98% with no overturn no collision. If the accident involves an overturn, the next most likely outcome is generally a large spill with no fire (approximately 5% to 35%). If there is no overturn, the next most likely outcome is a fire with no release of the DG load (approximately 7% with and 2% without a collision).

2. The probabilities of spills and leaks with fire are higher for accidents with overturns compared with no overturns. If there is no overturn, the probability of a release is less than 1%.

3. The most probable fire outcome is large spill with a fire for a truck carrying a large load of flammable liquids and involved in an accident with an overturn and collision (approximately 6% large spills with fire). The least likely accident outcomes include a release with a fire if there is no overturn and no collision (approximately .02% to .04% releases with fires). The probability of a large spill with fire is in the range of 300 to 800 times greater (depending on the type of DG load) for a truck carrying a large load with an overturn and collision, compared with a truck carrying a small load that simply runs off the road.

Non-Accident Scenarios

For the non-accident scenarios, the model output is the number of non-accident incidents per Bvkm.

1. For all non-accident release scenarios, by far the highest incident rate is for small spills or leaks with no fire. We can expect between approximately 1.4 and 6.5 small leaks with no fire per Bvkm, depending on the non-accident scenario.

2. For non-accident scenarios, the incident rate for large spills with fire is over 80 times greater for a tanker truck in a rural area (approximately .07 to .22 large spills with fire per Bvkm), compared with a non-tanker truck in an urban area (approximately .001 to .002 large spills with fire per Bvkm). The incident rates vary with the type of DG load.

3. For each non-accident fire scenario, the incident rates for small leaks and spills with fire are higher (approximately .07 to .75 small releases with fire per Bvkm) than those for large leaks or spills with fire (approximately .001 to .31 large releases with fire per Bvkm).

4. The non-accident fire incident rate tends to be higher for rural than urban roads, regardless of the type of release (approximately .23 to .81 fires per Bvkm for rural roads, compared with .08 to .27 fires per Bvkm for urban roads).

5. A tanker truck carrying toxic liquid on a rural road has the highest incident rate of large spills with fire (approximately .22 large spills with fire per Bvkm), compared with other non-accident scenarios.

11.1.7 Sample Application of Research Results

The model application involved a tanker truck carrying a large load of flammable liquid on two sample roads, an urban road and a rural road. The urban road has a higher accident rate but a lower proportion of accidents with overturns. The application provided the following observations and conclusions.

1. For both roads, by far the most frequent type of incident is expected to be no release no fire.

2. For both roads, spills are expected to be more common than leaks, and large releases more common than small, with and without fires.

3. The model predicts that small releases will be approximately 60% non-accident for the urban road and 30% non-accident for the rural road. Only about 5% of the large releases are expected to be non-accident for both roads.

4. Although the urban road has the higher accident rate, the rural road is expected to have more releases per Bvkm, for all types of releases, with and without fires. The most apparent difference in the incident rates between the two roads is for large spills no fire. The higher release rate is related to the higher proportion of overturn accidents on the rural road.

5. For both roads, each of the probability distributions for the incident rates is positively skewed, as is compatible with a lognormal distribution.

6. For all types of release rates for both highways, with and without fires, the mean value from the output probability distribution is higher than the point estimate.

7. For each type of incident rate, the 97th percentile is two to five times greater than the mean value for the probability distribution. This indicates the high level of uncertainty associated with these estimates.

11.2 RECOMMENDATIONS

The following recommendations are offered regarding the application of the thesis results to risk analysis, and regarding future research on release and fire incident rates for trucks carrying DG loads.

1. The thesis illustrates how we can combine accident and non-accident information to predict total expected releases and fire incident rates for trucks carrying DG loads. The sample model application for Highways 7 and 17 shows the high level of uncertainty associated with the resulting estimates of release and fire incident rates. In our sample application, the mean values of the predicted release incident rates are higher for Highway 17. However, there is a large overlap of the probability distributions for the incident rates for the two highways. There is a substantial probability that Highway 7 could have higher release incident rates.

   Analysts should not ignore this uncertainty when estimating incident rates from the model and applying the incident rates to risk analysis. There is further uncertainty in the impacts of the incidents to the environment and to the public. The combined uncertainty in the incident rates and incident impacts results in a significant amount of uncertainty in the predicted risks of transporting DG loads by truck.

2. Currently, there are limited data on DG incidents. In this thesis, data limitations restricted the analysis of fires and explosions to a combined category called "fires". Data limitations restricted the number of significant factors that the model could include. Even with restricting the number of factors, for some input variables only two data points were available.

Further data are required to improve the model by including all significant factors, separating fires and explosions, and reducing uncertainty in the input variables. Therefore it is imperative that agencies continue to collect data on DG incidents. It would also be interesting to investigate why there are differences between data sources, and identify differences in the methods of reporting and recording incidents.

3. One of the factors that greatly affects accident-induced release and fire incident rates is the expected type of accident (whether the accident includes an overturn and/or a collision). To improve the application of the model, it would be useful to further examine factors that lead to overturns and collisions, for different road and vehicle characteristics.

APPENDIX A

RESULTS OF STEPWISE LOGISTIC REGRESSION FOR INPUT VARIABLES

Parameter Coding for Logistic Regression for Input Variables

Data Source: DGAIS

Variable	Value	Parameter Coding (1)	(2)	(3)
truck type	straight truck	1	0	0
	straight truck with full trailer	0	1	0
	tractor with semi-trailer	0	0	1
	tractor with double trailers	0	0	0
type of DG	DG1: toxic PLG	1	0	0
	DG2: flammable PLG	0	1	0
	DG3: flammable liquid	0	0	1
	DG4: toxic liquid	0	0	0
spill	leak	1		
	spill	0		
overturn	no overturn	1		
	overturn	0		
collision	no collision	1		
	collision	0		
tanker truck	non-tanker truck	1		
	tanker truck	0		
load size	small	1		
	large	0		
urban	rural	1		
	urban	0		
fire	no fire	1		
	fire	0		

Results of Stepwise Logistic Regression for Input Variables Accident Scenarios

Dependent Variable: P(release | accident)

Variables in the Equation	Significance						Beta
	test run 1	test run 2	test run 3	test run 4	test run 5	test run 6	
overturn	.0000	.0000	.0000	.0000	.0000	.0000	-1.1615
type of DG	.0000	.0000	.0000	.0000	.0000	.0000	
DG1	.0000	.0000	.0000	.0001	.0001	.0000	-1.5368
DG2	.0000	.0000	.0000	.0000	.0000	.0000	-2.0746
DG3	.0205	.0167	.0162	.0075	.0075	.0007	.8710
load size	.1429	.1133	.1133	.2164	.2171		
collision	.7828	.7831	.7957	.7784			
truck type	.3776	.3777	.3778				
truck type 1	.2594	.2592	.2603				
truck type 2	.3591	.3560	.3521				
truck type 3	.8560	.8565	.8573				
urban	.8891	.8892					
tanker truck	.9874						
constant	.0001	.0001	.0000	.0000	.0000	.0000	1.4082

P(release | accident) = exp(U) / (1+ exp(U))

U = 1.4082 - 1.1615*(overturn) - 1.5368*(DG1) - 2.0746*(DG2) + 0.8710*(DG3)

Model Chi-Square:	229.005
Significance:	.0000
Cox & Snell R-Square:	.237
Nagelkerke R-Square:	.348

Results of Stepwise Logistic Regression for Input Variables Accident Scenarios

Dependent Variable: P(fire | accident)

Variables in the Equation	Significance							Beta
	test run 1	test run 2	test run 3	test run 4	test run 5	test run 6	test run 7	
collision	.0001	.0000	.0000	.0000	.0000	.0000	.0000	-1.4393
release	.0007	.0008	.0013	.0048	.0053	.0084	.0073	-.9231
urban	.0753	.0652	.0707	.0900	.0978	.4777		
load size	.3030	.0817	.0881	.1058	.2091			
tanker truck	.2114	.1767	.1233	.2366				
type of DG	.1048	.1483	.1626					
DG1	.1191	.1413	.1639					
DG2	.0149	.0234	.0255					
DG3	.1136	.1408	.1445					
overturn	.2152	.2049						
truck type	.2474							
truck type 1	.1353							
truck type 2	.3398							
truck type 3	.8326							
constant	.0001	.0000	.0001	.0000	.0000	.0000	.0000	-1.2467

P(fire | accident) = exp(U) / (1+ exp(U))

U = - 1.2467 - 1.4393*(collision) - 0.9231*(release)

Model Chi-Square:	37.357
Significance:	.0000
Cox & Snell R-Square:	.043
Nagelkerke R-Square:	.096

Results of Stepwise Logistic Regression for Input Variables
Accident Scenarios

Dependent Variable: P(spill | accident-induced release)

Variables in the Equation	Significance								Beta
	test run 1	test run 2	test run 3	test run 4	test run 5	test run 6	test run 7	test run 8	
load size	.1733	.1392	.0248	.0206	.0188	.0228	.0186	.0006	-.8406
type of DG	.0000	.0000	.0000	.0000	.0000	.0000	.0000		
DG1	.1439	.1412	.1126	.1184	.1060	.0838	.0966		
DG2	.0139	.0126	.0042	.0042	.0045	.0040	.0078		
DG3	.0064	.0046	.0157	.0136	.0121	.0165	.0162		
fire	.2885	.2860	.1956	.1939	.1804	.1226			
collision	.2030	.2032	.1708	.1764	.2318				
urban	.2760	.2762	.2427	.2422					
overturn	.6403	.6411	.6724						
truck type	.1897	.1825							
truck type 1	.5080	.5061							
truck type 2	.8053	.8057							
truck type 3	.1843	.1827							
tanker truck	.9718								
constant	.0099	.0086	.0007	.0005	.0000	.0001	.0000	.0000	2.0739

P(spill | accident-induced release) = exp(U) / (1+ exp(U))

U = 2.0739 - 0.8406*(load size)

Model Chi-Square:	11.435
Significance:	.0007
Cox & Snell R-Square:	.020
Nagelkerke R-Square:	.035

Results of Stepwise Logistic Regression for Input Variables
Accident Scenarios

Dependent Variable: P(large release | accident-induced release)

Variables in the Equation	Significance								Beta
	test run 1	test run 2	test run 3	test run 4	test run 5	test run 6	test run 7	test run 8	
load size	.0000	.0000	.0000	.0000	.0000	.0000	.0000	.0000	-2.1299
spill	.0000	.0000	.0000	.0000	.0000	.0000	.0000	.0000	-1.7240
fire	.0841	.0556	.0516	.0267	.0140	.0225	.0206	.	
urban	.0247	.0156	.0162	.0222	.0329	.0242			
tanker truck	.1260	.1666	.1890	.1185	.1373				
collision	.4296	.3931	.1843	.2243					
type of DG	.1829	.2438	.2517						
DG1	.0432	.0537	.0571						
DG2	.1598	.2397	.2337						
DG3	.2533	.2954	.3059						
overturn	.5303	.5313							
truck type	.1157								
truck type 1	.0320								
truck type 2	.8825								
truck type 3	.6481								
constant	.0013	.0011	.0003	.0000	.0000	.0000	.0000	.0000	1.9612

P(large release | accident-induced release) = exp(U) / (1+ exp(U))

U = 1.9612 - 2.1299*(load size) - 1.7240*(spill)

Model Chi-Square:	150.776
Significance:	.0000
Cox & Snell R-Square:	.233
Nagelkerke R-Square:	.333

Results of Stepwise Logistic Regression for Input Variables Non-Accident Scenarios

Dependent Variable: P(fire | non-accident release)

Variables in the Equation	Significance					Beta
	test run 1	test run 2	test run 3	test run 4	test run 5	
urban	.0069	.0057	.0057	.0148	.0127	1.1601
type of DG	.0307	.0257	.0246	.0203		
DG1	.0121	.0114	.0108	.0250		
DG2	.0539	.0190	.0192	.0033		
DG3	.4598	.2453	.2505	.0714		
load size	.2691	.3575	.2792			
tanker truck	.4155	.8622				
truck type	.2364					
truck type 1	.4262					
truck type 2	.7826					
truck type 3	.0531					
constant	.0005	.0000	.0000	.0000	.0000	-3.8169

P(fire | non-accident release) = exp(U) / (1+ exp(U))

U = - 3.8169 + 1.1601*(urban)

Model Chi-Square:	6.357
Significance:	.0117
Cox & Snell R-Square:	.011
Nagelkerke R-Square:	.043

Results of Stepwise Logistic Regression for Input Variables Non-Accident Scenarios

Dependent Variable: P(spill | non-accident release)

Variables in the Equation	Significance					
	test run 1	test run 2	test run 3	test run 4	test run 5	test run 6
fire	.2697	.2399	.2310	.2419	.2156	.4235
type of DG	.2655	.0117	.0155	.0126	.0130	
DG1	.1082	.0032	.0038	.0031	.0033	
DG2	.1786	.0638	.0860	.0799	.0767	
DG3	.4567	.4164	.4173	.3679	.3843	
urban	.3361	.4353	.4640	.5567		
tanker truck	.3137	.4941	.5124			
truck type	.7084	.6720				
truck type 1	.2824	.3872				
truck type 2	.7449	.8198				
truck type 3	.5121	.7273				
load size	.8684					
constant	.7402	.4600	.2222	.1436	.1055	.3744

Results of Stepwise Logistic Regression for Input Variables Non-Accident Scenarios

Dependent Variable: P(large release | non-accident release)

Variables in the Equation	Significance				Beta
	test run 1	test run 2	test run 3	test run 4	
tanker truck	.0002	.0002	.0002	.0000	-2.2634
spill	.0025	.0022	.0018	.0041	-.9728
type of DG	.0007	.0004	.0002		
DG1	.0005	.0002	.0001		
DG2	.0008	.0008	.0004		
DG3	.0171	.0177	.0127		
load size	.0237	.0197	.0178		
urban	.0412	.0345	.0191	.0005	1.1683
fire	.2909	.3182			
truck type	.6332				
truck type 1	.9277				
truck type 2	.2157				
truck type 3	.9343				
constant	.3875	.3287	.0021	.0000	-1.3582

P(large release | non-accident release) = exp(U) / (1+ exp(U))

U = - 1.3582 - 2.2634*(tanker truck) - 0.9728*(spill) + 1.1683*(urban)

Model Chi-Square:	80.698
Significance:	.0000
Cox & Snell R-Square:	.135
Nagelkerke R-Square:	.292

APPENDIX B

DATA FOR INPUT VARIABLES

Data for Input Variables - Accident Scenarios

Variable 1: P(overturn | release)
for a truck carrying a DG load and involved in an accident

time interval	number of accidents with release by type of DG load											
	toxic PLG			flammable PLG			flammable liquid			toxic liquid		
	no overturn	overturn	total	no overturn	overturn	total	no overturn	overturn	total	no overturn	overturn	total
Transport Canada DGAIS												
88		3	3	4	4	8	9	51	60	3	8	11
89	1	3	4	1		1	8	70	78	5	10	15
90	1	5	6	1	4	5	6	61	67	4	8	12
91		2	2	1	2	3	15	58	73	1	12	13
92		2	2	1	4	5	8	52	60	2	8	10
93	1	3	4		1	1	7	40	47	4	6	10
94	1	1	2	1	7	8	7	48	55	2	4	6
95		5	5		3	3	4	42	46		5	5
88,89	1	6	7	5	4	9	17	121	138	8	18	26
90,91	1	7	8	2	6	8	21	119	140	5	20	25
92,93	1	5	6	1	5	6	15	92	107	6	14	20
94,95	1	6	7	1	10	11	11	90	101	2	9	11
total	4	24	28	9	25	34	64	422	486	21	61	82
88,89	.143	.857	1.000	.556	.444	1.000	.123	.877	1.000	.308	.692	1.000
90,91	.125	.875	1.000	.250	.750	1.000	.150	.850	1.000	.200	.800	1.000
92,93	.167	.833	1.000	.167	.833	1.000	.140	.860	1.000	.300	.700	1.000
94,95	.143	.857	1.000	.091	.909	1.000	.109	.891	1.000	.182	.818	1.000
mean		.857			.735			.868			.744	
MOE ORIS												
88			0	2		2	13	12	25	5		5
89	1		1	2		2	12	11	23	4	6	10
90		1	1	1	1	2	8	8	16	4	2	6
91	1		1	2		2	5	13	18	2	2	4
92			0	1	2	3	7	18	25	1		1
93	3	1	4	2	1	3	7	6	13		3	3
94		1	1			0	7	8	15	1		1
95			0	1	1	2	4	17	21	1	3	4
96			0			0	3	17	20	1	2	3
97		1	1	1		1	6	13	19		1	1
88 to 92	2	1	3	8	3	11	45	62	107	16	10	26
93 to 97	3	3	6	4	2	6	27	61	88	3	9	12
total	5	4	9	12	5	17	72	123	195	19	19	38
88 to 92	.667	.333	1.000	.727	.273	1.000	.421	.579	1.000	.615	.385	1.000
93 to 97	.500	.500	1.000	.667	.333	1.000	.307	.693	1.000	.250	.750	1.000
mean		.444			.294			.631			.500	
Transport Canada DGAIS & MOE ORIS combined												
combined total	9	28	37	21	30	51	136	545	681	40	80	120
combined mean		.757			.588			.800			.667	

Data for Input Variables - Accident Scenarios

Variable 2: P(type of DG load | release)
for a truck carrying a DG load and involved in an accident

time interval	number of accidents with release by type of DG load				
	toxic PLG	flammable PLG	flammable liquid	toxic liquid	total
Transport Canada DGAIS					
88	3	8	60	11	82
89	4	1	78	15	98
90	6	5	67	12	90
91	2	3	73	13	91
92	2	5	60	10	77
93	4	1	47	10	62
94	2	8	55	6	71
95	5	3	46	5	59
88,89	7	9	138	26	180
90,91	8	8	140	25	181
92,93	6	6	107	20	139
94,95	7	11	101	11	130
total	28	34	486	82	630
88,89	.039	.050	.767	.144	1.000
90,91	.044	.044	.773	.138	1.000
92,93	.043	.043	.770	.144	1.000
94,95	.054	.085	.777	.085	1.000
mean	.044	.054	.771	.130	1.000
MOE ORIS					
88		2	25	5	32
89	1	2	23	10	36
90	1	2	16	6	25
91	1	2	18	4	25
92		3	25	1	29
93	4	3	13	3	23
94	1		15	1	17
95		2	21	4	27
96			20	3	23
97	1	1	19	1	22
88,89	1	4	48	15	68
90,91	2	4	34	10	50
92,93	4	6	38	4	52
94,95	1	2	36	5	44
96,97	1	1	39	4	45
total	9	17	195	38	259
88,89	.015	.059	.706	.221	1.000
90,91	.040	.080	.680	.200	1.000
92,93	.077	.115	.731	.077	1.000
94,95	.023	.045	.818	.114	1.000
96,97	.022	.022	.867	.089	1.000
mean	.035	.066	.753	.147	1.000
Transport Canada DGAIS & MOE ORIS combined					
combined total	37	51	681	120	889
combined mean	.042	.057	.766	.135	1.000

Data for Input Variables - Accident Scenarios

Variable 3: P(release)
for a loaded truck involved in an accident

time interval	number of accidents		
	no release	release	total
MTO ADS			
88	3128	78	3206
89	3207	76	3283
90	2913	69	2982
91	2706	72	2778
92	2892	44	2936
93	2688	38	2726
94	3174	55	3229
95	2955	77	3032
total	23663	509	24172
88	.976	.024	1.000
89	.977	.023	1.000
90	.977	.023	1.000
91	.974	.026	1.000
92	.985	.015	1.000
93	.986	.014	1.000
94	.983	.017	1.000
95	.975	.025	1.000
mean		.021	
WSDOT MARS			
90	1581	17	1598
91	1427	13	1440
92	1480	13	1493
93	1550	20	1570
94	1744	19	1763
95	1927	14	1941
96	1071	10	1081
total	10780	106	10886
90	.989	.011	1.000
91	.991	.009	1.000
92	.991	.009	1.000
93	.987	.013	1.000
94	.989	.011	1.000
95	.993	.007	1.000
96	.991	.009	1.000
mean		.010	
MTO ADS & WSDOT MARS combined			
combined total	34443	615	35058
combined mean		.018	

Data for Input Variables - Accident Scenarios

Variable 4: P(overturn)
for a loaded truck involved in an accident

time interval	number of accidents		
	no overturn	overturn	total
MTO ADS			
88	2942	264	3206
89	3057	227	3284
90	2756	228	2984
91	2591	188	2779
92	2732	205	2937
93	2527	199	2726
94	3054	180	3234
95	2839	194	3033
total	22498	1685	24183
88	.918	.082	1.000
89	.931	.069	1.000
90	.924	.076	1.000
91	.932	.068	1.000
92	.930	.070	1.000
93	.927	.073	1.000
94	.944	.056	1.000
95	.936	.064	1.000
mean		.070	
WSDOT MARS			
90	1565	33	1598
91	1410	30	1440
92	1453	40	1493
93	1533	37	1570
94	1735	28	1763
95	1897	44	1941
96	1054	27	1081
total	10647	239	10886
90	.979	.021	1.000
91	.979	.021	1.000
92	.973	.027	1.000
93	.976	.024	1.000
94	.984	.016	1.000
95	.977	.023	1.000
96	.975	.025	1.000
mean		.022	
MTO ADS & WSDOT MARS combined			
combined total	33145	1924	35069
combined mean		.055	

Data for Input Variables - Accident Scenarios

Variable 5: P(type of DG load)
for a truck carrying a DG load

time interval	maximum estimated road vehicle kilometres by type of DG load				
	toxic PLG	flammable PLG	flammable liquid	toxic liquid	total
Transport Canada					
86	497,039,513	490,165,358	4,281,708,084	2,503,036,367	7,771,949,322
87	553,861,864	577,082,140	4,761,060,312	2,738,718,884	8,630,723,200
88	479,320,934	600,184,085	6,242,264,582	2,079,057,571	9,400,827,172
89	404,619,217	519,715,641	7,035,258,891	2,204,144,969	10,163,738,718
90	470,538,001	618,302,046	8,156,752,080	2,747,869,504	11,993,461,631
total	2,405,379,529	2,805,449,270	30,477,043,949	12,272,827,295	47,960,700,043
86	.064	.063	.551	.322	1.000
87	.064	.067	.552	.317	1.000
88	.051	.064	.664	.221	1.000
89	.040	.051	.692	.217	1.000
90	.039	.052	.680	.229	1.000
mean	.050	.058	.635	.256	1.000

Data for Input Variables - Accident Scenarios

Variable 6: **P(fire | release)**
for a truck carrying a DG load and involved in an accident

time interval	number of accidents with releases					
	no collision			collision		
	no fire	fire	total	no fire	fire	total
Transport Canada DGAIS						
88	56	6	62	14	6	20
89	63	4	67	27	4	31
90	68	2	70	16	4	20
91	65	6	71	13	7	20
92	57	6	63	10	4	14
93	46	2	48	11	3	14
94	53	5	58	11	2	13
95	47	1	48	10	1	11
88,89	119	10	129	41	10	51
90,91	133	8	141	29	11	40
92,93	103	8	111	21	7	28
94,95	100	6	106	21	3	24
total	455	32	487	112	31	143
88,89	.922	.078	1.000	.804	.196	1.000
90,91	.943	.057	1.000	.725	.275	1.000
92,93	.928	.072	1.000	.750	.250	1.000
94,95	.943	.057	1.000	.875	.125	1.000
mean		.066			.217	
France MTMD						
87	28	4	32	22	5	27
88	25		25	35	3	38
89	23	3	26	39	6	45
90	30	3	33	30	4	34
91	25		25	16	1	17
92	24	1	25	14	3	17
87,88	53	4	57	57	8	65
89,90	53	6	59	69	10	79
91,92	49	1	50	30	4	34
total	155	11	166	156	22	178
87,88	.930	.070	1.000	.877	.123	1.000
89,90	.898	.102	1.000	.873	.127	1.000
91,92	.980	.020	1.000	.882	.118	1.000
mean		.066			.124	
Transport Canada DGAIS & France MTMD combined						
combined total	610	43	653	268	53	321
combined mean		.066			.165	

Data for Input Variables - Accident Scenarios

Variable 7: **P(fire | no release)**
for a truck carrying a DG load and involved in an accident

time interval	number of accidents without releases					
	no collision			collision		
	no fire	fire	total	no fire	fire	total
Transport Canada DGAIS						
88	19		19	9	1	10
89	23		23	13		13
90	19		19	18		18
91	18		18	5	1	6
92	19	1	20	8	3	11
93	14	1	15	2	2	4
94	13	1	14	5	1	6
95	21		21	1		1
90 to 92	56	1	57	31	4	35
93 to 95	48	2	50	8	3	11
total	146	3	149	61	8	69
90 to 92	.982	.018	1.000	.886	.114	1.000
93 to 95	.960	.040	1.000	.727	.273	1.000
mean		.020			.116	
France MTMD						
87	35		35	77	1	78
88	27		27	88		88
89	28		28	86	4	90
90	33		33	84		84
91	45		45	92	2	94
92	15		15	58		58
87,88	62		62	165	1	166
89,90	61		61	170	4	174
91,92	60		60	150	2	152
total	183		183	485	7	492
87,88	1.000	.000	1.000	.994	.006	1.000
89,90	1.000	.000	1.000	.977	.023	1.000
91,92	1.000	.000	1.000	.987	.013	1.000
mean		.000			.014	
Transport Canada DGAIS & France MTMD combined						
combined total	329	3	332	546	15	561
combined mean		.009			.027	

Data for Input Variables - Accident Scenarios

Variable 8: P(spill | release)
for a truck carrying a DG load and involved in an accident

time interval	number of accidents with releases					
	small load			large load		
	leak	spill	total	leak	spill	total
	Transport Canada DGAIS					
88	7	17	24	6	40	46
89	4	18	22	7	64	71
90	6	22	28	4	55	59
91	3	22	25	3	56	59
92		15	15	10	46	56
93	7	12	19	1	28	29
94	5	8	13	9	36	45
95	5	13	18	5	33	38
88,89	11	35	46	13	104	117
90,91	9	44	53	7	111	118
92,93	7	27	34	11	74	85
94,95	10	21	31	14	69	83
total	37	127	164	45	358	403
88,89	.239	.761	1.000	.111	.889	1.000
90,91	.170	.830	1.000	.059	.941	1.000
92,93	.206	.794	1.000	.129	.871	1.000
94,95	.323	.677	1.000	.169	.831	1.000
mean		.774			.888	

Data for Input Variables - Accident Scenarios

Variable 9: P(large release | spill)
for a truck carrying a DG load and involved in an accident

time interval	number of accidents with spill					
	small load			large load		
	small release	large release	total	small release	large release	total
Transport Canada DGAIS						
88	9	8	17	5	35	40
89	9	9	18	9	55	64
90	14	8	22	4	51	55
91	9	13	22	6	50	56
92	7	8	15	7	39	46
93	8	4	12	2	26	28
94	5	3	8	4	32	36
95	9	4	13	6	27	33
88,89	18	17	35	14	90	104
90,91	23	21	44	10	101	111
92,93	15	12	27	9	65	74
94,95	14	7	21	10	59	69
total	70	57	127	43	315	358
88,89	.514	.486	1.000	.135	.865	1.000
90,91	.523	.477	1.000	.090	.910	1.000
92,93	.556	.444	1.000	.122	.878	1.000
94,95	.667	.333	1.000	.145	.855	1.000
mean		.449			.880	

Data for Input Variables - Accident Scenarios

Variable 10: P(large release | leak)
for a truck carrying a DG load and involved in an accident

time interval	number of accidents with leak					
	small load			large load		
	small release	large release	total	small release	large release	total
Transport Canada DGAIS						
88	4	3	7	3	3	6
89	4		4	2	5	7
90	6		6	2	2	4
91	3		3	2	1	3
92			0	8	2	10
93	5	2	7		1	1
94	5		5	1	8	9
95	4	1	5	3	2	5
88 to 91	17	3	20	9	11	20
92 to 95	14	3	17	12	13	25
total	31	6	37	21	24	45
88,89	.850	.150	1.000	.450	.550	1.000
90,91	.824	.176	1.000	.480	.520	1.000
mean		.162			.533	

Data for Input Variables - Non-Accident Scenarios

Variable 1: rate of non-accident releases
for a truck carrying a DG load

time interval	number of non-accident releases by type of DG load			
	toxic PLG	flammable PLG	flammable liquid	toxic liquid
Transport Canada DGAIS				
88	3	3	26	23
89	6	2	31	37
90	6	2	41	38
91	5	3	23	28
92	3	2	29	32
93	3	6	42	53
94	7	3	36	21
95	2	3	29	7
88 to 90	15	7	98	98

time interval	maximum estimated road vehicle kilometres by type of DG load			
	toxic PLG	flammable PLG	flammable liquid	toxic liquid
Transport Canada				
1986	497,039,513	490,165,358	4,281,708,084	2,503,036,367
1987	553,861,864	577,082,140	4,761,060,312	2,738,718,884
1988	479,320,934	600,184,085	6,242,264,582	2,079,057,571
1989	404,619,217	519,715,641	7,035,258,891	2,204,144,969
1990	470,538,001	618,302,046	8,156,752,080	2,747,869,504
88 to 90	1,354,478,152	1,738,201,772	21,434,275,553	7,031,072,044

time interval	number of non-accident releases per Bvkm			
	toxic PLG	flammable PLG	flammable liquid	toxic liquid
88	6.26	5.00	4.17	11.06
89	14.83	3.85	4.41	16.79
90	12.75	3.23	5.03	13.83
mean	11.07	4.03	4.57	13.94

Data for Input Variables - Non-Accident Scenarios

Variable 2: P(fire)
for a non-accident release from a truck carrying a DG load

time interval	number of non-accident releases					
	rural			urban		
	fire	no fire	total	fire	no fire	total
Transport Canada DGAIS						
88	1	29	30	1	24	25
89	4	32	36		40	40
90	3	31	34		53	53
91	1	16	17	1	41	42
92	2	22	24	1	41	42
93		6	6	3	95	98
94	1	25	26	1	40	41
95		10	10	1	30	31
88,89	5	61	66	1	64	65
90,91	4	47	51	1	94	95
92,93	2	28	30	4	136	140
94,95	1	35	36	2	70	72
total	12	171	183	8	364	372
88,89	.076	.924	1.000	.015	.985	1.000
90,91	.078	.922	1.000	.011	.989	1.000
92,93	.067	.933	1.000	.029	.971	1.000
94,95	.028	.972	1.000	.028	.972	1.000
mean	.066			.022		

Data for Input Variables - Non-Accident Scenarios

Variable 3: **P(spill)**
for a non-accident release from a truck carrying a DG load

time interval	number of non-accident releases		
	leak	spill	total
Transport Canada DGAIS			
88	31	24	55
89	20	56	76
90	43	44	87
91	11	48	59
92	35	31	66
93	70	34	104
94	39	28	67
95	22	19	41
88,89	51	80	131
90,91	54	92	146
92,93	105	65	170
94,95	61	47	108
total	271	284	555
88,89	.389	.611	1.000
90,91	.370	.630	1.000
92,93	.618	.382	1.000
94,95	.565	.435	1.000
mean		.512	

Data for Input Variables - Non-Accident Scenarios

Variable 4: P(large release | spill)
for a non-accident release from a truck carrying a DG load

time interval	number of non-accident spills											
	rural						urban					
	non-tanker truck			tanker truck			non-tanker truck			tanker truck		
	small release	large release	total	small release	large release	total	small release	large release	total	small release	large release	total
	Transport Canada DGAIS											
88	7	1	8	3	3	6	5		5	4	1	5
89	17		17	4	5	9	24		24	5	1	6
90	5		5	7	2	9	21		21	6	3	9
91	8	2	10	5		5	25	2	27	3	3	6
92	3	3	6	2	3	5	17		17	3		3
93	2		2	1	1	2	26		26	4		4
94	8		8	1	2	3	13		13	3	1	4
95			0		2	2	14		14	3		3
88 to 91	37	3	40	19	10	29	75	2	77	18	8	26
92 to 95	13	3	16	4	8	12	70	0	70	13	1	14
total	50	6	56	23	18	41	145	2	147	31	9	40
88 to 91	.925	.075	1.000	.655	.345	1.000	.974	.026	1.000	.692	.308	1.000
92 to 95	.813	.188	1.000	.333	.667	1.000	1.000	.000	1.000	.929	.071	1.000
mean		.107			.439			.014			.225	

Data for Input Variables - Non-Accident Scenarios

Variable 5: P(large release | leak)
for a non-accident release from a truck carrying a DG load

time interval	number of non-accident spills											
	rural						urban					
	non-tanker truck			tanker truck			non-tanker truck			tanker truck		
	small release	large release	total	small release	large release	total	small release	large release	total	small release	large release	total
Transport Canada DGAIS												
88	7	1	8	7	1	8	8		8	6	1	7
89	3		3	6	1	7	6	1	7	3		3
90	10		10	9	1	10	20		20	2	1	3
91			0	2		2	7		7	2		2
92	9		9	2	2	4	17		17	4	1	5
93	2		2			0	59	1	60	7	1	8
94	6		6	7	2	9	17		17	7		7
95	3		3	2	3	5	9		9	5		5
88 to 91	20	1	21	24	3	27	41	1	42	13	2	15
92 to 95	20	0	20	11	7	18	102	1	103	23	2	25
total	40	1	41	35	10	45	143	2	145	36	4	40
88 to 91	.952	.048	1.000	.889	.111	1.000	.976	.024	1.000	.867	.133	1.000
92 to 95	1.000	.000	1.000	.611	.389	1.000	.990	.010	1.000	.920	.080	1.000
mean		.024			.222			.014			.100	

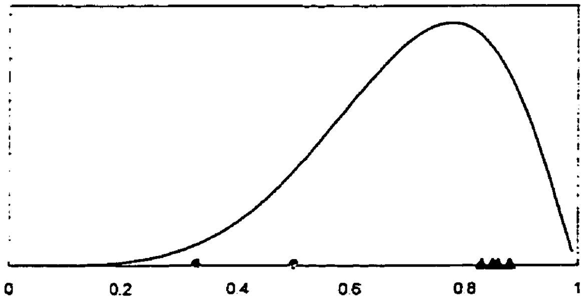
APPENDIX C

DISTRIBUTIONS FOR INPUT VARIABLES

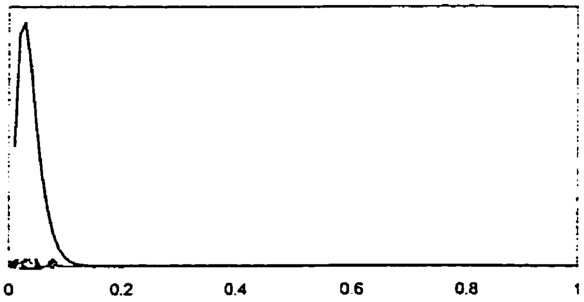
Probability Distributions for Input Variables - Accident Scenarios

Legend:	black triangles:	observed values from first data source
	grey circles:	observed values from second data source

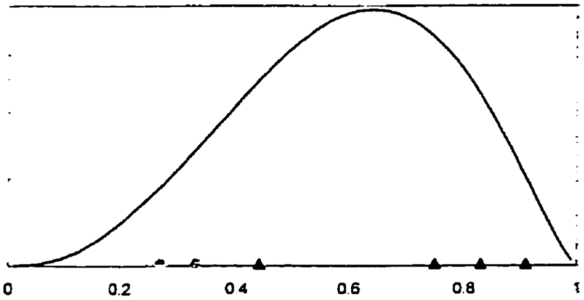
V1.1: P(overturn | release) for toxic PLG



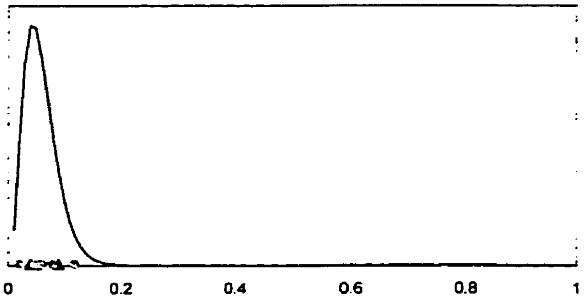
V2.1: P(toxic PLG | release)



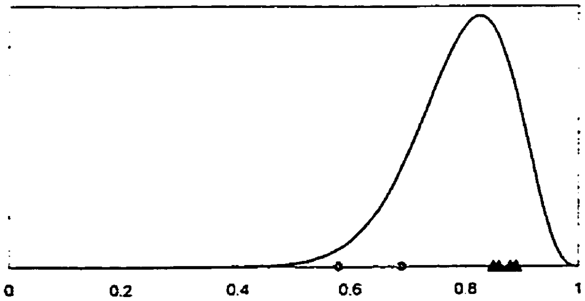
V1.2: P(overturn | release) for flammable PLG



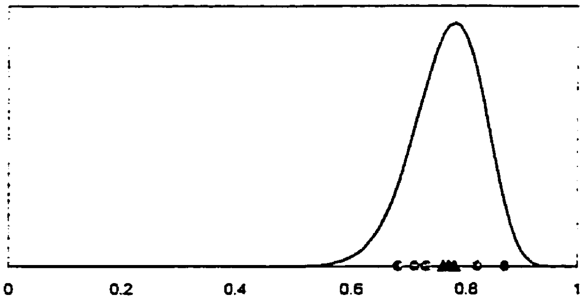
V2.2: P(flammable PLG | release)



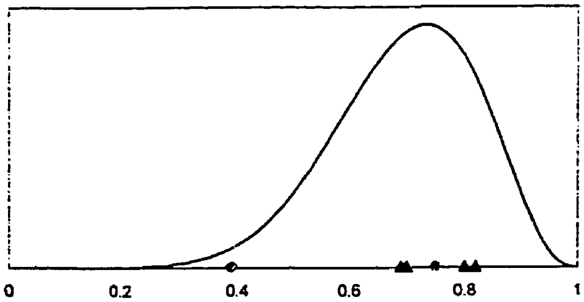
V1.3: P(overturn | release) for flammable liquid



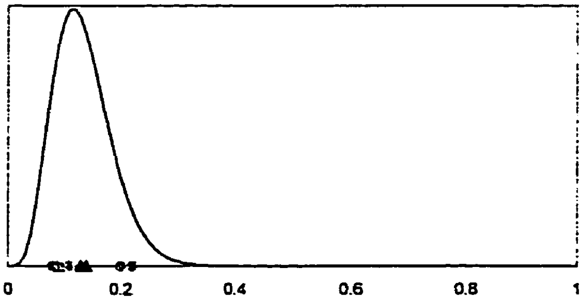
V2.3: P(flammable liquid | release)



V1.4: P(overturn | release) for toxic liquid

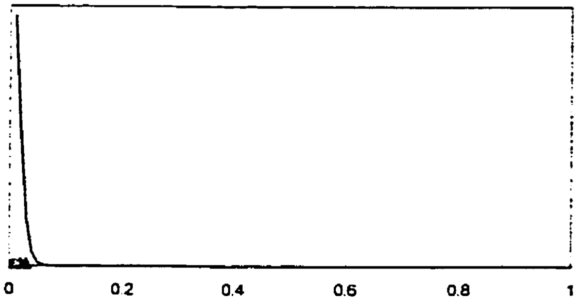


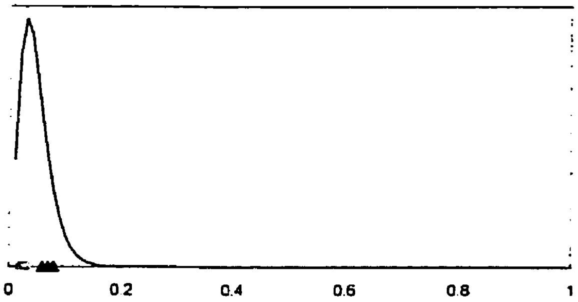
V2.4: P(toxic liquid | release)

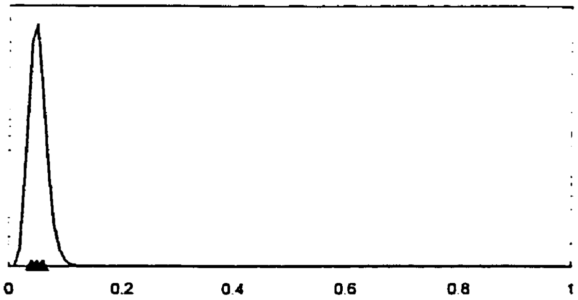


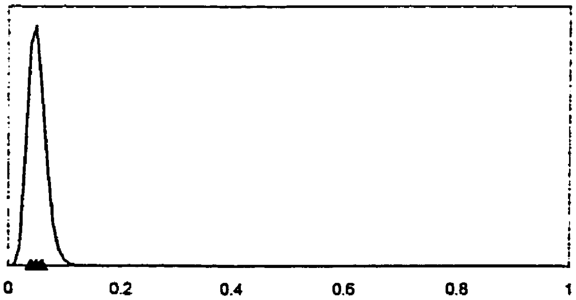
Probability Distributions for Input Variables - Accident Scenarios (continued)

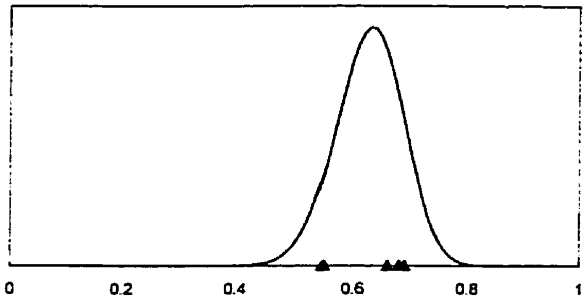
Legend: black triangles: observed values from first data source
grey circles: observed values from second data source

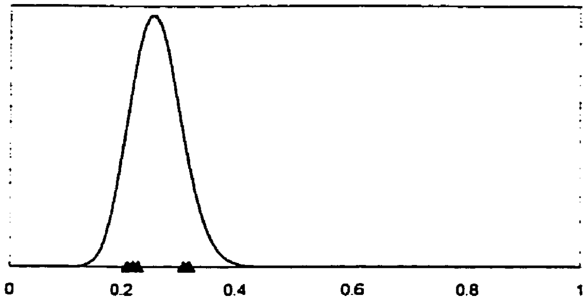

V3: P(release | accident)

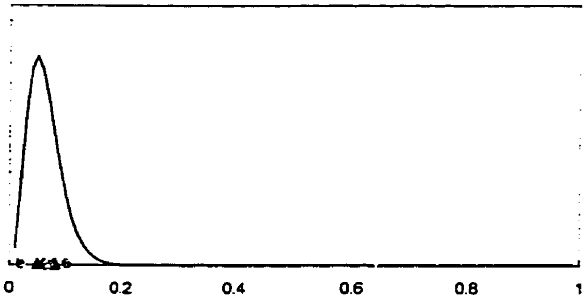

V4: P(overturn | accident)

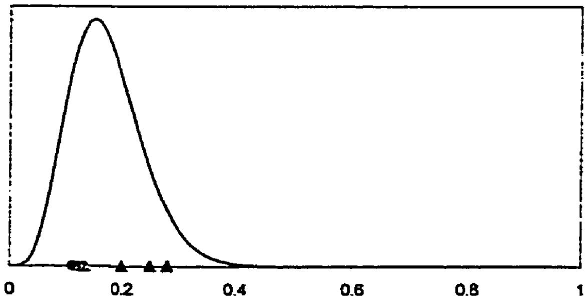

V5.1: P(toxic PLG)


V5.2: P(flammable PLG)


V5.3: P(flammable liquid)


V5.4: P(toxic liquid)

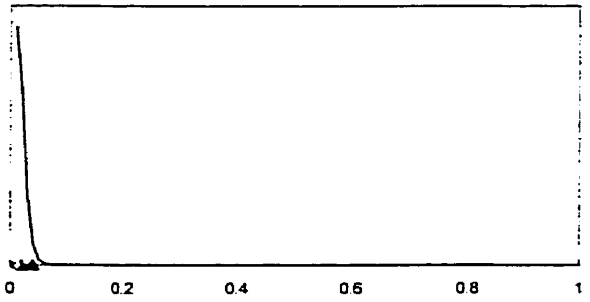

V6.1: P(fire | release, no collision)


V6.2: P(fire | release, collision)

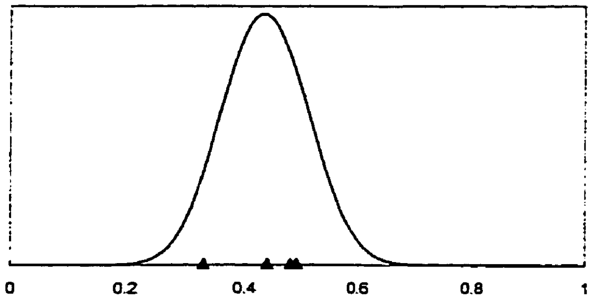
Probability Distributions for Input Variables - Accident Scenarios (continued)

Legend: black triangles: observed values from first data source
grey circles: observed values from second data source

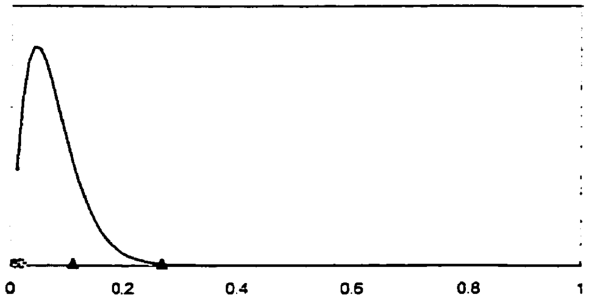
V7.1: P(fire | no release, no collision)



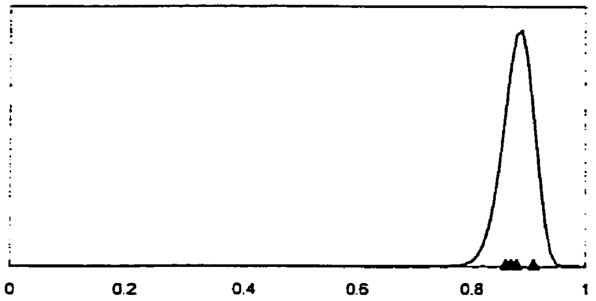
V9.1: P(large release | spill, small load)



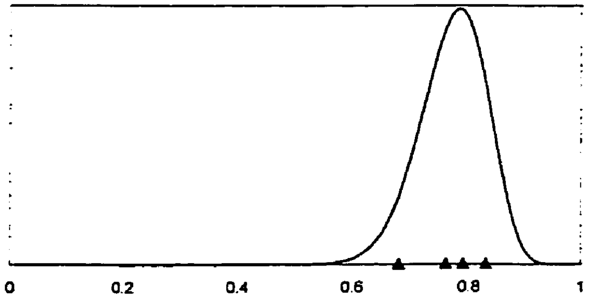
V7.2: P(fire | no release, collision)



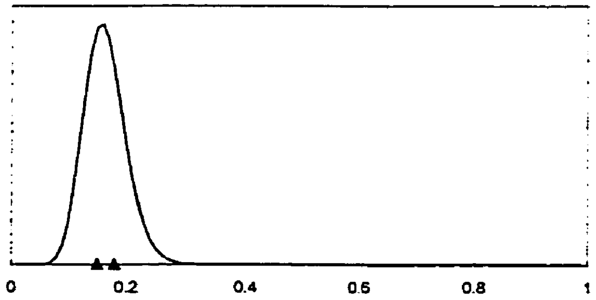
V9.2: P(large release | spill, large load)



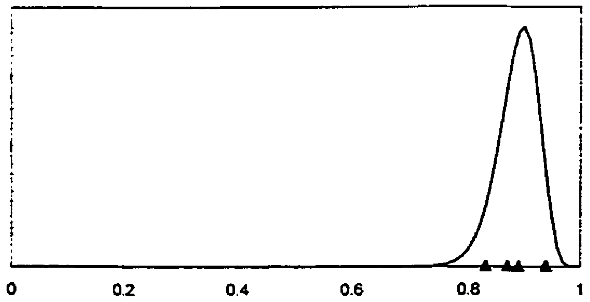
V8.1: P(spill | release, small load)



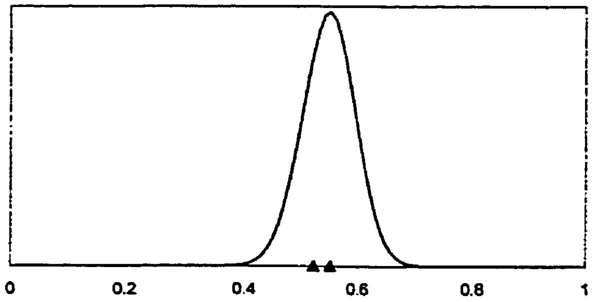
V10.1: P(large release | leak, small load)



V8.2: P(spill | release, large load)



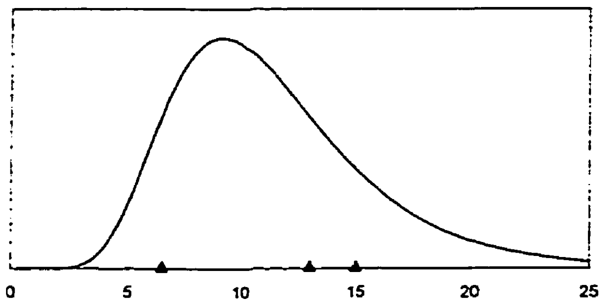
V10.2: P(large release | leak, large load)



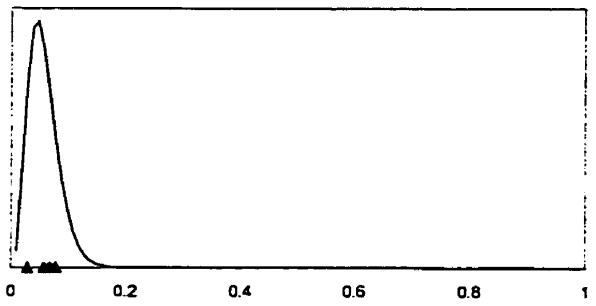
Probability Distributions for Input Variables - Non-Accident Scenarios

Legend: black triangles: observed values from first data source
grey circles: observed values from second data source

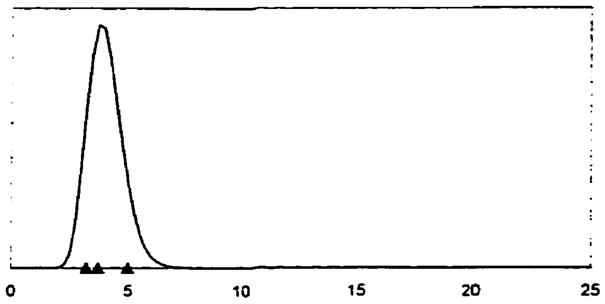
V1.1: Releases per Bvkm for toxic PLG



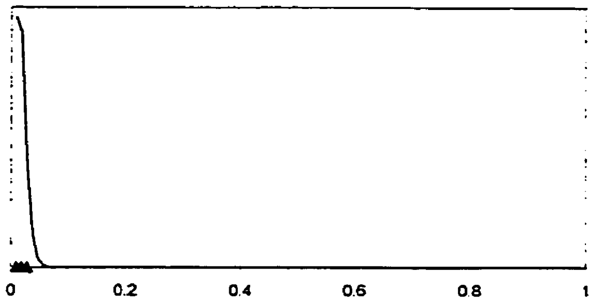
V2.1: P(fire | release, rural road)



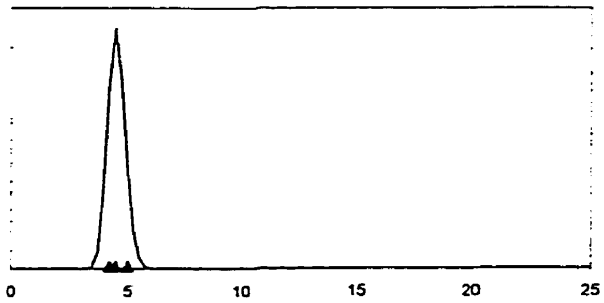
V1.2: Releases per Bvkm for flammable PLG



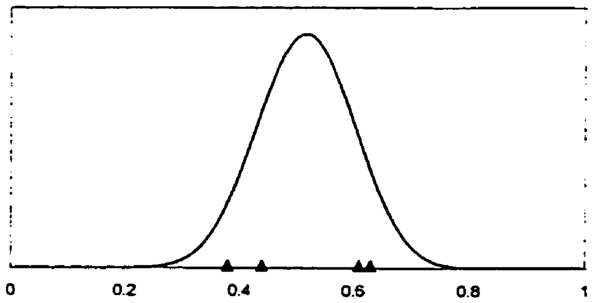
V2.2: P(fire | release, urban road)



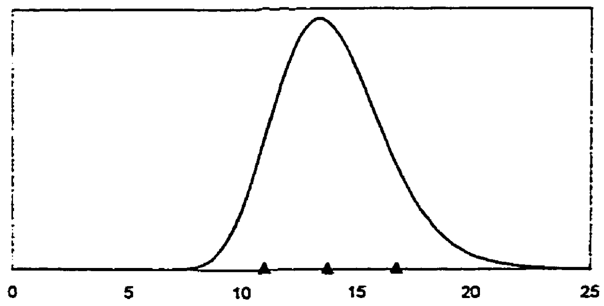
V1.3: Releases per Bvkm for flammable liquid



V3: P(spill | release)

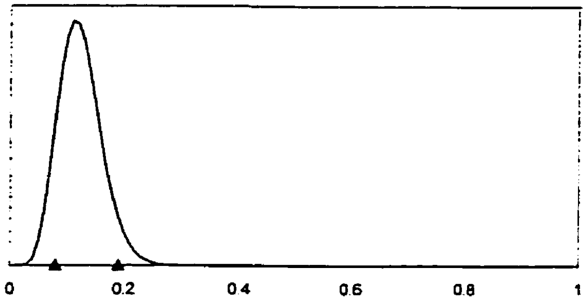


V1.4: Releases per Bvkm for toxic liquid

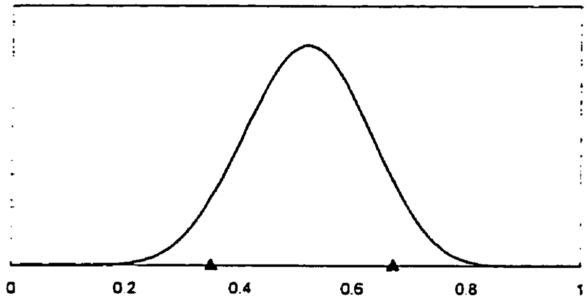


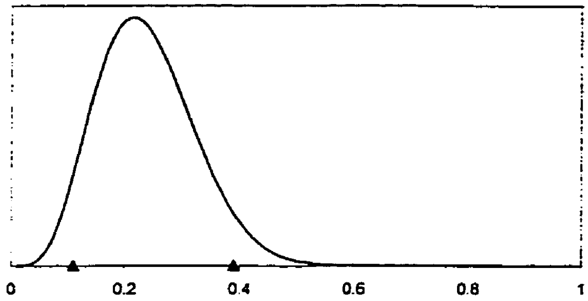
Probability Distributions for Input Variables - Non-Accident Scenarios (continued)

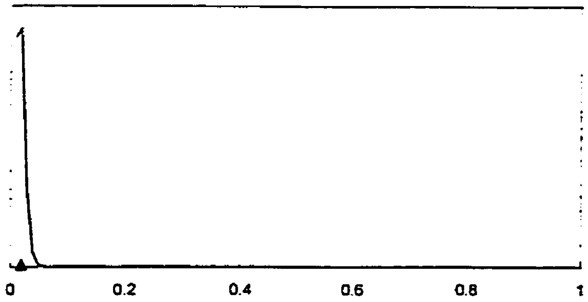
Legend:	black triangles:	observed values from first data source
	grey circles:	observed values from second data source

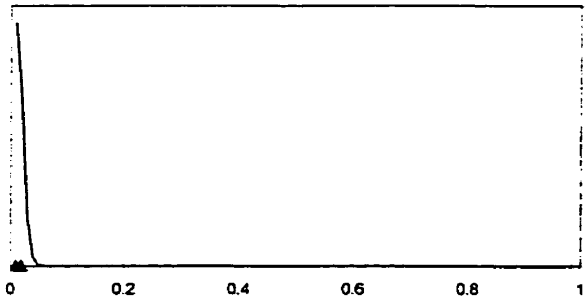

V4.1: P(large release | spill, rural non-tanker)

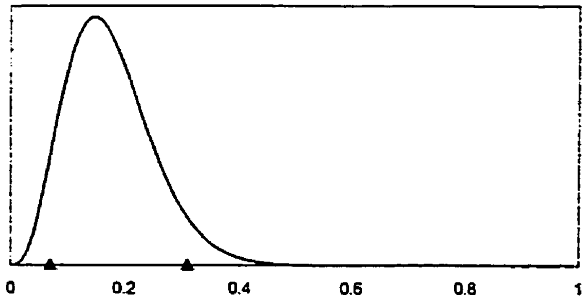

V5.1: P(large release | leak, rural non-tanker)

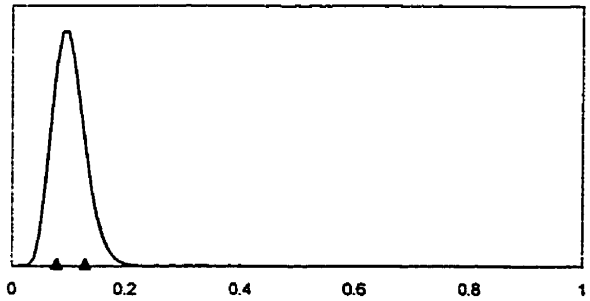

V4.2: P(large release | spill, rural tanker)


V5.2: P(large release | leak, rural tanker)


V4.3: P(large release | spill, urban non-tanker)


V5.3: P(large release | leak, urban non-tanker)


V4.4: P(large release | spill, urban tanker)


V5.4: P(large release | leak, urban tanker)

APPENDIX D

STATISTICS FOR INPUT VARIABLE DISTRIBUTIONS

Statistics for Input Variable Distributions - Accident Scenarios

	Type of Distribution	Alpha	Beta	Mean	Standard Deviation
V1.1: P(overturn | release) for toxic PLG	beta	5.48	2.29	.706	.154
V1.2: P(overturn | release) for flammable PLG	beta	3.51	2.40	.594	.187
V1.3: P(overturn | release) for flammable liquid	beta	16.88	4.35	.795	.086
V1.4: P(overturn | release) for toxic liquid	beta	8.67	3.80	.695	.125
V2.1: P(toxic PLG | release)	beta	3.07	77.77	.038	.021
V2.2: P(flammable PLG | release)	beta	3.65	58.63	.059	.030
V2.3: P(flammable liquid | release)	beta	35.92	10.84	.768	.061
V2.4: P(toxic liquid | release)	beta	5.94	38.75	.133	.050
V3: P(release | accident)	beta	2.46	161.09	.015	.009
V4: P(overturn | accident)	beta	2.83	58.11	.046	.027
V5.1: P(toxic PLG)	beta	10.29	191.48	.051	.015
V5.2: P(flammable PLG)	beta	13.96	222.66	.059	.015
V5.3: P(flammable liquid)	beta	44.79	26.40	.629	.057
V5.4: P(toxic liquid)	beta	24.59	69.84	.260	.045
V6.1: P(fire | release, no collision)	beta	4.14	61.96	.063	.030
V6.2: P(fire | release, collision)	beta	5.68	27.57	.171	.064
V7.1: P(fire | no release, no collision)	beta	3.19	177.44	.018	.010
V7.2: P(fire | no release, collision)	beta	2.18	27.06	.075	.048
V8.1: P(spill | release, small load)	beta	40.02	11.75	.773	.058
V8.2: P(spill | release, large load)	beta	66.68	8.43	.888	.036
V9.1: P(large release | spill, small load)	beta	19.25	24.78	.437	.074
V9.2: P(large release | spill, large load)	beta	125.31	16.92	.881	.027
V10.1: P(large release | leak, small load)	beta	18.40	94.64	.163	.035
V10.2: P(large release | leak, large load)	beta	62.29	51.41	.548	.046

Statistics for Input Variable Distributions - Non-Accident Scenarios

	Type of Distribution	Alpha	Beta	Mean	Standard Deviation
V1.1: Releases per Bvkm for toxic PLG	lognormal			11.07	3.66
V1.2: Releases per Bvkm for flammable PLG	lognormal			4.03	0.73
V1.3: Releases per Bvkm for flammable liquid	lognormal			4.57	0.36
V1.4: Releases per Bvkm for toxic liquid	lognormal			13.94	2.34
V2.1: P(fire | release, rural road)	beta	4.48	72.50	.058	.027
V2.2: P(fire | release, urban road)	beta	3.60	184.61	.019	.010
V3: P(spill | release)	beta	18.01	16.92	.516	.083
V4.1: P(large release | spill, rural non-tanker)	beta	9.40	66.94	.123	.037
V4.2: P(large release | spill, rural tanker)	beta	11.19	10.45	.517	.105
V4.3: P(large release | spill, urban non-tanker)	beta	5.10	277.08	.018	.008
V4.4: P(large release | spill, urban tanker)	beta	4.39	20.70	.175	.074
V5.1: P(large release | leak, rural non-tanker)	beta	8.37	277.64	.029	.010
V5.2: P(large release | leak, rural tanker)	beta	5.70	18.33	.237	.085
V5.3: P(large release | leak, urban non-tanker)	beta	4.08	244.76	.016	.008
V5.4: P(large release | leak, urban tanker)	beta	11.95	105.21	.102	.028

APPENDIX E

STATISTICS FOR OUTPUT VARIABLE DISTRIBUTIONS

Statistics for Output Variable Distributions for Accident Scenarios

Units: Probability of accident outcome

Accident Outcome	Scenario	Overturn	Collision	Large Load	Type of DG Load *	2.5th percentile	97.5th percentile	Mean	Median	Standard Deviation	Skewness	Kurtosis	Coeff. of Variation
large spill with fire	1	y	y	y	1	.00133	.19458	.03802	.01810	.07194	9.94	197.17	1.89
	2	y	y	y	2	.00149	.20900	.04141	.01988	.09244	42.56	4455.65	2.23
	3	y	y	y	3	.00452	.28292	.06431	.03781	.10164	18.07	1089.22	1.58
	4	y	y	y	4	.00127	.11628	.02418	.01293	.04319	14.60	577.66	1.79
	5	y	y	n	1	.00055	.08671	.01649	.00771	.03154	9.71	185.68	1.91
	6	y	y	n	2	.00061	.09232	.01801	.00849	.04116	40.38	3967.90	2.29
	7	y	y	n	3	.00187	.12507	.02794	.01609	.04501	17.20	983.11	1.61
	8	y	y	n	4	.00053	.05103	.01051	.00548	.01894	13.82	527.32	1.80
	9	y	n	y	1	.00045	.07295	.01391	.00635	.02817	13.41	430.55	2.03
	10	y	n	y	2	.00048	.07935	.01512	.00698	.03582	56.70	7221.57	2.37
	11	y	n	y	3	.00146	.10564	.02342	.01326	.03924	23.55	1783.87	1.68
	12	y	n	y	4	.00041	.04242	.00882	.00452	.01690	18.40	895.49	1.92
	13	y	n	n	1	.00018	.03235	.00602	.00270	.01221	12.61	370.45	2.03
	14	y	n	n	2	.00020	.03463	.00656	.00298	.01574	54.45	6684.26	2.40
	15	y	n	n	3	.00060	.04652	.01017	.00567	.01721	22.43	1649.60	1.69
	16	y	n	n	4	.00017	.01875	.00383	.00193	.00731	17.36	833.92	1.91
	17	n	y	y	1	.00002	.00241	.00051	.00028	.00073	5.31	65.00	1.42
	18	n	y	y	2	.00004	.00405	.00092	.00054	.00116	3.92	31.80	1.26
	19	n	y	y	3	.00005	.00189	.00053	.00038	.00050	2.51	13.31	.95
	20	n	y	y	4	.00002	.00134	.00034	.00022	.00037	3.26	22.30	1.09
	21	n	y	n	1	.00001	.00106	.00022	.00012	.00032	5.52	67.18	1.46
	22	n	y	n	2	.00002	.00177	.00040	.00023	.00052	4.15	35.10	1.30
	23	n	y	n	3	.00002	.00085	.00023	.00016	.00022	2.64	14.54	.98
	24	n	y	n	4	.00001	.00060	.00015	.00010	.00017	3.47	25.64	1.13
	25	n	n	y	1	.00001	.00091	.00019	.00010	.00028	7.31	175.25	1.52
	26	n	n	y	2	.00001	.00151	.00033	.00019	.00045	4.69	52.43	1.34
	27	n	n	y	3	.00001	.00072	.00019	.00013	.00020	2.91	18.33	1.01
	28	n	n	y	4	.00001	.00051	.00012	.00008	.00014	3.55	25.14	1.16
	29	n	n	n	1	.00000	.00040	.00008	.00004	.00013	9.51	347.36	1.57
	30	n	n	n	2	.00001	.00067	.00014	.00008	.00020	4.80	52.48	1.37
	31	n	n	n	3	.00001	.00032	.00008	.00006	.00009	3.06	19.93	1.04
	32	n	n	n	4	.00000	.00023	.00005	.00003	.00006	3.70	27.99	1.20

* Type of DG Load
1 = toxic PLG
2 = flammable PLG
3 = flammable liquid
4 = toxic liquid

Statistics for Output Variable Distributions for Accident Scenarios (continued)

Units: Probability of accident outcome

Accident Outcome	Scenario	Overturn	Collision	Large Load	Type of DG Load *	2.5th percentile	97.5th percentile	Mean	Median	Standard Deviation	Skewness	Kurtosis	Coeff. of Variation
small spill with fire	1	y	y	y	1	.00017	.02687	.00514	.00239	.00977	8.94	162.94	1.90
	2	y	y	y	2	.00019	.02888	.00558	.00262	.01103	13.16	401.99	1.98
	3	y	y	y	3	.00057	.03939	.00868	.00496	.01331	8.43	150.51	1.53
	4	y	y	y	4	.00016	.01595	.00326	.00170	.00569	9.48	176.70	1.75
	5	y	y	n	1	.00073	.10917	.02117	.01000	.04069	10.40	220.35	1.92
	6	y	y	n	2	.00080	.11639	.02299	.01096	.05097	38.48	3726.13	2.22
	7	y	y	n	3	.00244	.15963	.03573	.02081	.05664	16.54	892.83	1.59
	8	y	y	n	4	.00068	.06426	.01343	.00712	.02404	13.87	501.27	1.79
	9	y	n	y	1	.00006	.01004	.00188	.00084	.00371	9.81	206.28	1.98
	10	y	n	y	2	.00006	.01098	.00203	.00092	.00410	13.83	495.59	2.02
	11	y	n	y	3	.00018	.01449	.00315	.00176	.00495	8.42	163.94	1.57
	12	y	n	y	4	.00005	.00577	.00119	.00060	.00219	11.44	279.73	1.85
	13	y	n	n	1	.00024	.04083	.00774	.00350	.01590	13.51	421.66	2.05
	14	y	n	n	2	.00026	.04419	.00839	.00384	.01961	50.79	6112.37	2.34
	15	y	n	n	3	.00079	.05916	.01300	.00734	.02167	21.19	1475.18	1.67
	16	y	n	n	4	.00022	.02339	.00490	.00250	.00941	17.37	769.85	1.92
	17	n	y	y	1	.00000	.00033	.00007	.00004	.00010	5.49	69.14	1.47
	18	n	y	y	2	.00001	.00055	.00012	.00007	.00016	4.42	41.90	1.32
	19	n	y	y	3	.00001	.00026	.00007	.00005	.00007	2.76	16.71	.99
	20	n	y	y	4	.00000	.00019	.00005	.00003	.00005	3.54	25.78	1.14
	21	n	y	n	1	.00001	.00136	.00029	.00015	.00041	5.15	61.18	1.43
	22	n	y	n	2	.00002	.00228	.00051	.00030	.00065	3.90	30.68	1.28
	23	n	y	n	3	.00003	.00106	.00029	.00021	.00028	2.62	14.53	.97
	24	n	y	n	4	.00001	.00075	.00019	.00012	.00021	3.37	23.56	1.11
	25	n	n	y	1	.00000	.00013	.00003	.00001	.00004	7.60	192.39	1.57
	26	n	n	y	2	.00000	.00021	.00005	.00002	.00006	5.26	69.17	1.39
	27	n	n	y	3	.00000	.00010	.00003	.00002	.00003	3.15	21.74	1.05
	28	n	n	y	4	.00000	.00007	.00002	.00001	.00002	3.70	26.77	1.21
	29	n	n	n	1	.00000	.00051	.00010	.00005	.00016	7.10	160.95	1.53
	30	n	n	n	2	.00001	.00085	.00019	.00010	.00025	4.77	55.46	1.36
	31	n	n	n	3	.00001	.00041	.00011	.00007	.00011	3.06	20.62	1.03
	32	n	n	n	4	.00000	.00029	.00007	.00004	.00008	3.63	25.77	1.18

* Type of DG Load
1 = toxic PLG
2 = flammable PLG
3 = flammable liquid
4 = toxic liquid

Statistics for Output Variable Distributions for Accident Scenarios (continued)

Units: Probability of accident outcome

Accident Outcome	Scenario	Overturn	Collision	Large Load	Type of DG Load *	2.5th percentile	97.5th percentile	Mean	Median	Standard Deviation	Skewness	Kurtosis	Coeff. of Variation
large leak with fire	1	y	y	y	1	.00009	.01610	.00301	.00135	.00625	13.94	477.65	2.07
	2	y	y	y	2	.00010	.01722	.00329	.00148	.01008	.00	+Infinity	3.06
	3	y	y	y	3	.00031	.02356	.00511	.00280	.00996	46.75	5406.37	1.95
	4	y	y	y	4	.00009	.00958	.00192	.00096	.00402	32.87	2912.23	2.10
	5	y	y	n	1	.00006	.00949	.00179	.00081	.00363	11.69	291.01	2.03
	6	y	y	n	2	.00006	.01012	.00195	.00089	.00460	41.42	4289.75	2.36
	7	y	y	n	3	.00018	.01380	.00303	.00168	.00518	17.72	991.58	1.71
	8	y	y	n	4	.00005	.00564	.00114	.00058	.00222	15.61	580.34	1.95
	9	y	n	y	1	.00003	.00596	.00110	.00047	.00248	19.64	945.66	2.25
	10	y	n	y	2	.00003	.00639	.00120	.00052	.00405	.00	+Infinity	3.38
	11	y	n	y	3	.00010	.00871	.00186	.00099	.00393	61.72	8255.55	2.12
	12	y	n	y	4	.00003	.00354	.00070	.00034	.00160	43.08	4339.59	2.30
	13	y	n	n	1	.00002	.00354	.00065	.00028	.00143	18.27	942.02	2.19
	14	y	n	n	2	.00002	.00384	.00071	.00031	.00179	55.06	6888.33	2.51
	15	y	n	n	3	.00006	.00518	.00111	.00059	.00201	22.56	1571.10	1.82
	16	y	n	n	4	.00002	.00210	.00042	.00020	.00087	19.50	910.10	2.09
	17	n	y	y	1	.00000	.00020	.00004	.00002	.00006	6.36	97.77	1.55
	18	n	y	y	2	.00000	.00034	.00007	.00004	.00010	4.45	43.17	1.37
	19	n	y	y	3	.00000	.00016	.00004	.00003	.00004	2.99	17.97	1.05
	20	n	y	y	4	.00000	.00011	.00003	.00002	.00003	4.10	38.13	1.21
	21	n	y	n	1	.00000	.00012	.00002	.00001	.00004	6.00	84.10	1.53
	22	n	y	n	2	.00000	.00020	.00004	.00002	.00006	4.71	47.17	1.37
	23	n	y	n	3	.00000	.00010	.00002	.00002	.00003	3.01	18.93	1.04
	24	n	y	n	4	.00000	.00007	.00002	.00001	.00002	3.66	27.80	1.19
	25	n	n	y	1	.00000	.00007	.00001	.00001	.00003	17.28	1120.97	1.71
	26	n	n	y	2	.00000	.00013	.00003	.00001	.00004	4.86	49.33	1.43
	27	n	n	y	3	.00000	.00006	.00002	.00001	.00002	3.28	22.79	1.11
	28	n	n	y	4	.00000	.00004	.00001	.00001	.00001	4.11	34.45	1.27
	29	n	n	n	1	.00000	.00004	.00001	.00000	.00001	6.82	124.71	1.61
	30	n	n	n	2	.00000	.00008	.00002	.00001	.00002	5.19	59.06	1.44
	31	n	n	n	3	.00000	.00004	.00001	.00001	.00001	3.49	27.74	1.11
	32	n	n	n	4	.00000	.00003	.00001	.00000	.00001	3.88	29.58	1.25

* Type of DG Load
1 = toxic PLG
2 = flammable PLG
3 = flammable liquid
4 = toxic liquid

Statistics for Output Variable Distributions for Accident Scenarios (continued)

Units: Probability of accident outcome

Accident Outcome	Scenario	Overturn	Collision	Large Load	Type of DG Load *	2.5th percentile	97.5th percentile	Mean	Median	Standard Deviation	Skewness	Kurtosis	Coeff. of Variation
small leak with fire	1	y	y	y	1	.00008	.01340	.00249	.00111	.00514	12.05	302.97	2.06
	2	y	y	y	2	.00008	.01419	.00271	.00122	.00723	60.61	7553.02	2.67
	3	y	y	y	3	.00025	.01970	.00421	.00232	.00772	27.63	2147.48	1.83
	4	y	y	y	4	.00007	.00800	.00158	.00079	.00322	22.17	1245.85	2.03
	5	y	y	n	1	.00030	.04852	.00922	.00426	.01813	10.34	216.34	1.97
	6	y	y	n	2	.00033	.05187	.01005	.00468	.02406	52.51	6338.10	2.39
	7	y	y	n	3	.00100	.07067	.01561	.00882	.02662	22.35	1539.59	1.71
	8	y	y	n	4	.00028	.02867	.00586	.00302	.01131	18.04	831.74	1.93
	9	y	n	y	1	.00003	.00495	.00091	.00039	.00200	15.87	600.93	2.20
	10	y	n	y	2	.00003	.00525	.00099	.00043	.00282	.00	+Infinity	2.86
	11	y	n	y	3	.00008	.00724	.00153	.00082	.00294	35.68	3519.70	1.92
	12	y	n	y	4	.00002	.00291	.00058	.00028	.00125	28.05	1915.69	2.17
	13	y	n	n	1	.00010	.01797	.00337	.00149	.00709	13.22	409.31	2.10
	14	y	n	n	2	.00011	.01966	.00367	.00164	.00957	68.10	9437.47	2.60
	15	y	n	n	3	.00032	.02628	.00569	.00312	.01037	28.72	2433.10	1.82
	16	y	n	n	4	.00009	.01056	.00214	.00106	.00447	23.48	1350.89	2.09
	17	n	y	y	1	.00000	.00016	.00003	.00002	.00005	5.93	78.87	1.54
	18	n	y	y	2	.00000	.00028	.00006	.00003	.00008	4.20	34.58	1.36
	19	n	y	y	3	.00000	.00013	.00003	.00002	.00004	2.95	17.67	1.05
	20	n	y	y	4	.00000	.00009	.00002	.00001	.00003	3.96	33.21	1.22
	21	n	y	n	1	.00000	.00060	.00012	.00007	.00019	6.56	109.83	1.51
	22	n	y	n	2	.00001	.00101	.00022	.00013	.00030	4.37	39.71	1.33
	23	n	y	n	3	.00001	.00048	.00013	.00009	.00013	2.84	16.65	1.01
	24	n	y	n	4	.00001	.00034	.00008	.00005	.00009	3.47	24.12	1.15
	25	n	n	y	1	.00000	.00006	.00001	.00001	.00002	13.60	698.88	1.68
	26	n	n	y	2	.00000	.00011	.00002	.00001	.00003	4.93	53.52	1.43
	27	n	n	y	3	.00000	.00005	.00001	.00001	.00001	3.58	33.87	1.12
	28	n	n	y	4	.00000	.00004	.00001	.00000	.00001	4.21	36.24	1.28
	29	n	n	n	1	.00000	.00023	.00005	.00002	.00007	8.07	196.19	1.60
	30	n	n	n	2	.00000	.00038	.00008	.00004	.00011	5.43	73.04	1.41
	31	n	n	n	3	.00000	.00018	.00005	.00003	.00005	3.21	22.51	1.07
	32	n	n	n	4	.00000	.00013	.00003	.00002	.00004	3.99	33.15	1.23

* Type of DG Load
1 = toxic PLG
2 = flammable PLG
3 = flammable liquid
4 = toxic liquid

Statistics for Output Variable Distributions for Accident Scenarios (continued)

Units: Probability of accident outcome

Accident Outcome	Scenario	Overturn	Collision	Large Load	Type of DG Load *	2.5th percentile	97.5th percentile	Mean	Median	Standard Deviation	Skewness	Kurtosis	Coeff. of Variation
large spill no fire	1	y	y	y	1	.00802	.90047	.18290	.09402	.31877	9.65	207.76	1.74
	2	y	y	y	2	.00878	.95722	.19902	.10317	.37957	29.99	2602.73	1.91
	3	y	y	y	3	.02794	.99999	.30889	.19524	.42808	13.31	605.18	1.39
	4	y	y	y	4	.00769	.51546	.11614	.06668	.18678	12.17	371.15	1.61
	5	y	y	n	1	.00332	.39694	.07931	.03991	.13947	9.36	191.70	1.76
	6	y	y	n	2	.00364	.42295	.08648	.04397	.16939	29.71	2419.31	1.96
	7	y	y	n	3	.01145	.55925	.13419	.08312	.19031	12.84	548.58	1.42
	8	y	y	n	4	.00315	.23034	.05045	.02830	.08172	11.27	322.97	1.62
	9	y	n	y	1	.00917	.99999	.20702	.10675	.35936	9.38	190.91	1.74
	10	y	n	y	2	.00991	.99999	.22531	.11723	.43267	30.97	2740.09	1.92
	11	y	n	y	3	.03165	.99999	.34978	.22179	.48551	13.71	645.78	1.39
	12	y	n	y	4	.00877	.58527	.13150	.07580	.21107	12.20	379.64	1.61
	13	y	n	n	1	.00376	.44682	.08978	.04542	.15742	9.16	179.89	1.75
	14	y	n	n	2	.00416	.47765	.09792	.04989	.19319	30.27	2497.34	1.97
	15	y	n	n	3	.01301	.63433	.15196	.09427	.21594	13.22	585.37	1.42
	16	y	n	n	4	.00359	.26077	.05713	.03211	.09247	11.35	333.64	1.62
	17	n	y	y	1	.00011	.01090	.00248	.00147	.00320	4.95	67.19	1.29
	18	n	y	y	2	.00025	.01792	.00442	.00284	.00502	3.35	23.58	1.14
	19	n	y	y	3	.00029	.00817	.00256	.00199	.00211	2.04	9.71	.82
	20	n	y	y	4	.00014	.00587	.00164	.00117	.00158	2.61	14.32	.96
	21	n	y	n	1	.00005	.00480	.00107	.00063	.00144	5.77	107.93	1.34
	22	n	y	n	2	.00010	.00800	.00192	.00121	.00225	3.59	27.09	1.17
	23	n	y	n	3	.00012	.00365	.00111	.00085	.00095	2.21	11.09	.86
	24	n	y	n	4	.00006	.00264	.00071	.00050	.00071	2.79	16.22	1.00
	25	n	n	y	1	.00012	.01234	.00280	.00167	.00361	4.77	57.84	1.29
	26	n	n	y	2	.00028	.02023	.00500	.00322	.00565	3.29	22.41	1.13
	27	n	n	y	3	.00033	.00921	.00290	.00226	.00237	2.00	9.36	.82
	28	n	n	y	4	.00016	.00667	.00185	.00132	.00178	2.61	14.41	.96
	29	n	n	n	1	.00005	.00541	.00122	.00071	.00162	5.39	83.85	1.33
	30	n	n	n	2	.00012	.00904	.00217	.00137	.00254	3.54	26.25	1.17
	31	n	n	n	3	.00014	.00411	.00126	.00096	.00107	2.18	10.80	.85
	32	n	n	n	4	.00007	.00297	.00080	.00056	.00080	2.78	16.09	1.00

* Type of DG Load
1 = toxic PLG
2 = flammable PLG
3 = flammable liquid
4 = toxic liquid

Statistics for Output Variable Distributions for Accident Scenarios (continued)

Units: Probability of accident outcome

Accident Outcome	Scenario	Overturn	Collision	Large Load	Type of DG Load *	2.5th percentile	97.5th percentile	Mean	Median	Standard Deviation	Skewness	Kurtosis	Coeff. of Variation
small spill no fire	1	y	y	y	1	.00101	.12207	.02472	.01234	.04316	8.13	134.74	1.75
	2	y	y	y	2	.00111	.13126	.02680	.01358	.04722	10.64	290.27	1.76
	3	y	y	y	3	.00347	.17534	.04166	.02577	.05673	7.09	108.11	1.36
	4	y	y	y	4	.00096	.07115	.01566	.00878	.02513	9.65	213.00	1.60
	5	y	y	n	1	.00435	.49911	.10180	.05172	.17994	9.71	204.42	1.77
	6	y	y	n	2	.00470	.53747	.11049	.05682	.20980	26.68	2130.10	1.90
	7	y	y	n	3	.01511	.70941	.17155	.10769	.23842	12.28	502.34	1.39
	8	y	y	n	4	.00416	.28865	.06450	.03680	.10473	11.95	341.91	1.62
	9	y	n	y	1	.00116	.13730	.02798	.01403	.04875	8.05	132.46	1.74
	10	y	n	y	2	.00125	.14719	.03034	.01540	.05358	10.56	273.88	1.77
	11	y	n	y	3	.00396	.19755	.04719	.02920	.06434	7.19	112.41	1.36
	12	y	n	y	4	.00109	.08121	.01773	.00997	.02834	9.39	198.91	1.60
	13	y	n	n	1	.00494	.56994	.11523	.05860	.20293	9.49	190.73	1.76
	14	y	n	n	2	.00531	.60323	.12508	.06471	.23921	27.67	2251.57	1.91
	15	y	n	n	3	.01701	.80073	.19428	.12206	.27059	12.62	533.71	1.39
	16	y	n	n	4	.00471	.33012	.07303	.04176	.11824	11.90	344.47	1.62
	17	n	y	y	1	.00001	.00150	.00033	.00019	.00045	5.15	70.43	1.34
	18	n	y	y	2	.00003	.00248	.00060	.00037	.00071	3.68	28.71	1.18
	19	n	y	y	3	.00004	.00114	.00035	.00026	.00030	2.27	12.11	.87
	20	n	y	y	4	.00002	.00083	.00022	.00015	.00022	2.86	16.99	1.01
	21	n	y	n	1	.00006	.00612	.00138	.00081	.00180	4.77	59.54	1.31
	22	n	y	n	2	.00014	.01005	.00245	.00156	.00282	3.35	23.39	1.15
	23	n	y	n	3	.00016	.00464	.00142	.00109	.00120	2.14	10.64	.84
	24	n	y	n	4	.00008	.00334	.00091	.00064	.00089	2.70	15.25	.98
	25	n	n	y	1	.00002	.00170	.00038	.00022	.00051	4.94	59.31	1.34
	26	n	n	y	2	.00004	.00279	.00068	.00042	.00080	3.63	27.63	1.18
	27	n	n	y	3	.00004	.00129	.00039	.00030	.00034	2.25	12.04	.86
	28	n	n	y	4	.00002	.00093	.00025	.00017	.00025	2.86	16.96	1.01
	29	n	n	n	1	.00007	.00697	.00156	.00092	.00202	4.59	50.89	1.30
	30	n	n	n	2	.00015	.01133	.00278	.00177	.00317	3.28	22.10	1.14
	31	n	n	n	3	.00018	.00525	.00161	.00124	.00135	2.10	10.23	.84
	32	n	n	n	4	.00009	.00375	.00103	.00073	.00101	2.70	15.33	.98

* Type of DG Load
1 = toxic PLG
2 = flammable PLG
3 = flammable liquid
4 = toxic liquid

Statistics for Output Variable Distributions for Accident Scenarios (continued)

Units: Probability of accident outcome

Accident Outcome	Scenario	Overturn	Collision	Large Load	Type of DG Load *	2.5th percentile	97.5th percentile	Mean	Median	Standard Deviation	Skewness	Kurtosis	Coeff. of Variation
large leak no fire	1	y	y	y	1	.00055	.07352	.01447	.00694	.02754	12.59	380.95	1.90
	2	y	y	y	2	.00060	.07846	.01576	.00768	.03937	.00	+Infinity	2.50
	3	y	y	y	3	.00186	.10599	.02446	.01458	.04062	33.24	3200.89	1.66
	4	y	y	y	4	.00052	.04276	.00919	.00495	.01693	23.51	1593.82	1.84
	5	y	y	n	1	.00033	.04378	.00860	.00420	.01613	11.97	369.49	1.87
	6	y	y	n	2	.00036	.04731	.00937	.00462	.01890	28.85	2468.38	2.02
	7	y	y	n	3	.00111	.06253	.01456	.00873	.02193	13.02	541.10	1.51
	8	y	y	n	4	.00031	.02536	.00548	.00300	.00960	13.20	407.80	1.75
	9	y	n	y	1	.00063	.08308	.01638	.00787	.03106	12.32	363.69	1.90
	10	y	n	y	2	.00068	.08868	.01786	.00870	.04517	.00	+Infinity	2.53
	11	y	n	y	3	.00212	.11941	.02771	.01656	.04630	34.46	3391.83	1.67
	12	y	n	y	4	.00058	.04866	.01041	.00562	.01920	24.21	1699.72	1.84
	13	y	n	n	1	.00038	.04968	.00974	.00475	.01816	11.32	312.13	1.86
	14	y	n	n	2	.00041	.05337	.01061	.00524	.02154	29.86	2610.51	2.03
	15	y	n	n	3	.00126	.07110	.01649	.00989	.02484	13.31	574.85	1.51
	16	y	n	n	4	.00035	.02888	.00620	.00340	.01085	13.17	408.40	1.75
	17	n	y	y	1	.00001	.00090	.00020	.00011	.00028	8.69	315.27	1.43
	18	n	y	y	2	.00002	.00151	.00035	.00021	.00043	3.96	32.42	1.24
	19	n	y	y	3	.00002	.00070	.00020	.00015	.00019	2.51	13.77	.92
	20	n	y	y	4	.00001	.00050	.00013	.00009	.00014	3.18	20.87	1.07
	21	n	y	n	1	.00000	.00054	.00012	.00006	.00016	5.36	67.91	1.40
	22	n	y	n	2	.00001	.00091	.00021	.00013	.00026	4.00	33.80	1.24
	23	n	y	n	3	.00001	.00042	.00012	.00009	.00011	2.50	13.78	.92
	24	n	y	n	4	.00001	.00030	.00008	.00005	.00008	3.07	19.38	1.06
	25	n	n	y	1	.00001	.00102	.00022	.00012	.00031	7.58	220.68	1.42
	26	n	n	y	2	.00002	.00171	.00039	.00024	.00049	3.90	31.13	1.24
	27	n	n	y	3	.00002	.00079	.00023	.00017	.00021	2.50	13.61	.92
	28	n	n	y	4	.00001	.00057	.00015	.00010	.00016	3.21	21.92	1.07
	29	n	n	n	1	.00001	.00061	.00013	.00007	.00018	5.26	63.68	1.39
	30	n	n	n	2	.00001	.00103	.00024	.00014	.00029	3.94	32.10	1.24
	31	n	n	n	3	.00001	.00047	.00014	.00010	.00012	2.46	13.16	.92
	32	n	n	n	4	.00001	.00034	.00009	.00006	.00009	3.04	19.03	1.06

* Type of DG Load
1 = toxic PLG
2 = flammable PLG
3 = flammable liquid
4 = toxic liquid

Statistics for Output Variable Distributions for Accident Scenarios (continued)

Units: Probability of accident outcome

Accident Outcome	Scenario	Overturn	Collision	Large Load	Type of DG Load *	2.5th percentile	97.5th percentile	Mean	Median	Standard Deviation	Skewness	Kurtosis	Coeff. of Variation
small leak no fire	1	y	y	y	1	.00045	.06206	.01196	.00573	.02260	10.90	263.68	1.89
	2	y	y	y	2	.00049	.06491	.01301	.00634	.02932	45.24	4757.85	2.25
	3	y	y	y	3	.00151	.08661	.02020	.01201	.03200	19.41	1194.48	1.58
	4	y	y	y	4	.00043	.03527	.00760	.00408	.01374	16.92	728.04	1.81
	5	y	y	n	1	.00178	.22145	.04434	.02206	.08050	9.79	206.76	1.82
	6	y	y	n	2	.00197	.23687	.04826	.02420	.09862	37.09	3715.98	2.04
	7	y	y	n	3	.00618	.31571	.07493	.04570	.11143	16.04	854.15	1.49
	8	y	y	n	4	.00169	.12873	.02816	.01567	.04847	14.66	538.78	1.72
	9	y	n	y	1	.00051	.06966	.01355	.00651	.02553	10.71	248.13	1.88
	10	y	n	y	2	.00056	.07385	.01474	.00717	.03350	46.20	4931.86	2.27
	11	y	n	y	3	.00173	.09873	.02289	.01357	.03648	20.33	1283.95	1.59
	12	y	n	y	4	.00048	.04028	.00860	.00464	.01559	17.42	775.49	1.81
	13	y	n	n	1	.00202	.25006	.05018	.02498	.09074	9.55	192.18	1.81
	14	y	n	n	2	.00222	.26806	.05463	.02748	.11222	38.36	3943.36	2.05
	15	y	n	n	3	.00700	.35834	.08484	.05187	.12651	16.68	919.45	1.49
	16	y	n	n	4	.00194	.14608	.03188	.01776	.05483	14.77	552.45	1.72
	17	n	y	y	1	.00001	.00075	.00016	.00009	.00023	7.20	194.91	1.42
	18	n	y	y	2	.00001	.00125	.00029	.00017	.00036	3.98	33.34	1.25
	19	n	y	y	3	.00002	.00058	.00017	.00012	.00015	2.55	14.45	.93
	20	n	y	y	4	.00001	.00042	.00011	.00007	.00012	3.24	21.21	1.09
	21	n	y	n	1	.00002	.00272	.00060	.00034	.00082	5.95	101.33	1.37
	22	n	y	n	2	.00006	.00450	.00107	.00066	.00129	4.00	36.40	1.21
	23	n	y	n	3	.00006	.00209	.00062	.00047	.00055	2.33	12.13	.88
	24	n	y	n	4	.00003	.00149	.00040	.00027	.00041	2.90	17.05	1.02
	25	n	n	y	1	.00001	.00084	.00018	.00010	.00026	6.48	141.25	1.41
	26	n	n	y	2	.00002	.00142	.00033	.00020	.00040	3.89	31.27	1.24
	27	n	n	y	3	.00002	.00066	.00019	.00014	.00017	2.52	13.99	.92
	28	n	n	y	4	.00001	.00047	.00012	.00008	.00013	3.21	20.67	1.08
	29	n	n	n	1	.00003	.00308	.00068	.00039	.00093	5.85	96.22	1.36
	30	n	n	n	2	.00006	.00508	.00121	.00075	.00146	3.87	32.37	1.20
	31	n	n	n	3	.00007	.00235	.00070	.00053	.00062	2.30	11.79	.88
	32	n	n	n	4	.00004	.00168	.00045	.00031	.00046	2.87	16.78	1.02

- Type of DG Load
  1 = toxic PLG
  2 = flammable PLG
  3 = flammable liquid
  4 = toxic liquid

Statistics for Output Variable Distributions for Accident Scenarios (continued)

Units: Probability of accident outcome

Accident Outcome	Scenario	Overturn	Collision	Large Load	Type of DG Load *	2.5th percentile	97.5th percentile	Mean	Median	Standard Deviation	Skewness	Kurtosis	Coeff. of Variation
fire no release	1	y	y	y	1	.00000	.16228	.05342	.04761	.05625	4.96	122.89	1.05
	2	y	y	y	2	.00000	.16064	.05157	.04656	.06182	17.91	1363.51	1.20
	3	y	y	y	3	.00000	.14250	.03885	.03652	.06370	11.12	498.52	1.64
	4	y	y	y	4	.00434	.16898	.06126	.05330	.04670	.82	39.09	.76
	5	y	y	n	1	.00000	.16228	.05342	.04761	.05625	4.96	122.89	1.05
	6	y	y	n	2	.00000	.16064	.05157	.04656	.06182	17.91	1363.51	1.20
	7	y	y	n	3	.00000	.14250	.03885	.03652	.06370	11.12	498.52	1.64
	8	y	y	n	4	.00434	.16898	.06126	.05330	.04670	.82	39.09	.76
	9	y	n	y	1	.00000	.03492	.01267	.01186	.01187	4.47	106.79	.94
	10	y	n	y	2	.00000	.03471	.01223	.01157	.01280	6.76	192.91	1.05
	11	y	n	y	3	.00000	.03093	.00922	.00927	.01389	6.88	149.22	1.51
	12	y	n	y	4	.00168	.03641	.01450	.01312	.00979	.66	24.44	.68
	13	y	n	n	1	.00000	.03492	.01267	.01186	.01187	4.47	106.79	.94
	14	y	n	n	2	.00000	.03471	.01223	.01157	.01280	6.76	192.91	1.05
	15	y	n	n	3	.00000	.03093	.00922	.00927	.01389	6.88	149.22	1.51
	16	y	n	n	4	.00168	.03641	.01450	.01312	.00979	.66	24.44	.68
	17	n	y	y	1	.01093	.19116	.07438	.06495	.04767	1.14	4.69	.64
	18	n	y	y	2	.01085	.19071	.07416	.06479	.04753	1.14	4.69	.64
	19	n	y	y	3	.01092	.19108	.07437	.06497	.04766	1.14	4.69	.64
	20	n	y	y	4	.01093	.19141	.07448	.06507	.04773	1.14	4.69	.64
	21	n	y	n	1	.01093	.19116	.07438	.06495	.04767	1.14	4.69	.64
	22	n	y	n	2	.01085	.19071	.07416	.06479	.04753	1.14	4.69	.64
	23	n	y	n	3	.01092	.19108	.07437	.06497	.04766	1.14	4.69	.64
	24	n	y	n	4	.01093	.19141	.07448	.06507	.04773	1.14	4.69	.64
	25	n	n	y	1	.00394	.04123	.01760	.01585	.00974	1.07	4.65	.55
	26	n	n	y	2	.00393	.04110	.01755	.01580	.00972	1.07	4.65	.55
	27	n	n	y	3	.00394	.04120	.01760	.01585	.00974	1.07	4.64	.55
	28	n	n	y	4	.00394	.04126	.01763	.01587	.00976	1.07	4.64	.55
	29	n	n	n	1	.00394	.04123	.01760	.01585	.00974	1.07	4.65	.55
	30	n	n	n	2	.00393	.04110	.01755	.01580	.00972	1.07	4.65	.55
	31	n	n	n	3	.00394	.04120	.01760	.01585	.00974	1.07	4.64	.55
	32	n	n	n	4	.00394	.04126	.01763	.01587	.00976	1.07	4.64	.55

* Type of DG Load
1 = toxic PLG
2 = flammable PLG
3 = flammable liquid
4 = toxic liquid

Statistics for Output Variable Distributions for Accident Scenarios (continued)

Units: Probability of accident outcome

Accident Outcome	Scenario	Overturn	Collision	Large Load	Type of DG Load *	2.5th percentile	97.5th percentile	Mean	Median	Standard Deviation	Skewness	Kurtosis	Coeff. of Variation
no fire no release	1	y	y	y	1	.00000	.94690	.66386	.78214	.45367	-9.20	186.32	.68
	2	y	y	y	2	.00000	.94473	.64085	.76968	.55191	-32.82	3019.89	.86
	3	y	y	y	3	.00000	.90516	.48362	.64164	.61583	-14.33	714.92	1.27
	4	y	y	y	4	.18961	.95083	.75922	.82123	.27056	-12.17	393.29	.36
	5	y	y	n	1	.00000	.94690	.66386	.78214	.45367	-9.20	186.32	.68
	6	y	y	n	2	.00000	.94473	.64085	.76968	.55191	-32.82	3019.89	.86
	7	y	y	n	3	.00000	.90516	.48362	.64164	.61583	-14.33	714.92	1.27
	8	y	y	n	4	.18961	.95083	.75922	.82123	.27056	-12.17	393.29	.36
	9	y	n	y	1	.00000	.97293	.70460	.83908	.48204	-9.48	197.58	.68
	10	y	n	y	2	.00000	.97106	.68018	.82454	.58760	-34.06	3205.01	.86
	11	y	n	y	3	.00000	.94024	.51325	.68463	.65446	-14.78	760.67	1.28
	12	y	n	y	4	.20037	.97347	.80598	.88041	.28439	-12.79	427.42	.35
	13	y	n	n	1	.00000	.97293	.70460	.83908	.48204	-9.48	197.58	.68
	14	y	n	n	2	.00000	.97106	.68018	.82454	.58760	-34.06	3205.01	.86
	15	y	n	n	3	.00000	.94024	.51325	.68463	.65446	-14.78	760.67	1.28
	16	y	n	n	4	.20037	.97347	.80598	.88041	.28439	-12.79	427.42	.35
	17	n	y	y	1	.80475	.98609	.92180	.93118	.04790	-1.13	4.65	.05
	18	n	y	y	2	.80196	.98428	.91902	.92819	.04808	-1.10	4.58	.05
	19	n	y	y	3	.80483	.98558	.92168	.93102	.04778	-1.13	4.67	.05
	20	n	y	y	4	.80585	.98680	.92300	.93237	.04779	-1.14	4.67	.05
	21	n	y	n	1	.80475	.98609	.92180	.93118	.04790	-1.13	4.65	.05
	22	n	y	n	2	.80196	.98428	.91902	.92819	.04808	-1.10	4.58	.05
	23	n	y	n	3	.80483	.98558	.92168	.93102	.04778	-1.13	4.67	.05
	24	n	y	n	4	.80585	.98680	.92300	.93237	.04779	-1.14	4.67	.05
	25	n	n	y	1	.95274	.99412	.97857	.98044	.01088	-1.20	6.59	.01
	26	n	n	y	2	.94639	.99300	.97563	.97782	.01232	-1.27	6.36	.01
	27	n	n	y	3	.95412	.99347	.97845	.98015	.01024	-.98	4.40	.01
	28	n	n	y	4	.95565	.99432	.97985	.98155	.01004	-1.01	4.49	.01
	29	n	n	n	1	.95274	.99412	.97857	.98044	.01088	-1.20	6.59	.01
	30	n	n	n	2	.94639	.99300	.97563	.97782	.01232	-1.27	6.36	.01
	31	n	n	n	3	.95412	.99347	.97845	.98015	.01024	-.98	4.40	.01
	32	n	n	n	4	.95565	.99432	.97985	.98155	.01004	-1.01	4.49	.01

* Type of DG Load
1 = toxic PLG
2 = flammable PLG
3 = flammable liquid
4 = toxic liquid

Statistics for Output Variable Distributions for Non-Accident Scenarios

Units: Incidents per Bvkm

Incident	Scenario	Urban/Rural	Tanker Truck	Type of DG Load *	2.5th percentile	97.5th percentile	Mean	Median	Standard Deviation	Skewness	Kurtosis	Coeff. of Variation
large spill with fire	33	rural	y	1	.03732	.46008	.17126	.14372	.11232	1.82	8.85	.66
	34	rural	y	2	.01548	.15256	.06236	.05494	.03591	1.42	6.39	.58
	35	rural	y	3	.01868	.16827	.07082	.06308	.03876	1.29	5.62	.55
	36	rural	y	4	.05426	.52422	.21564	.19028	.12304	1.39	6.16	.57
	37	rural	n	1	.00798	.11517	.04088	.03360	.02898	2.16	12.55	.71
	38	rural	n	2	.00331	.03880	.01490	.01277	.00941	1.69	8.09	.63
	39	rural	n	3	.00394	.04273	.01692	.01470	.01021	1.56	7.15	.60
	40	rural	n	4	.01150	.13403	.05153	.04432	.03231	1.68	7.82	.63
	41	urban	y	1	.00259	.06070	.01897	.01460	.01570	2.29	12.24	.83
	42	urban	y	2	.00104	.02042	.00691	.00555	.00522	1.92	9.30	.76
	43	urban	y	3	.00122	.02275	.00785	.00639	.00574	1.81	8.62	.73
	44	urban	y	4	.00361	.07026	.02387	.01926	.01795	1.94	9.36	.75
	45	urban	n	1	.00027	.00638	.00197	.00150	.00167	2.52	15.62	.85
	46	urban	n	2	.00011	.00218	.00072	.00057	.00055	2.02	9.64	.77
	47	urban	n	3	.00013	.00242	.00082	.00066	.00061	1.89	8.65	.75
	48	urban	n	4	.00038	.00750	.00248	.00198	.00191	2.02	9.80	.77
small spill with fire	33	rural	y	1	.03396	.43924	.16042	.13471	.10625	1.81	8.60	.66
	34	rural	y	2	.01410	.14456	.05842	.05124	.03410	1.44	6.29	.58
	35	rural	y	3	.01686	.15764	.06633	.05899	.03677	1.31	5.75	.55
	36	rural	y	4	.04911	.49665	.20204	.17736	.11700	1.42	6.30	.58
	37	rural	n	1	.06900	.74840	.29079	.25023	.17829	1.62	7.39	.61
	38	rural	n	2	.02880	.24523	.10588	.09518	.05619	1.24	5.47	.53
	39	rural	n	3	.03458	.26553	.12023	.10979	.06015	1.10	4.95	.50
	40	rural	n	4	.10107	.84082	.36616	.33003	.19239	1.22	5.39	.53
	41	urban	y	1	.01797	.24376	.08965	.07549	.05992	1.79	9.17	.67
	42	urban	y	2	.00737	.08094	.03269	.02858	.01938	1.38	6.15	.59
	43	urban	y	3	.00881	.08848	.03713	.03305	.02094	1.22	5.30	.56
	44	urban	y	4	.02609	.27868	.11309	.09926	.06678	1.39	6.13	.59
	45	urban	n	1	.02154	.28657	.10665	.09024	.07028	1.74	8.57	.66
	46	urban	n	2	.00894	.09470	.03888	.03424	.02266	1.34	5.94	.58
	47	urban	n	3	.01059	.10379	.04417	.03959	.02445	1.17	5.11	.55
	48	urban	n	4	.03137	.32752	.13448	.11868	.07794	1.34	5.90	.58

- Type of DG Load
  1 = toxic PLG
  2 = flammable PLG
  3 = flammable liquid
  4 = toxic liquid

Statistics for Output Variable Distributions for Non-Accident Scenarios (continued)

Units: Incidents per Bvkm

Incident	Scenario	Urban/Rural	Tanker Truck	Type of DG Load *	2.5th percentile	97.5th percentile	Mean	Median	Standard Deviation	Skewness	Kurtosis	Coeff. of Variation
large leak with fire	33	rural	y	1	.01303	.21994	.07412	.05946	.05536	2.08	10.37	.75
	34	rural	y	2	.00529	.07360	.02698	.02264	.01811	1.73	7.86	.67
	35	rural	y	3	.00635	.08105	.03062	.02613	.01970	1.63	7.46	.64
	36	rural	y	4	.01863	.25384	.09328	.07858	.06209	1.71	7.77	.67
	37	rural	n	1	.00171	.02666	.00912	.00737	.00671	2.16	11.56	.74
	38	rural	n	2	.00070	.00895	.00332	.00281	.00219	1.80	8.62	.66
	39	rural	n	3	.00084	.00975	.00377	.00323	.00237	1.63	7.54	.63
	40	rural	n	4	.00245	.03061	.01147	.00970	.00748	1.75	8.35	.65
	41	urban	y	1	.00181	.03056	.01041	.00842	.00777	2.19	12.07	.75
	42	urban	y	2	.00074	.01034	.00379	.00320	.00253	1.74	8.22	.67
	43	urban	y	3	.00087	.01131	.00431	.00368	.00276	1.57	6.98	.64
	44	urban	y	4	.00259	.03565	.01312	.01106	.00873	1.72	8.05	.67
	45	urban	n	1	.00020	.00562	.00167	.00125	.00148	2.61	15.68	.88
	46	urban	n	2	.00008	.00190	.00061	.00048	.00049	2.18	11.46	.81
	47	urban	n	3	.00010	.00212	.00069	.00055	.00054	2.04	10.07	.79
	48	urban	n	4	.00029	.00662	.00211	.00165	.00171	2.19	11.38	.81
small leak with fire	33	rural	y	1	.05503	.62303	.23787	.20313	.14981	1.73	8.43	.63
	34	rural	y	2	.02301	.20378	.08654	.07729	.04727	1.32	5.90	.55
	35	rural	y	3	.02742	.22140	.09825	.08927	.05056	1.16	5.22	.51
	36	rural	y	4	.08013	.70025	.29935	.26836	.16213	1.30	5.75	.54
	37	rural	n	1	.07246	.77893	.30288	.26007	.18659	1.66	7.77	.62
	38	rural	n	2	.02987	.25547	.11020	.09914	.05860	1.25	5.51	.53
	39	rural	n	3	.03609	.27637	.12511	.11446	.06250	1.09	4.92	.50
	40	rural	n	4	.10470	.87210	.38116	.34385	.20065	1.22	5.38	.53
	41	urban	y	1	.01811	.24969	.09190	.07738	.06127	1.78	8.64	.67
	42	urban	y	2	.00754	.08259	.03347	.02954	.01964	1.33	5.77	.59
	43	urban	y	3	.00895	.09003	.03802	.03396	.02124	1.17	5.07	.56
	44	urban	y	4	.02646	.28303	.11577	.10190	.06755	1.33	5.88	.58
	45	urban	n	1	.01986	.27362	.10063	.08490	.06703	1.78	8.63	.67
	46	urban	n	2	.00829	.09016	.03665	.03235	.02148	1.33	5.76	.59
	47	urban	n	3	.00986	.09835	.04163	.03725	.02321	1.17	5.03	.56
	48	urban	n	4	.02898	.30970	.12678	.11156	.07388	1.33	5.86	.58

* Type of DG Load
1 = toxic PLG
2 = flammable PLG
3 = flammable liquid
4 = toxic liquid

Statistics for Output Variable Distributions for Non-Accident Scenarios (continued)

Units: Incidents per Bvkm

Incident	Scenario	Urban/Rural	Tanker Truck	Type of DG Load *	2.5th percentile	97.5th percentile	Mean	Median	Standard Deviation	Skewness	Kurtosis	Coeff. of Variation
large spill no fire	33	rural	y	1	1.08285	5.70517	2.77221	2.55496	1.19441	1.26	5.93	.43
	34	rural	y	2	.48750	1.74765	1.00993	.97137	.32590	.74	3.92	.32
	35	rural	y	3	.59790	1.83257	1.14663	1.12251	.31615	.45	3.22	.28
	36	rural	y	4	1.70772	5.96406	3.49220	3.36542	1.09951	.70	3.85	.31
	37	rural	n	1	.22597	1.46270	.66131	.59850	.32506	1.48	7.16	.49
	38	rural	n	2	.09815	.46709	.24113	.22649	.09551	.97	4.60	.40
	39	rural	n	3	.11891	.49837	.27375	.26106	.09777	.78	3.91	.36
	40	rural	n	4	.34133	1.60280	.83382	.78575	.32490	.94	4.45	.39
	41	urban	y	1	.23776	2.43074	.97735	.85254	.57596	1.57	7.23	.59
	42	urban	y	2	.09940	.78471	.35603	.32469	.17865	1.07	4.80	.50
	43	urban	y	3	.11878	.84961	.40416	.37545	.18984	.90	4.14	.47
	44	urban	y	4	.34777	2.68833	1.22983	1.12617	.60867	1.05	4.69	.49
	45	urban	n	1	.02545	.25599	.10120	.08759	.06047	1.66	7.86	.60
	46	urban	n	2	.01072	.08297	.03683	.03328	.01882	1.21	5.38	.51
	47	urban	n	3	.01281	.08997	.04185	.03840	.02009	1.06	4.74	.48
	48	urban	n	4	.03720	.28691	.12747	.11581	.06468	1.20	5.31	.51
small spill no fire	33	rural	y	1	.99731	5.36759	2.59419	2.39062	1.13799	1.27	5.97	.44
	34	rural	y	2	.44337	1.66467	.94514	.90509	.31435	.76	3.99	.33
	35	rural	y	3	.54379	1.73505	1.07308	1.04843	.30724	.46	3.24	.29
	36	rural	y	4	1.54631	5.68290	3.26867	3.14883	1.06198	.71	3.83	.32
	37	rural	n	1	2.14621	8.99818	4.70510	4.41155	1.76538	1.15	5.36	.38
	38	rural	n	2	1.00173	2.65860	1.71394	1.67087	.42696	.61	3.63	.25
	39	rural	n	3	1.27893	2.68989	1.94596	1.93238	.36392	.22	3.00	.19
	40	rural	n	4	3.50902	9.05111	5.92704	5.79969	1.41906	.56	3.58	.24
	41	urban	y	1	2.05487	8.88326	4.61211	4.31496	1.76758	1.17	5.47	.38
	42	urban	y	2	.95357	2.65376	1.68022	1.63498	.43830	.63	3.66	.26
	43	urban	y	3	1.20840	2.70663	1.90771	1.88867	.38547	.27	3.02	.20
	44	urban	y	4	3.34272	9.05284	5.81176	5.67094	1.46763	.59	3.62	.25
	45	urban	n	1	2.52189	10.39198	5.48827	5.15658	2.03880	1.15	5.37	.37
	46	urban	n	2	1.18281	3.08342	1.99941	1.95322	.48805	.59	3.58	.24
	47	urban	n	3	1.51121	3.09940	2.27003	2.25714	.40950	.18	2.98	.18
	48	urban	n	4	4.15105	10.44720	6.91412	6.77242	1.61877	.54	3.56	.23

* Type of DG Load
1 = toxic PLG
2 = flammable PLG
3 = flammable liquid
4 = toxic liquid

Statistics for Output Variable Distributions for Non-Accident Scenarios (continued)

Units: Incidents per Bvkm

Incident	Scenario	Urban/Rural	Tanker Truck	Type of DG Load *	2.5th percentile	97.5th percentile	Mean	Median	Standard Deviation	Skewness	Kurtosis	Coeff. of Variation
large leak no fire	33	rural	y	1	.34483	2.81728	1.19939	1.07053	.64609	1.46	7.01	.54
	34	rural	y	2	.14631	.90442	.43692	.40574	.19668	1.01	4.75	.45
	35	rural	y	3	.17654	.96844	.49581	.46856	.20502	.80	3.92	.41
	36	rural	y	4	.51089	3.11145	1.51080	1.40820	.67104	.97	4.51	.44
	37	rural	n	1	.04621	.34044	.14752	.13154	.07715	1.49	7.03	.52
	38	rural	n	2	.01992	.10994	.05375	.04993	.02332	1.11	5.16	.43
	39	rural	n	3	.02427	.11804	.06101	.05760	.02421	.93	4.43	.40
	40	rural	n	4	.06968	.37708	.18583	.17307	.07932	1.07	4.97	.43
	41	urban	y	1	.18792	1.16836	.53542	.48599	.25509	1.36	6.26	.48
	42	urban	y	2	.08318	.37065	.19497	.18450	.07371	.93	4.37	.38
	43	urban	y	3	.10205	.39248	.22134	.21249	.07463	.73	3.78	.34
	44	urban	y	4	.29130	1.27143	.67471	.63717	.25232	.91	4.29	.37
	45	urban	n	1	.01836	.22817	.08619	.07358	.05563	1.77	8.53	.65
	46	urban	n	2	.00766	.07500	.03135	.02785	.01761	1.34	6.03	.56
	47	urban	n	3	.00912	.08232	.03562	.03213	.01901	1.19	5.32	.53
	48	urban	n	4	.02673	.25922	.10852	.09682	.06070	1.33	6.00	.56
small leak no fire	33	rural	y	1	1.65280	7.52050	3.85101	3.59139	1.52663	1.14	5.25	.40
	34	rural	y	2	.75676	2.28629	1.40205	1.36262	.38963	.65	3.73	.28
	35	rural	y	3	.95403	2.34387	1.59195	1.57166	.35593	.33	3.09	.22
	36	rural	y	4	2.66740	7.80713	4.84991	4.71494	1.31202	.61	3.54	.27
	37	rural	n	1	2.20065	9.35973	4.90287	4.60573	1.85230	1.10	5.13	.38
	38	rural	n	2	1.02288	2.79404	1.78522	1.74248	.45234	.61	3.68	.25
	39	rural	n	3	1.30094	2.82743	2.02676	2.01330	.38934	.20	2.98	.19
	40	rural	n	4	3.61489	9.51342	6.17488	6.04209	1.51170	.55	3.50	.24
	41	urban	y	1	2.11881	9.00443	4.72466	4.43675	1.78685	1.10	5.17	.38
	42	urban	y	2	.98759	2.69843	1.72026	1.67851	.43647	.62	3.75	.25
	43	urban	y	3	1.25696	2.72641	1.95297	1.93888	.37551	.21	2.99	.19
	44	urban	y	4	3.47862	9.13432	5.94974	5.81689	1.45595	.55	3.50	.24
	45	urban	n	1	2.32603	9.84760	5.17390	4.86029	1.94958	1.10	5.16	.38
	46	urban	n	2	1.08666	2.95006	1.88389	1.83890	.47453	.61	3.68	.25
	47	urban	n	3	1.38088	2.97300	2.13869	2.12771	.40617	.19	2.97	.19
	48	urban	n	4	3.83650	9.99827	6.51593	6.38115	1.58405	.55	3.47	.24

* Type of DG Load
1 = toxic PLG
2 = flammable PLG
3 = flammable liquid
4 = toxic liquid

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GLOSSARY

ADS	Accident Data System
Bvkm	billion vehicle kilometres
DG	dangerous goods
DGAIS	Dangerous Goods Accident Information System
MARS	Master Accident Record System
MOE	Ministry of Environment of Ontario
MTMD	Mission Transport des Matières Dangereuses
MTO	Ministry of Transportation of Ontario
Mvkm	million vehicle kilometres
NAERG	North American Emergency Response Guidebook
ORIS	Occurrence Report Information System
PIN	Product Identification Number
PLG	pressure-liquefied gas
QRA	quantitative risk assessment
WSDOT	Washington State Department of Transportation