COST-EFECTIVENESS OF REDUCING ENVIRONMENTAL RISK FROM RAILROAD TANK CAR TRANSPORTATION OF HAZARDOUS MATERIALS

BY

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ABSTRACT

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Research on hazardous materials transportation safety and risk has traditionally focused on acute hazards to human health and property. This research describes the first transportation risk analysis to consider the potential impact on the environment. The environmental risk from transportation of 24 of the chemicals most commonly shipped in railroad tank cars was calculated and the cost-effectiveness of using more damage-resistant tank car designs evaluated. The Association of American Railroads (AAR) initiated this project after a series of expensive environmental clean-up accidents in the 1990s and early 2000s. Of particular interest was the impact on soil and groundwater. The analysis was conducted for those commodities that are currently permitted under United States Department of Transportation (US DOT) regulations to be transported in non-pressure specification tank cars. A quantitative risk assessment (QRA) model was used to conduct consequence analysis in terms of remediation cost for spills of each chemical. Exposure analysis involved use of geographic information system (GIS) software to conduct a probabilistic assessment of the occurrence of 15 environmental scenarios (three soil types x five ranges of groundwater depth) near railway lines. These results were combined with the probability distribution of spill quantities for each tank

car type, commodity, environmental scenario, and remediation cost, and several metrics of clean-up-cost risk were developed.

Tank car specifications vary substantially in their resistance to damage in accidents as do the hazards associated with the various materials they are intended to transport. In general the packaging requirements are commensurate with a chemical's hazard, but as stated above this has not generally accounted for environmental impact. The US DOT 111A100W1 tank car was found to be the most common specification used for the commodities considered. A variety of alternative tank cars with more protective features such as, half- or full-height head shields, jacket and insulation and top fittings protection were considered for each of the chemicals and the consequent reduction in risk calculated. Although these risk reduction options improve the safety of the car, they also reduce its capacity because of their extra weight; and they increase the cost of the car as well. A new specification for an enhanced safety, 286,000 pound (286K) gross rail load (GRL) 111 tank car was also evaluated and its performance compared to the current 263,000 (263K) pound car.

A cost-benefit analysis was conducted to determine the cost-effectiveness of replacing the current tank cars with alternate design cars. Three replacement schedules were considered: attrition-based, immediate, and a 10-year retrofit schedule. The benefit is the reduction in the clean-up cost risk per unit of exposure. The cost is the difference in capital and operating expenses between the current car and the alternate. A net present value (NPV) approach was used to estimate the value over the life cycle of the car of

investing in various alternatives compared to the current car. Sensitivity analyses of car utilization rate and discount rate were also conducted to determine their effect on NPV.

The clean-up cost risk for the different chemicals ranged from 0.11 cents per car-mile, to 29.10 cents per mile. The enhanced safety 286K 111 was the only tank car specification for which all the commodities yielded a positive NPV. This tank car is unique among the alternatives because in addition to being safer, its higher maximum gross rail load allows it to transport a larger payload without suffering a loss in capacity due to the extra weight of the more robust design features. There were a few cost-beneficial 263K alternatives for certain chemicals and replacement schedules: 111A100W2, 111S100W1, and 111S100W2, but the enhanced 286K 111 car yielded the largest NPVs.

To My Family

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LIST OF ABBREVIATIONS

AAR	Association of American Railroads
BTS	Bureau of Transportation Statistics
CARS	Chemical Assessment & Ranking System
CASRAM	Chemical Accident Statistical Risk Assessment Model
CEESA	Center for Energy, Environment and Economic Systems Analysis
CERCLA	Comprehensive Environmental Response, Compensation, and Liability Act
CFR	Code of Federal Regulations
CMTI	Indiana Clean Manufacturing Technology and Safe Materials Institute
COC	Certificate of Construction
CRS	Chemical Ranking and Scoring
DIPPR	Design Institute for Physical Properties
DNAPL	Dense Non Aqueous Phase Liquid
DOT	Department of Transportation
EPA	Environmental Protection Agency
ESC	Environmentally Sensitive Chemicals
FRA	Federal Railroad Administration
FRTR	Federal Remediation Technologies Roundtable
GIS	Geographic Information System
GRL	Gross Rail Load
HAP	Hazardous Air Pollutant
HS	Head Shield
ICC	Interstate Commerce Commission
IIRSTF	InterIndustry Rail Safety Task Force
IRCHS	Indiana Relative Chemical Hazard Score
LNAPL	Light Non Aqueous Phase Chemical
LPG	Liquid Petroleum Gas
NAR	Non Accident Releases
NIST	National Institute of Standards and Technology
NPV	Net Present Value
RCRA	Resource Conservation and Recovery Act
RRO	Risk Reduction Option
RSPA	Research and Special Programs Administration
SOCC	Social Opportunity Cost of Capital
STATSGO	State Soil Geographic (Database)
STB	Surface Transportation Board
STPR	Social Time Preference Rate
TCC	Tank Car Committee
TFP	Top Fittings Protection
TRAIN II	TeleRail Automated Information Network
UMLER	Universal Machine Language Equipment Register
URCS	Uniform Rail Costing System
USDA	United States Department of Agriculture
USGS	United States Geological Survey
UTC	Union Tank Car
WfWP	Working for Water Programme

CHAPTER 1

INTRODUCTION

Each year a large volume of hazardous materials is transported by rail in North America. In 2003 approximately 1.60 million hazardous material shipments originated in the United States and Canada (BOE 2005). Although hazardous materials are shipped in various types of rail cars including tank cars, covered hoppers, boxcars, intermodal equipment, etc., tank cars carry the majority. In 2003, about 1.26 million carloads of hazardous material shipments in the U.S. and Canada were in tank cars (BOE 2005), approximately 79% of the total hazardous material shipments. Although over 1,000 different hazardous materials are transported by rail, a substantial fraction (71 %) of the shipments are accounted for by the top 125 hazardous materials (BOE 2005).

Until the early 1990s hazardous material transportation risk was considered primarily in terms of the danger posed to human health and property damage. Consequently, the packaging regulations for hazardous materials were based on factors such as toxic inhalation hazard, explosivity, corrosiveness and flammability. These hazards largely eclipsed the environmental aspects of transportation risk. However, as the understanding of the environmental impact of chemicals grew, so did regulations and requirements for cleanup of spilled chemicals. By the late 1980s, environmental cleanup had become a major contributor to railroad hazardous material accident costs (Barkan et al 1991). Legal settlement expenses and environmental remediation costs together accounted for more than 85% of the accident costs incurred by the railroads in the period 1982 to 1992 (Dennis 1996). Unpublished data from the Association of American Railroads (AAR) indicate that the environmental clean-up expense incurred by railroads due to accident-caused spills in the 1990s and early 2000s was over 30 million dollars.

1.1 Background

The first recognition that environmental hazard was an aspect of risk to be considered in tank car design was in the late 1970s and early 1980s the work developing a program to prioritize the application of bottom-outlet fittings protection for tank cars (Heller et al 1981, AAR 2004). Subsequently, AAR petitioned the Department of Transportation (DOT) to incorporate by reference all Environmental Protection Agency (EPA) hazardous substances into the DOT hazardous materials table through a CERCLA amendment (CERCLA 1986). This was done so that the railroads would be notified whenever hazardous substances were being shipped. Prior to this, railroads had no way of knowing if they were transporting these materials unless the shipper volunteered the information. In 1991 a spill of metam sodium into the Sacramento River near Dunsmuir, California highlighted another gap in the regulations and led to the recognition of marine pollutants as hazardous materials during land transport (US DOT 1992).

Over roughly the same time period as the events described above, the railroads had a series of accidents that caused expensive environmental cleanups and the AAR initiated research to investigate the risk (Barkan 1991). The focus of that work was on a group of ten halogenated hydrocarbons that included, carbon tetrachloride, chloroform, ethylene dichloride and others. These chemicals came to be referred to as 'Environmentally Sensitive Chemicals' (ESC) within the railroad and chemical industries because, although they did not generally pose an acute safety or health hazard when spilled, they often resulted in costly long-term environmental clean-ups. The risk analysis also included a cost benefit analysis of using tank cars more robust than the general purpose DOT '111' car, that was then commonly used to transport most of these products. Although '105A300W' and '105A500W' specification tank cars were more expensive to construct and operate, it was cost-effective to use them for these products because of their more damage-resistant features and consequent lower probability of release in accidents, compared to 111s.

Based on this research the railroad, chemical and tank car industries reached agreement on new packaging requirements for the ten chemicals. However, this was superceded by new regulations promulgated by the US DOT that further changed the packaging requirements and expanded the list of ESCs to include all halogenated hydrocarbon products or mixtures containing them (US DOT 1995). Although there was also interest in the environmental risk posed by certain non-halogenated products such as benzene, styrene, toluene, etc. the halogenated compounds were considered more important and the non-halogenated products were not addressed at that time.

The research described in this dissertation follows directly from this prior work. It is specifically devoted to analyzing the environmental risk of hazardous material transportation by tank cars, but addresses a broader and more diverse group of chemicals than Barkan et al. (1991) considered. It also develops a more detailed and sophisticated methodology to calculate chemical-specific environmental risk as well as assess the cost effectiveness of a wide array of tank car designs and implementation schedules.

Motivation for the Research:

In the late 1990s and early 2000s, a series of rail accidents led to spills of some of the products not addressed in the previous study that resulted in multi-million dollar clean ups. One was a derailment in Eunice, Louisiana in May, 2000 that involved a spill of acrylic acid and phenol among other chemicals and an estimated environmental cost of 26 million dollars. Another incident was a benzene spill in Scottsbluff, Nebraska in September 2000 where the total environmental clean up cost will be more than 14 million dollars. These events reopened the question in the railroad industry about the risk of transporting materials with the potential to cause such costly clean ups.

The AAR initiated a new project to quantify this risk and evaluate the cost-effectiveness of using more damage resistant tank cars to transport products currently permitted for shipment in non-pressure cars such as 111s. Their goal was to better understand the magnitude of the risk, which materials contributed to it, and the cost-effectiveness of using more robust tank cars to reduce it. Although there may be a variety of types of costs associated with a spill, including litigation, natural resource damages, etc., the focus of the AAR study was on the soil and groundwater remediation costs which have historically formed the largest cost component of these types of spills and for which the science needed to model them is most developed.

In my master's research (Anand 2004) I conducted exposure assessment of soil and groundwater to the probability of spills from railroad transportation of hazardous materials, using Geographic Information System (GIS) techniques. Evaluation of the impact of these spills requires knowledge of the variation in soil types and groundwater depths along rail lines in the United States. The exposure assessment study developed a geographic probability distribution for soil type and groundwater depth across the 48 contiguous states. The State Soil Geographic database (STATSGO), a Geographic Information System (GIS) database from the United States Department of Agriculture (USDA) was used to analyze soils, and real-time data from the United States Geological Survey (USGS) were used to analyze groundwater depth. A set of values for soil type (three soil categories) and groundwater depth (five groundwater depth range categories) was developed. The objective was to develop a probability distribution of these two parameters in the vicinity of rail lines. The 'rail2m' GIS database available from the Bureau of Transportation Statistics (BTS) was used to conduct overlay analyses with the soil GIS data to obtain the probability of occurrence of various soil types beneath rail lines.

Statistical analysis of the data showed that the location of U.S. rail lines is independent of soil type. The same method could not be used for groundwater exposure because although it is the most comprehensive nationwide dataset of groundwater depths, the real time groundwater monitoring well dataset does not have enough data. Therefore, it was assumed that the distribution of depth categories near rail lines would be no different from the overall distribution of groundwater depths in the nation. An overlay of groundwater wells was conducted with the soil type map and a statistical analysis showed that distributions of soil type categories and groundwater depth range categories were not independent of each other. Thus a joint probability distribution was developed for the two parameters. This study, quantifying the geographical relationship between rail lines, soil types and groundwater depths provided crucial input to the current research (Anand and Barkan 2006).

1.2 Changes in Packaging and Tank Car Accident Performance

The safety of hazardous materials transportation by rail has improved a great deal over the past two decades. The mainline train accident rate has decreased by around 75% since 1980 (Dennis 2002, Barkan et al 2003). This change has taken place due to improvement in equipment, physical plant, and investments in better employee training programs (Dennis 2002). Over approximately the same time period the release rate of hazardous materials from tank cars has decreased by 90% (Harvey et al 1987, Barkan et al 2000). This is due to the decrease in the train accident rate, and the improvement in the damage resistance of tank cars transporting these materials. More often than not spills from tank cars are not due to train accidents and these are termed “non-accident releases” (NAR). Their causes, consequences and preventive steps are different from accident-caused releases and they are the subject of research in their own right (Barkan et al 2000). This has included development of risk assessment methodology to prioritize prevention efforts (Elliot & Mitchell 2002, BOE 2005). Although NARs have occasionally led to major environmental cleanups such as the arsenic acid spill in Chattanooga, Tennessee in 1995 (NTSB 1995), in general the consequences from these releases is considerably less than accident-caused releases, because the quantity spilled is usually much smaller. Consequently these releases were not the principal concern of the AAR in the context of this study.

Reducing train accident rate and improving tank car accident performance are the two principal approaches to reducing the risk of rail transport of hazardous materials. This study deals with the second, improving tank car performance. The safety of a tank car can be improved by incorporating design features to make them more resistant to damage such as improved top fittings protection, installation of a jacket or head shields, or making the tank thicker. Some types of protective features may be applied to all tank cars. For example, all DOT specification tank cars have been required to have double shelf couplers since 1978 (Phillips & Role 1989) and protective designs have been required on all bottom-fittings-equipped DOT 111 tank cars, built since 1978 (Griger & Phillips 1992) and subsequently retrofitted on the rest of these cars. Alternatively, design changes may be applied to a more select group of cars transporting certain products. For example, installation of head shields, thermal protection and shelf couplers on 112/114 tank cars carrying Liquid Petroleum Gas (LPG) (Phillips & Role 1989). Tank cars vary widely in terms of their risk reduction features, consequently so does their performance in accidents. In some cases, instead of modifying individual design features, it may be better to change to a different tank car class altogether. For example, the study by Barkan et al (1991) showed that the transportation risk for chlorinated solvents was reduced if they were transported in 105 tank cars instead of general-purpose 111 tank cars. In comparison to a 111, 105 tank cars have a thicker tank constructed of stronger steel, top fittings protection, no bottom outlet and a jacket for insulation.

For the materials studied in this research, the 111 is the most commonly used class of tank car. The 111 tank car class is more likely to suffer a release in an accident than most other cars. Therefore, I evaluated a variety of packaging options for each chemical of interest. These options included replacement of the current tank cars used for the chemical with alternative specifications that have better damage resistance, or addition of various protective features on the current specification cars. I also considered the differential capital and operational costs, and the effect of different replacement schedules on the cost effectiveness.

1.3 Objectives of Study

Following are the principal objectives of my research.

1. Evaluation of environmental risk for each chemical under study: This embodies the following steps:

    a) Evaluate the conditional probability of release, given a derailment, for each tank car specification that is currently in use for the chemicals of interest, or could be used as an alternative.
    b) Evaluate the tank car derailment rate in the United States.
    c) Estimate the frequency of spill for each chemical combining the metrics estimated above.
    d) Anand (2004) developed a set of environmental scenarios, based on soil and groundwater attributes over the 48 contiguous states that could be exposed to risk from transportation of hazardous materials. Use the probability values for exposure of these 15 environmental scenarios to spills of the hazardous materials of interest.
    e) Assess the impact to soil and groundwater as a result of the spill for each chemical under various environmental scenarios, using an environmental consequence model. The impact was to be assessed in terms of the cost of restoration of the media.
    f) Evaluate the risk due to each chemical, having ascertained the likelihood and consequence of its spill. Rank the chemicals in order of their hazard level.
2. Ascertain the cost-effectiveness of using more robust tank cars for each chemical: The following steps are taken to achieve this objective:
    a) Identify the alternative tank car specifications to be considered for each chemical, based on accident performance of the alternatives compared to the current car considered for replacement.

b) Estimate the costs involved in buying and operating these alternative cars and also the cost of continuing to use the current tank cars, for each chemical.
c) Conduct a cost-benefit analysis for each of the alternatives for each chemical.
d) For each chemical, summarize for each alternative, whether it would be cost beneficial to use the alternative in order to reduce the clean up expenses.

1.4 Conclusions

Railroad hazardous material spills have the potential to cause expensive environmental cleanups. A series of costly environmental clean up accidents in the 1980s and 1990s highlighted the importance of environmental risk due to rail transport of hazardous materials. The AAR recognized this risk and sponsored research to develop a better quantitative understanding of it and the cost-effectiveness of risk reduction efforts. This study focuses on candidate chemicals from the 125 hazardous materials with the highest annual shipment volume; however, the method developed here can be applied to any hazardous material transported in railroad tank cars. The study develops estimates of the risk per unit of exposure and the annual risk posed by these materials. It also analyzes the cost effectiveness of investing in more robust tank cars by comparing the capital and operating costs of operating various alternative tank car designs and contrasting this with reduction in environmental cleanup cost risk associated with the alternate designs.

CHAPTER 2

REVIEW OF RISK CONCEPTS AND LITERATURE

Considerable work has been conducted on certain aspects of hazardous material transportation risk, especially with regard to acutely hazardous chemicals, human health, property damage, routing and emergency response. Considerably less attention has been paid to environmental aspects of this risk and the effect of various tank car design features on reducing it. In this chapter I review pertinent literature on the latter aspects as they relate to and provide critical background to my research.

2.1 Risk Concepts and Definitions

Consistent understanding of the terminology used in risk is helpful for clear communication of the methods and findings. The risk of an incident is sometimes confused with terms like hazard, likelihood, or the consequence of an incident. All these terms have different implications that are explained here. Some commonly used terms have been defined in the risk assessment literature as follows:

> A hazard is *"a chemical or physical condition that has the potential for causing damage to people, property, or the environment"* (CCPS 1994).

In the context of this study, transportation of hazardous materials is characterized as a ‘hazard’.

> The likelihood of an event is *“a measure of the expected probability or frequency of occurrence of an event”* (CCPS 1994).

In general likelihood is obtained as a product of the probabilities of the ‘initiating event’ and the conditional probabilities of the ‘subsequent events’.

> *“An initiating event is the first in a sequence of events that may lead to an undesirable consequence”* (Rhyne 1994).

In the context of this study, involvement of a train in an accident, be it a derailment or a collision is the ‘initiating event’. The subsequent event is the derailment of a tank car as a result of the accident. These events lead to the ‘event of concern’ or the incident that is the damage incurred to the derailed car and subsequent release of material. The US DOT defines an ‘incident’ as a release occurring during loading or unloading, while the vehicle is en route or when it is in temporary storage related to transportation (Rhyne 1994). This study analyzes the risk only due to the accident-initiated releases, as these incidents generally have a higher potential to incur serious consequences compared to non-accident releases that are typically relatively small-quantity releases caused due to a loose valve or fitting on a tank car.

The outcome or the consequence of the incident is defined as follows (Rhyne 1994):

> *"Consequence is the direct effect, usually undesirable, of the accident or incident"*

The consequences can be human fatalities, injuries, and/or damage to property or the environment. In this research, I was principally concerned with the analysis of the effects of spills on soil and groundwater. Finally, the risk of an incident is defined as follows (CCPS 1994):

> *"A measure of potential economic loss, human injury, or environmental damage in terms of both the incident likelihood and the magnitude of the loss, injury, or damage*."

In general, risk is calculated as a product of the likelihood and the consequence of the incident. The mathematical methods involved in calculating risk estimates for railroad transportation of hazardous materials are presented in detail in Chapters 3, 4 and 5.

Hazardous materials are referred to as dangerous goods in many other parts of the world; therefore, the two terms are used interchangeably in this chapter. The DOT defines a hazardous material as any substance or material that could adversely affect the safety of the public, handlers or carriers during transportation (49CFR171.8 2005).

2.2 Literature Review

2.2.1 Quantitative Risk Assessment and Cost Benefit Analysis

The primary objective of this research was to evaluate the risk posed to environment (soil and groundwater) from the transportation of chemicals of interest in the railroad tank cars and investigate the cost effectiveness of using more robust cars. There have been quite a few studies on the risk of hazardous material transportation by road and rail, focusing on specific chemicals, sites, routes or hazard classes (Saccomanno 1987, Batta & Chiu 1988, Zografos & Davis 1989, Glickman 1991, Glickman & Raj 1993, Kempe & Grondin 1993, Purdy 1993, Riley 1993, Saccomanno & Shortreed 1993, Sivakumar et al 1993, Stjerman 1993, Helander et al 1997, Jin & Batta 1997, Sherali et al 1997, Leonelli et al 2000, List & Mirchandani 1991, List et al 1991). However all of these studies dealt with the human aspect of transporting hazardous materials and none dealt specifically with transportation in tank cars. Most of them consider toxicity or flammability hazards that present an acute potential danger to human life and health.

Although relatively little attention has been paid to the environmental aspects of the risk from hazardous materials transportation in tank cars, there have been a few studies in this area that will be discussed below. Calculation of risk involves probability and consequence calculations. The probability side of the equation involves accident rate calculations for railroads and release probability estimation for various tank cars. There has been a considerable amount of work done in these areas. The discussion below also encompasses studies conducted in the field of tank car improvements and railroad accident data collection.

Studies of Hazardous Materials Transportation Risk

Raj and Pritchard (2000) presented a summary of a study conducted by the FRA to assess the public risk associated with transportation of hazardous material in general purpose 111 class tank cars. Exposure areas were calculated for 14 chemicals using a heavy gas dispersion model “ADAM” developed by the U. S. Air Force. Risk was calculated for various permutations of parameters namely, different sizes of puncture in the tank, types of weather, hazardous material behaviors and population areas in which the accident was assumed to occur. These calculations were repeated for various tank car and hazardous material combinations. This was a study of risk to humans rather than the environment but there is considerable overlap and parallel with the requirements for the current research, e.g., the various environmental scenarios in which a spill could occur, the various spill sizes, properties of different chemicals and the various tank car specifications that could be used as alternatives for transportation of these chemicals.

The precedent for the current research was a risk analysis conducted by Barkan et al (1991) in which they evaluated the cost-effectiveness of switching from general purpose 111 tank cars to more robust cars for transportation of halogenated hydrocarbons. Their analysis focused exclusively on the environmental risk and was the first quantitative risk assessment of railroad-transportation-caused chemical spills on the environment. It was an empirical study wherein the risk results were developed based on a survey of railroad-accident-caused environmental clean up costs incurred over a ten-year period, due to spills of the ten chemicals considered in the study. On the basis of past trends in cleanup expense, the authors extrapolated estimates of future costs and determined the anticipated savings over the lifetime of the car if more robust tank cars were used. The risk per carload was estimated to be $788, and could be reduced to as low as $129 using the more damage resistant car designs considered in that study. My research differs from Barkan et al (1991) in a number of important respects including, consequence modeling, tank car analysis, replacement schedule, and extensive sensitivity analysis

Dennis (1996) conducted a study to estimate risk costs associated with railroad transportation of hazardous materials. The risk cost estimates were developed based on a survey of the railroads for major releases for the time span 1982 to 1992. The study estimated that the major releases in that period of eleven years cost a total of about of $348 million dollars (in 1994 dollars). Litigation costs were the major expense, accounting for about 56%, followed by environmental costs at around 33%. Risk cost per unit of exposure was also calculated for seven commodity classes that ranged from 0.17 cents to around 28.00 cents per loaded car-mile for most hazardous materials. It also showed that for most commodities the risk costs could represent more than 13 percent of the cost of a typical movement.

Studies Estimating Railroad Accident Rate and Tank Car Performance:

While it is important to understand the consequences of these releases on soil and groundwater, it is equally important to understand the probability of spills from railroad tank cars. This involves quantification of the probability of an accident in which a hazardous materials car is derailed and the conditional probability of release from a derailed tank car. There have been several studies in this field (Nayak et al 1983, Glickman and Rosenfield 1984, Harvey et al 1987, Glickman 1988, Treichel 1996). The most recent work in the area of railroad accident statistics was done by Anderson (2005). He has worked extensively in the area of derailment rate calculation and derailment severity quantification. His results on the derailment probability of freight cars on Class I mainline track were used for risk estimation in the current study.

Once a car is derailed, it might or might not be damaged. Tank car accident performance statistics were developed by Phillips (1990) for aluminum and alloy tank cars and until recently Phillips et al (1995) was the most up-to-date accident performance analysis available for the most common cars, which have carbon steel tanks. Recently Treichel et al (2006) developed a new approach to evaluate the accident performance of tank cars, using the accident database developed and maintained by the RSI-AAR Railroad Tank Car Safety Research and Test Project. This database has extensive records of a wide variety of tank car designs damaged in accidents. Using these data a logistic regression model was developed to obtain source-specific conditional probabilities of release, from tank head, shell, top fittings and bottom fittings and multiple sources. Using basic probabilistic principles, the overall conditional probability of release from tank cars built to various specifications can be obtained from combination of these four source-specific probabilities. Work by Phillips (1990), Phillips et al (1995) and Treichel et al (2006) has been extensively used for conducting the probability analysis as will be explained in Chapter 3.

Studies for Improvement and Optimization of Railroad Tank Cars:

Improving tank car damage resistance has been a critical aspect of industry and government's efforts to reduce spills. This can be accomplished by using more robust tank car classes, like the 105s, as suggested in Barkan et al (1991) for reducing the risk per carload for transportation of halogenated hydrocarbons. Another way to achieve a reduction in risk is by enhancing the damage resistant design elements of tank cars. Although improving damage resistance of a tank car decreases the probability of spilling material in an accident, it will generally decrease the capacity of the car because of the extra weight of the enhanced safety features. This results in an increased number of shipments needed to transport the same quantity of product, thereby increasing the exposure to accidents. Barkan et al (2005) developed a model to find the optimum thickness of a tank car that minimizes the release probability that takes into account the increased exposure to accidents as a result of the decrease in capacity.

Saat & Barkan (2005) extended the Barkan et al model and introduced a metric called "release risk" which they define as the expected value of the quantity lost from a tank car given that it is in an accident. This metric not only accounts for the release probability of a tank car but also the quantity of product lost. They compared the optimal solutions using minimization of release probability (Barkan et al 2005) with minimization of release risk as objective functions and found that the solutions differed. Both Barkan et al

(2005) and Saat & Barkan (2005) conducted their analysis dichotomizing simply between tank components (head and shell) and non-tank components (top and bottom fittings).

Most of the cars currently used for the chemicals in this study have a gross rail load (GRL) of 263,000 lbs (263K). The U.S. and Canadian governments and the railroad industry have developed guidelines (Rader & Gagnon 1999) and requirements (AAR 2004), respectively, for enhanced safety features for hazardous material tank cars with a GRL exceeding 263K. The design requirements AAR used for hazardous material cars exceeding 263K GRL were based on an analysis by Barkan (2005) in which tank car risk reduction options (RROs) were evaluated, using a multi-attribute decision analysis approach, to determine how to use the extra weight to enhance safety most efficiently.

2.2.2 Chemical Ranking Systems

It was envisioned that another useful output of the current research would be that shippers and carriers could rank order chemicals based on remediation hazard. This would allow them to focus their attention on the high risk chemicals and make a better-informed decision if a chemical required more robust packaging. Therefore, before embarking on the current research, the literature was reviewed to evaluate chemical ranking systems. There have been several efforts by industry and government to develop ranking schemes for chemicals, for purposes of regulatory actions, risk management, pollution prevention, waste minimization and impact evaluation of chemical releases. Two examples of these ranking schemes include, the

Indiana Relative Chemical Hazard Score (IRCHS) method (CMTI 2002) developed at the Indiana Clean Manufacturing Technology and Safe Materials Institute (CMTI) and the Chemical Assessment & Ranking System (CARS), an initiative of Zero Waste Alliance (ZWA 2002). Both these systems assign a weight to the chemical depending on whether the chemical is a carcinogen, an ozone depleting substance, a hazardous air pollutant (HAP) or belongs to some other hazard categories. These systems are strictly based on the priorities and concerns of the organizations that developed these systems, in this case, CMTI and ZWA respectively. Davis et al (1994) evaluate and compare 51 Chemical Ranking and Scoring (CRS) systems developed by governmental agencies, industries, and academia. Among the things they compared were the criteria and endpoints used by these studies for human health and environmental effects. In the chemical ranking systems considered in this study, the environmental effects are most commonly measured in terms of non-mammalian toxicity, aquatic toxicity and plant toxicity, while some common ways in which exposure was measured are half life in the environment, number of potential receptors, and annual releases to the environment.

In the ranking systems mentioned above, and the ones reviewed by Davis et al (1994), the consequences were measured in terms of attributes like toxicity that directly or indirectly relate to health of humans or that of fauna and flora. None of these schemes were based on the damage to soil and groundwater, whether it be in terms of degree of contamination or clean up cost incurred. Also, neither of these schemes was developed to assess transportation risk. However, there have been a few relatively simple ranking schemes developed by the railroad industry.

Early Railroad Chemical Ranking Studies:

AAR Tank Car Committee: A simple ranking system was developed by the AAR Tank Car Committee (TCC) (Heller et al 1981) to assess risk and categorize DOT-regulated materials that were authorized to be transported in tank cars with bottom outlets or bottom discontinuities. The ranking system was developed with the objective of determining if the requirement for bottom outlet protection could be relaxed for certain commodities and to prioritize the level of protection required. A 'Railroad Transportation Risk Factor" was estimated for each commodity based on the following criteria:

1. Exposure Factor or Probability of a derailment with loss of product through the bottom outlet.
2. Difficulty of clean up.
3. Safety of personnel and environment.

The rank obtained from this system is a combination of qualitative and quantitative factors. Each commodity was given a rank on a scale of 1 to 5 (5 being the worst) in each of the two categories, difficulty of clean up and safety of personnel and environment. It is not clear what parameters were used to arrive at these ranks but it seems that expert opinion and experience were used. A base risk factor was developed for each commodity by taking the worst rank of the two categories. The base risk factor is then adjusted to account for the first category, the exposure factor, by scaling it up or down by one depending on how high or low was the frequency of a derailment resulting in release from bottom outlet.

Eder Associates/CSX Transportation: Another ranking system was developed by Eder Associates (1992) for CSX Transportation Inc. to assist CSX in ascertaining the potential risks for transporting specific commodities. The scheme assigns a rank to each commodity on a scale of 1 to 100 by summing up its scores in three categories: health risk factors, environmental risk factors and property damage risk factors. Higher scores represent higher risks. Health risk factors are assigned 80 points and include corrosiveness, explosiveness, flammability, radioactivity, reactivity, acute toxicity, chronic toxicity and vapor pressure. Environmental risk factors are assigned 15 points and they include potential for adverse impact on soil, groundwater and surface water, EPA reportable quantities, aquatic toxicity rating, persistence, biodegradability and cost of remedial technologies used. Property damage risk factors are assigned 5 points. These scores, wherever applicable, reflected the general experience of the research team with the chemical.

Both of the ranking schemes described above (Heller et al 1981, Eder Associates 1992) employ a qualitative ranking system based on assigning subjective weights to different chemical hazards and expert opinion to come up with environmental risk factors. These studies represented two stages of sophistication in the area of environmental risk assessment for chemicals transported in railroad tank cars but neither provided a thoroughly robust scientific basis for determining environmental risk. This aspect is considered essential to justify cost-intensive projects such as replacement of tank cars. Both of these methods are chemical ranking studies (CRS) because one of the criteria for a risk ranking system to be classified as a CRS is that it yields relative ranks, not quantitative measures of risk (Davis et al 1994). In other words, they provide ordinal rather than cardinal risk metrics. Cost-benefit analyses of the type conducted in this research require cardinal estimates for risk and thus a simple CRS is not adequate. The environmental consequence module of the InterIndustry Rail Safety Task Force (IIRSTF) quantitative risk assessment model does provide such a metric and after consideration of various possible alternatives, I decided that this was the best option. Further discussion of this model can be found in Chapter 4.

2.3 Conclusions

In this chapter I reviewed the concepts related to hazardous material transportation risk and some of the previous research in the field. Considerable literature is available on the risk of transporting hazardous materials by rail but most of it deals with human hazard rather than the environmental aspect. Nevertheless, a review of these studies helped in recognizing the crucial inputs required for the current research and the sources where these data could be found. Although this analysis is specifically devoted to environmental risk of spills of hazardous material in transportation, studies of human health risk assessment provided a general insight into the risk assessment methodology.

In addition to risk assessment studies, chemical ranking studies were also reviewed. A feature that characterizes most of the chemical ranking systems is that they rank chemicals in qualitative terms, which, in most of the cases, are based on subjective criteria tailored to the needs of the organization, whose objective has generally been to achieve a relative ranking for the chemicals. This study falls in the realm of quantitative risk assessment rather than a chemical ranking scheme and was aimed at improving or strengthening the scientific criteria by which we characterize environmental hazard, by developing a more thorough and analytical approach.

CHAPTER 3

PROBABILITY ANALYSIS

The risk from a hazardous material spill depends in part on the probability of its occurrence. The probability of a spill is a function of car derailment rate and release probability of a derailed car. The probability that a chemical is spilled is related to the design of the tank cars used to transport the chemical and the number and distribution of different tank car types used in its transport. In this chapter, a general formulation is developed to estimate the probability of release for each chemical of interest using the conditional release probability values for various tank car specifications in which the chemicals are transported.

In risk analysis the event that is the cause of concern must be precisely defined as well as the initiating events that lead to the event's occurrence.

- Initiating event: The events that lead to a hazardous material spill, from a tank car, are as follows:
    - A train carrying hazardous material tank cars is involved in an accident.
    - One or more hazardous materials tank cars are derailed as a result of the accident.

    - One or more derailed hazardous materials tank cars are damaged as a result of the derailment.
- Event of concern: Some or all of the contents are spilled from a damaged hazardous material car.

Probability analysis involves calculation of the likelihood of the event of concern that, in this case, will be the frequency of release of hazardous materials from tank cars. The frequency of release for hazardous material cars ($F_{release}$) depends on the following two factors:

- Car derailment rate (F_{derail})
- Probability of release from a tank car, given that the car derails ($P_{release|derail}$)

The statistic F_{derail} is independent of the tank car specification that transports the commodity of concern but $P_{release|derail}$ varies from one tank car specification to another. This is because tank cars differ in their resistance to damage due to differences in safety design features. Thus while the derailment rate is treated as a constant for all chemicals, the probability of release varies.

3.1. Car Derailment Rate (F_{derail})

Car derailment rate is a key parameter in determining the risk associated with transportation of hazardous material by rail. Basic train accident rate statistics are available from FRA. However calculation of hazardous material risk requires careful use of accident rates depending on the combination of the appropriate accident rate metrics (Anderson & Barkan 2004). FRA data can be used to calculate accident rates tailored to various parameters of interest such as accident type, railroad type, track type, track class, train type, etc. The most up-to-date analysis of U.S. freight train accident statistics is that of Anderson (2005). Based on his work, I have used the following criteria to define the conditions of interest in this analysis:

- Accident Type: The term 'accident' herein implies a derailment or a collision of a train on a railroad mainline. Other accidents such as highway grade crossing accidents are not included in the accident rate calculations. These accidents only include the FRA reportable events, i.e., events that cause more than $6,700 in damages to track, equipment and structures and thus are legally required to be reported to the FRA (Treichel et al 2006).
- Railroad Type: Accident rates differ for Class I vs. non Class I railroads where Class I railroads are defined as "line haul freight railroads with operating revenue in excess of $289.4 million" by the AAR. The mainline accident rate for non Class I railroads was five times that of Class I railroads in the year 2001 (Anderson & Barkan 2004). A route specific risk analysis of a shipment traversing these types of railroads should use an average of the two accident rates weighted by the distance traveled on each of the two railroad classes. But the majority of traffic is transported on Class I railroads (Anderson & Barkan 2004); consequently in the analysis of risk described here I used Class I railroad statistics for accident rate calculations.

- Track Type: The various types of trackage include mainline, yard, industry and siding. Only mainline track was considered for accident rate purposes because yard accidents generally occur at low speeds and generally do not result in serious, high consequence hazardous material accidents.
- Train Type: Accident rates differ for passenger and freight trains. This analysis deals with hazardous material transportation and hence clearly deals only with freight trains, not with passenger trains.
- Traffic Type: Calculation of derailment rates requires knowledge of the car-miles traveled and the number of cars derailed. This information is readily available for freight cars and trains as a whole but not specifically for hazardous materials. Consequently, I made the following assumption for this study: the car derailment rate, in the event of an accident, remains the same irrespective of whether or not the car contains hazardous materials. The effect of this assumption will be underestimation of risk if tank cars derail at a higher rate than other cars, and overestimation if their derailment rate is lower.
- Track Class Type: Traffic over the track classes, X through 6, was considered for this study. These classes represent nearly all mainline freight railroad trackage.

The accident rate for the set of conditions selected above is not directly available from the FRA but can be calculated using accident, train-mile and freight traffic data available from FRA (Anderson & Barkan 2004). Recent analyses of train-mile and train accident data were available for the ten-year period from 1992 to 2001 (Anderson & Barkan 2004). Since this study was concerned with estimation of current and future risk, statistics for the most recent years available (2000 and 2001) were considered most relevant (Table 3.1). In fact, Class I railroad mainline derailment and collision rates have remained nearly constant over the ten-year period, 1992-2001, studied by Anderson and Barkan (2004).

	Year		
	2000	**2001**	**1992-2001**
Freight Train Miles	512,074,619	501,389,151	4,752,047,395
Derailments	464	469	4,460
Derailment Rate (per million FRTRNMI)	0.91	0.94	0.94
Average Length	88.2	88.6	84.4
Total Cars Derailed	4,254	4,111	39,737
Average Cars Derailed	9.2	8.8	8.9
Total Hazmat Cars Derailed	324	272	2492
Average Hazmat Cars Derailed	0.698	0.580	0.559
Total Hazmat Cars Released	55	38	273
Average Hazmat Cars Released	0.119	0.081	0.061
Collisions	27	32	267
Collision Rate (per million FRTRNMI)	0.05	0.06	0.06
Average Length	65.8	91.1	76.9
Total Cars Derailed	80	343	2,056
Average Cars Derailed	3.0	10.7	7.7
Total Hazmat Cars Derailed	15	18	150
Average Hazmat Cars Derailed	0.556	0.563	0.562
Total Hazmat Cars Released	1	1	16
Average Hazmat Cars Released	0.037	0.031	0.060

Table 3.1 Accident and Train-Mile Data for Mainline Freight on Class I Railroads: 1992-2001 ***(Anderson 2005)***

Using the data from Table 3.1, car derailment rate is calculated using Equation 3.1:

$F_{derail} = N_{derail}/(D_{CM})$ (per unit car-mile) (3.1)

where,

N_{derail} = Total number of cars derailed in accidents over the time span considered

D_{CM} = Total car-miles traveled over the time span considered

The total train miles traveled by U.S. freight trains is available from AAR (Table 3.1). The average number of cars per train is needed to convert the derailment rate from a train-mile to a car-mile basis (Equation 3.2). The value used was 68.6 cars per train (AAR 2001).

$$D_{CM} = D_{TM}L_{avg} \tag{3.2}$$

where,

D_{TM} = Total train-miles traveled over the time span considered

L_{avg} = Average number of cars per train

= 68.6 cars per train

Using Table 3.1, I calculated the total number of freight cars derailed (Table 3.2) and total freight train-miles traveled (Table 3.3) over Class I railroad mainlines for the years 2000 and 2001.

	Year		**Total**
	2000	**2001**	(Both yrs.)
Number of Cars Derailed in Train Derailments	4,254	4,111	8,365
Number of Cars Derailed in Train Collisions	80	343	423
Total Number of Cars Derailed in Derailments + Collisions	4,334	4,454	8,788

Table 3.2 Car Derailment Data for Class I Railroad Mainline Freight Traffic

	Year	
	2000	**2001**
Total Train-Miles Traveled	512,074,619	501,389,151
Total Train-Miles Traveled for the Years 2000 and 2001	1,013,463,770	

Table 3.3 Train-Mile Data for Class I Railroad Mainline Freight Traffic

The values used for calculation of F_{derail} are as follows:

N_{derail} = Total number of cars derailed in accidents in the years 2000 and 2001

= 8,788 (Table 3.2)

D_{TM} = Total Class I freight train-miles traveled in the years 2000 and 2001

= 1,013,463,770 train-miles (Table 3.3)

L_{avg} = 68.6 cars per train (AAR 2001)

Substituting the values for variables in Equation 3.1, I obtain the car derailment rate per car-mile as shown below:

$$F_{derail} = 8{,}788/(1{,}013{,}463{,}770 \text{ x } 68.6)$$

$$= 1.26 \text{ x } 10^{-7}$$

Therefore, $1.26 \text{ x } 10^{-7}$ cars derail per car-mile traveled or, on average one car derails for every 7,911,198 miles traveled.

3.2 Release Probability of a Derailed Tank Car ($P_{release|derail}$)

The second important parameter for probability analysis is the probability of release from a tank car that has been derailed. The conditional probability of release depends on design features of the derailed tank car, which in turn is reflected by the tank car type or specification. Chemicals are transported in different tank car specifications, so the conditional release probability is different for different chemicals. Another factor in the release probability calculation is that in general more than one type of tank car specification is used to transport a chemical. Therefore, unlike other aspects of probability analysis discussed above, release probability is chemical specific and hence analysis on a chemical-by-chemical basis is necessary. The conditional release probability of a chemical depends on:

- Release probabilities of tank car specifications used for transporting the chemical.
- Frequency distribution of tank car specifications used to transport the chemical.

3.2.1 Carload Distribution for Chemicals of Interest

A merge of the AAR TeleRail Automated Information Network (TRAIN II) database with the AAR Universal Machine Language Equipment Register (UMLER) database, for the year 2004, was used to tabulate the tank car specifications used for each chemical under study and the annual number of carloads of the chemical transported in each of those classes (Appendix A).

3.2.1.1 Tank Car Specifications

Table 3.4 shows all the tank car specifications used in 2004 for transportation of the chemicals in this study.

103A-ALW
103AW
103W
105J100W
105S100W
105J200W
105A300W
105J300W
105J400W
105A500W
105J500W
111A100ALW
111A100ALW2
111S100ALW2
111A100W1
111A100W2
111A100W3
111A100W4
111A100W5
111A100W6
111A60W7
111A60ALW1
111A60ALW2
111A60W1
111S100W1
111S100W2
111J100W3
111S60ALW1
111S60ALW2
112A200W
112T200W
112J340W
112S340W
112J400W
115A60W6
120J200W
211A100W1

Table 3.4 Tank Car Specifications Used in the Year 2004 for Transportation of the Chemicals Under Study

Though information on carloads was available in this dataset it was not always possible to determine all of the characteristics of tank cars used, e.g., presence or absence of insulation, head shields or bottom outlet. In absence of these data, I assumed the tank car configuration to be the base car available for that specification, i.e., the car with the fewest risk reduction options. For example, if a chemical was transported in a 105J100W (that can have half or full-height headshields, abbreviated as HS), the tank car was assumed to have half-height headshields, in other words, a 105J100W-1/2HS. The Union Tank Car specifications (UTC 1996) specify insulation criteria for most of the chemicals on the list. But if information regarding insulation was not available for a chemical in the UTC specifications then I assumed it to be transported in non-insulated cars. So, for example, the UTC specifications do not have insulation criteria for butyl acrylates and isopropanol, therefore I assumed these chemicals to be transported in non-insulated cars. On the other hand, according to the UTC specifications, benzene should be transported in an insulated tank car. Table 3.5 shows the annual carload distribution for benzene as available from the databases and how each tank car specification is treated according to the procedure described above.

Hazmat Code	Chemical	Tank Car Specification	Tank Car Specification Treated as	Carloads
4908110	Benzene	111A100W1	111A100W1 – INS	3,576
		111A100W3	111A100W3	181
		111J100W3	111J100W3 -1/2 HS	24
		211A100W1	211A100W1 – INS	10
		105J100W	105J100W -1/2 HS	1

Table 3.5 Annual Traffic Information for Benzene *(for the year 2004)*

3.2.1.2 Hazmat Codes

The Hazmat Code is a 7-digit code assigned to each hazardous material. The code begins with the two digits “49” for all the hazardous materials which helps railroads track their hazardous material shipments. A chemical can be transported under more than one Hazmat Code. For example, for methanol there are two Hazmat Codes, therefore, the carload data for both was extracted from the joint database and summed to get the total carload information (Table 3.6).

Hazmat Code	Tank Car Specification	Carloads	Percent Carloads	Cumulative %
4909381	111A100W1	2,504	99.92	99.92
	111A100W3	1	0.04	99.96
	211A100W1	1	0.04	100.00
	Total	2,506	100.00	
4909230	111A100W1	20,689	99.90	99.90
	111A100W3	11	0.05	99.95
	211A100W1	8	0.04	99.99
	112J340W	1	0.00	100.00
	105J500W	1	0.00	100.00
	Total	20,710	100.00	
Total:	111A100W1	23,193	99.90	99.90
	111A100W3	12	0.05	99.95
	211A100W1	9	0.04	99.99
	112J340W	1	0.00	100.00
	105J500W	1	0.00	100.00
	Total	23,216	100.00	

Table 3.6 Carload Data for Various Hazmat Codes of Methanol under Study

3.2.2 Release Probability for Various Tank Car Specifications

The most up-to-date statistics for carbon steel tank cars damaged in accidents have been developed by Treichel et al (2006). They used data collected on tank cars in accidents over a 31-year period from 1965-1995. In their analysis, the authors undertook a number of statistical and engineering analysis steps to account for changes in tank car design over the span when data were collected. Their statistics are considered to represent the best estimates of the current performance of tank cars in accidents.

Treichel et al (2006) did not consider cars with aluminum or alloy steel tanks. The most recent analysis of lading loss probability of aluminum tank cars was conducted by Phillips (1990). The two reports used somewhat different approaches; therefore, the rates in one must be reconciled with those in the other in order to make comparisons between carbon steel and aluminum and alloy steel tank cars. The 2006 report uses more sophisticated analytical methods and the conditional release probabilities are considered more accurate, hence these were used as a basis to which the rates in the 1990 report were adjusted for comparison. Treichel et al (2006) present release probability data based on the following categories:

1. Tank car specification
2. Cause or source of lading loss:
    a. Head Puncture (H)
    b. Shell Puncture (S)
    c. Top Fittings Damage (T)
    d. Bottom Fittings Damage (B)
    e. Various combinations of the four causes above, counted as a loss for each applicable source.
3. Risk reduction options (RROs) applied
    a. Jacket Effectiveness
    b. Head Shield Effectiveness
    c. Top Fittings Protection Effectiveness
    d. Bottom Fittings Protection Effectiveness
    e. Added Tank Thickness Effectiveness

4. Location of the accident site: mainline or yard
5. Speed of the train (only for mainline accidents)

3.2.2.1 Release Quantity

The amount of lading lost from a tank car, in a spill event, can vary from a small amount to loss of the car's entire contents. Treichel et al (2006) calculated the percentage of spills that result in the following percentages of tank capacity lost in mainline accidents:

- 0-5%
- >5-20%
- >20-50%
- >50-80%
- >80-100%

The report by Treichel et al (2006) became available only after this research was largely complete. Until that time, Phillips et al (1995) was the most comprehensive work on lading loss probabilities of tank cars. Phillips et al (1995) developed a probability distribution of quantity lost using the following four categories that differ only slightly from Treichel et al (2006):

- 0-5%
- >5-20%
- >20-80%
- >80-100%

The choice of lading loss categories affects not only the probability analysis but also determines the values of lading loss quantities at which spill simulations would be carried out for consequence analysis. Though the conditional release probability values for tank cars were updated using the values and the methodology available in Treichel et al (2006), the percent distribution of spills as a function of lading lost was condensed to match the four categories in Phillips et al (1995) because all the spill simulations had already been completed using the scheme presented in Phillips et al (1995). Phillips et al (1995) identifies cars as type 1, 2, 3, 4 or 5 of which types 1 and 2 are non-pressure cars and types 3, 4 and 5 are pressure cars. Table 3.7 presents the percent distribution of spills for non-pressure cars (Types 1 and 2) and pressure cars (Types 3, 4 and 5).

	Percent Tank Capacity Lost			
Car Type	**0-5%**	**>5-20%**	**>20-80%**	**>80-100%**
Type 1, 2 (non-pressure cars)	19	9	27	45
Type 3, 4, 5 (pressure cars)	22	5	15	58

Table 3.7 Percent Distribution of Spill Quantity for Non Pressure and Pressure Tank Cars *(Treichel et al 2006)*

Table 3.8 shows the tank car specifications for which the release probability values were required. This set includes all the tank cars shown in Table 3.4 with the exception of 103A-ALW, 103AW, 103W, 115A100W6 and 120J200W because Treichel et al (2006) cannot be used to estimate release probability for these classes. These account for only a very small percentage of traffic (less than 1%) and hence were eliminated from further analysis.

105A100W
105J100W
105S100W
105J200W
105A300W
105J300W
105J400W
105A500W
105J500W
111A100ALW
111A100ALW2
111S100ALW2
111A100W1
111A100W2
111A100W3
111A100W4
111A100W5
111A100W6
111A60W7
111A60ALW1
111A60ALW2
111A60W1
111S100W1
111S100W2
111J100W3
111S60ALW1
111S60ALW2
112A200W
112J200W
112S200W
112T200W
112A340W
112J340W
112S340W
112J400W
211A100W1
Enhanced Safety 286K ‘111’

Table 3.8 Tank Car Specifications Selected for Study

Table 3.8 also has a few tank car specifications that are not presently used for transportation of the chemicals in this study but are possible candidates for use as alternative tank cars for these products. One such tank car is the “Enhanced Safety 286K 111” tank car. Most of the tank cars currently in use for the chemicals of interest have a maximum GRL of 263K lbs. But the AAR has recently developed specifications for an enhanced safety, 286K maximum GRL tank car (AAR 2004). The pertinent characteristics of this car, in the context of this study are as follows (Dalrymple 2003, AAR 2004):

- Non-Insulated, 286K: Top fittings protection, at least 1/2" thick tank constructed of TC-128 steel and equipped with half-height head shields.
- Insulated, 286K: Top fittings protection, at least 7/16” thick tank constructed of TC-128 steel and equipped with a jacket and 1/2" thick jacket heads.

Therefore compared to a base 263K ‘111’ tank car an enhanced safety 286K ‘111’ tank car has more risk reduction options and consequently a lower release probability.

Head and shell thickness values are required to calculate the release probability values using the methodology in Treichel et al (2006) (Table 3.9)

Car Class	Head Thickness	Shell Thickness
105A100W	1/2"	1/2"
105J100W	1/2"	1/2"
105S100W	1/2"	1/2"
105J200W	1/2"	1/2"
105A300W	9/16”	9/16”
105J300W	9/16”	9/16”
105J400W	11/16”	11/16”
105A500W	13/16”	25/32”
105J500W	13/16”	25/32”
111A100W1	7/16”	7/16”
111A100W2	7/16”	7/16”
111A100W3	7/16”	7/16”
111A100W4	7/16”	7/16”
111A100W5	7/16”	7/16”
111A60W1	7/16”	7/16”
111J100W3	7/16”	7/16”
111S100W1	7/16”	7/16”
111S100W2	7/16”	7/16”
112A200W	1/2"	1/2"
112J200W	1/2"	1/2"
112S200W	1/2"	1/2"
112T200W	1/2"	1/2"
112A340W	5/8”	5/8”
112J340W	5/8”	5/8”
112S340W	5/8”	5/8”
112J400W	5/8”	5/8”
211A100W1	7/16”	7/16”
Enhanced Safety 286K 111 - NI	1/2”	1/2”
Enhanced Safety 286K 111 - INS	7/16”	7/16”

Table 3.9 Head and Shell Thickness for Tank Car Specifications
(AAR 2004, Phillips et al 1995)

3.2.2.2 Release Probability Calculation for Aluminum and Alloy Steel Tank Cars

Some of the chemicals of interest are transported in alloy or aluminum tank cars (around 6.5% in the year 2004). Phillips (1990) calculated the conditional release probability values for aluminum and alloy steel tank cars as well as carbon steel cars. The values in the 1990 report are developed from accident data over a 22-year period, 1965-1986, but the probability values for the carbon-steel cars considered there were developed using a different statistical approach than in the Treichel et al (2006) report. Therefore the release probability values for aluminum and alloy steel tank cars from Phillips (1990) were prorated based on the probability estimates for steel tank cars available from both the reports, and a linear relationship was assumed.

Treichel et al (2006) deals only with ‘stub sill’ (S/S) steel cars whereas Phillips (1990) has data for stub sill and ‘underframe’ (U/F) steel cars. Very few U/F cars are still in service transporting the products considered in this study, and those that are, are expected to be retired within a relatively short time. Therefore only S/S car data were used for comparison. The probability of release due to various causes was prorated separately and then these values were used in accordance with the methodology available in Treichel et al (2006) to yield the overall conditional release probability for the aluminum and alloy steel tank cars. Treichel et al (2006) does not have a separate category for spills caused from the combination of two or more of the four causes (head damage, shell damage, top fittings damage or bottom fittings damage); because the calculations for each individual category account for multiple cause spills as well. Phillips (1990) treats the spills from multiple causes as a separate category. The various causes or sources of lading loss in Phillips (1990) are as follows:

1. Head Puncture (H)
2. Shell Puncture (S)
3. Top Fittings Damage (T)
    a. Mechanical Damage
    b. Fire Damage
    c. No Damage (Loose)
    d. Details Unknown
4. Bottom Fittings Damage (B)
5. More Than One Cause (M)

Prorated values were developed in a three-step process:

1. In Phillips (1990) the release probability due to multiple causes (M) was assumed to be unaffected by insulation and hence the non-insulated and insulated cars were grouped together for this cause. This cause is not considered separately in Treichel et al (2006); hence before prorating the values in Phillips (1990) the probability of release due to multiple causes (M) was attributed equally to the four causes 'H', 'S', 'T' and 'B' and therefore, 1/4th of the probability of release due to cause 'M' was added to the causes 'H', 'S', 'T' and 'B'. The cause category 'M' was removed from further consideration.
2. The release probabilities due to head (H) and shell (S) punctures were prorated separately for non-insulated and insulated aluminum tank cars against head and

shell puncture release probability values for non-insulated and insulated 111A100W S/S tank cars respectively.

3. The release probabilities due to top (T) and bottom (B) fitting damages are different for insulated 111A100W cars than non-insulated cars according to Treichel et al (2006) but in Phillips (1990) it is assumed that these probabilities are not affected by insulation on the car and hence the values are not separately available for the two categories. Therefore, the same values from Phillips (1990) were prorated separately for non-insulated and insulated aluminum tank cars, again using the corresponding release probability values for 111A100W1 car available from the two reports, as the basis for prorating.

The alloy cars are dealt with in the same manner except that they are treated as non-insulated cars for the purpose of probability calculations for releases due to head and shell punctures. This is due to unavailability of separate data for non-insulated and insulated cars in Phillips (1990). Some chemicals that are transported in alloy steel tank cars (111A100W6 or 111A100W7), e.g., acrylic acid, require insulation but because probability data could not be developed for insulated alloy cars, the values for non-insulated alloy cars are used for calculations. Calculations for updating the aluminum and alloy steel tank car conditional release probabilities are shown in Appendix B. The probability of release could also not be calculated for 111S60ALW1, 111S60ALW2 or 111S100ALW2, in other words the ‘S’ specification, which implies presence of a half-height or a full-height head shield on the tank car. This is because the data on damaged tank cars in Phillips (1990) did not include any detail on whether the tank car was equipped with head shields or not. I assumed its probability to equal that of

111A60ALW1, 111A60ALW2 and 111A100ALW2, respectively. A head shield improves the damage resistance of the tank car and hence reduces the probability of release from the car in the event of an accident. Therefore the risk estimates for the chemicals carried in these cars would be an overestimate of the actual values. A 111A100ALW car was assumed to perform identically to a 111A100ALW1. Phillips (1990) does not specify whether the damaged car data pertained to the non pressure cars or the pressure cars, hence aluminum and alloy steel tank cars are assumed to be non-pressure cars for the purpose of release probability distribution as a function of lading lost.

I was able to find or develop the conditional probabilities of releases for all the tank car specifications tabulated in Table 3.8. These values are presented in Table 3.10 and Figure 3.1 wherein the tank car specifications are arranged in descending order of their conditional probability of release values.

Car Class	**Car Type**	**Release Probability of a Derailed Tank Car ($P_{release\|derail}$)**
105A100W	Type 3/4/5	11.58%
105J100W –1/2 HS	Type 3/4/5	9.97%
105S100W –1/2 HS	Type 3/4/5	9.97%
105J200W –1/2 HS	Type 3/4/5	9.97%
105A300W	Type 3/4/5	10.28%
105J300W- 1/2 HS	Type 3/4/5	8.83%
105J400W –1/2 HS	Type 3/4/5	7.13%
105A500W	Type 3/4/5	5.04%
105J500W - 1/2 HS	Type 3/4/5	4.09%
111A100W1 – NI	Type 1/2	35.27%
111A100W1 – INS	Type 1/2	20.72%
111A100W2 – NI	Type 1/2	30.96%
111A100W2 – INS	Type 1/2	17.03%
111A100W3	Type 1/2	20.72%

Car Class	**Car Type**	**Release Probability of a Derailed Tank Car ($P_{release\|derail}$)**
111A100W4	Type 1/2	17.03%
111A100W5 – NI	Type 1/2	30.96%
111A100W5 – INS	Type 1/2	17.03%
111A100W6 – NI	Type 1/2	10.76%
111A60W7 – NI	Type 1/2	10.76%
111J100W3 -1/2 HS	Type 1/2	19.10%
111S100W1 – NI, 1/2 HS	Type 1/2	19.10%
111S100W1 – INS, 1/2 HS	Type 1/2	19.10%
111S100W2 – NI, 1/2 HS	Type 1/2	27.77%
111S100W2 – INS, 1/2 HS	Type 1/2	19.10%
111A60W1 – NI	Type 1/2	35.27%
111A60W1 – INS	Type 1/2	20.72%
111A100ALW1 - NI	Type 1/2	46.88%
111A100ALW1 - INS	Type 1/2	39.67%
111A100ALW2 - NI	Type 1/2	43.85%
111A100ALW2 - INS	Type 1/2	35.79%
111S100ALW2 - NI	Type 1/2	43.85%
111S100ALW2 - INS	Type 1/2	35.79%
111A60ALW1 - NI	Type 1/2	46.88%
111A60ALW1 - INS	Type 1/2	39.67%
111A60ALW2 - NI	Type 1/2	43.85%
111A60ALW2 - INS	Type 1/2	35.79%
111S60ALW1 – NI	Type 1/2	46.88%
111S60ALW1 - INS	Type 1/2	39.67%
111S60ALW2 – NI	Type 1/2	43.85%
111S60ALW2 - INS	Type 1/2	35.79%
112A200W – NI	Type 3/4/5	22.35%
112A200W – INS	Type 3/4/5	11.58%
112J200W –1/2 HS	Type 3/4/5	9.97%
112S200W – NI, 1/2 HS	Type 3/4/5	19.06%
112T200W – NI, 1/2 HS	Type 3/4/5	19.06%
112A340W – NI	Type 3/4/5	18.42%
112A340W – INS	Type 3/4/5	9.20%
112J340W –1/2 HS	Type 3/4/5	7.89%
112S340W – NI, 1/2 HS	Type 3/4/5	15.65%
112J400W –1/2 HS	Type 3/4/5	7.89%
211A100W1 – NI	Type 1/2	35.27%
211A100W1 – INS	Type 1/2	20.72%
Enhanced Safety 286K 111 – NI	Type 1/2	24.12%
Enhanced Safety 286K 111 – INS	Type 1/2	15.31%

Table 3.10 Probabilities of Release from Tank Cars of Interest Derailed in a FRA-Reportable Accident

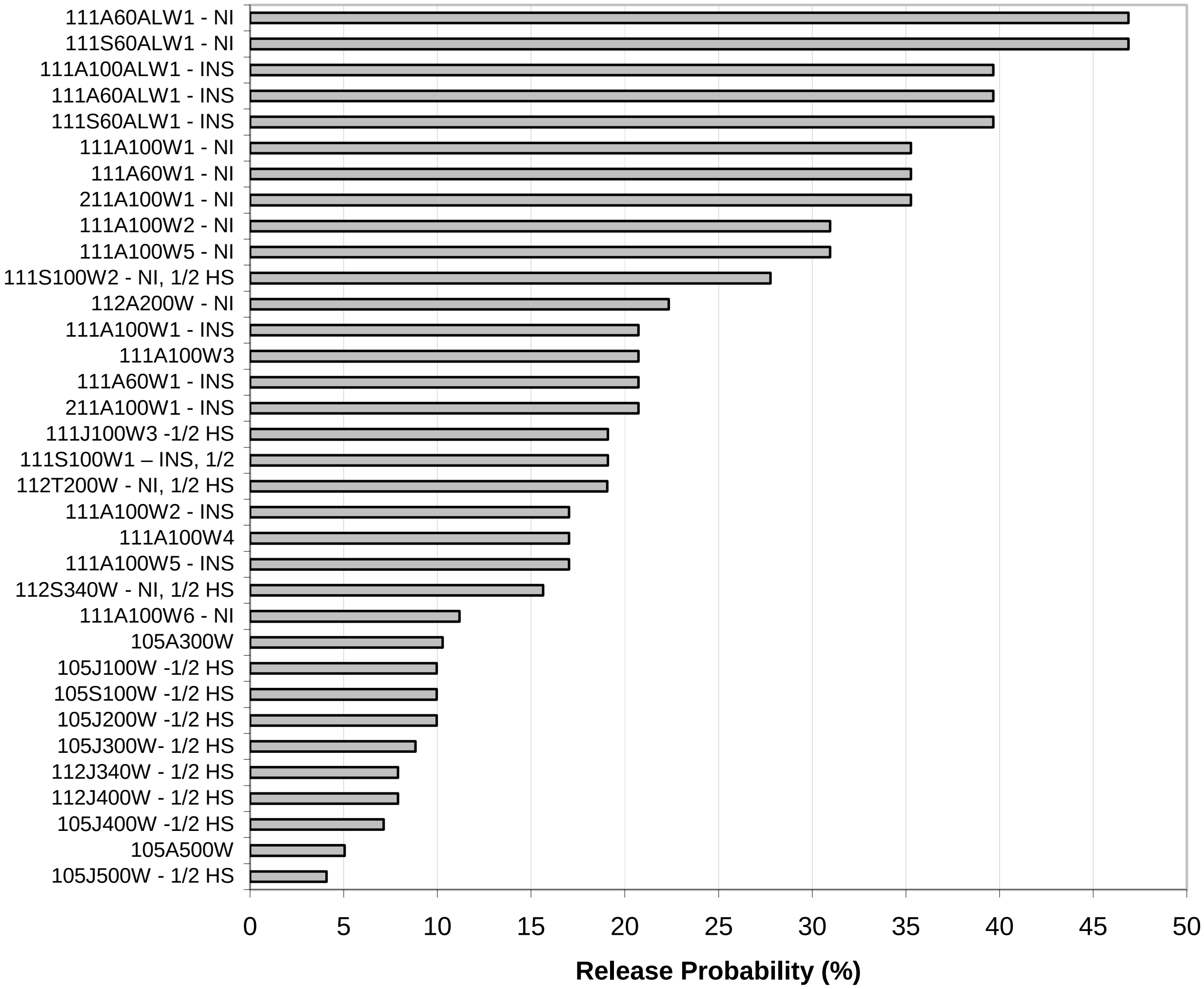


Figure 3.1 Probabilities of Release from Derailed Tank Cars of Interest

The conditional release probability values developed above can be used to develop condition release probabilities in various lading loss categories using Equation 3.3:

$$P_{iq} = P_iM_{iq} \tag{3.3}$$

where,

P_{iq} = Probability of release from a damaged tank car specification ‘i’ in the lading loss category ‘q’

P_i = Probability of release from a damaged tank car ($P_{release|derail}$) specification ‘i’ (from Table 3.10)

M_{iq} = Percentage of spills occurring in the lading loss category ‘q’ from a tank car specification ‘i’ (available from Table 3.7)

Conditional release probability values for each specification and quantity of lading lost are calculated (Table 3.11), using Equation 3.3 and information from Tables 3.7 and 3.10. Having found the release probability values for various tank car specifications, the next step was to calculate release probability for each chemical, which is discussed in the next section (Sec. 3.3).

Car Class	Conditional Release Probability (P_i)	Conditional Release Probability for Categories of Percent Tank Capacity Lost			
		0-5%	>5-20%	>20-80%	>80-100%
105A100W	11.59%	2.55%	0.58%	1.74%	6.72%
105J100W -1/2 HS	9.97%	2.19%	0.50%	1.50%	5.78%
105S100W -1/2 HS	9.97%	2.19%	0.50%	1.50%	5.78%
105J200W -1/2 HS	9.97%	2.19%	0.50%	1.50%	5.78%
105A300W	10.27%	2.26%	0.51%	1.54%	5.96%
105J300W- 1/2 HS	8.82%	1.94%	0.44%	1.32%	5.12%
105J400W -1/2 HS	7.14%	1.57%	0.36%	1.07%	4.14%
105A500W	5.04%	1.11%	0.25%	0.76%	2.92%
105J500W - 1/2 HS	4.08%	0.90%	0.20%	0.61%	2.37%
111A100W1 – NI	35.26%	6.70%	3.17%	9.52%	15.87%
111A100W1 – INS	20.71%	3.94%	1.86%	5.59%	9.32%
111A100W2 – NI	30.96%	5.88%	2.79%	8.36%	13.93%
111A100W2 - INS	17.03%	3.24%	1.53%	4.60%	7.66%
111A100W3	20.71%	3.94%	1.86%	5.59%	9.32%
111A100W4	17.03%	3.24%	1.53%	4.60%	7.66%
111A100W5 – NI	30.96%	5.88%	2.79%	8.36%	13.93%
111A100W5 - INS	17.03%	3.24%	1.53%	4.60%	7.66%
111A100W6 – NI	10.76%	2.04%	0.97%	2.91%	4.84%
111A100W7 – NI	10.76%	2.04%	0.97%	2.91%	4.84%
111J100W3 -1/2 HS	19.11%	3.63%	1.72%	5.16%	8.60%
111S100W1 – NI, 1/2 HS	32.22%	6.12%	2.90%	8.70%	14.50%
111S100W1 – INS, 1/2 HS	19.11%	3.63%	1.72%	5.16%	8.60%
111S100W2 - NI, 1/2 HS	27.78%	5.28%	2.50%	7.50%	12.50%
111S100W2 - INS, 1/2 HS	15.33%	2.91%	1.38%	4.14%	6.90%
111A60W1 – NI	35.26%	6.70%	3.17%	9.52%	15.87%
111A60W1 – INS	20.71%	3.94%	1.86%	5.59%	9.32%
111A100ALW1 – NI	46.89%	8.91%	4.22%	12.66%	21.10%
111A100ALW1 - INS	39.67%	7.54%	3.57%	10.71%	17.85%
111A100ALW2 – NI	43.85%	8.33%	3.95%	11.84%	19.73%
111A100ALW2 - INS	35.79%	6.80%	3.22%	9.66%	16.11%
111S100ALW2 – NI	43.85%	8.33%	3.95%	11.84%	19.73%
111S100ALW2 - INS	35.79%	6.80%	3.22%	9.66%	16.11%
111A60ALW1 – NI	46.89%	8.91%	4.22%	12.66%	21.10%
111A60ALW1 - INS	39.67%	7.54%	3.57%	10.71%	17.85%
111A60ALW2 – NI	43.85%	8.33%	3.95%	11.84%	19.73%
111A60ALW2 - INS	35.79%	6.80%	3.22%	9.66%	16.11%
111S60ALW1 – NI	46.89%	8.91%	4.22%	12.66%	21.10%
111S60ALW1 - INS	39.67%	7.54%	3.57%	10.71%	17.85%
111S60ALW2 – NI	43.85%	8.33%	3.95%	11.84%	19.73%
111S60ALW2 – INS	35.79%	6.80%	3.22%	9.66%	16.11%
112A200W – NI	22.35%	4.92%	1.12%	3.35%	12.96%
112A200W – INS	11.59%	2.55%	0.58%	1.74%	6.72%
112J200W – 1/2 HS	9.97%	2.19%	0.50%	1.50%	5.78%
112S200W – NI, 1/2 HS	19.05%	4.19%	0.95%	2.86%	11.05%
112T200W - NI, 1/2 HS	19.05%	4.19%	0.95%	2.86%	11.05%
112A340W - NI	18.41%	4.05%	0.92%	2.76%	10.68%
112A340W - NI	9.20%	2.02%	0.46%	1.38%	5.34%
112J340W - 1/2 HS	7.89%	1.74%	0.39%	1.18%	4.58%
112S340W - NI, 1/2 HS	15.65%	3.44%	0.78%	2.35%	9.08%
112J400W - 1/2 HS	7.89%	1.74%	0.39%	1.18%	4.58%
211A100W1 - NI	35.26%	6.70%	3.17%	9.52%	15.87%
211A100W1 - INS	20.71%	3.94%	1.86%	5.59%	9.32%

Table 3.11 Conditional Release Probabilities for a Range of Tank Capacities Lost, from Derailed Tank Cars of Interest

3.3 Release Probability for Chemicals of Interest

Most of the chemicals considered are transported in more than one class of tank car. Therefore, the conditional release probability value for a chemical is not the conditional release probability of a single tank car specification. Instead, it needs to be calculated as a weighted average of the release probability values of the different tank car specifications used to transport it. The weighting factor is the number of carloads of the chemical carried in each tank car specification. It is valuable to know the conditional probability of release averaged over all tank car specifications transporting a chemical. However, from a risk assessment aspect, it is also important to ascertain how much risk is incurred by each of these tank car specifications such that the candidates posing a higher risk can be recognized and the replacement or retrofitting procedure can thus be prioritized. Therefore, a probability analysis was conducted for each tank car specification for each chemical as well as for the whole fleet used for the chemical.

3.3.1 Release Probability for Each Tank Car Specification for Chemicals of Interest

Using information from Table 3.11, conditional release probability values as a function of lading lost could be assembled for each tank car specification for each chemical. For example, the conditional release probability values for all the tank cars for benzene are presented in Table 3.12.

Chemical	Tank Car Specification	Percent Tank Capacity Lost			
		0-5%	>5-20%	>20-80%	>80-100%
Benzene	111A100W1 – INS	3.94%	1.86%	5.59%	9.32%
	111A100W3	3.94%	1.86%	5.59%	9.32%
	111J100W3 -1/2 HS	3.63%	1.72%	5.16%	8.60%
	211A100W1 – INS	3.94%	1.86%	5.59%	9.32%
	105J100W -1/2 HS	2.19%	0.50%	1.50%	5.78%

Table 3.12 Conditional Probability Values for Each Tank Car Specification Used for Transporting Benzene, as a Function of Percent Tank Capacity Lost

3.3.2 Release Probability Weighted across All Tank Car Specifications for Chemicals of Interest

The weighted conditional probability of release can be calculated using Equation 3.4 for each of the four lading loss categories mentioned in Table 3.7.

$$P_{cq} = \sum_{i=1}^{n} (P_{iq} T_{ic} / T_c) \qquad (3.4)$$

where,

P_{cq} = Probability of release from a derailed tank car carrying chemical ‘c’, in lading loss category ‘q’

n = Number of tank car specifications used to transport the chemical of interest

T_{ic} = Total annual carloads of the chemical ‘c’ transported in tank car specification ‘i’

T_c = Total annual carloads of chemical ‘c’

The values for P_{iq} are available from Table 3.11 and the values for n, T_{ic} and T_c can be obtained from the annual carload distribution presented in Appendix A for the chemicals considered in this study. The weighted probabilities of release estimates are developed for each chemical using the formula stated in Equation 3.4 (Table 3.13) that can then be summed together to obtain the conditional release probability for a chemical, given derailment (Equation 3.5).

$$P_c = \sum_{q=1}^{4} P_{cq} \qquad (3.5)$$

where,

P_c = Probability of release from a derailed tank car carrying chemical ‘c’

Commodity Name	**P_c**	**P_c Distributed among Categories of Percent Tank Capacity Lost**			
		0-5%	**>5-20%**	**>20-80%**	**>80-100%**
Acetaldehyde	29.43%	5.66%	2.56%	7.67%	13.54%
Acetic Acid	20.20%	3.84%	1.82%	5.45%	9.09%
Acetic Anhydride	22.86%	4.34%	2.06%	6.17%	10.29%
Acetone	35.04%	6.66%	3.15%	9.46%	15.77%
Acrylic Acid	13.65%	2.59%	1.23%	3.69%	6.14%
Acrylonitrile	22.27%	4.42%	1.75%	5.26%	10.84%
Benzene	20.70%	3.93%	1.86%	5.59%	9.32%
Butanol	34.96%	6.64%	3.15%	9.44%	15.73%
n-Butyl Acrylate	21.53%	4.22%	1.76%	5.28%	10.27%
Cyclohexane	35.03%	6.66%	3.15%	9.46%	15.76%
Ethanol	33.75%	6.41%	3.04%	9.11%	15.19%
Ethyl Acetate	35.12%	6.67%	3.16%	9.48%	15.81%
Ethyl Acrylate	23.14%	4.52%	1.92%	5.76%	10.94%
Hydrogen Peroxide	17.47%	3.32%	1.57%	4.72%	7.86%
Isopropanol	34.96%	6.64%	3.15%	9.44%	15.73%
Methanol	35.26%	6.70%	3.17%	9.52%	15.87%
Methyl Methacrylate Monomer	19.78%	3.91%	1.58%	4.73%	9.56%
Methyl Tert Butyl Ether	35.26%	6.70%	3.17%	9.52%	15.87%
Nitric Acid	18.91%	3.59%	1.70%	5.11%	8.51%
Phenol	20.71%	3.94%	1.86%	5.59%	9.32%
Potassium Hydroxide Solution	20.71%	3.94%	1.86%	5.59%	9.32%
Sodium Hydroxide Solution	20.70%	3.93%	1.86%	5.59%	9.32%
Styrene	20.49%	3.90%	1.84%	5.51%	9.24%
Sulfuric Acid	30.87%	5.87%	2.78%	8.33%	13.89%
Toluene	35.07%	6.66%	3.16%	9.47%	15.78%
Vinyl Acetate	33.32%	6.35%	2.97%	8.91%	15.09%
Xylenes	32.33%	6.14%	2.91%	8.73%	14.55%

Table 3.13 Weighted Conditional Release Probability for 27 Chemicals of Concern, as a Function of Tank Capacity Lost

3.4 Probability as a Metric for Rank Ordering Chemicals

There are several metrics that can be used to rank order chemicals depending on which aspect of risk is focused upon. Frequency of release indicates the likelihood of release of a chemical from the tank car transporting the chemical and can be used as the rank ordering metric. Frequency of release is the product of car derailment rate (F_{derail}) and conditional release probability for the chemical (P_c). But as car derailment rate (F_{derail}) is constant for all the chemicals, weighted conditional release probability estimates (P_{cq}) for the chemicals (Table 3.13) can be used for rank ordering. Figure 3.2 shows chemicals in order of decreasing average conditional release probability.

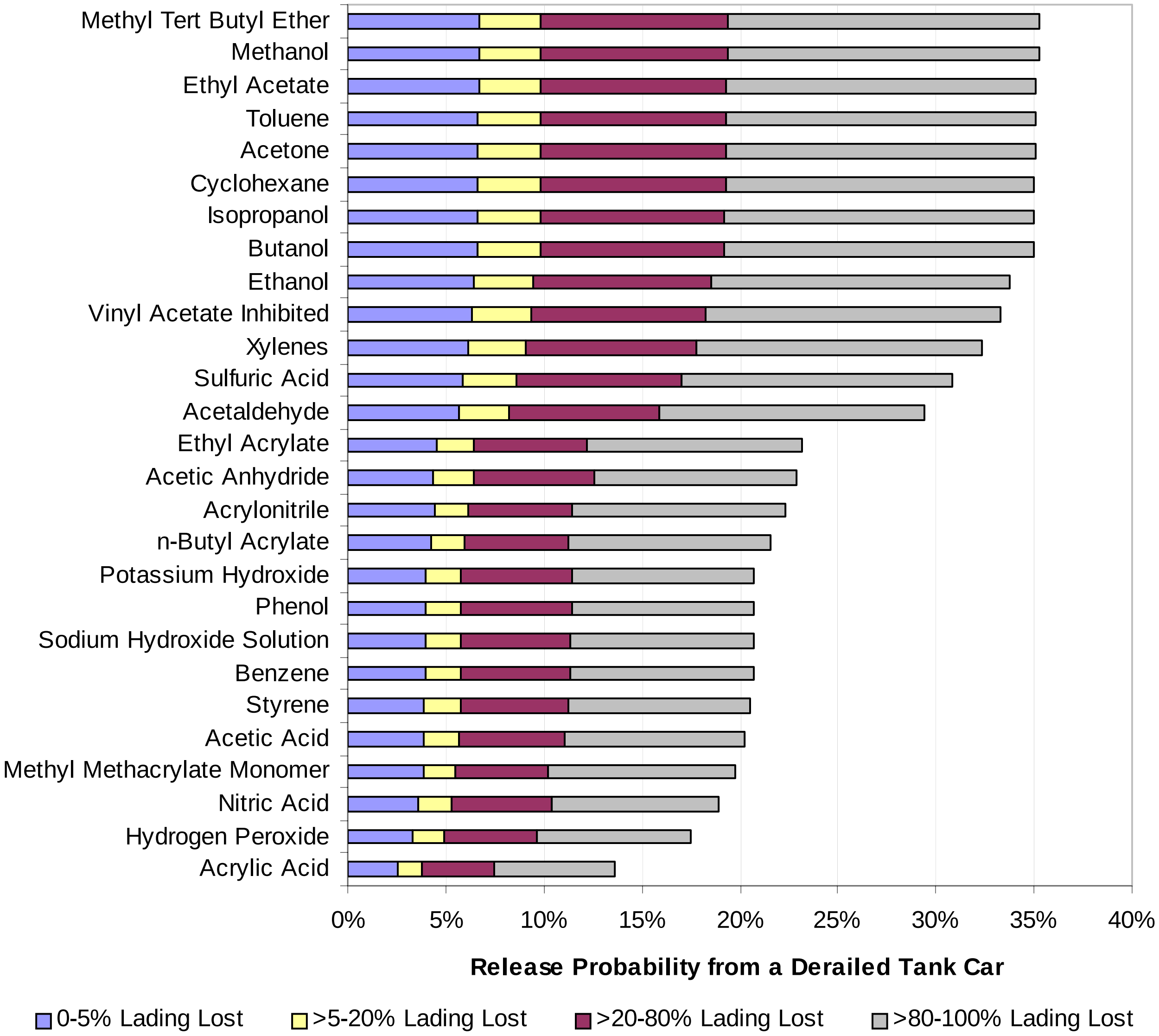


Figure 3.2 Rank Ordering of Chemicals Based on Conditional Probability of Release

This ordering depends on the constitution of the tank car fleet used to transport a chemical. While pressure cars, insulated non-pressure cars and alloy cars tend to reduce the release probability, non-insulated cars and aluminum cars have the opposite effect. Acrylic acid, with the lowest release probability, is required to be transported in insulated cars and is primarily transported in alloy cars (83% alloy, 7% aluminum and 10% insulated 111s) while methyl tert-butyl ether, with the highest release probability, is transported only in non-insulated 111A100W1 cars. All the chemicals between methyl tert-butyl ether and xylenes are transported primarily (more than 90% carloads) in non insulated, non pressure tank cars and hence appear on the higher end of the spectrum. For xylenes, 80% of the carloads are in non insulated, non pressure cars but 20% are in insulated, non pressure cars, and hence xylenes have a slightly lower release probability. Sulfuric acid is also transported in non insulated tank cars but without bottom outlets and hence has a slightly better accident performance. Use of pressure cars for acetaldehyde (30% carloads), ethyl acrylate (45% carloads), acrylonitrile (48% carloads), butyl acrylates (51% carloads) and methyl methacrylate monomer (56% carloads) reduces the probability of release for these chemicals, even though all these chemicals do not require insulation by specification (UTC 1996). Potassium hydroxide, phenol, sodium hydroxide, benzene and styrene have a low release probability because for all these chemicals more than 95% of the shipments are in insulated non pressure cars. Like acrylic acid, alloy and aluminum cars are also heavily used for acetic anhydride (40% alloy cars, 30% aluminum cars and 28%, insulated 111A100W1), acetic acid (67% alloy cars, 33% aluminum cars), nitric acid (73% alloy, 24% aluminum, 3% 112J200W) and hydrogen peroxide (80% alloy and 20% aluminum). Due to low release probability of the alloy cars these chemicals appear towards the lower end of the spectrum, their release frequency decreasing with the increase of alloy cars in the mix.

3.5 Conclusions

In this chapter, a methodology was developed to determine the frequency of release of tank cars for each chemical. The variables in the equation are: number of cars derailed in mainline derailments and collisions, total train-miles traveled by mainline freight trains, the average length of freight trains and the conditional probability of release of a derailed tank car. Various sources are used to obtain or estimate these data. The conditional probability of release is specific for a chemical and is dependent on the frequency distribution of the specifications of tank cars used for transporting that chemical. Conditional release probability values are developed for the whole tank car fleet used to transport a chemical as well as each tank car specification in that fleet. The probability analysis addresses one part of risk analysis; the other equally important area is consequence analysis that will be considered in Chapter 4.

CHAPTER 4

CONSEQUENCE ANALYSIS

The risk from an event can be assessed by knowing the probability of its occurrence and the consequences that can occur as a result. Probability analysis was discussed in Chapter 3. In this chapter I discuss the second term in the equation, consequence analysis.

The first objective of my research was to evaluate the risk to the environment due to transportation of a group of chemicals in railroad tank cars. Like probability analysis it is important to first define the scope of the consequence analysis. The following steps were undertaken:

- Identify the source of risk: Release of one of the 125 commodities of interest transported by rail
- Identify the receptors of concern: Soil and groundwater
- Identification and selection of outcomes of interest: Contamination of soil and groundwater with the spilled chemical.
- Quantify the consequence: Volume of soil and groundwater contaminated due to spill of chemical.
- Determine clean up cost: Identify appropriate treatment or waste disposal options and evaluate the cost of cleaning up soil and groundwater.

4.1 Chemicals of Interest

The top 125 hazardous materials measured by total number of originations in the U.S. and Canada in 1999 (BOE 2000) were selected by the sponsors of this research, the Association of American Railroads (AAR), to be considered for risk analysis. These commodities (Table 4.1) were chosen because they represent a substantial portion (approximately 88%) of all hazardous material tank car shipments in the U.S. and Canada (BOE 2000). Of these 125 materials the products authorized by regulation for shipment in non-pressure tank cars were selected for further analysis. This was because pressure tank cars have considerably lower probability of release in accidents than non-pressure cars (Table 3.10, Figure 3.1). The purpose of the study was to understand the risk of those products currently authorized for shipment in non-pressure tank cars, and evaluate the possible benefit of shipping them in more robust cars.

Rank	Hazmat code	Commodity Name	Total Number of Originations (U.S. + Canada)
1	4950130	FAK – Hazardous Materials	248,776
2	4950150	FAK – Hazardous Materials	171,932
3	4935240	Sodium Hydroxide Solution	90,818
4	4905752	Petroleum Gases Liquefied	89,418
5	4930040	Sulfuric Acid	69,860
6	4961605	Elevated Temperatures Liquid N.O.S.	66,524
7	4904210	Ammonia Anhydrous	60,463
8	4920523	Chlorine	50,493
9	4945770	Sulfur Molten	35,762
10	4917403	Sulfur Molten	31,421
11	4905792	Vinyl Chloride, Inhibited	31,298
12	4905421	Propane	30,659
13	4912210	Fuel Oil	27,689
14	4909152	Denatured Alcohol	25,080
15	4909230	Methanol	24,844

Rank	Hazmat code	Commodity Name	Total Number of Originations (U.S. + Canada)
16	4908175	Gasoline	23,595
17	4930247	Phosphoric Acid	23,026
18	4930228	Hydrochloric Acid	19,793
19	4907265	Styrene Monomer, Inhibited	19,751
20	4904509	Carbon Dioxide, Refrigerated Liquid	19,554
21	4918311	Ammonium Nitrate	14,438
22	4908177	Gasoline	13,763
23	4918723	Sodium Chlorate	13,675
24	4914166	Diesel Fuel	13,417
25	4905423	Butane	12,172
26	4910165	Petroleum Crude Oil	11,708
27	4921598	Phenol, Molten	11,262
28	4912217	Fuel Oil	9,906
29	4905704	Butadienes, Inhibited	9,594
30	4914164	Fuel Oil	9,448
31	4920353	Ethylene Oxide	8,802
32	4908224	Methyl Tert Butyl Ether	8,455
33	4909215	Fuel, Aviation, Turbine Engine	8,296
34	4905430	Isobutane	8,208
35	4966326	Environmentally Hazardous Substances, Solid, N.O.S.	8,087
36	4966325	Environmentally Hazardous Substances, Solid, N.O.S.	8,060
37	4960196	Environmentally Hazardous Substances, Liquid, N.O.S.	8,020
38	4905784	Propylene	7,738
39	4906620	Propylene Oxide	7,151
40	4907270	Vinyl Acetate, Inhibited	6,939
41	4966110	Environmentally Hazardous Substances, Solid, N.O.S.	6,543
42	4960133	Environmentally Hazardous Substances, Solid, N.O.S.	6,152
43	4915165	Petroleum Crude Oil	6,130
44	4909351	Xylenes	6,042
45	4962137	Other Regulated Substances, Liquid	5,634
46	4908132	Cyclohexane	5,431
47	4918335	Hydrogen Peroxide, Stabilized	5,431
48	4935640	Hexamethylenediamine, Solid	5,386
49	4931405	Acrylic Acid, Inhibited	5,292
50	4930042	Sulfuric Acid, Spent	5,270
51	4907250	Methyl Methacrylate Monomer, Inhibited	5,197
52	4963102	Environmentally Hazardous Substances, Solid, N.O.S.	5,159
53	4935230	Potassium Hydroxide, Solution	5,144
54	4921575	Toluene Diisocyanate	5,071
55	4930248	Phosphoric Acid	4,994
56	4931303	Acetic Acid, Glacial	4,504
57	4932059	Formaldehyde, Solutions	4,319
58	4912215	Butyl Acrylates, Inhibited	4,266
59	4960131	Environmentally Hazardous Substances, Liquid, N.O.S.	4,266

Rank	Hazmat code	Commodity Name	Total Number of Originations (U.S. + Canada)
60	4914256	Petroleum Distillates, N.O.S.	4,195
61	4908105	Acetone	4,150
62	4912247	Compounds, Cleaning Liquid	4,081
63	4909305	Toluene	4,060
64	4966329	Environmentally Hazardous Substances, Solid, N.O.S.	4,058
65	4918803	Ammonium Nitrate Fertilizers	4,003
66	4909159	Ethanol	3,919
67	4945706	White Asbestos	3,898
68	4961614	Elevated Temperatures Liquid, N.O.S.	3,869
69	4905424	Liquefied Petroleum Gas	3,593
70	4906420	Acrylonitrile, Inhibited	3,516
71	4905437	Liquefied Petroleum Gas	3,504
72	4910256	Petroleum Distillates, N.O.S.	3,488
73	4961384	Environmentally Hazardous Substances, Liquid	3,483
74	4875648	Hazardous Waste, Solid, N.O.S.	3,481
75	4908110	Benzene	3,373
76	4912216	Fuel Oil	3,369
77	4909166	Ethylene Dichloride	3,295
78	4930024	Hydrogen Fluoride, Anhydrous	3,257
79	4905439	Liquefied Petroleum Gas	3,040
80	4920508	Sulfur Dioxide	3,038
81	4961602	Elevated Temperatures Liquid, N.O.S.	3,025
82	4912511	Elevated Temperatures Liquid, Flammable, N.O.S.	2,988
83	4962131	Elevated Temperatures Liquid, N.O.S.	2,969
84	4914170	Diesel Fuel	2,927
85	4810560	Waste Flammable Liquids	2,878
86	4941104	Other Regulated Substances, Liquid, N.O.S.	2,831
87	4905759	Isobutane	2,796
88	4909205	Isopropanol	2,764
89	4918765	Sodium Chlorate, Aqueous Solution	2,658
90	4966109	Other Regulated Substances, N.O.S.	2,590
91	4916141	Phosphorus, White, Dry	2,570
92	4932329	Ferrous Chloride, Solution	2,546
93	4961619	Elevated Temperatures Liquid, N.O.S.	2,500
94	4909381	Methanol	2,416
95	4909382	Petroleum Distillates, N.O.S.	2,370
96	4961606	Elevated Temperatures Liquid, N.O.S.	2,361
97	4905782	Propylene	2,359
98	4910185	Flammable Liquids N.O.S.	2,311
99	4963101	Environmentally Hazardous Substances, Solid, N.O.S.	2,278
100	4909130	Butanols	2,206
101	4930223	Nitric Acid	2,163
102	4941144	Polymer Beads, Expandable	2,124
103	4913250	Combustible Liquid, N.O.S.	2,108

Rank	Hazmat code	Commodity Name	Total Number of Originations (U.S. + Canada)
104	4931304	Acetic Anhydride	2,074
105	4914848	Fuel Oil	2,025
106	49405427	Liquefied Petroleum Gas	2,012
107	4914168	Fuel Oil	1,978
108	4905715	Butylene	1,970
109	4932342	Ferric Chloride, Solution	1,967
110	4950110	FAK – Hazardous Materials	1,946
111	4907210	Acetaldehyde	1,879
112	4941102	Other Regulated Substances, N.O.S.	1,879
113	4936556	Batteries, Wet, Filled with Acid	1,859
114	4936330	Maleic Anhydride	1,838
115	4907428	Hydrocarbons, Liquid, N.O.S.	1,779
116	4930030	Sulfuric Acid, Fuming	1,770
117	4930030	Sulfuric Acid, Fuming	1,770
118	4918774	Ammonium Nitrate, Liquid	1,763
119	4905761	Methyl Chloride	1,757
120	4910102	Alcoholic Beverages	1,729
121	4960156	Elevated Temperatures Liquid, N.O.S.	1,702
122	4915185	Combustible Liquid, N.O.S.	1,647
123	4909160	Ethyl Acetate	1,573
124	4907215	Ethyl Acrylate, Inhibited	1,557
125	4912271	Kerosene	1,553
126	4962136	Other Regulated Substances, Liquid	1,531

Table 4.1 Top 125 Hazardous Commodities as Measured by Total Number of Originations in the U.S. and Canada, 1999 *(BOE 2000)*

Fifteen commodities were removed from consideration, most of which were solids and were not transported in tank cars. Waste flammable liquids were removed because they were not listed in the 2001 Code of Federal Regulations (CFR), Title 49 (49CFR172.101 2001) (Table 4.2).

Hazmat code	Commodity name
4950130	FAK
4950150	FAK
4950110	FAK
4810560	Waste Flammable Liquids*
4936556	Batteries, Wet Filled With Acid
4918803	Ammonium Nitrate, Fertilizers
4904509	Carbon Dioxide, Refrigerated Liquid
4966326	Environmentally Hazardous Substance, Solid, N.O.S.
4966325	Environmentally Hazardous Substance, Solid, N.O.S.
4966110	Environmentally Hazardous Substance, Solid, N.O.S.
4960133	Environmentally Hazardous Substance, Solid, N.O.S.
4963102	Environmentally Hazardous Substance, Solid, N.O.S.
4966329	Environmentally Hazardous Substance, Solid, N.O.S.
4963101	Environmentally Hazardous Substance, Solid, N.O.S.
4941144	Polymer Beads, Expandable

* Commodities for which a packaging regulation could not be found in 49CFR172.101.

Table 4.2 Commodities Not Transported in Tank Cars and Excluded from Consideration for Risk Analysis

From the remaining 110 commodities, similar products but with different hazmat codes were grouped together. Packaging requirements were determined for these commodities from the 2001 CFR. Fifty nine commodities were not required by the 2001 CFR title 49 to be transported in the pressure tank cars (Table 4.3).

Acetaldehyde
Acetic Acid, Glacial
Acetic Anhydride
Acetone
Acrylonitrile, Inhibited
Acrylic Acid, Inhibited
Alcoholic Beverages
Ammonium Nitrate, Liquid
Benzene
Butanols
Butyl Acrylates, Inhibited
Combustible Liquid, N.O.S.
Compounds, Cleaning Liquid
Cyclohexane
Denatured Alcohol
Diesel Fuel
Elevated Temperatures Liquid, Flammable, N.O.S.
Elevated Temperatures Liquid, N.O.S.
Environmentally Hazardous Substances, Liquid, N.O.S.
Ethanol
Ethyl Acetate
Ethyl Acrylate, Inhibited
Ferric Chloride, Solution
Ferrous Chloride, Solution
Flammable Liquids N.O.S.
Formaldehyde, Solutions
Fuel Oil
Fuel, Aviation, Turbine Engine
Gasoline
Hexamethylenediamine, Solid
Hydrocarbons, Liquid, N.O.S.
Hydrochloric Acid
Hydrogen Peroxide, Stabilized
Isopropanol
Kerosene
Maleic Anhydride
Methanol
Methyl Methacrylate Monomer, Inhibited
Methyl Tert Butyl Ether
Nitric Acid
Other Regulated Substances, Liquid
Other Regulated Substances, N.O.S.
Petroleum Crude Oil
Petroleum Distillates, N.O.S.
Phenol, Molten
Phosphoric Acid
Phosphorus, White, Dry
Potassium Hydroxide, Solution
Propylene Oxide
Sodium Chlorate, Aqueous Solution
Sodium Hydroxide Solution
Styrene Monomer, Inhibited
Sulfur Molten
Sulfuric Acid
Sulfuric Acid, Spent
Toluene
Toluene Diisocyanate
Vinyl Acetate, Inhibited
Xylenes

Table 4.3 Commodities Authorized for Transport in Non Pressure Tank Cars (Packaging requirements determined from Sections 240, 241, 242 or 243 in Chapter 173, Part F of CFR 49 for hazardous materials transportation via rail)

4.2 Quantitative Risk Assessment Model

The next step was to determine an appropriate means of conducting a quantitative hazard analysis. A model was needed that could simulate the effects of a chemical spill from a railroad tank car and determine the extent of contamination of soil and groundwater as a result of the spill, for any given combination of the following:

- Chemical transported
- Soil types on the transportation routes
- Groundwater depth on the transportation routes

Apart from this the model should also be able to quantify hazard in terms of the following parameters:

- Volume of soil and groundwater contaminated
- Clean up cost for the contaminated site

4.2.1 Search for Models

A search was conducted of the literature and online resources for hazard assessment models that could simulate a relatively rapid release of a large quantity of material and the consequent environmental damage. Some of the models considered were:

- CalTOX (ver 2.3): CalTOX is a spreadsheet based risk assessment model developed by the Office of Scientific Affairs in the California Department of Toxic Substances Control. The model components include a multimedia transport and transformation model and a multi-pathway exposure scenario model. The multi-media transport model calculates the concentration of a released chemical in various environmental compartments including air, soil, water, plants and sediments. The exposure assessment model focuses on exposure of human population to the released chemical from different pathways. The model was not deemed suitable for the purpose of this study, because the output of the environmental fate model is the concentration of the chemical in various media (McKone 1993). The output required for the purpose of my study is the area or the volume of the media contaminated and the required output could not be easily generated using CalTOX.

- RACER (2001): The Remedial Action Cost Engineering and Requirements system is a cost estimating software. The software has a database that includes material, labor and equipment cost. The cost database has been compiled using information from remediation projects done in the past. This software was not chosen because of the level of detail required to calculate the costs and the consequent inability to apply it generally in the wide variety of possible scenarios in which a transportation spill may occur. The program requires site-specific characteristics and tailors solutions to specific project needs. Thus it is best suited for specific remediation cost studies. The ESC study required more general input regarding the site details because the objective is transportation risk analysis with probabilistic rather than site-specific environmental characteristics.
- Other Models: I also looked at other models such as the Chemical Accident Statistical Risk Assessment Model (CASRAM) from the Center for Energy, Environment and Economic Systems Analysis (CEEESA) and GRAIL, from Lawrence Livermore National Laboratory. These models were not chosen because they were designed to model the effect of a hazardous materials release on human populations, not the environmental impact.

4.2.2 Selected Model

InterIndustry Rail Safety Task Force (IIRSTF) Quantitative Risk Assessment Model: This is a risk analysis model specifically designed for hazardous material releases in rail transportation. The model was well suited to the needs of my research because it included an environmental module. This module was designed to estimate the environmental effects of chemical releases on soil and groundwater. The IIRSTF model includes a screening model and a detailed model. Both these models were evaluated to determine which one matched the study requirements best.

IIRSTF Screening Model: This model, though similar to the detailed model (described below) in some respects, provides a coarse-grained comparison of risks for various chemicals. The advantage of using this model was that it had an extensive chemical database with property data on most of the commodities in Table 4.3. But there are certain limitations to this model that made it less suitable for my research needs. The principal one is that it assumes a single environment and it is not possible to specify soil types and groundwater depths. It also employs a coarse approach for analyzing ground infiltration of the released chemical; it does not allow for pool formation or evaporation of the released product, and the volume of the chemical that infiltrates is assumed equal to the volume of the chemical spilled (Arthur D. Little Inc. 1996a).

IIRSTF Detailed Model: The detailed model was designed with objectives similar to the requirements of the ESC project. This model has two principal components:

- The frequency submodel: The first component, also called the probability analysis component, calculates the probability of a release as a function of train speed, track class, tank car type and track type. The probability analysis for this study was conducted without the use of the IIRSTF detailed model (see Chapter 3). The principal reason for this was that more up-to-date train accident data were available from Anderson & Barkan (2004) and on tank car release probability statistics from Treichel et al (2006). I used a nationwide average for car derailment rate and developed a separate spreadsheet probability model.

- The consequence submodel: Also called the consequence analysis component, it estimates the consequence of a spill of a specified quantity of chemical on human populations as well as soil and groundwater. The factors that led to selecting the IIRSTF model were as follows:
    - It allows the user to specify the depth to groundwater and select the soil type from among coarse, silt and clay.
    - The model allows the user to add data for any chemicals as desired. It also has eight chemicals in its chemical database, four of which were among the chemicals of interest for this research.
    - It allows changing environmental scenarios for any chemical-soil combination (Anand 2004). Therefore, one can change groundwater depth or groundwater pumping rate or the time until initiation of

    remediation efforts and other parameters for any chemical-soil combination.

- It generates the output most relevant to the current project. The environmental risk resulting from the hazardous material spill is estimated in terms of the following risk measures (Arthur D. Little Inc. 1996b):
    - A risk profile for frequency versus remediation cost
    - The expected remediation cost
    - The expected volume of soil contaminated
    - The expected volume of groundwater contaminated

Unlike the screening model, the detailed model has a complex infiltration module that allows for pool formation and evaporation of the released product. In general it handles a spill in 5 phases:

- Initial Outflow: Indicates the release of chemical from the tank car.
- Pool Formation: Calculates the spread of the released chemical on the land surface
- Pool Diminution: Analyzes the decrease in pool volume and spread as a result of evaporation into the atmosphere, infiltration into the soil and cessation of flow from the tank car.
- Transport in Unsaturated Zone: Analyzes the chemical's movement as a bulk flow into the unsaturated soil matrix.
- Groundwater Contamination: Analyzes the final stage of chemical infiltration into the ground, i.e., mixing with groundwater.

After infiltration into the soil, the chemical continues to move downward in the unsaturated soil matrix until either it has insufficient volume to occupy all the residual capacity of the soil or it reaches the groundwater. The model assumes that the chemical spreads laterally as it penetrates deeper into the soil and therefore calculates the volume of soil contaminated by assuming it to be a truncated cone. Although in actual spills the shape and distribution will vary, the approach used by the model enabled relative comparisons. The length and route of the chemical's movement after infiltration are a function of the properties of the soil, the chemical and their interaction with each other. For example, sands are more permeable than clay and therefore, allow faster infiltration and less spreading of the chemical through the unsaturated zone. Similarly, soils with higher organic content have more sorption capacity. The chemical can affect the soil permeability, as well as the extent of sorption. Whether the chemical reaches groundwater also depends in part on the depth of the water table and how soon the groundwater remediation efforts begin. The solubility and viscosity of the chemical can affect its extent of dispersion in the water.

The model uses a 2-D numerical model to calculate the extent of groundwater contamination and the time of treatment once the groundwater remediation efforts have started. To select a pump and treat groundwater remediation design, the plume capture problem needs to be solved. To solve this problem, the model uses an approach proposed by Nelson (1978) based on the distribution of arrival time of the contaminant to the capture wells installed for decontaminating groundwater. The number of wells required is calculated using the plume width and the capture zone of a single well.

Although the soil contamination model is well described in the model documentation, there are uncertainties about the groundwater model used by the IIRSTF detailed model. Because of the gaps in documentation such as missing equations and undefined variables, groundwater clean up algorithm used by the model is not fully understood. Consequently, the output for the groundwater clean up cost could not be validated. This will be further discussed later in this chapter when the output for the total clean up cost for the chemicals is presented.

Figure 4.1 shows the general structure of the risk assessment model.

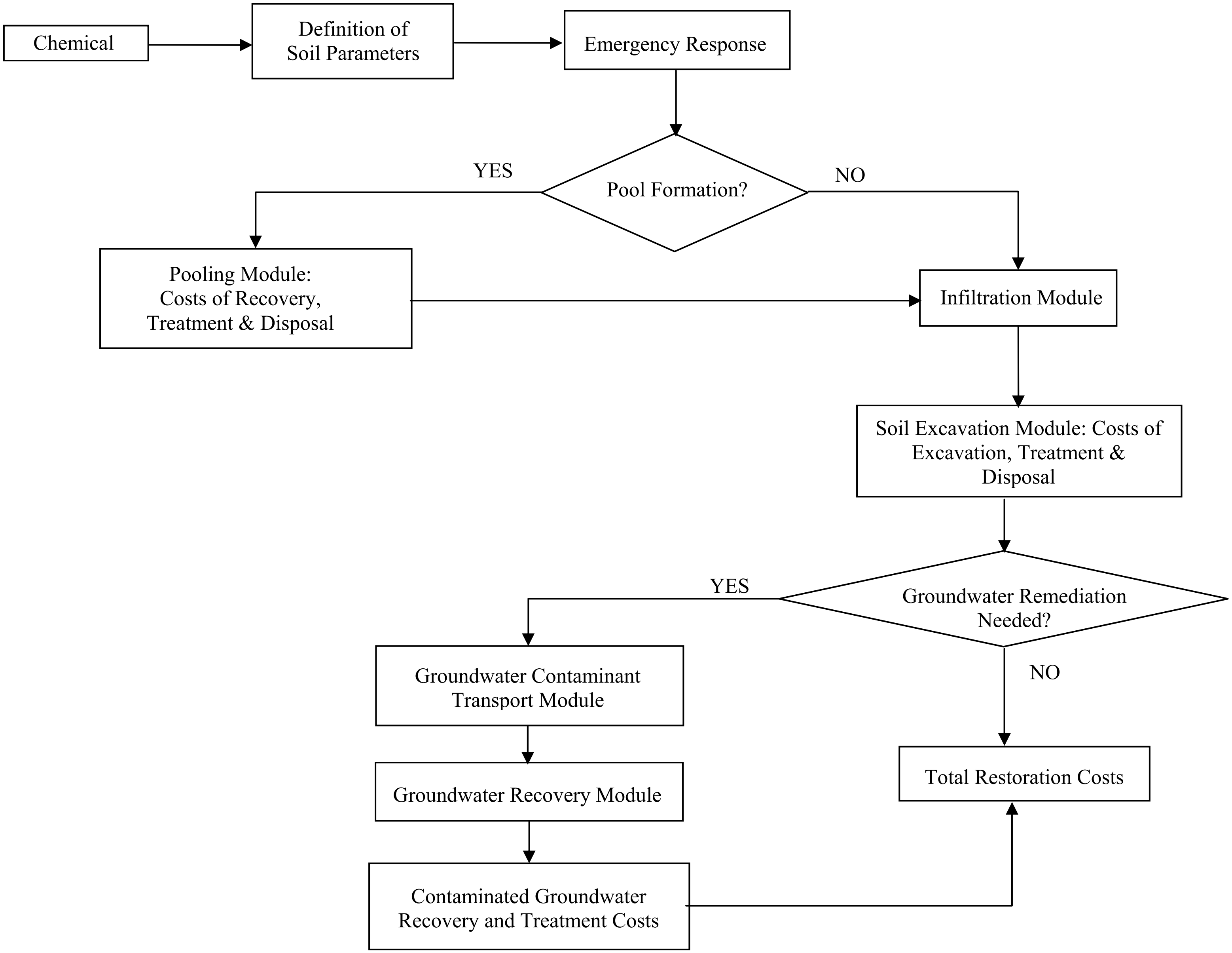


Figure 4.1 Structure of Risk Assessment Model (Environmental Risk Sciences Inc. 1994)

The groundwater treatment module has the following remediation techniques in its database:

- Biological treatment
- In situ biodegradation
- Carbon absorption
- Precipitation/neutralization
- Reverse osmosis
- Deepwell injection
- Oxidation

The soil remediation module has the following treatment technologies in the database:

- Incineration
- Physical chemical neutralization
- Physical chemical precipitation
- Physical chemical reduction

The following section describes the data requirements of the consequence model.

4.2.2.1 Data Requirements

4.2.2.1.1 Chemical Data

The model has a chemical database that contains data on physicochemical properties, regulatory cleanup requirements, and the emergency response protection level required in the event of a spill, soil treatment technology and groundwater treatment technology for each chemical. The chemical properties are divided into two categories, constant property data (MODCON) such as molecular weight of the chemical and temperature dependent data (MODTDP) such as its liquid density. The complete list of physicochemical properties required by the model is given in Table 4.4. Other properties required for each chemical are listed in Table 4.5.

The model has data on eight chemicals of which four – (acetaldehyde, methanol, sodium hydroxide solution and styrene) were among the chemicals of interest (Table 4.3). For other chemicals most of the chemical data were taken from the online chemical database of the Design Institute for Physical Properties (DIPPR 2001) and from the DIPPR Data Compilation of Pure Compound Properties, 1994, Version 9.0, provided by National Institute of Standards and Technology (NIST) Standard Reference Data Program. The DIPPR database contains information on most of the properties stated in Table 4.4 for the chemicals. The information on properties stated in Table 4.5 is found in the manual of the IIRSTF model (Environmental Risk Sciences Inc. 1994). Additional data were obtained from books on hazardous chemicals (Sax 1975, Verschueren 1983) and material safety data sheets available online (Cambridgesoft 2002). The constant property data for materials under study are presented in Appendix C while the temperature dependent property data are presented in Appendix D. A number of chemicals are transported as solutions rather than in their pure form. This was verified with railroad hazardous materials experts (Student 2003). Information on the state in which the chemicals under study are transported can be found in Appendix E. Due to lack of sufficient data on aqueous solutions, data for the corresponding pure chemical were used when required.

MODCON	MODTDP
Molecular Weight	Solid Density
Critical Temperature	Liquid Density
Critical Pressure	Vapor Pressure
Critical Volume	Heat of Vaporization
Critical Compressibility Factor	Solid Heat Capacity
Melting Point	Ideal Gas Heat Capacity
Triple Point Temperature	Liquid Heat Capacity
Triple Point Pressure	Second Virial Coefficient
Normal Boiling point	Liquid Viscosity
Reference Liquid Molar Volume and Temperature	Vapor Viscosity
Ideal Gas Heat of Formation	Liquid Thermal Conductivity
Ideal Gas Free Energy of Formation	Vapor Thermal Conductivity
Ideal Gas Absolute Entropy	Surface Tension
Enthalpy of Fusion	Reduced Ideal Heat Capacity
Standard Net Heat of Combustion	Solid Thermal Conductivity
Acentric Factor	
Radius of Gyration	
Solubility Parameter	
Dipole Moment	
Van der Waal's Area and Volume Parameters	
Refractive Index	
Flammability Limits	
Flash Point/ Auto ignition Temperature	
Equations of state-m and state-n factors	

Table 4.4 Physicochemical Properties Required by the Model for Each Chemical

Limiting Toxic Criteria
NFPA Rating
Physical State Code
Regulatory level
Solubility in Water at STDC
Carbon Absorption Coefficient
Biodegradation Rate
Emergency Response Protective Level Code
Soil Treatment Train Code
Groundwater Treatment Train Code
Alternative Groundwater Treatment Train Code

Table 4.5 Other Properties Required by the Model for Each Chemical

The properties listed under Table 4.5 are grouped under a category called “auxiliary data” under the constant property data for a chemical. Among these properties “Limiting Toxic Criteria” and “NFPA Rating” are related to the toxicity and flammability of the chemical and affects the human aspect of risk from the chemical but the rest of the properties (Table 4.5) have a direct bearing on the environmental risk. “Physical State Code” indicated the physical state in which the chemical is transported, “Soil Treatment Code”, “Groundwater Treatment Code” and “Alternative Groundwater Treatment Code” indicate the types of soil and groundwater treatment technologies that will be used for remediation of the spill. “Emergency Response Protective Level Code” is a code assigned on the basis of human health (NIOSH 1990) where level ‘A’ is the highest protection required and level ‘C’ is the lowest protection required.

The property “ Regulatory Level” indicates the values for regulatory clean up criteria specified by EPA for each chemical. The biodegradation rate varies widely; the values used in this research are only an approximation and, as stated before, have been taken from the IIRSTF manual. A sensitivity analysis was conducted to observe the effect of variation in “ Regulatory Level”, “Solubility in Water”, “Carbon Absorption Coefficient” and “Biodegradation Rate” on the clean up cost. All simulations were conducted for a full carload spill of benzene on sandy soils with a 20 ft. deep groundwater table. For all these simulations, the volume of soil contaminated (and hence the soil clean up cost) and emergency response cost remains constant but the groundwater clean up cost varies with the changes in the variables tested. This is because each of these four variables affects only the groundwater clean up efforts. From Figures 4.2 through 4.5, it is evident that the groundwater clean up cost increases linearly with increase in carbon absorption coefficient but decreases almost in a logarithmic fashion with increasing water solubility, biodegradation rate and regulatory clean up levels.

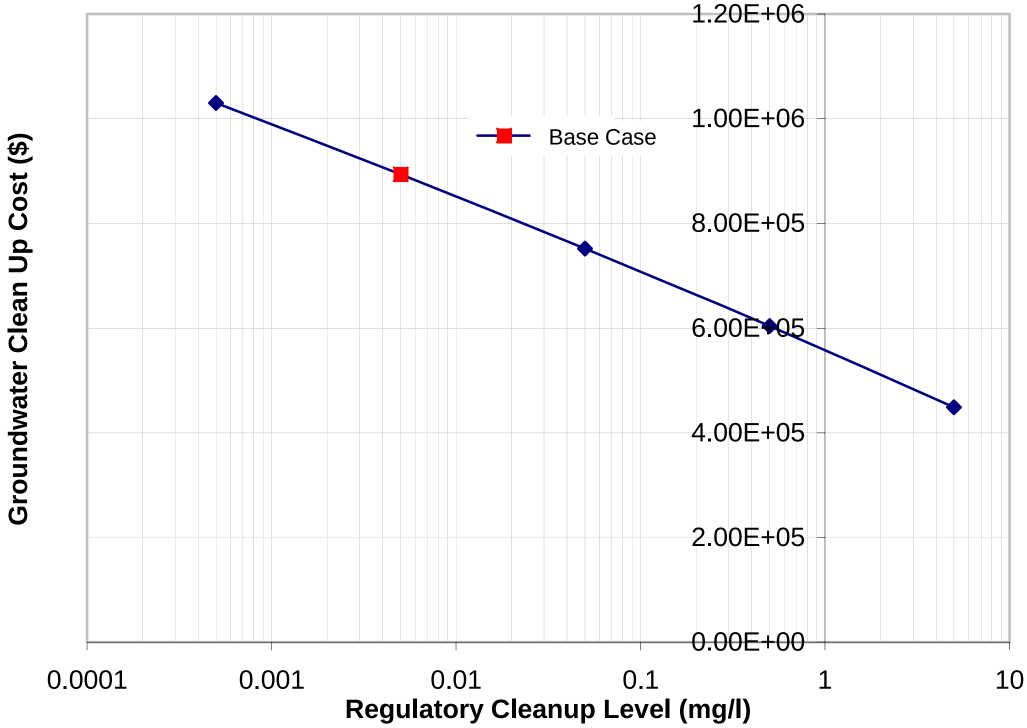


Figure 4.2 Sensitivity of Groundwater Cleanup Cost to Regulatory Clean Up Level

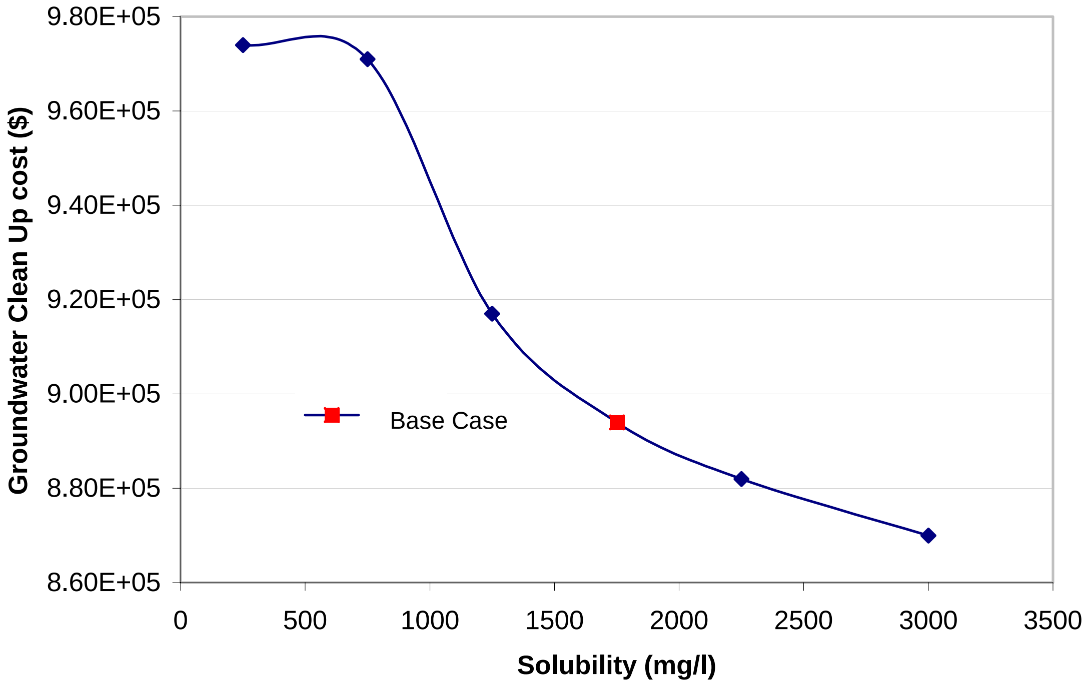


Figure 4.3 Sensitivity of Groundwater Cleanup Cost to Solubility

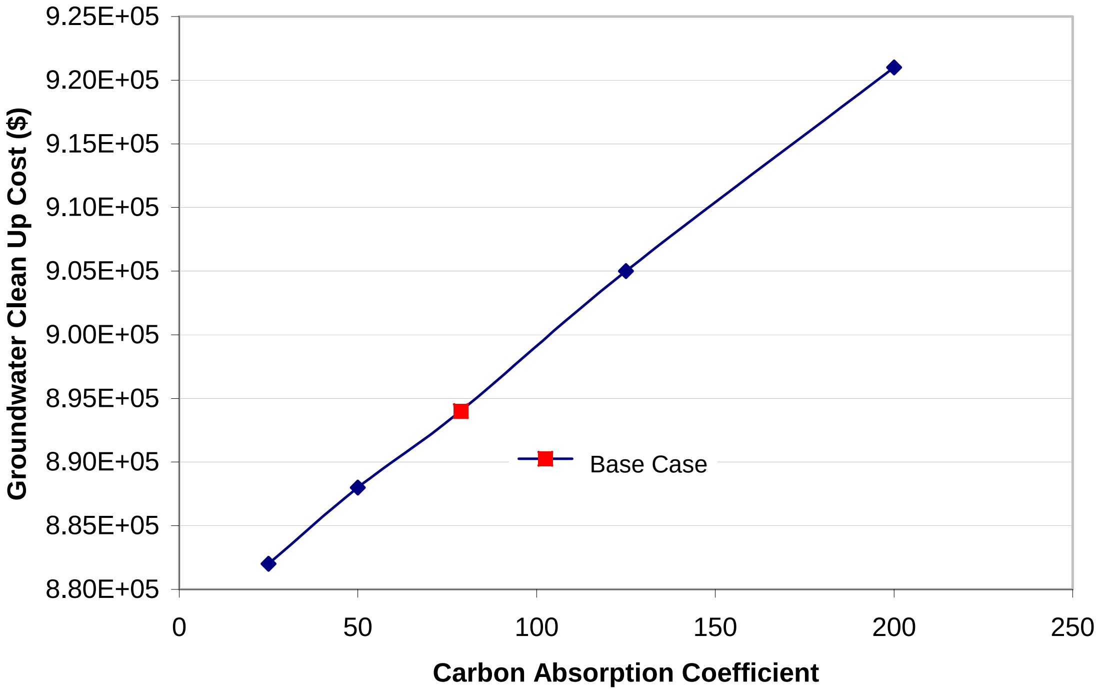


Figure 4.4 Sensitivity of Groundwater Clean Up Cost to Carbon Absorption Coefficient

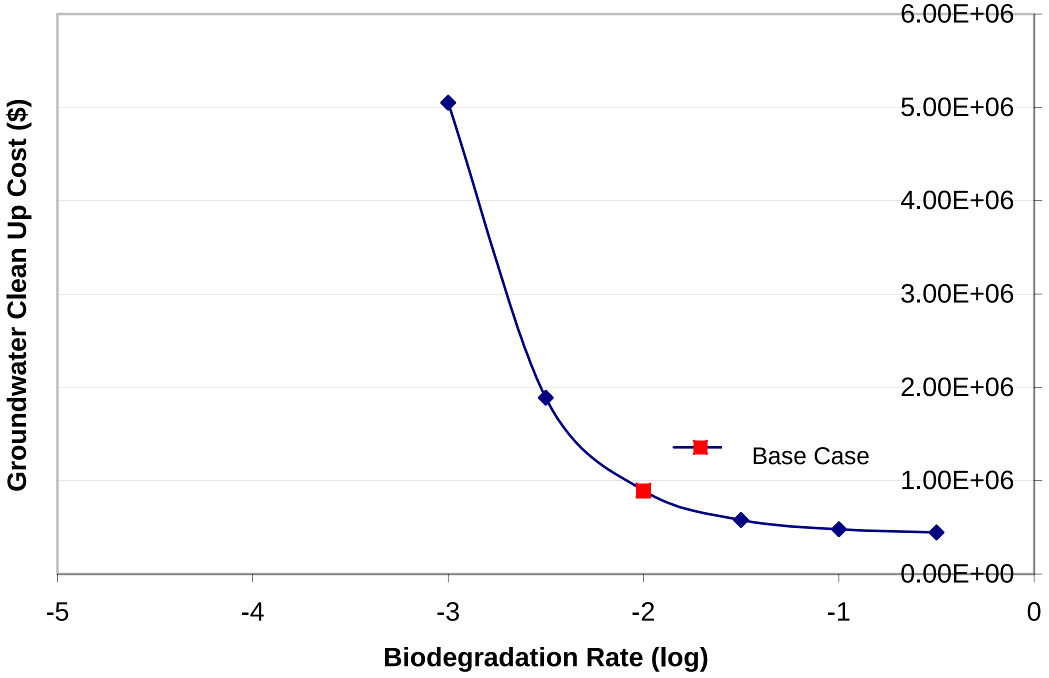


Figure 4.5 Sensitivity of Groundwater Cleanup Cost to Biodegradation Rate

The decrease in groundwater clean up cost with increase in regulatory clean up level (which implies less stringent clean up levels) is as expected. The decrease in clean up cost with increase in solubility is also readily explained by the fact that the IIRSTF model assumes that the dissolution rate of the chemical is proportional to the solubility of the chemical. So, the higher the solubility, the more quickly the chemical is removed and hence the lower the cost due to a shorter pumping time. The increasing trend of the groundwater clean up cost with the increase in carbon absorption coefficient is not expected and cannot be readily explained. The underlying equations in the IIRSTF model suggest that an increase in carbon absorption coefficient increases the retardation of the contaminant movement and hence leads to a smaller groundwater plume which should lead to a reduction in cost. Thus, it is difficult to justify the trend observed here (Figure

4.4). The decrease in groundwater clean up cost with the increase in biodegradation rate is because the higher the biodegradation rate, the quicker the contaminant gets degraded and hence the mass remaining in the groundwater is smaller.

The DIPPR database does not have data for mixtures and some pure compounds. Data could not be found for 2 out of 40 chemicals nor for any of the 19 mixtures. Part of the reason is that some of these are non-specific mixtures, therefore, there is not a single set of properties applicable to such commodities. Table 4.6 shows the list of these 21 commodities for which data were not available from DIPPR and could not be found elsewhere.

Alcoholic Beverages
Combustible Liquid, N.O.S. *
Compounds, Cleaning Liquid *
Denatured Alcohol
Diesel Fuel
Elevated Temperatures Liquid, Flammable, N.O.S. *
Elevated Temperatures Liquid, N.O.S. *
Environmentally Hazardous Substances, Liquid, N.O.S. *
Ferric Chloride, Solution
Ferrous Chloride, Solution
Flammable Liquids N.O.S. *
Fuel Oil
Fuel, Aviation, Turbine Engine
Gasoline
Hydrocarbons, Liquid, N.O.S. *
Kerosene
Other Regulated Substances, Liquid *
Other Regulated Substances, N.O.S. *
Petroleum Crude Oil
Petroleum Distillates, N.O.S. *
Sulfuric Acid, Spent

* Non-specific mixtures

Table 4.6 Commodities for which Property Data were Unavailable

For most of the properties, the user also needs to input a code called the quality code. The quality code is indicative of the source of the data and its reliability, or in other words, the data quality. For the temperature dependent properties, the model requires a 2-digit code (0-12) that indicates the accuracy of the data. For all other properties, the model uses a 5-digit code, wherein the 5 digits serve different purposes (Table 4.7). More information on these codes can be found in Appendix F.

Digit	**Range of Values**	**Implication of the Digit**
First digit	0-5	Type of data
Second digit	0-2	Nature of data source
Third digit	0-9	Accuracy of data
Fourth digit	0-3	Nature of evaluation of data
Fifth digit	0	Unused

Table 4.7 Explanation of the 5-digit Quality Code

The study uses data from a variety of sources, some of which had little or no information on the quality of data, or for which the coding system was different from the one used in the risk model. Therefore, to integrate the data and maintain consistency, a quality code of 10110 was used wherever a 5-digit code was required, except for the equation of state-m and equation of state-n factors. The data for the state-m and equation of state-n factors could not be found for any of the chemicals, therefore the data and the quality code information for these two properties for the chemical of concern was assumed to be equal to the information for one of the eight chemicals in the database that it is most similar to. For the temperature dependent data, the quality codes were available in most cases.

The chemical database of the model is contained within SuperChems, which is a proprietary software program built into the QRA model. It is designed to handle emergency relief systems and the design of effluent handling systems. The model accesses SuperChems while running, and based on the inputs of the user, SuperChems executes several modules within SuperChems to produce results. There are some properties that are not required by the SuperChems database (Arthur D. Little Inc. 1996c). These are indicated in Table 4.8. Hence these properties were included only if they were easily available. Also, there is a minimum set of properties for which the quality code is an essential input for the model to run (Table 4.9). If unavailable for any chemical, the quality code and/or the data for these properties was copied from one of the eight chemicals already in the database and is most comparable to the chemical in question.

MODCON	MODTDP
Triple Point Temperature	Solid Density
Triple Point Pressure	Solid Heat Capacity
Radius of Gyration	Second Virial Coefficient
Solubility Parameter	Solid Thermal Conductivity
Dipole Moment	
Van der Waal's Area and Volume Parameters	
Refractive Index	
Flash Point/ Auto ignition Temperature	

Table 4.8 Physicochemical Properties Not Required by the Model

MODCON	MODTDP
Critical Temperature	Liquid Density
Critical Pressure	Vapor Pressure
Critical Volume	Heat of Vaporization
Critical Compressibility Factor	Ideal Gas Heat Capacity
Melting Point	Liquid Heat Capacity
Normal Boiling point	Liquid Viscosity
Reference Liquid Molar Volume and Temperature	Vapor Viscosity
Acentric Factor	Liquid Thermal Conductivity
Equations of state-m and state-n factors	Vapor Thermal Conductivity
	Surface Tension
	Reduced Ideal Heat Capacity

Table 4.9 Properties for which Quality Codes are Required

4.2.2.1.2 Environmental Data

The environmental database defines the characteristics of the environment in which the spill takes place. It specifies the geological, hydrogeological and other properties at the spill location. The consequence of a spill is dependent not only on the chemical that is spilled but also the environmental characteristics of the spill site (Anand 2004). The user-specified environmental variables required by the model are as follows:

1. Soil Type: For each chemical, spill scenarios were run for each of the three soil types, i.e., coarse (sand), silt and fine (clay). The model gives an option to the user to select a soil type from among these three options. For the purpose of this study it was assumed that the soil is homogenous throughout the depth of the vadose zone at a spill site.
2. Time elapsed before remediation begins: This is the time interval between the spill and the onset of groundwater remediation. This term was kept constant at its default model value of four days throughout all the spill scenarios (Environmental Risk Sciences Inc. 1994). This value was verified as reasonable by experts who had considerable experience in railroad spill response clean up and environmental risk assessment (Richardson 2002, Kuhlmeier 2002, Clark 2005, Williams 2005). As expected, an increase in response time increased ground water contamination and hence groundwater remediation time.
3. Depth to Groundwater: For each chemical, for each soil type, spill scenarios were run for five different depths to groundwater: 10 ft., 20 ft., 50 ft., 100 ft. and 200 ft. I chose these depths after analyzing the groundwater data obtained from the USGS (Figure 4.6) (Anand 2004). The first four depth values are the averages of

the following groundwater depth ranges: 5 – 15 ft., 15 – 25 ft., 25 – 75 ft., 75 – 125 ft. For the last category, 200 ft. was arbitrarily chosen; it also served as an upper limit of groundwater depth values for the purpose of this analysis.

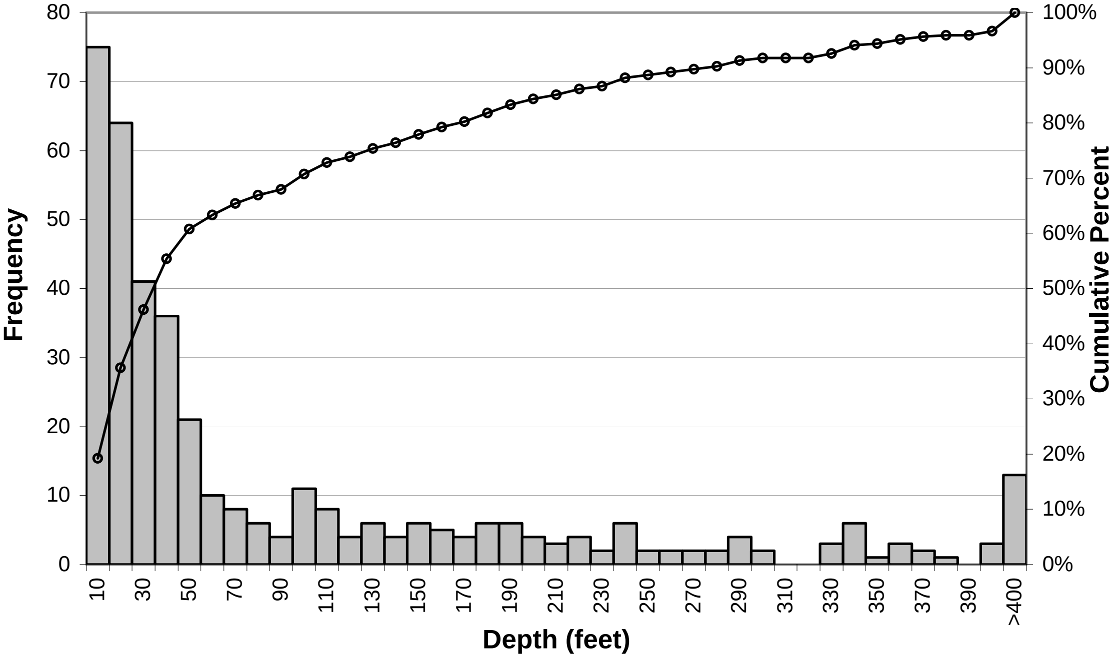


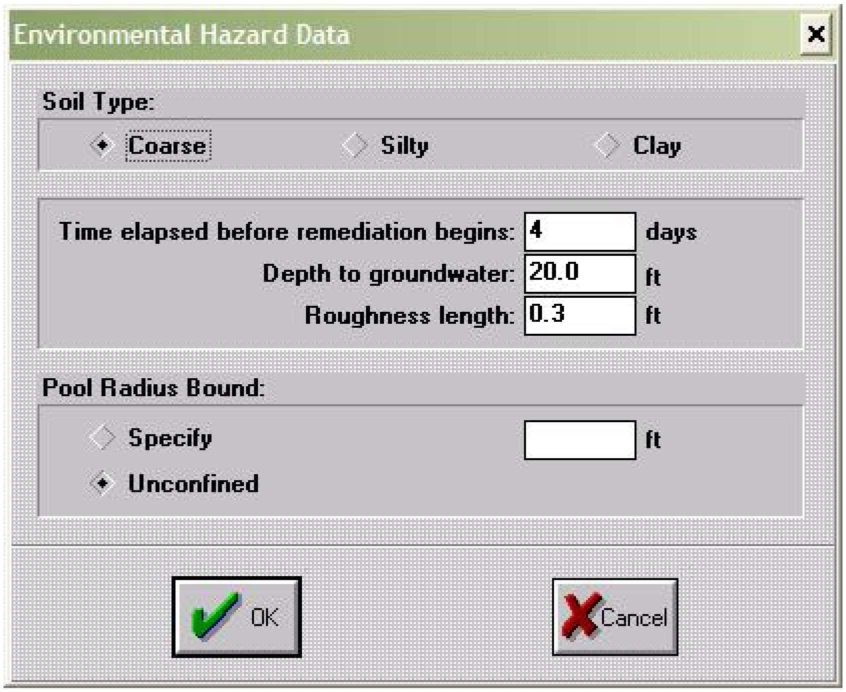
Figure 4.6 Frequency Distribution of Groundwater Depths in the 48 Contiguous States for April 2003 ***(Anand 2004)***

4. Roughness Length: This term is ostensibly a function of the topography of the spill site. The default value of 0.3 was kept constant throughout the model runs (Arthur D. Little 1996c). However, sensitivity analysis of this variable found no effect on the results, which may indicate a problem with this aspect of the model. A review of literature on surface roughness (Zeman 2005) revealed that surfaces with higher roughness generally have higher infiltration rate (Darboux 2005) and store more water than smoother surfaces (Hansen 1999). It was also found that

surface roughness depends on a variety of factors, some of them intrinsic, e.g., microrelief variations, surface variation, difference in elevation, etc. (Borselli 1999) and some extrinsic, e.g., tillage, rainfall, plant growth, freezing and thawing, etc. (Kamphorst 2000). Therefore, it is not possible to estimate soil roughness based only on the soil type. Also, based on the range of estimates (0.016 ft – 0.16 ft) of surface roughness available from literature (Choudhury 1979, Steichen 1984), 0.3 ft is a safe overestimate and might have the effect of overestimating the consequences of a spill except that as mentioned above, the variable in the software appeared not to have any effect.

5. Pool Radius Bound: This indicates the extent to which the spilled material can spread. This was set as "unconfined" which causes the model to calculate the radius of the spill itself. The user is also given an option to confine the pool spread to a value set by the user. This can be used in specific cases of spill scenarios where there is sufficient information about the topography of the spill site and hence the user is aware of any barriers that will constrain the spread of the pool.

The screenshot of the environmental hazard data (Figure 4.7) dialogue box from the model specifies the environmental parameters for a spill on a sandy soil where depth to groundwater is 20 ft.



Environmental Hazard Data

Soil Type:

● Coarse ○ Silty ○ Clay

Time elapsed before remediation begins: 4 days

Depth to groundwater: 20.0 ft

Roughness length: 0.3 ft

Pool Radius Bound:

○ Specify ft

● Unconfined

Figure 4.7 Environmental Parameters for a Spill on a Sandy Soil with 20 ft. Depth to Groundwater

Apart from the above parameters, the model also requires other environmental parameters, as follows:

1. Remediation Efficiency for lighter-than-water non-aqueous phase chemicals (LNAPLs) and more-dense-than-water non-aqueous phase chemicals (DNAPLs): The extent to which a chemical can be restored from soil by excavation, before it reaches the groundwater, is defined as the remediation efficiency. The model assumes that: 95% by weight of a LNAPL, 95% by weight of an aqueous phase chemical, and 85% by weight of a DNAPL can be removed by excavation. The default values for these parameters are used for all the spill scenarios.

2. Groundwater pumping rate: The rate at which contaminated groundwater is pumped out to remediate the spill site depends on the soil type. The values for the three different soil types were reached at by referring to the model documentation (Environmental Risk Sciences Inc. 1994), in addition to consultation with the experts in the field (Lowenbach 2003; Richardson 2002, Kuhlmeier 2002). The values used are 81.756 cubic meters per day for sand and 8.18 cubic meters per day for silt and clay.
3. Pore velocity: The rate at which the groundwater flows in the aquifer, which also controls the rate at which the contaminant moves away from the source where it entered the water table. It is soil specific, with the lowest value for clay and the highest for sand. The values used for pore velocity were 0.05 meters per day for clay, 0.10 meters per day for silt and 2 meters/day for sand (Freeze et al 1979).
4. Saturated Aquifer Thickness: The distance from the top of the water table to the top of the lower confining layer. The default value of 10 meters was used throughout the runs.
5. Aquifer Bulk Density: The bulk density of the dry mass of a sample of the aquifer material. The value assumed was 1.8 grams/cubic centimeter (Freeze et al 1979).
6. Aquifer absorption fraction: The total organic carbon concentration in the aquifer materials. The default value of 1% was used for all the runs.
7. Effective Porosity and Residual Porosity: Effective porosity represents the portion of the void spaces in the soil that are interconnected and therefore allow the contaminant to travel through soil whereas residual porosity represents the portion of void spaces that are not connected and hence can trap some of the contaminant

thus preventing it from reaching the aquifer. The values for effective porosity were assumed to be 32%, 33% and 42% for clay, silt and sand respectively. The residual porosity was assumed to be 2% for all three soil types.

8. Specific interfacial area: A shape factor that indicates the contact area between the contaminant and the aqueous phase. It is soil specific and the values were calculated using Equation 4.1.

$$Ai = (0.03Neff)/Dgrain \quad (4.1)$$

where,

Ai = Specific interfacial area (per meter)

Neff = Effective porosity of the soil

Dgrain = Grain diameter (meter)

The values for Dgrain are soil specific and are assumed to be 0.001 meters for sand, 0.0001 meters for silt and 0.00001 meters for clay.

9. Mass transfer rate coefficient and Mass transfer coefficient: These parameters are specific for each soil-chemical combination. These parameters are required to calculate the dissolution of the NAPLs in groundwater. These parameters are calculated using Equations 4.2 (Powers et al 1992) and 4.3 (Environmental Risk Sciences Inc. 1994).

$$K = 165\ [(Dmol^{0.5})/(Dgrain^{1.25})](u^{0.75})(Neff^{0.6}) \quad (4.2)$$

k = K/Ai (4.3)

where,

K = Mass transfer rate coefficient (1/day)

u = Pore velocity (meter/sec)

k = Mass transfer coefficient (m/day)

Dmol = $[(5.06E\text{-}07) * T] / (V^{0.6})$

where,

Dmol = Molecular diffusion coefficient (square meter/sec)

T = 288 K

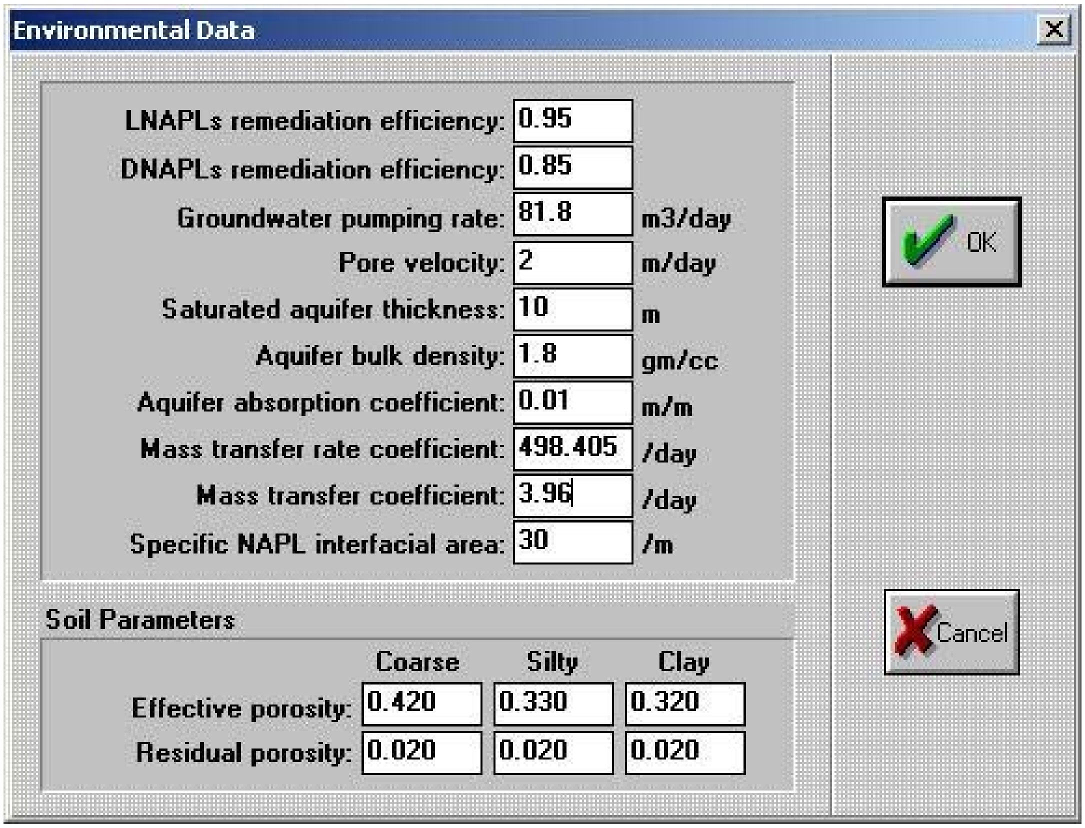
V = Molar volume for the chemical (cubic meter/mol)

The values of these coefficients for benzene are shown in Table 4.10.

	Fine	**Medium**	**Coarse**
Mass Transfer Rate Coefficient (K) (1/day)	8,417.40	810.90	498.41
Specific Interfacial Area (Ai) (per meter)	9,600	990	126
Mass Transfer Coefficient (k) (m/day)	0.88	0.82	3.96

Table 4.10 Mass Transfer Coefficient and Mass Transfer Rate Coefficient Values for Benzene

The screenshot of the environmental data (Figure 4.8) dialogue box from the model specifies other environmental parameters discussed above, for a benzene spill on a sandy soil (the mass transfer rate coefficient and the mass transfer coefficient values correspond to benzene spill on sand).



LNAPLs remediation efficiency: 0.95

DNAPLs remediation efficiency: 0.85

Groundwater pumping rate: 81.8 m3/day

Pore velocity: 2 m/day

Saturated aquifer thickness: 10 m

Aquifer bulk density: 1.8 gm/cc

Aquifer absorption coefficient: 0.01 m/m

Mass transfer rate coefficient: 498.405 /day

Mass transfer coefficient: 3.96 /day

Specific NAPL interfacial area: 30 /m

Soil Parameters

	Coarse	Silty	Clay
Effective porosity:	0.420	0.330	0.320
Residual porosity:	0.020	0.020	0.020

Figure 4.8 Other Environmental Parameters Required by the Model
(Benzene spill on a sandy soil)

4.2.2.1.3 Cost Database

The cost database contains information on the capital costs and operating and maintenance costs of the treatment technologies that are in the database or are specified by the user. For most of the chemicals in Table 4.3 the model documentation (Environmental Risk Sciences Inc. 1994) suggests a technology to treat contaminated soil and one or more technologies for groundwater treatment. I used the groundwater treatment technologies suggested by the model for most of the chemicals but for soil treatment, I updated the database to be consistent with the most common soil remediation methods currently in use (FRTR 2003, EPA 2003). The underlying algorithm of the model is such that the clean up cost and volume of soil contaminated are linearly related to each other. The soil clean up cost is obtained by multiplying the volume of the soil contaminated by the unit rate of the treatment technologies and the associated procedures. I used the algorithm but adopted a new approach for soil remediation different from what was followed in the model. The soil remediation part of the model assumed that all of the contaminated soil was excavated and treated using an ex-situ treatment technology, disposed and the spill site backfilled. Discussions with the railroad remediation experts (Clark 2002, Richardson 2002, Williams 2005) indicated that excavating all of the contaminated soil is not a practical approach. In most spills only the first 5-20 ft of soil is excavated. Therefore, I obtained the volume of contaminated soil using the model and then used a separate spreadsheet model to calculate the costs of soil restoration at the spill site. The spreadsheet model was based on the following principles:

- A maximum of 20 ft. of contaminated soil is excavated.
- The excavated soil is treated using an ex-situ treatment method or deposited at a Resource Conservation and Recovery Act (RCRA) permitted facility.
- The rest of the contaminated soil is treated using an in-situ soil treatment technology.
- The excavated site is backfilled with fresh dirt.

Therefore, the total cost involved in the soil remediation procedure is as follows (Equation 4.4):

$$C_{soil} = C_{excavate} + C_{ex\text{-}situ} + C_{dispose} + C_{backfill} + C_{in\text{-}situ} \qquad (4.4)$$

where,

C_{soil} = Total cost of contaminated soil treatment

$C_{excavate}$ = Cost of excavation of the upper 20 ft. (or less) of contaminated soil

$C_{ex\text{-}situ}$ = Cost of ex-situ treatment of the excavated soil

$C_{dispose}$ = Cost of disposal of the excavated soil

$C_{backfill}$ = Backfill cost for the spill location

$C_{in\text{-}situ}$ = Cost of in-situ treatment of the unexcavated contaminated soil

There are some materials for which the excavated soil can be directly landfilled without any treatment; for those materials there is no ex-situ treatment cost. Soil contaminated by any of the “land banned” materials must be treated in accordance with federal regulations (40CFR268 1997) before disposal. The excavated soil is, therefore, subjected to treatment, and hence ex-situ treatment as well as disposal costs were calculated for such materials. Table 4.11 shows the chemicals that are land-banned. Table 4.12 shows the soil and groundwater remediation technologies adopted for 38 out of the 59 chemicals listed in Table 4.3, for which data were available.

Acetaldehyde
Acetone
Acrylonitrile, Inhibited
Acrylic Acid, Inhibited
Benzene
Butanols
Cyclohexane
Ethyl Acetate
Ethyl Acrylate, Inhibited
Formaldehyde, Solutions
Methanol
Methyl Methacrylate Monomer
Phenol, Molten
Toluene
Xylenes

Table 4.11 List of Chemicals with Land Disposal Restrictions (CFR 1997)

Chemical	Excavated Soil Treatment	In-situ Soil Treatment	Groundwater Treatment
Acetaldehyde	Incineration	Soil Vapor Extraction	Biological
Acetic Acid, Glacial	Landfill	No Action	Biological
Acetic Anhydride	Landfill	Soil Vapor Extraction	Biological Carbon Absorption
Acetone	Incineration	Soil Vapor Extraction	Biological Carbon Absorption
Acrylonitrile, Inhibited	Incineration	Soil Vapor Extraction	Deep Well Injection
Acrylic Acid, Inhibited	Incineration	No Action	Biological Carbon Absorption
Ammonium Nitrate, Liquid	No Action	No Action	Reverse Osmosis
Benzene	Incineration	Soil Vapor Extraction	Biological Carbon Absorption
Butanols	Incineration	Soil Vapor Extraction	Biological Carbon Absorption
Butyl Acrylates, Inhibited	Landfill	Soil Vapor Extraction	Biological Carbon Absorption
Cyclohexane	Incineration	Soil Vapor Extraction	Carbon Absorption
Ethanol	Landfill	Soil Vapor Extraction	Biological Carbon Absorption
Ethyl Acetate	Incineration	Soil Vapor Extraction	Biological
Ethyl Acrylate, Inhibited	Incineration	Soil Vapor Extraction	Biological Carbon Absorption
Formaldehyde, Solutions	Incineration	Soil Vapor Extraction	Biological Carbon Absorption
Hexamethylenediamine, Solid	No Action	No Action	No Action
Hydrochloric Acid	Physical Chemical	No Action	No Action
Hydrogen Peroxide, Stabilized	No Action	No Action	No Action
Isopropanol	Landfill	Soil Vapor Extraction	Biological Carbon Absorption
Maleic Anhydride	Landfill	Soil Vapor Extraction	Biological Carbon Absorption
Methanol	Incineration	Soil Vapor Extraction	Biological
Methyl Methacrylate Monomer	Incineration	Soil Vapor Extraction	Biological Carbon Absorption
Methyl tert Butyl Ether	Landfill	No Action	Carbon Absorption
Nitric Acid	Physical Chemical	No Action	Reverse Osmosis
Phenol, Molten	Incineration	Soil Vapor Extraction	Biological
Phosphoric Acid	Physical Chemical	No Action	No Action
Phosphorus, White, Dry	No Action	No Action	No Action
Potassium Hydroxide, Solution	Physical Chemical	No Action	No Action
Propylene Oxide	Incineration	Soil Vapor Extraction	Biological Carbon Absorption
Sodium Chlorate, Aqueous	No Action	No Action	Biological Carbon Absorption
Sodium Hydroxide Solution	Physical Chemical	No Action	No Action
Styrene Monomer, Inhibited	Landfill	Soil Vapor Extraction	Carbon Absorption
Sulfur Molten	No Action	No Action	No Action
Sulfuric Acid	Physical Chemical	No Action	No Action
Toluene	Incineration	Soil Vapor Extraction	Biological Carbon Absorption
Toluene Diisocyanate	Incineration	No Action	Carbon Absorption
Vinyl Acetate, Inhibited	Landfill	Soil Vapor Extraction	Biological
Xylenes	Incineration	Soil Vapor Extraction	Carbon Absorption

Table 4.12 Remediation Technologies for 38 Chemicals of Interest

The remediation technologies for soil treatment were determined based on information from the EPA (EPA 2003) and Federal Remediation Technologies Roundtable (FRTR 2003) and reviewed by several experts in railroad environmental remediation (Clark 2002, Kuhlmeier 2002). The values for the costs for various remediation technologies used for soil treatment are shown in Table 4.13.

Technology	**Rate**
Incineration *(includes excavation and disposal costs)*	\$220 – 1,100 per metric ton
Landfill *(includes excavation and disposal costs)*	\$300 – 510 per metric ton
Physical Chemical Neutralization	\$204 per cubic meter
Soil Vapor Extraction	\$10 – 50 per cubic meter

Table 4.13 Cost Data for Soil Remediation Technologies

For chemicals for which the information on soil or groundwater treatment technologies could not be found in the referenced resources, a technology was selected based on engineering judgment. Spills of some chemicals, e.g., hydrogen peroxide and acetic acid, would generally not require extensive treatment, so this was factored into the cost estimates of these materials. Wherever required, the excavation, disposal and backfilling cost rates were taken from the documentation for the IIRSTF model (Arthur D. Little Inc. 1996b).

The total site clean up cost is given by Equation 4.5.

$$C_{total} = C_{ER} + C_{soil} + C_{gw} \tag{4.5}$$

where,

C_{total} = Total cost of contaminated site treatment

C_{ER} = Emergency response cost

C_{soil} = Total cost of contaminated soil treatment

C_{gw} = Total cost of contaminated groundwater treatment

Therefore, the outputs from the model used for this research were:

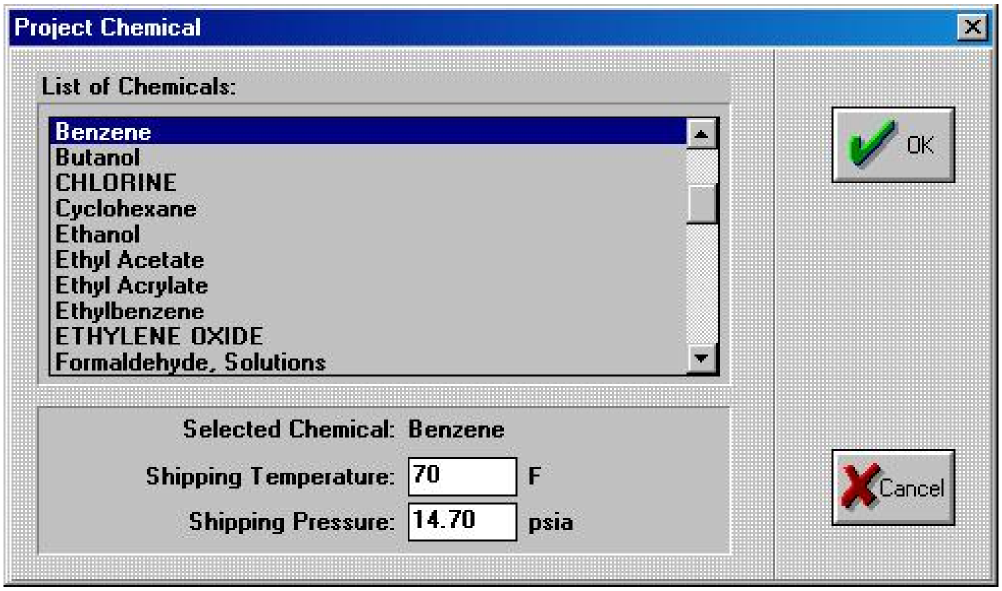
- Emergency response cost
- Volume of contaminated soil
- Clean up cost of contaminated groundwater

4.2.2.2 Model Set-up for Spill Simulations

4.2.2.2.1 Inputs for a Spill Scenario

Spills for each chemical were simulated in the four lading loss categories (Table 3.7) for fifteen environmental scenarios (a combination of three soil types and five groundwater depths) (Anand 2004). The inputs for each spill scenario are specified below in the same order as the input screens appear in the IIRSTF model.

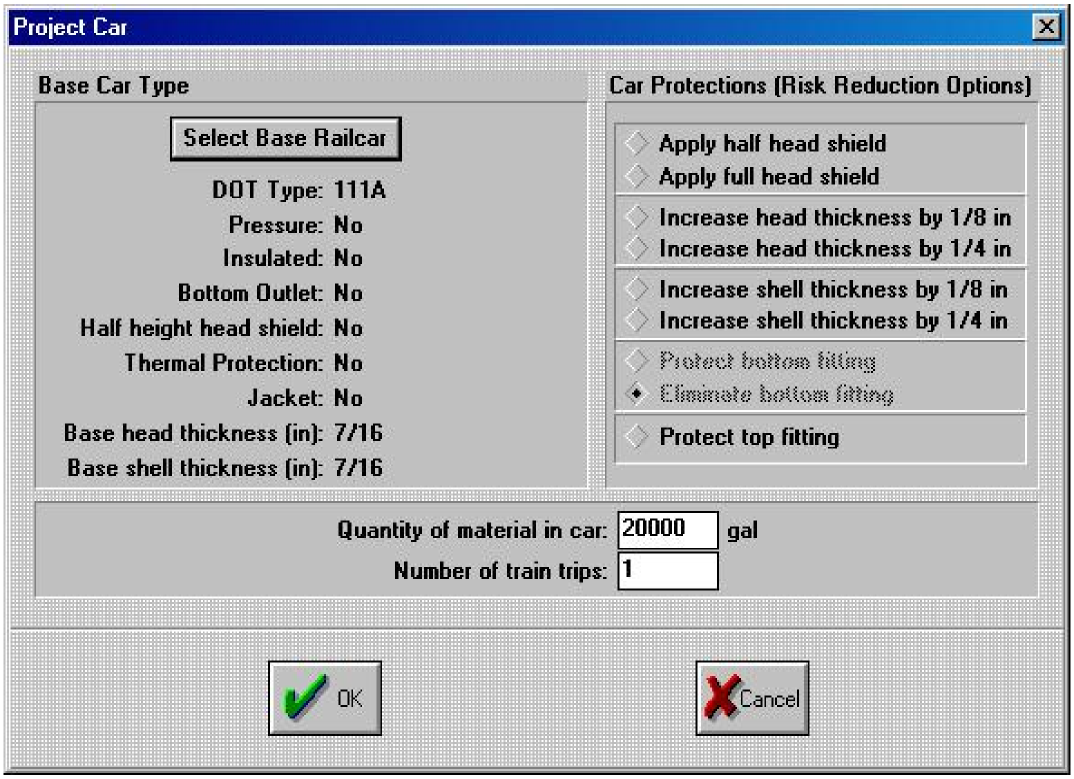
- Chemical and Shipping Data: For each spill scenario, the model requires the temperature and pressure of transit. Ambient conditions were assumed for most chemicals, i.e., a temperature of 70F and a pressure of 14.7 psia. In a few cases, e.g., acetaldehyde (shipping temperature = 68F), some adjustments were required to enable the model to treat the chemical in its proper physical state. These settings are shown for a benzene spill simulation, in Figure 4.9.



Selected Chemical: Benzene
Shipping Temperature: 70 F
Shipping Pressure: 14.70 psia

Figure 4.9 Input Screen for Chemical Transported and Shipping Conditions

Railcar and Quantity Data: Figure 4.10 shows the inputs for this screen. The tank car specification selected for all the spill scenarios was 111A100W1 NI and no changes were made to the default settings for the risk reduction options. The quantity of material transported was different for each chemical. Railcars are constrained in the total weight they can carry, and thus the volumetric capacity of a tank car is often optimized for the density of the chemical it is designed to transport. For each chemical, consequence results were required for the four lading loss categories discussed in the chapter on probability analysis (Table 3.7).



Base Car Type

DOT Type: 111A
Pressure: No
Insulated: No
Bottom Outlet: No
Half height head shield: No
Thermal Protection: No
Jacket: No
Base head thickness (in): 7/16
Base shell thickness (in): 7/16

Car Protections (Risk Reduction Options)

- ○ Apply half head shield
- ○ Apply full head shield
- ○ Increase head thickness by 1/8 in
- ○ Increase head thickness by 1/4 in
- ○ Increase shell thickness by 1/8 in
- ○ Increase shell thickness by 1/4 in
- ○ Protect bottom fitting
- ● Eliminate bottom fitting
- ○ Protect top fitting

Quantity of material in car: 20000 gal
Number of train trips: 1

Figure 4.10 Input Screen for Tank Car Specification Carrying the Chemical of Interest and Quantity of Chemical Transported

For the purpose of simulations, the four lading loss categories (i.e., 0-5%, >5-20%, >20-80% and >80-100%) were represented by the mean tank capacity lost for that category i.e., 2.5%, 12.5%, 50% and 90%, respectively. The capacity of a tank car optimized for a chemical was calculated using a tank car optimization program, Illitank developed at the University of Illinois (Saat & Chua 2004). Table 4.14 shows the density values and tank capacity for all the chemicals while Table 4.15 show the lading lost values for the four categories.

Chemical	Density lbs/gal	Insulation Requirement	Capacity of a 111A100W1 Tank Car (gal)
Acetaldehyde	6.50	Non-insulated	29,640
Acetic Acid	8.60	Insulated	22,629
Acetic Anhydride	9.00	Insulated	21,773
Acetone	6.60	Non-insulated	29,290
Acrylic Acid	8.60	Insulated	22,676
Acrylonitrile	6.70	Non-insulated	28,875
Benzene	7.30	Insulated	26,227
Butanol	6.80	Non-insulated	28,507
n-Butyl Acrylate	7.49	Non-insulated	26,204
Cyclohexane	6.50	Non-insulated	29,640
Ethanol	6.80	Non-insulated	28,507
Ethyl Acetate	7.50	Non-insulated	26,173
Ethyl Acrylate	7.60	Non-insulated	25,871
Hydrogen Peroxide	10.70	Non-insulated	19,046
Isopropanol	6.55	Non-insulated	29,445
Methanol	6.60	Non-insulated	29,252
Methyl Methacrylate Monomer	7.80	Non-insulated	25,286
Methyl Tert Butyl Ether	6.20	Non-insulated	30,866
Nitric Acid	12.44	Non-insulated	16,590
Phenol	8.90	Insulated	21,991
Potassium Hydroxide Solution	12.20	Insulated	16,532
Sodium Hydroxide Solution	12.70	Insulated	15,935
Styrene	7.60	Insulated	25,310
Sulfuric Acid	14.30	Non-insulated	14,579
Toluene	7.20	Non-insulated	27,125
Vinyl Acetate	7.80	Non-insulated	25,286
Xylenes	7.20	Non-insulated	27,125

Table 4.14 Density Data and Tank Capacity of a 111A100W1 Car for 27 Chemicals

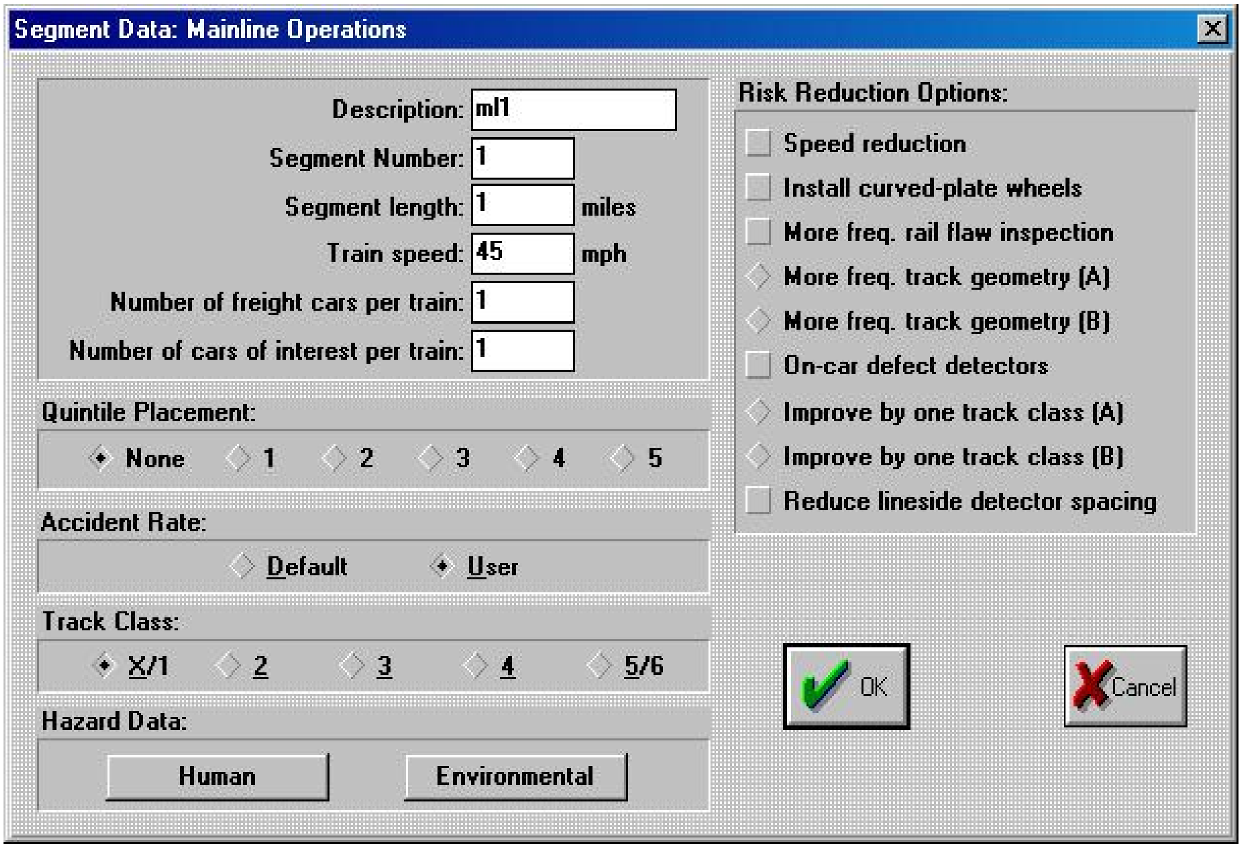
Chemical	**Percent Tank Capacity Lost**			
	0-5%	**>5-20%**	**>20-80%**	**>80-100%**
Acetaldehyde	741	3,705	14,820	26,676
Acetic Acid	566	2,829	11,315	20,366
Acetic Anhydride	544	2,722	10,887	19,596
Acetone	732	3,661	14,645	26,362
Acrylic Acid	567	2,835	11,338	20,409
Acrylonitrile	722	3,609	14,438	25,988
Benzene	656	3,278	13,114	23,604
Butanol	713	3,563	14,254	25,657
n-Butyl Acrylate	655	3,276	13,102	23,584
Cyclohexane	741	3,705	14,820	26,676
Ethanol	713	3,563	14,254	25,657
Ethyl Acetate	654	3,272	13,087	23,556
Ethyl Acrylate	647	3,234	12,936	23,284
Hydrogen Peroxide	476	2,381	9,523	17,141
Isopropanol	736	3,681	14,723	26,501
Methanol	731	3,657	14,626	26,327
Methyl Methacrylate Monomer	632	3,161	12,643	22,758
Methyl Tert Butyl Ether	772	3,858	15,433	27,780
Nitric Acid	415	2,074	8,295	14,931
Phenol	550	2,749	10,996	19,793
Potassium Hydroxide Solution	413	2,067	8,266	14,879
Sodium Hydroxide Solution	398	1,992	7,968	14,342
Styrene	633	3,164	12,655	22,779
Sulfuric Acid	364	1,822	7,290	13,121
Toluene	678	3,391	13,563	24,413
Vinyl Acetate	632	3,161	12,643	22,758
Xylenes	678	3,391	13,563	24,413

Table 4.15 Lading Lost (gal) for 27 Chemicals under the Four Lading Loss Categories

Therefore, the values shown in Table 4.15 serve as the inputs for the “Quantity of material in the car” in Figure 4.10. The simulation settings were modified such that all the contents of the car were released. In other words, the quantity of material in the car was also equal to the quantity lost from the car.

Because I was using the environmental consequence model within the context of the IIRSTF QRA Model, but performing the probability analysis separately, I had to take several steps to “control” the probability portion of the model to give me the spill quantity output I needed for my analysis.

- Segment and Accident Rate Data: The route length was taken as 1 mile. Number of freight cars per train and number of cars of interest per train was held constant at 1 and train speed at 45 mph. The quintile placement did not fall within the scope of this study and hence was not selected. The option of using user specified accident rates was selected and track class used was X/1 for all the simulations. None of these inputs have any effect on the consequence model results and are described here strictly for the purpose of completeness and consistency in describing the methodology used. No risk reduction options were chosen, and under hazard data, the environmental tab was selected to input data on the environmental characteristics of the spill location (Figure 4.11).



Segment Data: Mainline Operations

Description: ml1
Segment Number: 1
Segment length: 1 miles
Train speed: 45 mph
Number of freight cars per train: 1
Number of cars of interest per train: 1

Quintile Placement:
● None ○ 1 ○ 2 ○ 3 ○ 4 ○ 5

Accident Rate:
○ Default ● User

Track Class:
● X/1 ○ 2 ○ 3 ○ 4 ○ 5/6

Risk Reduction Options:
☐ Speed reduction
☐ Install curved-plate wheels
☐ More freq. rail flaw inspection
○ More freq. track geometry (A)
○ More freq. track geometry (B)
☐ On-car defect detectors
○ Improve by one track class (A)
○ Improve by one track class (B)
☐ Reduce lineside detector spacing

Hazard Data:

Figure 4.11 Segment and Accident Rate Data

- Hazard Data (Environmental): The environmental data includes the specification of the soil type, depth of groundwater and other parameters discussed under the section “Environmental Data”. These settings are shown in Figures 4.7 and 4.8.

4.2.2.2.2 Settings for the Probability Model

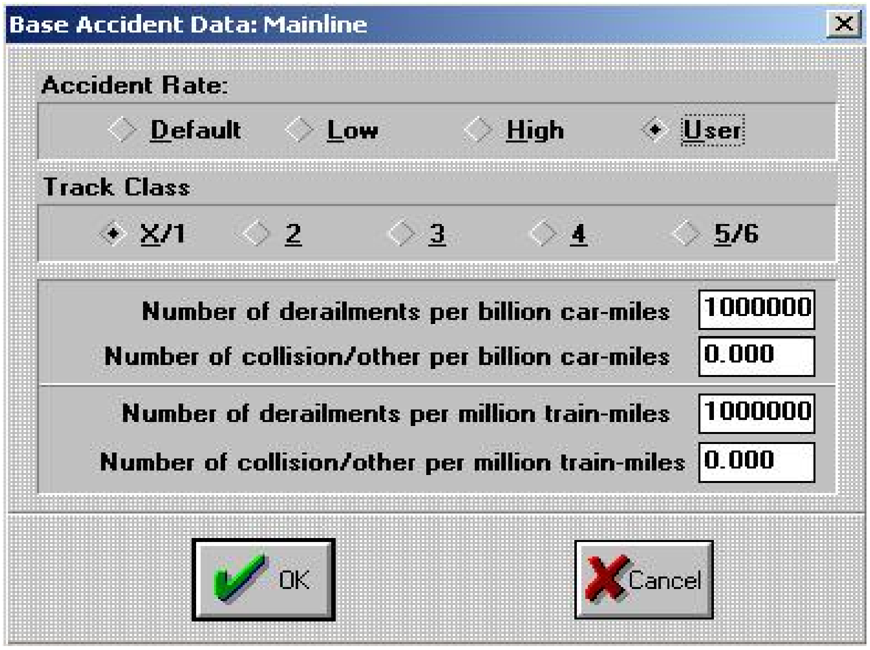
As discussed earlier, the QRA model was used only for consequence modeling. Therefore, the inputs were tailored so that the probability submodel was set to simulate a “sure” event, in other words:

- The train carrying the car with the chemical of interest gets derailed.

- The tank car carrying the chemical of interest gets damaged in the derailment.
- The damaged tank car releases all of its contents, which implies that the tank car released all the lading regardless of the lading quantity. The lading quantity varied from 2.5% to 90% of the carload.

The parameters affecting the probability of the event are the mainline accident rates for the selected track class, conditional spill probabilities for the selected tank car specification, speed of the train, number of cars derailed and number of cars released. The values for these parameters were changed in the following manner to achieve the objective above:

- The model has default mainline accident rates that vary with the track class. But the user can also specify the value. The user-specified values (Figure 4.12) were used to override the default accident rates in the model, for the selected track class X/1.



Base Accident Data: Mainline

Accident Rate:

○ Default ○ Low ○ High ● User

Track Class

● X/1 ○ 2 ○ 3 ○ 4 ○ 5/6

Number of derailments per billion car-miles 1000000

Number of collision/other per billion car-miles 0.000

Number of derailments per million train-miles 1000000

Number of collision/other per million train-miles 0.000

Figure 4.12 User-Specified Base Accident Data for Mainlines
(For the Selected Track Class X/1)

- The conditional probability of release for the selected tank car specification 111A100W1 NI (without bottom outlet) was set to 100%. Tank cars can release from one or more sources (tank head, shell, etc.), so the material loss was attributed to have occurred from multiple locations (Figure 4.13).

Conditional Spill Probabilities: Mainline

Base Car Type

DOT type: 111A
Pressure: No
Insulated: No
Bottom outlet: No
Half height head shield: No
Thermal protection: No
Jacket: No
Base head thickness (in): 7/16
Base shell thickness (in): 7/16

Conditional Spill Probabilities

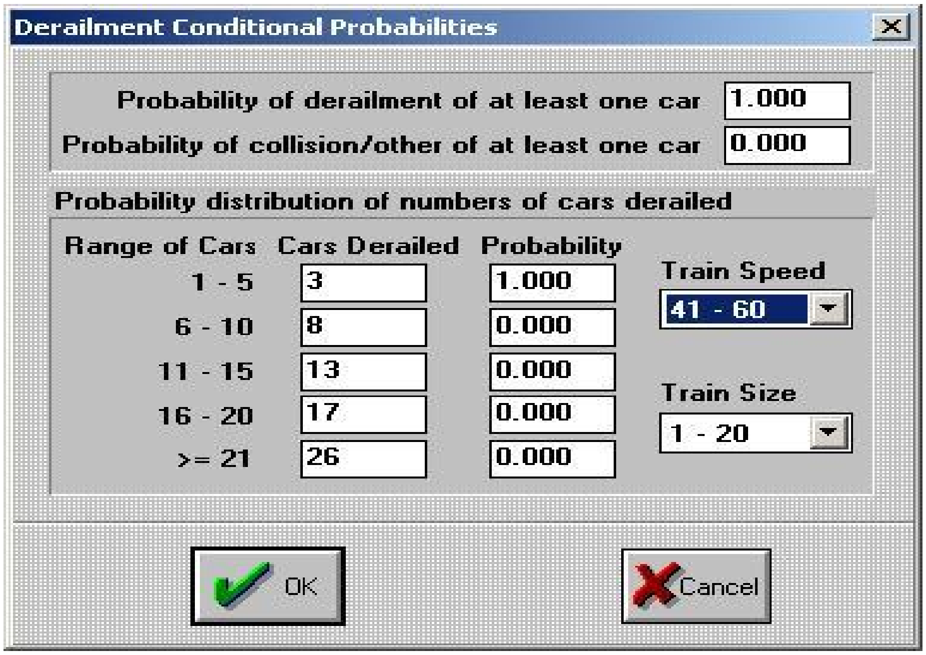
Tank head	0.000
Tank shell	0.000
Top fitting	0.000
Bottom fitting	0.000
Multiple locations	100.000

Car Protections (Risk Reduction Options)

- ○ Apply half head shield
- ○ Apply full head shield
- ○ Increase head thickness by 1/8 in
- ○ Increase head thickness by 1/4 in
- ○ Increase shell thickness by 1/8 in
- ○ Increase shell thickness by 1/4 in
- ○ Protect bottom fitting
- ● Eliminate bottom fitting
- ○ Protect top fitting

Figure 4.13 User-Specified Conditional Spill Probability Data for 111A100W1
(for mainline track)

- The number of cars derailing as a result of an accident depends on the speed of the train. All simulations were carried out for a single car in the train traveling at 45 mph. Therefore, the probability distribution of the number of cars derailed for the speed band 41-60 mph was set to a 100% for the category ‘1-5’ number of derailed cars (Figure 4.14).



Derailment Conditional Probabilities

Probability of derailment of at least one car: 1.000
Probability of collision/other of at least one car: 0.000

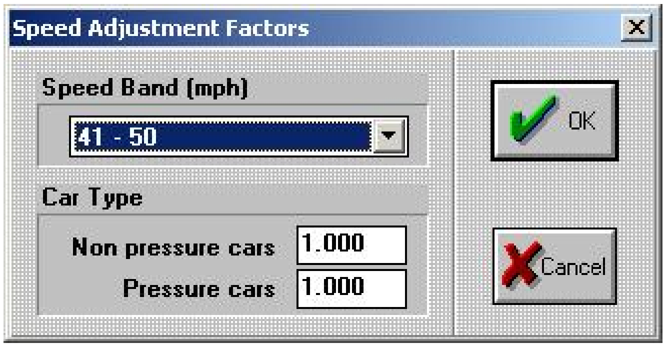
Probability distribution of numbers of cars derailed

Range of Cars	Cars Derailed	Probability
1 - 5	3	1.000
6 - 10	8	0.000
11 - 15	13	0.000
16 - 20	17	0.000
>= 21	26	0.000

Train Speed: 41 - 60
Train Size: 1 - 20

Figure 4.14 User-Specified Derailment Conditional Probabilities
(For a train speed of 45 mph and train size of 1 car)

- The probability of release also depends on the speed and is different for non-pressure car than pressure cars. The speed adjustment factors for both the categories of the cars were set to 1 (Figure 4.15).



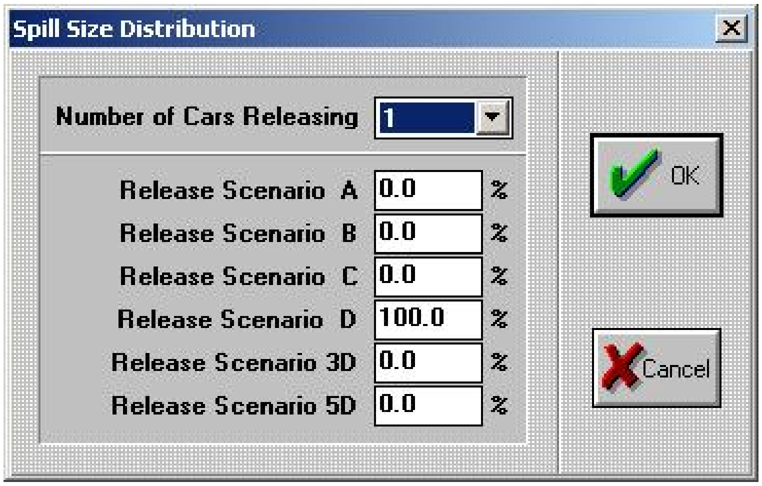
Speed Adjustment Factors

Speed Band (mph): 41 - 50

Car Type
Non pressure cars: 1.000
Pressure cars: 1.000

Figure 4.15 User-entered Speed Adjustment Factors
(For a train speed of 45 mph)

- To make sure that all the contents of a tank car are released, changes were made to the spill size distribution probabilities. The model has six built-in spill sizes or release scenarios (as they are called in the model) (Figure 4.16) with a default probability assigned to each of these release scenarios. These probabilities vary with the number of tank cars that spill. Of particular importance is the ‘Release Scenario D’ which models the 100% release case. All the simulations were carried out for 1 car in the train; therefore, the probability of release scenario ‘D’ happening for release from a single car, was set to a 100% with other spill sizes at a 0% (Figure 4.16).



Number of Cars Releasing: 1

Release Scenario A: 0.0 %

Release Scenario B: 0.0 %

Release Scenario C: 0.0 %

Release Scenario D: 100.0 %

Release Scenario 3D: 0.0 %

Release Scenario 5D: 0.0 %

Figure 4.16 User-entered Spill Size Distribution
(For loss of entire contents from a tank car)

All of the changes discussed in this section were committed to the database and kept constant throughout the course of the simulations.

4.2.2.3 Output From the Model

The IIRSTF QRA model could be run for 27 of the 38 chemicals in Table 4.12. Some of the chemicals are transported as solutions and due to incomplete data for these chemicals the model could not be executed for some cases and yielded unreliable results for others. The model also could not handle chemicals that are transported as solids suspended in slurry, e.g., hexamethylenediamine. And even for some pure chemicals transported in liquid form, the model did not produce proper results, either because of gaps in chemical data, problems with the groundwater treatment method or because of the specified shipping conditions.

Sixty simulations were run for each chemical to obtain the necessary output. The output for all sixty runs of the quantitative risk assessment model for benzene are shown in Tables 4.16 through 4.19.

Soil Type	Depth to Groundwater (ft.)	Total Soil Contaminated (Cubic Meter)	Total Groundwater Contaminated (Cubic Meter)	Groundwater Clean Up Cost ($)	Emergency Response Cost ($)
Clay	10	5,366	0	0	1.10E+05
	20	5,366	0	0	1.10E+05
	50	5,366	0	0	1.10E+05
	100	5,366	0	0	1.10E+05
	200	5,366	0	0	1.10E+05
Silt	10	2,951	49.5	2.38E+07	1.10E+05
	20	6,622	12.1	2.93E+07	1.10E+05
	50	8,074	0	0	1.10E+05
	100	8,074	0	0	1.10E+05
	200	8,074	0	0	1.10E+05
Sand	10	302	86.4	8.91E+05	1.10E+05
	20	988	84.9	8.95E+05	1.10E+05
	50	7204	80.4	9.09E+05	1.10E+05
	100	42,100	72.8	9.31E+05	1.10E+05
	200	284,000	57.7	9.73E+05	1.10E+05

Table 4.16 Output for Benzene Spills in 15 Environmental Scenarios, for 90% Loss

Soil Type	Depth to Groundwater (ft.)	Total Soil Contaminated (Cubic Meter)	Total Groundwater Contaminated (Cubic Meter)	Groundwater Clean Up Cost ($)	Emergency Response Cost ($)
Clay	10	3,180	0	0	6.16E+04
	20	3,180	0	0	6.16E+04
	50	3,180	0	0	6.16E+04
	100	3,180	0	0	6.16E+04
	200	3,180	0	0	6.16E+04
Silt	10	2,067	24.3	1.90E+07	6.16E+04
	20	4,791	0	0	6.16E+04
	50	4,791	0	0	6.16E+04
	100	4,791	0	0	6.16E+04
	200	4,791	0	0	6.16E+04
Sand	10	227	48.4	8.28E+05	6.16E+04
	20	804	47.6	8.33E+05	6.16E+04
	50	6449	45	8.48E+05	6.16E+04
	100	39,600	40.8	8.72E+05	6.16E+04
	200	275,000	32.3	9.18E+05	6.16E+04

Table 4.17 Output for Benzene Spills in 15 Environmental Scenarios, for 50% Loss

Soil Type	Depth to Groundwater (ft.)	Total Soil Contaminated (Cubic Meter)	Total Groundwater Contaminated (Cubic Meter)	Groundwater Clean Up Cost ($)	Emergency Response Cost ($)
Clay	10	959	0	0	1.54E+04
	20	959	0	0	1.54E+04
	50	959	0	0	1.54E+04
	100	959	0	0	1.54E+04
	200	959	0	0	1.54E+04
Silt	10	840	4.03	1.10E+07	1.54E+04
	20	1,472	0	0	1.54E+04
	50	1,472	0	0	1.54E+04
	100	1,472	0	0	1.54E+04
	200	1,472	0	0	1.54E+04
Sand	10	137	12.2	7.15E+05	1.54E+04
	20	571	12.0	7.21E+05	1.54E+04
	50	5,426	11.3	7.37E+05	1.54E+04
	100	36,100	10.2	7.63E+05	1.54E+04
	200	262,000	8.06	8.13E+05	1.54E+04

Table 4.18 Output for Benzene Spills in 15 Environmental Scenarios, for 12.5% Loss

Soil Type	Depth to Groundwater (ft.)	Total Soil Contaminated (Cubic Meter)	Total Groundwater Contaminated (Cubic Meter)	Groundwater Clean Up Cost ($)	Emergency Response Cost ($)
Clay	10	255	0	0	3.08E+03
	20	255	0	0	3.08E+03
	50	255	0	0	3.08E+03
	100	255	0	0	3.08E+03
	200	255	0	0	3.08E+03
Silt	10	369	0.189	6.69E+06	3.08E+03
	20	417	0	0	3.08E+03
	50	417	0	0	3.08E+03
	100	417	0	0	3.08E+03
	200	417	0	0	3.08E+03
Sand	10	95.8	2.34	6.03E+05	3.08E+03
	20	455	2.3	6.08E+05	3.08E+03
	50	4,877	2.18	6.25E+05	3.08E+03
	100	34,100	1.98	6.52E+05	3.08E+03
	200	254,000	1.57	7.03E+05	3.08E+03

Table 4.19 Output for Benzene Spills in 15 Environmental Scenarios, for 2.5% Loss

Using the volume of soil contaminated from Table 4.16 in combination with information on soil treatment procedures from Table 4.12 and cost information for various soil handling/treatment procedures from Table 4.13, the cost of various stages of soil treatment were calculated. Table 4.20 shows the costs for a benzene spill for 90% of a car's contents released.

Soil Type	Depth to Ground-water (ft.)	Ex-situ Soil Treatment Cost ($)		Backfill Cost ($)	In-situ Soil Treatment Cost ($)		Groundwater Treatment Cost ($)	Emergency Response Cost ($)
		Lower Limit	Upper Limit		Lower Limit	Upper Limit		
Clay	10	2.01E+06	1.00E+07	1.34E+05	0	0	0	1.10E+05
	20	2.01E+06	1.00E+07	1.34E+05	0	0	0	1.10E+05
	50	2.01E+06	1.00E+07	1.34E+05	0	0	0	1.10E+05
	100	2.01E+06	1.00E+07	1.34E+05	0	0	0	1.10E+05
	200	2.01E+06	1.00E+07	1.34E+05	0	0	0	1.10E+05
Silt	10	1.10E+06	5.52E+06	7.38E+04	0.00E+00	0.00E+00	2.38E+07	1.10E+05
	20	2.48E+06	1.24E+07	1.66E+05	0.00E+00	0.00E+00	2.93E+07	1.10E+05
	50	2.48E+06	1.24E+07	1.66E+05	1.45E+04	7.26E+04	0	1.10E+05
	100	2.48E+06	1.24E+07	1.66E+05	1.45E+04	7.26E+04	0	1.10E+05
	200	2.48E+06	1.24E+07	1.66E+05	1.45E+04	7.26E+04	0	1.10E+05
Sand	10	1.13E+05	5.65E+05	7.55E+03	0.00E+00	0.00E+00	8.91E+05	1.10E+05
	20	3.70E+05	1.85E+06	2.47E+04	0.00E+00	0.00E+00	8.95E+05	1.10E+05
	50	3.70E+05	1.85E+06	2.47E+04	6.22E+04	3.11E+05	9.09E+05	1.10E+05
	100	3.70E+05	1.85E+06	2.47E+04	4.11E+05	2.06E+06	9.31E+05	1.10E+05
	200	3.70E+05	1.85E+06	2.47E+04	2.83E+06	1.42E+07	9.73E+05	1.10E+05

Table 4.20 Cost Estimation for Remediation of Soil and Groundwater, for a 90% Tank Capacity Lost for Benzene

The total cost involved in clean up of a spill is obtained using Equation 4.5. As most of the clean up procedures state remediation costs as a range, the total cost is also presented as a range; the arithmetic mean of the range limits is taken as the average clean up cost for the spill scenario. Table 4.21 shows the total and average remediation cost for each of the spill scenarios for benzene, assuming a 90% lading loss.

Soil Type	Depth to Groundwater (ft.)	Total Clean up Cost ($)		Average Clean Up cost ($)
		Lower Limit	Upper Limit	
Clay	10	2.25E+06	1.03E+07	6.26E+06
	20	2.25E+06	1.03E+07	6.26E+06
	50	2.25E+06	1.03E+07	6.26E+06
	100	2.25E+06	1.03E+07	6.26E+06
	200	2.25E+06	1.03E+07	6.26E+06
Silt	10	2.51E+07	2.95E+07	2.73E+07
	20	3.21E+07	4.20E+07	3.70E+07
	50	2.77E+06	1.27E+07	7.75E+06
	100	2.77E+06	1.27E+07	7.75E+06
	200	2.77E+06	1.27E+07	7.75E+06
Sand	10	1.12E+06	1.57E+06	1.35E+06
	20	1.40E+06	2.88E+06	2.14E+06
	50	1.48E+06	3.20E+06	2.34E+06
	100	1.85E+06	4.97E+06	3.41E+06
	200	4.31E+06	1.71E+07	1.07E+07

Table 4.21 Total and Average Remediation Cost for Benzene Spills over 15 Environmental Scenarios, for 90% Lading Loss

As was discussed above (Sec. 4.2.2) it was not possible to validate the groundwater remediation algorithm of the IIRSTF model, hence there is uncertainty about the groundwater clean up cost estimates obtained. Therefore it is important to know how much the groundwater clean up cost contributes to the total clean up cost for each scenario (Table 4.22). For clay, there is no groundwater clean up cost but for silt and sand, the contribution of groundwater cost decreases with the increase in depth of the groundwater table and also with the increase in quantity of loading lost. This is because the groundwater clean up cost increases at a much lower rate with greater depth or quantity of lading lost, than the soil clean up cost (which is linear).

Soil Type	Depth to Groundwater (ft.)	Lading Lost			
		90%	50%	12.5%	2.5%
Clay	10	0.00%	0.00%	0.00%	0.00%
	20	0.00%	0.00%	0.00%	0.00%
	50	0.00%	0.00%	0.00%	0.00%
	100	0.00%	0.00%	0.00%	0.00%
	200	0.00%	0.00%	0.00%	0.00%
Silt	10	87.20%	88.65%	91.83%	94.01%
	20	79.18%	0.00%	0.00%	0.00%
	50	0.00%	0.00%	0.00%	0.00%
	100	0.00%	0.00%	0.00%	0.00%
	200	0.00%	0.00%	0.00%	0.00%
Sand	10	66.13%	72.00%	80.56%	84.22%
	20	41.86%	45.85%	51.82%	53.66%
	50	38.87%	42.38%	47.46%	48.73%
	100	27.32%	28.88%	30.53%	29.82%
	200	9.09%	9.06%	8.72%	7.96%

Table 4.22 Percent Contribution of Groundwater Clean up Cost to the Average Remediation Cost for Benzene Spills

The clean up cost remains constant for clayey soils irrespective of the depth to water table. This is because benzene does not reach the water table if spilled on clay. This was true for all 27 chemicals. On silty soils, the chemical reaches groundwater for shallow water tables, but not for deeper tables and hence the clean up cost becomes constant after a certain depth. For sands, the chemical reaches the maximum depth considered (200 feet). The average clean up cost for the various spill scenarios is shown for all 27 chemicals in Tables 4.23 through 4.34.

	Depth to Groundwater				
Chemical	**10 ft.**	**20 ft.**	**50 ft.**	**100 ft.**	**200 ft.**
Acetaldehyde	5.89E+06	5.89E+06	5.89E+06	5.89E+06	5.89E+06
Acetic Acid	4.35E+06	4.35E+06	4.35E+06	4.35E+06	4.35E+06
Acetic Anhydride	4.29E+06	4.29E+06	4.29E+06	4.29E+06	4.29E+06
Acetone	6.56E+06	6.56E+06	6.56E+06	6.56E+06	6.56E+06
Acrylic Acid	7.27E+06	7.27E+06	7.27E+06	7.27E+06	7.27E+06
Acrylonitrile	6.52E+06	6.52E+06	6.52E+06	6.52E+06	6.52E+06
Benzene	6.26E+06	6.26E+06	6.26E+06	6.26E+06	6.26E+06
Butanol	6.98E+06	6.98E+06	6.98E+06	6.98E+06	6.98E+06
n-Butyl Acrylate	4.78E+06	4.78E+06	4.78E+06	4.78E+06	4.78E+06
Cyclohexane	5.43E+06	5.43E+06	5.43E+06	5.43E+06	5.43E+06
Ethanol	4.56E+06	4.56E+06	4.56E+06	4.56E+06	4.56E+06
Ethyl Acetate	6.27E+06	6.27E+06	6.27E+06	6.27E+06	6.27E+06
Ethyl Acrylate	6.22E+06	6.22E+06	6.22E+06	6.22E+06	6.22E+06
Hydrogen Peroxide	8.05E+04	8.05E+04	8.05E+04	8.05E+04	8.05E+04
Isopropanol	4.27E+06	4.27E+06	4.27E+06	4.27E+06	4.27E+06
Methanol	7.51E+06	7.51E+06	7.51E+06	7.51E+06	7.51E+06
Methyl Methacrylate Monomer	6.13E+06	6.13E+06	6.13E+06	6.13E+06	6.13E+06
Methyl Tert Butyl Ether	3.41E+06	3.41E+06	3.41E+06	3.41E+06	3.41E+06
Nitric Acid	1.33E+06	1.33E+06	1.33E+06	1.33E+06	1.33E+06
Phenol	5.39E+06	5.39E+06	5.39E+06	5.39E+06	5.39E+06
Potassium Hydroxide Solution	4.76E+05	4.76E+05	4.76E+05	4.76E+05	4.76E+05
Sodium Hydroxide Solution	1.33E+06	1.33E+06	1.33E+06	1.33E+06	1.33E+06
Styrene	4.63E+06	4.63E+06	4.63E+06	4.63E+06	4.63E+06
Sulfuric Acid	2.22E+06	2.22E+06	2.22E+06	2.22E+06	2.22E+06
Toluene	7.15E+06	7.15E+06	7.15E+06	7.15E+06	7.15E+06
Vinyl Acetate	3.44E+06	3.44E+06	3.44E+06	3.44E+06	3.44E+06
Xylenes	7.85E+06	7.85E+06	7.85E+06	7.85E+06	7.85E+06

Table 4.23 Average Clean up Cost of Various Spill Scenarios on Clay Soils for 90% Loss
(27 chemicals of interest)

	Depth To Groundwater				
Chemical	**10 ft.**	**20 ft.**	**50 ft.**	**100 ft.**	**200 ft.**
Acetaldehyde	2.13E+07	3.00E+07	7.39E+06	7.39E+06	7.39E+06
Acetic Acid	2.63E+07	4.12E+06	4.12E+06	4.12E+06	4.12E+06
Acetic Anhydride	2.59E+07	4.21E+06	4.21E+06	4.21E+06	4.21E+06
Acetone	2.32E+07	3.23E+07	7.83E+06	7.83E+06	7.83E+06
Acrylic Acid	2.77E+07	6.36E+06	6.36E+06	6.36E+06	6.36E+06
Acrylonitrile	3.35E+07	8.74E+06	8.74E+06	8.74E+06	8.74E+06
Benzene	2.73E+07	3.70E+07	7.75E+06	7.75E+06	7.75E+06
Butanol	3.75E+07	7.78E+06	7.78E+06	7.78E+06	7.78E+06
n-Butyl Acrylate	3.07E+07	4.83E+06	4.83E+06	4.83E+06	4.83E+06
Cyclohexane	5.25E+06	9.29E+06	9.29E+06	9.29E+06	9.29E+06
Ethanol	2.93E+07	5.18E+06	5.18E+06	5.18E+06	5.18E+06
Ethyl Acetate	2.18E+07	3.05E+07	7.40E+06	7.40E+06	7.40E+06
Ethyl Acrylate	2.74E+07	3.65E+07	8.31E+06	8.31E+06	8.31E+06
Hydrogen Peroxide	8.05E+04	8.05E+04	8.05E+04	8.05E+04	8.05E+04
Isopropanol	3.60E+07	5.17E+06	5.17E+06	5.17E+06	5.17E+06
Methanol	2.77E+07	9.24E+06	9.24E+06	9.24E+06	9.24E+06
Methyl Methacrylate Monomer	2.65E+07	8.31E+06	8.31E+06	8.31E+06	8.31E+06
Methyl Tert Butyl Ether	5.34E+06	7.64E+06	4.69E+06	4.69E+06	4.69E+06
Nitric Acid	1.21E+06	1.35E+06	1.35E+06	1.35E+06	1.35E+06
Phenol	5.87E+06	5.87E+06	5.87E+06	5.87E+06	5.87E+06
Potassium Hydroxide Solution	1.96E+06	1.96E+06	1.96E+06	1.96E+06	1.96E+06
Sodium Hydroxide Solution	1.43E+06	1.43E+06	1.43E+06	1.43E+06	1.43E+06
Styrene	3.29E+07	4.21E+07	4.92E+06	4.92E+06	4.92E+06
Sulfuric Acid	1.20E+06	1.20E+06	1.20E+06	1.20E+06	1.20E+06
Toluene	2.78E+07	3.81E+07	7.54E+06	7.54E+06	7.54E+06
Vinyl Acetate	2.04E+07	2.75E+07	4.62E+06	4.62E+06	4.62E+06
Xylenes	3.72E+07	8.88E+06	8.88E+06	8.88E+06	8.88E+06

Table 4.24 Average Clean up Cost of Various Spill Scenarios on Silty Soils for 90% Loss
(27 chemicals of interest)

	Depth To Groundwater				
Chemical	**10 ft.**	**20 ft.**	**50 ft.**	**100 ft.**	**200 ft.**
Acetaldehyde	5.76E+05	1.27E+06	1.46E+06	2.50E+06	9.68E+06
Acetic Acid	4.75E+05	1.13E+06	1.14E+06	1.17E+06	1.21E+06
Acetic Anhydride	7.16E+05	1.33E+06	1.56E+06	2.71E+06	1.03E+07
Acetone	7.23E+05	1.48E+06	1.68E+06	2.74E+06	9.98E+06
Acrylic Acid	9.58E+05	2.05E+06	2.07E+06	2.09E+06	2.07E+06
Acrylonitrile	2.31E+06	3.24E+06	3.45E+06	4.58E+06	1.21E+07
Benzene	1.35E+06	2.14E+06	2.34E+06	3.41E+06	1.07E+07
Butanol	1.33E+06	2.87E+06	3.16E+06	4.49E+06	5.68E+06
n-Butyl Acrylate	1.02E+06	1.67E+06	1.89E+06	3.04E+06	1.07E+07
Cyclohexane	9.21E+05	1.91E+06	2.11E+06	3.22E+06	1.08E+07
Ethanol	7.96E+05	1.51E+06	1.76E+06	2.97E+06	1.07E+07
Ethyl Acetate	6.36E+05	1.39E+06	1.58E+06	2.64E+06	9.88E+06
Ethyl Acrylate	1.44E+06	2.29E+06	2.50E+06	3.59E+06	1.10E+07
Hydrogen Peroxide	8.05E+04	8.05E+04	8.05E+04	8.05E+04	8.05E+04
Isopropanol	9.79E+05	1.91E+06	2.20E+06	3.52E+06	5.66E+06
Methanol	8.14E+05	1.76E+06	1.98E+06	3.12E+06	1.07E+07
Methyl Methacrylate Monomer	9.27E+05	1.77E+06	1.98E+06	3.08E+06	1.05E+07
Methyl Tert Butyl Ether	1.55E+06	2.02E+06	1.99E+06	1.94E+06	1.84E+06
Nitric Acid	3.55E+05	5.79E+05	5.80E+05	5.80E+05	5.80E+05
Phenol	1.52E+06	3.37E+06	3.67E+06	3.94E+06	3.94E+06
Potassium Hydroxide Solution	1.23E+06	1.23E+06	1.23E+06	1.23E+06	1.23E+06
Sodium Hydroxide Solution	1.43E+06	1.43E+06	1.43E+06	1.43E+06	1.43E+06
Styrene	1.83E+06	2.35E+06	2.56E+06	3.66E+06	1.11E+07
Sulfuric Acid	7.53E+05	1.32E+06	1.32E+06	1.32E+06	1.32E+06
Toluene	9.23E+05	1.72E+06	1.93E+06	3.02E+06	1.03E+07
Vinyl Acetate	5.19E+05	1.01E+06	1.21E+06	2.29E+06	9.59E+06
Xylenes	1.13E+06	2.01E+06	2.23E+06	3.35E+06	1.08E+07

Table 4.25 Average Clean up Cost of Various Spill Scenarios on Sandy Soils for 90% Loss
(27 chemicals of interest)

	Depth To Groundwater				
Chemical	**10 ft.**	**20 ft.**	**50 ft.**	**100 ft.**	**200 ft.**
Acetaldehyde	3.47E+06	3.47E+06	3.47E+06	3.47E+06	3.47E+06
Acetic Acid	2.62E+06	2.62E+06	2.62E+06	2.62E+06	2.62E+06
Acetic Anhydride	2.56E+06	2.56E+06	2.56E+06	2.56E+06	2.56E+06
Acetone	3.88E+06	3.88E+06	3.88E+06	3.88E+06	3.88E+06
Acrylic Acid	4.36E+06	4.36E+06	4.36E+06	4.36E+06	4.36E+06
Acrylonitrile	3.91E+06	3.91E+06	3.91E+06	3.91E+06	3.91E+06
Benzene	3.71E+06	3.71E+06	3.71E+06	3.71E+06	3.71E+06
Butanol	4.54E+06	4.54E+06	4.54E+06	4.54E+06	4.54E+06
n-Butyl Acrylate	2.85E+06	2.85E+06	2.85E+06	2.85E+06	2.85E+06
Cyclohexane	3.24E+06	3.24E+06	3.24E+06	3.24E+06	3.24E+06
Ethanol	2.73E+06	2.73E+06	2.73E+06	2.73E+06	2.73E+06
Ethyl Acetate	3.72E+06	3.72E+06	3.72E+06	3.72E+06	3.72E+06
Ethyl Acrylate	3.71E+06	3.71E+06	3.71E+06	3.71E+06	3.71E+06
Hydrogen Peroxide	4.47E+04	4.47E+04	4.47E+04	4.47E+04	4.47E+04
Isopropanol	2.59E+06	2.59E+06	2.59E+06	2.59E+06	2.59E+06
Methanol	4.48E+06	4.48E+06	4.48E+06	4.48E+06	4.48E+06
Methyl Methacrylate Monomer	3.66E+06	3.66E+06	3.66E+06	3.66E+06	3.66E+06
Methyl Tert Butyl Ether	2.02E+06	2.02E+06	2.02E+06	2.02E+06	2.02E+06
Nitric Acid	8.04E+05	8.04E+05	8.04E+05	8.04E+05	8.04E+05
Phenol	3.45E+06	3.45E+06	3.45E+06	3.45E+06	3.45E+06
Potassium Hydroxide Solution	1.11E+06	1.11E+06	1.11E+06	1.11E+06	1.11E+06
Sodium Hydroxide Solution	8.58E+05	8.58E+05	8.58E+05	8.58E+05	8.58E+05
Styrene	2.74E+06	2.74E+06	2.74E+06	2.74E+06	2.74E+06
Sulfuric Acid	1.39E+06	1.39E+06	1.39E+06	1.39E+06	1.39E+06
Toluene	4.23E+06	4.23E+06	4.23E+06	4.23E+06	4.23E+06
Vinyl Acetate	2.05E+06	2.05E+06	2.05E+06	2.05E+06	2.05E+06
Xylenes	4.66E+06	4.66E+06	4.66E+06	4.66E+06	4.66E+06

Table 4.26 Average Clean up Cost of Various Spill Scenarios on Clay Soils for 50% Loss
(27 chemicals of interest)

	Depth To Groundwater				
Chemical	**10 ft.**	**20 ft.**	**50 ft.**	**100 ft.**	**200 ft.**
Acetaldehyde	1.46E+07	2.15E+07	4.72E+06	4.72E+06	4.72E+06
Acetic Acid	1.79E+07	2.32E+06	2.32E+06	2.32E+06	2.32E+06
Acetic Anhydride	1.90E+07	2.42E+06	2.42E+06	2.42E+06	2.42E+06
Acetone	1.70E+07	2.43E+07	5.30E+06	5.30E+06	5.30E+06
Acrylic Acid	2.11E+07	3.77E+06	3.77E+06	3.77E+06	3.77E+06
Acrylonitrile	2.66E+07	5.19E+06	5.19E+06	5.19E+06	5.19E+06
Benzene	2.14E+07	5.56E+06	5.56E+06	5.56E+06	5.56E+06
Butanol	4.59E+06	4.59E+06	4.59E+06	4.59E+06	4.59E+06
n-Butyl Acrylate	2.25E+07	2.76E+06	2.76E+06	2.76E+06	2.76E+06
Cyclohexane	3.67E+06	5.48E+06	5.48E+06	5.48E+06	5.48E+06
Ethanol	2.20E+07	3.03E+06	3.03E+06	3.03E+06	3.03E+06
Ethyl Acetate	1.68E+07	2.39E+07	5.39E+06	5.39E+06	5.39E+06
Ethyl Acrylate	2.03E+07	5.00E+06	5.00E+06	5.00E+06	5.00E+06
Hydrogen Peroxide	4.47E+04	4.47E+04	4.47E+04	4.47E+04	4.47E+04
Isopropanol	2.62E+07	2.99E+06	2.99E+06	2.99E+06	2.99E+06
Methanol	1.95E+07	5.29E+06	5.29E+06	5.29E+06	5.29E+06
Methyl Methacrylate Monomer	2.01E+07	4.92E+06	4.92E+06	4.92E+06	4.92E+06
Methyl Tert Butyl Ether	4.39E+06	6.08E+06	3.27E+06	3.27E+06	3.27E+06
Nitric Acid	9.17E+05	8.08E+05	8.08E+05	8.08E+05	8.08E+05
Phenol	3.34E+06	3.34E+06	3.34E+06	3.34E+06	3.34E+06
Potassium Hydroxide Solution	1.14E+06	1.14E+06	1.14E+06	1.14E+06	1.14E+06
Sodium Hydroxide Solution	9.17E+05	9.17E+05	9.17E+05	9.17E+05	9.17E+05
Styrene	2.62E+07	3.16E+06	3.16E+06	3.16E+06	3.16E+06
Sulfuric Acid	6.86E+05	6.86E+05	6.86E+05	6.86E+05	6.86E+05
Toluene	2.23E+07	3.04E+07	5.70E+06	5.70E+06	5.70E+06
Vinyl Acetate	1.56E+07	3.24E+06	3.24E+06	3.24E+06	3.24E+06
Xylenes	2.77E+07	5.21E+06	5.21E+06	5.21E+06	5.21E+06

Table 4.27 Average Clean up Cost of Various Spill Scenarios on Silty Soils for 50% Loss
(27 chemicals of interest)

	Depth To Groundwater				
Chemical	**10 ft.**	**20 ft.**	**50 ft.**	**100 ft.**	**200 ft.**
Acetaldehyde	4.10E+05	9.92E+05	1.17E+06	2.15E+06	9.14E+06
Acetic Acid	3.48E+05	8.94E+05	9.09E+05	9.35E+05	9.71E+05
Acetic Anhydride	5.58E+05	1.04E+06	1.24E+06	2.30E+06	9.58E+06
Acetone	5.72E+05	1.21E+06	1.40E+06	2.41E+06	9.48E+06
Acrylic Acid	6.98E+05	1.53E+06	1.54E+06	1.56E+06	1.58E+06
Acrylonitrile	2.08E+06	2.86E+06	3.05E+06	4.11E+06	1.14E+07
Benzene	1.15E+06	1.82E+06	2.00E+06	3.02E+06	1.01E+07
Butanol	9.57E+05	2.14E+06	2.38E+06	3.57E+06	4.42E+06
n-Butyl Acrylate	7.89E+05	1.29E+06	1.49E+06	2.55E+06	9.85E+06
Cyclohexane	6.84E+05	1.48E+06	1.67E+06	2.71E+06	9.97E+06
Ethanol	6.16E+05	1.18E+06	1.40E+06	2.52E+06	9.97E+06
Ethyl Acetate	4.88E+05	1.13E+06	1.31E+06	2.31E+06	9.39E+06
Ethyl Acrylate	1.25E+06	1.95E+06	2.14E+06	3.17E+06	1.03E+07
Hydrogen Peroxide	4.47E+04	4.47E+04	4.47E+04	4.47E+04	4.47E+04
Isopropanol	7.28E+05	1.44E+06	1.68E+06	2.87E+06	4.59E+06
Methanol	6.10E+05	1.39E+06	1.58E+06	2.65E+06	9.93E+06
Methyl Methacrylate Monomer	7.36E+05	1.44E+06	1.63E+06	2.67E+06	9.82E+06
Methyl Tert Butyl Ether	1.08E+06	1.47E+06	1.45E+06	1.43E+06	1.38E+06
Nitric Acid	2.94E+05	4.80E+05	4.80E+05	4.81E+05	4.81E+05
Phenol	1.08E+06	2.48E+06	2.72E+06	2.86E+06	2.86E+06
Potassium Hydroxide Solution	7.34E+05	7.34E+05	7.34E+05	7.34E+05	7.34E+05
Sodium Hydroxide Solution	8.89E+05	8.89E+05	8.89E+05	8.89E+05	8.89E+05
Styrene	1.64E+06	2.09E+06	2.28E+06	3.32E+06	1.05E+07
Sulfuric Acid	4.99E+05	8.12E+05	8.12E+05	8.12E+05	8.12E+05
Toluene	7.41E+05	1.42E+06	1.60E+06	2.63E+06	9.73E+06
Vinyl Acetate	3.99E+05	8.13E+05	9.98E+05	2.01E+06	9.13E+06
Xylenes	9.06E+05	1.65E+06	1.84E+06	2.90E+06	1.01E+07

Table 4.28 Average Clean up Cost of Various Spill Scenarios on Sandy Soils for 50% Loss
(27 chemicals of interest)

	Depth To Groundwater				
Chemical	**10 ft.**	**20 ft.**	**50 ft.**	**100 ft.**	**200 ft.**
Acetaldehyde	1.04E+06	1.04E+06	1.04E+06	1.04E+06	1.04E+06
Acetic Acid	8.15E+05	8.15E+05	8.15E+05	8.15E+05	8.15E+05
Acetic Anhydride	7.86E+05	7.86E+05	7.86E+05	7.86E+05	7.86E+05
Acetone	1.16E+06	1.16E+06	1.16E+06	1.16E+06	1.16E+06
Acrylic Acid	1.34E+06	1.34E+06	1.34E+06	1.34E+06	1.34E+06
Acrylonitrile	1.21E+06	1.21E+06	1.21E+06	1.21E+06	1.21E+06
Benzene	1.12E+06	1.12E+06	1.12E+06	1.12E+06	1.12E+06
Butanol	1.58E+06	1.58E+06	1.58E+06	1.58E+06	1.58E+06
n-Butyl Acrylate	8.71E+05	8.71E+05	8.71E+05	8.71E+05	8.71E+05
Cyclohexane	1.00E+06	1.00E+06	1.00E+06	1.00E+06	1.00E+06
Ethanol	8.45E+05	8.45E+05	8.45E+05	8.45E+05	8.45E+05
Ethyl Acetate	1.12E+06	1.12E+06	1.12E+06	1.12E+06	1.12E+06
Ethyl Acrylate	1.13E+06	1.13E+06	1.13E+06	1.13E+06	1.13E+06
Hydrogen Peroxide	1.11E+04	1.11E+04	1.11E+04	1.11E+04	1.11E+04
Isopropanol	8.20E+05	8.20E+05	8.20E+05	8.20E+05	8.20E+05
Methanol	1.37E+06	1.37E+06	1.37E+06	1.37E+06	1.37E+06
Methyl Methacrylate Monomer	1.12E+06	1.12E+06	1.12E+06	1.12E+06	1.12E+06
Methyl Tert Butyl Ether	6.13E+05	6.13E+05	6.13E+05	6.13E+05	6.13E+05
Nitric Acid	2.51E+05	2.51E+05	2.51E+05	2.51E+05	2.51E+05
Phenol	1.24E+06	1.24E+06	1.24E+06	1.24E+06	1.24E+06
Potassium Hydroxide Solution	5.33E+05	5.33E+05	5.33E+05	5.33E+05	5.33E+05
Sodium Hydroxide Solution	3.08E+05	3.08E+05	3.08E+05	3.08E+05	3.08E+05
Styrene	8.23E+05	8.23E+05	8.23E+05	8.23E+05	8.23E+05
Sulfuric Acid	4.58E+05	4.58E+05	4.58E+05	4.58E+05	4.58E+05
Toluene	1.27E+06	1.27E+06	1.27E+06	1.27E+06	1.27E+06
Vinyl Acetate	6.27E+05	6.27E+05	6.27E+05	6.27E+05	6.27E+05
Xylenes	1.41E+06	1.41E+06	1.41E+06	1.41E+06	1.41E+06

Table 4.29 Average Clean up Cost of Various Spill Scenarios on Clay Soils for 12.5% Loss
(27 chemicals of interest)

	Depth To Groundwater				
Chemical	**10 ft.**	**20 ft.**	**50 ft.**	**100 ft.**	**200 ft.**
Acetaldehyde	8.45E+06	2.26E+06	2.26E+06	2.26E+06	2.26E+06
Acetic Acid	6.92E+05	6.92E+05	6.92E+05	6.92E+05	6.92E+05
Acetic Anhydride	7.31E+05	7.31E+05	7.31E+05	7.31E+05	7.31E+05
Acetone	9.62E+06	1.99E+06	1.99E+06	1.99E+06	1.99E+06
Acrylic Acid	1.13E+06	1.13E+06	1.13E+06	1.13E+06	1.13E+06
Acrylonitrile	1.52E+07	1.53E+06	1.53E+06	1.53E+06	1.53E+06
Benzene	1.20E+07	1.70E+06	1.70E+06	1.70E+06	1.70E+06
Butanol	1.26E+06	1.26E+06	1.26E+06	1.26E+06	1.26E+06
n-Butyl Acrylate	1.18E+07	8.14E+05	8.14E+05	8.14E+05	8.14E+05
Cyclohexane	1.75E+06	1.62E+06	1.62E+06	1.62E+06	1.62E+06
Ethanol	8.80E+05	8.80E+05	8.80E+05	8.80E+05	8.80E+05
Ethyl Acetate	9.00E+06	1.80E+06	1.80E+06	1.80E+06	1.80E+06
Ethyl Acrylate	1.22E+07	1.53E+06	1.53E+06	1.53E+06	1.53E+06
Hydrogen Peroxide	1.11E+04	1.11E+04	1.11E+04	1.11E+04	1.11E+04
Isopropanol	8.19E+05	8.19E+05	8.19E+05	8.19E+05	8.19E+05
Methanol	1.07E+07	1.61E+06	1.61E+06	1.61E+06	1.61E+06
Methyl Methacrylate Monomer	1.02E+07	1.45E+06	1.45E+06	1.45E+06	1.45E+06
Methyl Tert Butyl Ether	3.40E+06	1.31E+06	1.31E+06	1.31E+06	1.31E+06
Nitric Acid	2.43E+05	2.43E+05	2.43E+05	2.43E+05	2.43E+05
Phenol	9.42E+05	9.42E+05	9.42E+05	9.42E+05	9.42E+05
Potassium Hydroxide Solution	3.64E+05	3.64E+05	3.64E+05	3.64E+05	3.64E+05
Sodium Hydroxide Solution	3.25E+05	3.25E+05	3.25E+05	3.25E+05	3.25E+05
Styrene	1.51E+07	9.50E+05	9.50E+05	9.50E+05	9.50E+05
Sulfuric Acid	2.17E+05	2.17E+05	2.17E+05	2.17E+05	2.17E+05
Toluene	1.17E+07	1.75E+06	1.75E+06	1.75E+06	1.75E+06
Vinyl Acetate	9.02E+06	9.93E+05	9.93E+05	9.93E+05	9.93E+05
Xylenes	1.49E+07	1.56E+06	1.56E+06	1.56E+06	1.56E+06

Table 4.30 Average Clean up Cost of Various Spill Scenarios on Silty Soils for 12.5% Loss
(27 chemicals of interest)

	Depth To Groundwater				
Chemical	**10 ft.**	**20 ft.**	**50 ft.**	**100 ft.**	**200 ft.**
Acetaldehyde	2.19E+05	6.91E+05	8.49E+05	1.78E+06	8.55E+06
Acetic Acid	1.70E+05	5.39E+05	5.55E+05	5.80E+05	6.08E+05
Acetic Anhydride	3.83E+05	7.25E+05	8.90E+05	1.85E+06	8.72E+06
Acetone	3.69E+05	8.47E+05	1.01E+06	1.94E+06	8.73E+06
Acrylic Acid	4.40E+05	1.02E+06	1.03E+06	1.05E+06	1.02E+06
Acrylonitrile	1.72E+06	2.28E+06	2.43E+06	3.39E+06	1.03E+07
Benzene	8.88E+05	1.39E+06	1.55E+06	2.50E+06	9.33E+06
Butanol	5.28E+05	1.26E+06	1.44E+06	2.43E+06	2.76E+06
n-Butyl Acrylate	5.13E+05	8.71E+05	1.04E+06	2.00E+06	8.89E+06
Cyclohexane	4.27E+05	9.85E+05	1.14E+06	2.08E+06	8.97E+06
Ethanol	3.97E+05	7.78E+05	9.52E+05	1.94E+06	8.90E+06
Ethyl Acetate	2.81E+05	7.70E+05	9.28E+05	1.87E+06	8.67E+06
Ethyl Acrylate	9.96E+05	1.51E+06	1.68E+06	2.62E+06	9.46E+06
Hydrogen Peroxide	1.11E+04	1.11E+04	1.11E+04	1.11E+04	1.11E+04
Isopropanol	4.42E+05	8.85E+05	1.07E+06	2.08E+06	3.08E+06
Methanol	3.47E+05	8.92E+05	1.06E+06	2.02E+06	8.89E+06
Methyl Methacrylate Monomer	4.63E+05	9.76E+05	1.14E+06	2.08E+06	8.92E+06
Methyl Tert Butyl Ether	7.12E+05	1.02E+06	1.01E+06	1.01E+06	9.93E+05
Nitric Acid	2.30E+05	3.65E+05	3.65E+05	3.65E+05	3.65E+05
Phenol	5.23E+05	1.34E+06	1.49E+06	1.53E+06	1.53E+06
Potassium Hydroxide Solution	2.14E+05	2.14E+05	2.14E+05	2.14E+05	2.14E+05
Sodium Hydroxide Solution	2.56E+05	2.56E+05	2.56E+05	2.56E+05	2.56E+05
Styrene	1.27E+06	1.60E+06	1.76E+06	2.71E+06	9.55E+06
Sulfuric Acid	2.07E+05	3.58E+05	3.58E+05	3.58E+05	3.58E+05
Toluene	4.51E+05	9.58E+05	1.12E+06	2.08E+06	8.92E+06
Vinyl Acetate	2.35E+05	5.48E+05	7.07E+05	1.65E+06	8.47E+06
Xylenes	4.86E+05	1.02E+06	1.18E+06	2.13E+06	8.97E+06

Table 4.31 Average Clean up Cost of Various Spill Scenarios on Sandy Soils for 12.5% Loss
(27 chemicals of interest)

	Depth To Groundwater				
Chemical	**10 ft.**	**20 ft.**	**50 ft.**	**100 ft.**	**200 ft.**
Acetaldehyde	2.73E+05	2.73E+05	2.73E+05	2.73E+05	2.73E+05
Acetic Acid	2.23E+05	2.23E+05	2.23E+05	2.23E+05	2.23E+05
Acetic Anhydride	2.12E+05	2.12E+05	2.12E+05	2.12E+05	2.12E+05
Acetone	3.07E+05	3.07E+05	3.07E+05	3.07E+05	3.07E+05
Acrylic Acid	3.64E+05	3.64E+05	3.64E+05	3.64E+05	3.64E+05
Acrylonitrile	3.32E+05	3.32E+05	3.32E+05	3.32E+05	3.32E+05
Benzene	2.96E+05	2.96E+05	2.96E+05	2.96E+05	2.96E+05
Butanol	4.30E+05	4.30E+05	4.30E+05	4.30E+05	4.30E+05
n-Butyl Acrylate	2.34E+05	2.34E+05	2.34E+05	2.34E+05	2.34E+05
Cyclohexane	2.73E+05	2.73E+05	2.73E+05	2.73E+05	2.73E+05
Ethanol	2.30E+05	2.30E+05	2.30E+05	2.30E+05	2.30E+05
Ethyl Acetate	2.97E+05	2.97E+05	2.97E+05	2.97E+05	2.97E+05
Ethyl Acrylate	3.04E+05	3.04E+05	3.04E+05	3.04E+05	3.04E+05
Hydrogen Peroxide	2.24E+03	2.24E+03	2.24E+03	2.24E+03	2.24E+03
Isopropanol	2.28E+05	2.28E+05	2.28E+05	2.28E+05	2.28E+05
Methanol	3.66E+05	3.66E+05	3.66E+05	3.66E+05	3.66E+05
Methyl Methacrylate Monomer	3.01E+05	3.01E+05	3.01E+05	3.01E+05	3.01E+05
Methyl Tert Butyl Ether	1.64E+05	1.64E+05	1.64E+05	1.64E+05	1.64E+05
Nitric Acid	6.94E+04	6.94E+04	6.94E+04	6.94E+04	6.94E+04
Phenol	3.76E+05	3.76E+05	3.76E+05	3.76E+05	3.76E+05
Potassium Hydroxide Solution	1.62E+05	1.62E+05	1.62E+05	1.62E+05	1.62E+05
Sodium Hydroxide Solution	9.57E+04	9.57E+04	9.57E+04	9.57E+04	9.57E+04
Styrene	2.17E+05	2.17E+05	2.17E+05	2.17E+05	2.17E+05
Sulfuric Acid	1.28E+05	1.28E+05	1.28E+05	1.28E+05	1.28E+05
Toluene	3.35E+05	3.35E+05	3.35E+05	3.35E+05	3.35E+05
Vinyl Acetate	1.69E+05	1.69E+05	1.69E+05	1.69E+05	1.69E+05
Xylenes	3.71E+05	3.71E+05	3.71E+05	3.71E+05	3.71E+05

Table 4.32 Average Clean up Cost of Various Spill Scenarios on Clay Soils for 2.5% Loss
(27 chemicals of interest)

	Depth To Groundwater				
Chemical	**10 ft.**	**20 ft.**	**50 ft.**	**100 ft.**	**200 ft.**
Acetaldehyde	4.18E+06	7.00E+05	7.00E+05	7.00E+05	7.00E+05
Acetic Acid	1.80E+05	1.80E+05	1.80E+05	1.80E+05	1.80E+05
Acetic Anhydride	1.92E+05	1.92E+05	1.92E+05	1.92E+05	1.92E+05
Acetone	5.25E+06	5.69E+05	5.69E+05	5.69E+05	5.69E+05
Acrylic Acid	2.91E+05	2.91E+05	2.91E+05	2.91E+05	2.91E+05
Acrylonitrile	3.97E+05	3.97E+05	3.97E+05	3.97E+05	3.97E+05
Benzene	7.12E+06	4.81E+05	4.81E+05	4.81E+05	4.81E+05
Butanol	3.34E+05	3.34E+05	3.34E+05	3.34E+05	3.34E+05
n-Butyl Acrylate	2.26E+05	2.26E+05	2.26E+05	2.26E+05	2.26E+05
Cyclohexane	4.22E+05	4.22E+05	4.22E+05	4.22E+05	4.22E+05
Ethanol	2.27E+05	2.27E+05	2.27E+05	2.27E+05	2.27E+05
Ethyl Acetate	4.65E+06	5.12E+05	5.12E+05	5.12E+05	5.12E+05
Ethyl Acrylate	4.21E+05	4.21E+05	4.21E+05	4.21E+05	4.21E+05
Hydrogen Peroxide	2.24E+03	2.24E+03	2.24E+03	2.24E+03	2.24E+03
Isopropanol	2.08E+05	2.08E+05	2.08E+05	2.08E+05	2.08E+05
Methanol	4.24E+05	4.24E+05	4.24E+05	4.24E+05	4.24E+05
Methyl Methacrylate Monomer	4.03E+05	4.03E+05	4.03E+05	4.03E+05	4.03E+05
Methyl Tert Butyl Ether	2.96E+06	3.76E+05	3.76E+05	3.76E+05	3.76E+05
Nitric Acid	6.31E+04	6.31E+04	6.31E+04	6.31E+04	6.31E+04
Phenol	2.45E+05	2.45E+05	2.45E+05	2.45E+05	2.45E+05
Potassium Hydroxide Solution	9.61E+04	9.61E+04	9.61E+04	9.61E+04	9.61E+04
Sodium Hydroxide Solution	9.90E+04	9.90E+04	9.90E+04	9.90E+04	9.90E+04
Styrene	2.62E+05	2.62E+05	2.62E+05	2.62E+05	2.62E+05
Sulfuric Acid	5.67E+04	5.67E+04	5.67E+04	5.67E+04	5.67E+04
Toluene	6.41E+06	4.93E+05	4.93E+05	4.93E+05	4.93E+05
Vinyl Acetate	4.35E+06	2.81E+05	2.81E+05	2.81E+05	2.81E+05
Xylenes	4.21E+05	4.21E+05	4.21E+05	4.21E+05	4.21E+05

Table 4.33 Average Clean up Cost of Various Spill Scenarios on Silty Soils for 2.5% Loss
(27 chemicals of interest)

	Depth To Groundwater				
Chemical	**10 ft.**	**20 ft.**	**50 ft.**	**100 ft.**	**200 ft.**
Acetaldehyde	1.59E+05	5.61E+05	7.09E+05	1.61E+06	8.24E+06
Acetic Acid	9.38E+04	3.80E+05	3.96E+05	4.21E+05	3.66E+05
Acetic Anhydride	2.76E+05	5.51E+05	7.00E+05	1.61E+06	8.27E+06
Acetone	2.56E+05	6.71E+05	8.18E+05	1.72E+06	8.37E+06
Acrylic Acid	2.87E+05	7.40E+05	7.49E+05	7.59E+05	7.34E+05
Acrylonitrile	1.47E+06	1.90E+06	2.05E+06	2.94E+06	9.60E+06
Benzene	7.16E+05	1.13E+06	1.28E+06	2.19E+06	8.83E+06
Butanol	3.11E+05	8.19E+05	9.64E+05	1.86E+06	2.02E+06
n-Butyl Acrylate	3.25E+05	6.05E+05	7.53E+05	1.66E+06	8.32E+06
Cyclohexane	3.33E+05	7.73E+05	9.10E+05	1.80E+06	8.47E+06
Ethanol	2.80E+05	5.68E+05	7.20E+05	1.64E+06	8.30E+06
Ethyl Acetate	1.56E+05	5.67E+05	7.16E+05	1.62E+06	8.28E+06
Ethyl Acrylate	8.28E+05	1.25E+06	1.40E+06	2.30E+06	8.96E+06
Hydrogen Peroxide	2.24E+03	2.24E+03	2.24E+03	2.24E+03	2.24E+03
Isopropanol	2.95E+05	6.09E+05	7.60E+05	1.66E+06	2.37E+06
Methanol	1.82E+05	6.15E+05	7.67E+05	1.68E+06	8.38E+06
Methyl Methacrylate Monomer	2.72E+05	6.95E+05	8.42E+05	1.74E+06	8.39E+06
Methyl Tert Butyl Ether	5.90E+05	8.47E+05	8.46E+05	8.45E+05	8.42E+05
Nitric Acid	2.07E+05	3.16E+05	3.16E+05	3.16E+05	3.16E+05
Phenol	2.47E+05	7.92E+05	9.54E+05	9.53E+05	9.53E+05
Potassium Hydroxide Solution	5.09E+04	5.09E+04	5.09E+04	5.09E+04	5.09E+04
Sodium Hydroxide Solution	6.58E+04	6.58E+04	6.58E+04	6.58E+04	6.58E+04
Styrene	1.00E+06	1.27E+06	1.42E+06	2.33E+06	9.00E+06
Sulfuric Acid	6.81E+04	1.16E+05	1.16E+05	1.16E+05	1.16E+05
Toluene	2.98E+05	7.21E+05	8.74E+05	1.78E+06	8.45E+06
Vinyl Acetate	1.40E+05	4.00E+05	5.50E+05	1.45E+06	8.11E+06
Xylenes	8.61E+04	5.14E+05	6.65E+05	1.58E+06	8.26E+06

Table 4.34 Average Clean up Cost of Various Spill Scenarios on Sandy Soils for 2.5% Loss
(27 chemicals of interest)

4.3 Expected Clean up Cost

Once the remediation costs for each of the spill scenarios was calculated individually, I developed a weighted average cost. The average clean up cost for any scenario in any lading loss category represents the average cost that will be incurred to clean up a location with those environmental characteristics given that the spill has taken place in that particular lading loss category. Each scenario has a different probability of occurrence along the route of travel. Combining the probability of occurrence for each spill scenario (Table 4.35) based on nationwide exposure estimated by Anand (2004), with the clean up cost for that spill scenario, I obtained the expected clean up cost of a spill for a chemical for each lading loss category as expressed in Equation 4.6.

Depth to Groundwater (feet)	Clay	Silt	Sand	Total
>5 to ≤15	0%	6.9%	9.4%	16.4%
>15 to ≤25	0%	4.4%	8.2%	12.6%
>25 to ≤75	2.5%	5.7%	15.1%	23.3%
>75 to ≤125	0%	7.5%	4.4%	11.9%
>125	5%	11.9%	18.9%	35.8%
Total	7.5%	36.5%	56%	100%

Table 4.35 Joint Probability of Occurrence of 15 Soil-Groundwater Combination Scenarios

$$C_{cq} = \sum_{j=1}^{g} \sum_{k=1}^{s} P_{jk} C_{cqjk} \qquad (4.6)$$

where,

C_{cq} = Expected value of clean up of a spill for chemical ‘c’, in the lading loss category ‘q’ ($)

g = Number of types of groundwater regions considered = 5

s = Number of types of soils considered = 3

P_{jk} = Probability of occurrence of a groundwater depth region ‘j', on a soil type ‘k’, at spill location

C_{cqjk} = Average cost of clean up for a particular spill scenario (soil-type groundwater-depth combination) in lading loss category 'q', for chemical 'c' ($)

Using the values for P_{jk} (Table 4.35) and C_{cqjk} (Tables 4.23 through 4.34), the expected cost calculations are shown for benzene spills in Table 4.36. The expected clean up costs for all 27 chemicals are shown in Table 4.37.

Soil Type	**Depth to Groundwater (ft.)**	**$P_{jk}C_{cqjk}$**			
		0-5%	**>5-20%**	**>20-80%**	**>80-100%**
Sand	10	6.73E+04	8.34E+04	1.08E+05	1.27E+05
	20	9.29E+04	1.14E+05	1.49E+05	1.75E+05
	50	1.94E+05	2.35E+05	3.02E+05	3.53E+05
	100	9.62E+04	1.10E+05	1.33E+05	1.50E+05
	200	1.67E+06	1.76E+06	1.91E+06	2.02E+06
Silt	10	4.91E+05	8.27E+05	1.48E+06	1.88E+06
	20	2.12E+04	7.50E+04	2.45E+05	1.63E+06
	50	2.74E+04	9.71E+04	3.17E+05	4.42E+05
	100	3.61E+04	1.28E+05	4.17E+05	5.81E+05
	200	5.73E+04	2.03E+05	6.61E+05	9.22E+05
Clay	10	0.00E+00	0.00E+00	0.00E+00	0.00E+00
	20	0.00E+00	0.00E+00	0.00E+00	0.00E+00
	50	7.39E+03	2.79E+04	9.27E+04	1.57E+05
	100	0.00E+00	0.00E+00	0.00E+00	0.00E+00
	200	1.48E+04	5.58E+04	1.85E+05	3.13E+05
	Total = C_{cq} =	2.77E+06	3.72E+06	6.00E+06	8.76E+06

Table 4.36 Expected Clean up Cost Calculation for Each Lading Loss Category for Benzene Spills

	Expected Clean up Cost for a Lading Loss Category (C_{cq})			
Chemical	**0-5%**	**>5-20%**	**>20-80%**	**>80-100%**
Acetaldehyde	2.31E+06	3.23E+06	5.51E+06	7.40E+06
Acetic Acid	2.70E+05	5.97E+05	2.58E+06	3.95E+06
Acetic Anhydride	1.90E+06	2.29E+06	4.45E+06	5.83E+06
Acetone	2.41E+06	3.33E+06	6.12E+06	7.93E+06
Acrylic Acid	5.06E+05	1.03E+06	3.69E+06	5.39E+06
Acrylonitrile	2.72E+06	4.40E+06	6.88E+06	8.87E+06
Benzene	2.77E+06	3.72E+06	6.00E+06	8.76E+06
Butanol	8.59E+05	1.58E+06	3.63E+06	7.51E+06
n-Butyl Acrylate	1.94E+06	3.17E+06	4.96E+06	6.57E+06
Cyclohexane	2.09E+06	2.75E+06	4.55E+06	6.25E+06
Ethanol	1.92E+06	2.40E+06	4.98E+06	6.52E+06
Ethyl Acetate	2.30E+06	3.19E+06	6.05E+06	7.57E+06
Ethyl Acrylate	2.36E+06	3.75E+06	5.85E+06	8.98E+06
Hydrogen Peroxide	2.23E+03	1.11E+04	4.47E+04	8.04E+04
Isopropanol	8.07E+05	1.31E+06	4.32E+06	6.13E+06
Methanol	2.02E+06	3.35E+06	5.64E+06	7.88E+06
Methyl Methacrylate Monomer	2.04E+06	3.28E+06	5.52E+06	7.39E+06
Methyl Tert Butyl Ether	7.76E+05	1.20E+06	2.31E+06	3.19E+06
Nitric Acid	1.95E+05	2.99E+05	6.13E+05	8.84E+05
Phenol	5.72E+05	1.18E+06	2.85E+06	4.43E+06
Potassium Hydroxide Solution	7.56E+04	2.92E+05	9.09E+05	1.43E+06
Sodium Hydroxide Solution	8.01E+04	2.84E+05	8.96E+05	1.42E+06
Styrene	2.33E+06	3.82E+06	5.74E+06	8.70E+06
Sulfuric Acid	9.06E+04	2.99E+05	7.79E+05	1.29E+06
Toluene	2.51E+06	3.49E+06	7.01E+06	8.63E+06
Vinyl Acetate	2.12E+06	2.81E+06	4.26E+06	6.26E+06
Xylenes	1.96E+06	3.69E+06	6.34E+06	8.57E+06

Table 4.37 Expected Clean up Cost for Each Lading Loss Category for the 27 Chemicals of Interest

4.3.1 Expected Clean up Cost Weighted across All Car Specifications for Chemicals of Interest

To obtain the overall expected clean up cost for a chemical, given release, the expected clean up cost for each lading loss category (C_{cq}) (Table 4.37) should be multiplied by the probability that the spill occurs in that lading loss category which, in turn, can be obtained from the probability distribution for amount of lading loss presented in Chapter 3 (Table 3.7). This distribution differs for non-pressure cars compared to pressure cars. As a chemical is transported in a mix of various non-pressure and pressure cars, a weighted average of lading loss probabilities needs to be calculated using Equation 4.7 (Table 4.38).

$$M_{cq} = \sum_{i=1}^{n} (M_{iq} T_{ic} / T_c) \tag{4.7}$$

where,

M_{cq} = Percent of spills occurring in the lading loss category ‘q’ weighted over all tank car specifications used for chemical ‘c’

and as defined previously,

n = Number of types of tank car specifications used to transport the chemical of interest

M_{iq} = Percentage of spills occurring in the lading loss category ‘q’ from a tank car specification ‘i’ (available from Table 3.7)

T_{ic} = Total annual carloads of the chemical ‘c’ transported in tank cars of class ‘i’

T_c = Total annual carloads of the chemical

	Weighted Probability Distribution for Amount of Lading Loss (M_{cq})			
Chemical	**0-5%**	**>5-20%**	**>20-80%**	**>80-100%**
Acetaldehyde	19.69%	8.08%	24.23%	48.00%
Acetic Acid	19.00%	9.00%	27.00%	45.00%
Acetic Anhydride	19.00%	9.00%	27.00%	45.01%
Acetone	19.00%	9.00%	27.00%	45.00%
Acrylic Acid	19.00%	9.00%	27.00%	45.00%
Acrylonitrile	20.48%	7.03%	21.10%	51.39%
Benzene	19.00%	9.00%	27.00%	45.00%
Butanol	19.00%	9.00%	27.00%	45.00%
n-Butyl Acrylate	20.52%	6.98%	20.93%	51.58%
Cyclohexane	19.00%	9.00%	27.00%	45.00%
Ethanol	19.00%	9.00%	27.00%	45.00%
Ethyl Acetate	19.00%	9.00%	27.00%	45.00%
Ethyl Acrylate	20.37%	7.18%	21.53%	50.93%
Hydrogen Peroxide	19.00%	9.00%	27.00%	45.00%
Isopropanol	19.00%	9.00%	27.00%	45.00%
Methanol	19.00%	9.00%	27.00%	45.00%
Methyl Methacrylate Monomer	20.73%	6.70%	20.10%	52.48%
Methyl Tert Butyl Ether	19.00%	9.00%	27.00%	45.00%
Nitric Acid	19.00%	9.00%	27.00%	45.00%
Phenol	19.00%	9.00%	27.00%	45.00%
Potassium Hydroxide Solution	19.00%	9.00%	27.00%	45.00%
Sodium Hydroxide Solution	19.00%	9.00%	27.00%	45.00%
Styrene	19.06%	8.92%	26.76%	45.26%
Sulfuric Acid	19.00%	9.00%	27.00%	45.00%
Toluene	19.00%	9.00%	27.00%	45.00%
Vinyl Acetate	19.23%	8.69%	26.08%	45.99%
Xylenes	19.00%	9.00%	27.00%	45.00%

Table 4.38 Weighted Average of Lading Loss Probabilities, for the 27 Chemicals of Interest

Using the expected clean up cost for a lading loss category, C_{cq} (Table 4.37), and the probability of occurrence of that amount of lading loss, M_{cq} (Table 4.38), expected clean up cost can be calculated for each chemical using Equation 4.8.

$$C_c = \sum_{q=1}^{4} (M_{cq} C_{cq}) \qquad (4.8)$$

where,

C_c = Expected clean up cost for a chemical 'c', given spill

The expected clean up cost values are presented in Table 4.39.

Chemical	**Expected Clean up Cost ($)**
Acetaldehyde	5,606,096
Acetic Acid	2,578,017
Acetic Anhydride	4,392,421
Acetone	5,978,863
Acrylic Acid	3,608,774
Acrylonitrile	6,874,454
Benzene	6,422,367
Butanol	4,665,803
n-Butyl Acrylate	5,045,624
Cyclohexane	4,684,126
Ethanol	4,859,028
Ethyl Acetate	5,766,777
Ethyl Acrylate	6,581,974
Hydrogen Peroxide	49,669
Isopropanol	4,198,220
Methanol	5,753,933
Methyl Methacrylate Monomer	5,628,907
Methyl Tert Butyl Ether	2,312,833
Nitric Acid	627,319
Phenol	2,979,857
Potassium Hydroxide Solution	931,929
Sodium Hydroxide Solution	922,593
Styrene	6,259,709
Sulfuric Acid	834,856
Toluene	6,564,414
Vinyl Acetate	4,643,617
Xylenes	6,272,325

Table 4.39 Expected Clean up Cost, for the 27 Chemicals of Interest

4.3.2 Expected Clean up Cost for Each Tank Car Specification for Chemicals of Interest

For expected cost calculations for each tank car specification for each chemical, Equation 4.8 can be simplified as follows (Equation 4.9).

$$C_{ic} = \sum_{q=1}^{4} (M_{iq} C_{cq}) \tag{4.9}$$

where,

C_{ic} = Expected clean ups cost for a chemical ‘c’, given a spill, from tank car specification ‘i’

For example, the risk estimates for all the tank cars for benzene are presented in Table 4.40.

Chemical	Tank Car Specification	Expected Cost
Benzene	111A100W1 – INS	6,422,274
	111A100W3	6,422,274
	111J100W3 – 1/2 HS	6,422,274
	211A100W1 – INS	6,422,274
	105J100W – 1/2 HS	6,774,678

Table 4.40 Expected Clean up Cost Values for Each Tank Car Specification used for Transporting Benzene

The first four cars in Table 4.40 are non pressure cars and hence have the same M_{iq} values and hence the same expected cost which is different from the last tank car which is a pressure car. The pressure car has a higher expected clean up cost for the same set of C_{cq} values because it has a higher percent of spills occurring in the 80-100% lading loss category (Table 3.7) which has typically the highest consequence (C_{cq}). The expected cost values for all the chemical – tank car combinations are presented in Appendix G.

4.3 Consequence as a Metric for Rank Ordering Chemicals

If chemicals are rank ordered based only on the consequence term then the expected clean up cost (Table 4.39) can be used. Figure 4.17 shows the chemicals ranked in order of descending expected clean up cost (C_c), given a spill.

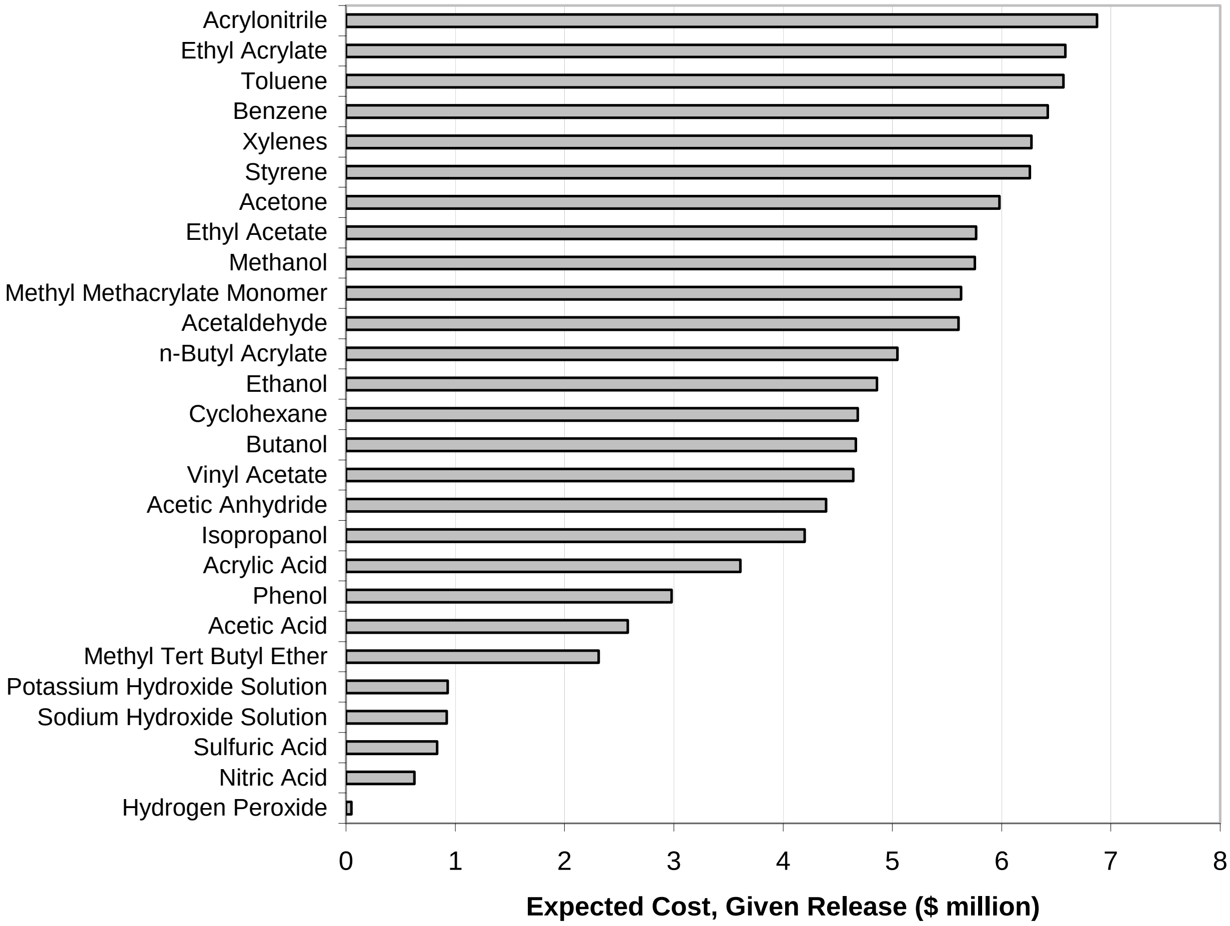


Figure 4.17 Rank Ordering of Chemicals Based on Expected Clean up Cost (C_c) given a Spill

This metric depends on chemical, soil properties, and the interaction between chemical and soil. It also depends on the cost of the remediation technologies that are used for treatment of a chemical. Hydrogen peroxide is not treated and hence is at the bottom of the series while acrylonitrile, a land-banned chemical treated using incineration and soil vapor extraction has the highest clean up cost.

The expected clean up cost is the amount required to restore a spill site given that the spill has occurred. Therefore, in that sense, expected clean up cost is an indicator of the environmental hazard posed by each of the chemicals, irrespective of the probability of release.

4.4 Conclusions

In this chapter, the consequence analysis methodology was described and conducted for the chemicals of interest. The IIRSTF QRA risk assessment model was used to assess the degree of contamination of soil and groundwater due to a chemical spill from a tank car. This was done for fifteen environmental scenarios developed based on three soil types and five groundwater depth ranges over the 48 contiguous states. The restoration cost is ascertained using the remediation technologies either suggested by the model documentation or the ones most commonly in use currently. Expected clean up cost given a spill for each chemical was calculated by combining the restoration cost with the probability of occurrence for each scenario.

CHAPTER 5

RISK ANALYSIS

Risk is defined as the product of the probability of a spill occurring, multiplied by the consequence of that spill. The probability and consequence analyses described in Chapters 3 and 4 respectively are combined to calculate the risk estimates for chemicals. In congruence with the calculations for likelihood of release and expected cost, the risk incurred is calculated for each tank car specification for a chemical and also weighted across all the tank car specifications that are used for the chemical.

5.1 Risk Calculation

5.1.1 Risk Estimates Weighted for All Tank Car Specifications for Chemicals of Interest

The conditional release probability values were developed for each chemical (Table 3.13), for the four lading loss categories (0-5%, >5-20%, >20-80%, >80-100%); the consequence analysis was conducted for the four lading loss categories for all the chemicals of interest (Table 4.37). Therefore risk estimates are obtained for each of the four lading loss categories and the overall risk of release for a chemical is the sum of the risk of release in each of the lading loss categories (Equation 5.1). The risk-per-car-mile estimates are presented in Table 5.1.

$$r_c = \sum_{q=1}^{4} r_{cq} = F_{derail} \sum_{q=1}^{4} (P_{cq} C_{cq}) \tag{5.1}$$

where,

r_c = Risk of a release for chemical 'c' ($ per car-mile)

r_{cq} = Risk of a release in the lading loss category 'q' for chemical 'c' ($ per car-mile)

and as defined previously,

F_{derail} = Car derailment rate

P_{cq} = Probability of release from a derailed tank car carrying chemical 'c', in the lading loss category 'q'

C_{cq} = Expected value of clean up of a spill for chemical 'c', in the lading loss category 'q' ($)

Chemical	Risk per Car-mile (Cents)
Acetaldehyde	20.72
Acetic Acid	6.58
Acetic Anhydride	12.70
Acetone	26.48
Acrylic Acid	6.23
Acrylonitrile	19.22
Benzene	16.81
Butanol	20.62
n-Butyl Acrylate	13.58
Cyclohexane	20.74
Ethanol	20.73
Ethyl Acetate	25.61
Ethyl Acrylate	18.93
Hydrogen Peroxide	0.11
Isopropanol	18.56
Methanol	25.65
Methyl Methacrylate Monomer	13.89
Methyl Tert Butyl Ether	10.31
Nitric Acid	1.50
Phenol	7.80
Potassium Hydroxide Solution	2.44
Sodium Hydroxide Solution	2.41
Styrene	16.20
Sulfuric Acid	3.26
Toluene	29.10
Vinyl Acetate	19.50
Xylenes	25.63

Table 5.1 Risk per Car-mile for the 27 Chemicals of Interest

To calculate the total annual risk of transporting a chemical in railroad tank cars, information on annual car-miles traveled for each chemical is required. The annual carload traffic for the chemicals is contained in the AAR TRAIN II database. The information on the average distance traveled by each chemical was obtained using the Surface Transportation Board (STB) Waybill sample for the year 2003.

The STB Waybill sample contains information on a sample of annual rail movements terminating in the United States. It also contains information on the number of carloads in the sampled waybill and the distance traveled by the shipment represented by the sampled waybill for each hazmat code. For each record, it also has information on the sampling rate used for the record and the theoretical expansion factor. The theoretical expansion factor is the inverse of the sampling rate and is used to estimate the number of carloads in the population (Expanded Carloads) from the number of carloads in the sampled waybill.

The traffic estimates from STB Waybill are somewhat different from those available from TRAIN II because unlike TRAIN II, the waybill database does not have information on shipments terminating outside the U.S.. Around 12% of the total Canada and U.S. hazardous material originations terminated in Canada (BOE 2005). After accounting for these differences, the U.S. tank car originations from the two databases are within 3% of each other. I used waybill sample data to estimate the average shipment distance for the chemicals of interest following a six-step process:

1) Waybill records (sampled waybills) are extracted for each chemical, using the hazmat code for the chemical for querying.
2) The attributes retrieved for each waybill record are the number of carloads, total distance, and the theoretical expansion factor.
3) Expanded number of carloads are estimated for each waybill record using Equation 5.2.

$$N_{wc}^{Exp} = E_{wc} N_{wc}^{Sample} \tag{5.2}$$

where,

N_{wc}^{Exp} = Expanded number of carloads for a sampled waybill ‘w’ of chemical ‘c’

N_{wc}^{Sample} = Number of carloads for a sampled waybill ‘w’ of chemical ‘c’

E_{wc} = Theoretical expansion factor for a sampled waybill ‘w’ of chemical ‘c’

4) Average Shipment distance for a chemical is calculated using Equation 5.3.

$$d_c = \sum_{w=1}^{m} (N_{wc}^{Exp} D_{wc}) / \sum_{w=1}^{m} N_{wc}^{Exp} \tag{5.3}$$

where,

d_c = Average shipment distance for a chemical ‘c’ (car-miles per car)

D_{wc} = Distance traveled for a sampled waybill ‘w’ of chemical ‘c’ (miles)

5) To obtain annual car-miles traveled by each chemical, the annual carload traffic for the chemical is multiplied by the average shipment distance obtained from the waybill database (Table 5.2, Figure 5.1) (Equation 5.4)

$$D_c = d_c T_c \tag{5.4}$$

where,

D_c = Total annual car-miles traveled by a chemical ‘c’

T_c = Total annual carloads of the chemical ‘c’

Chemical	Average Shipment Distance	Carloads	Annual Car-miles
Acetaldehyde	802	1,754	1,407,164
Acetic Acid	1,020	4,442	4,529,685
Acetic Anhydride	770	2,491	1,917,472
Acetone	824	4,128	3,400,440
Acrylic Acid	1,078	5,012	5,405,292
Acrylonitrile	673	3,174	2,135,594
Benzene	726	3,792	2,753,561
Butanol	1,168	2,285	2,668,606
n-Butyl Acrylate	1,179	4,443	5,236,875
Cyclohexane	369	4,665	1,719,659
Ethanol	772	5,310	4,101,656
Ethyl Acetate	741	1,430	1,059,387
Ethyl Acrylate	1,149	928	1,065,882
Hydrogen Peroxide	794	5,913	4,696,578
Isopropanol	935	2,544	2,378,665
Methanol	736	23,216	17,089,994
Methyl Methacrylate Monomer	1,111	6,133	6,814,131
Methyl Tert Butyl Ether	916	467	427,875
Nitric Acid	611	1,647	1,005,955
Phenol	925	12,436	11,498,574
Potassium Hydroxide Solution	911	5,561	5,068,073
Sodium Hydroxide Solution	632	86,239	54,503,048
Styrene	1,144	18,776	21,470,544
Sulfuric Acid	640	67,489	43,219,281
Toluene	999	3,000	2,997,690
Vinyl Acetate	1,126	7,236	8,148,098
Xylenes	672	7,116	4,781,169

Table 5.2 Average Distance per Carload and Annual Car-miles for the 27 Chemicals of Interest

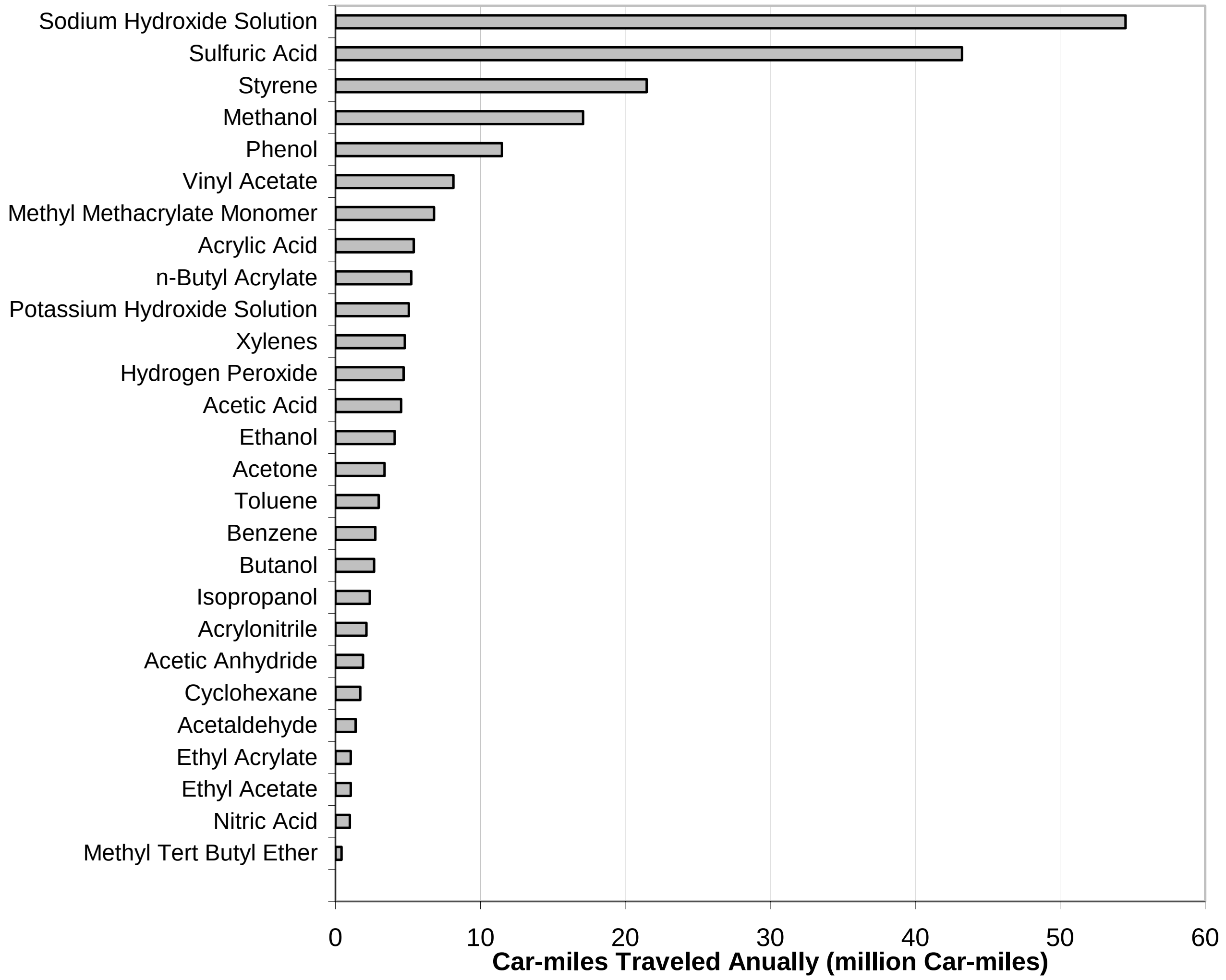


Figure 5.1 Chemicals Rank Ordered Based on Annual Car-miles Traveled

6) Annual risk for a chemical can now be calculated using Equation 5.5 (Table 5.3).

$$R_c = r_c D_c \qquad (5.5)$$

where,

R_c = Annual risk of a release for chemical ‘c’ ($)

Chemical	Annual Risk ($)
Acetaldehyde	291,517
Acetic Acid	298,159
Acetic Anhydride	243,444
Acetone	900,506
Acrylic Acid	336,587
Acrylonitrile	410,519
Benzene	462,871
Butanol	550,256
n-Butyl Acrylate	710,971
Cyclohexane	356,677
Ethanol	850,208
Ethyl Acetate	271,273
Ethyl Acrylate	201,795
Hydrogen Peroxide	5,151
Isopropanol	441,369
Methanol	4,382,757
Methyl Methacrylate Monomer	946,636
Methyl Tert Butyl Ether	44,119
Nitric Acid	15,090
Phenol	897,325
Potassium Hydroxide Solution	123,701
Sodium Hydroxide Solution	1,316,228
Styrene	3,477,286
Sulfuric Acid	1,408,015
Toluene	872,470
Vinyl Acetate	1,588,678
Xylenes	1,225,371

Table 5.3 Annual Risk for the 27 Chemicals of Interest

5.1.2 Risk Estimates for Each Tank Car Specification for Chemicals of Interest

Weighted risk estimates, as developed above, are useful for rank ordering the chemicals but for a detailed understanding, the risk incurred from each tank car specification needs to be calculated for each chemical. For risk-per-car-mile calculations, Equation 5.1 is simplified as follows (Equation 5.6):

$$r_{ic} = \sum_{q=1}^{4} r_{icq} = F_{derail} \sum_{q=1}^{4} (P_{iq} C_{cq}) \tag{5.6}$$

where,

r_{ic} = Risk of a release from tank car specification 'i' for chemical 'c' ($ per car-mile)

r_{icq} = Risk of a release, in the lading loss category 'q', from tank car specification 'i', for chemical 'c' ($ per car-mile)

P_{iq} = Probability of release from a damaged tank car specification 'i' in the lading loss category 'q' (as defined previously)

For annual risk incurred by each tank car specification, annual distance traversed by the chemical in each of the tank car specifications is calculated using Equation 5.7. The assumption for this calculation is that the average shipment distance is constant for a chemical and is independent of the tank car specification.

$$D_{ic} = d_c T_{ic} \tag{5.7}$$

where,

D_{ic} = Total annual car-miles traveled by a chemical 'c' in tank car specification 'i'

T_{ic} = Total annual carloads of the chemical 'c' transported in tank car specification 'i' (as defined previously)

The annual risk is calculated using Equation 5.8.

$$R_{ic} = r_{ic} D_{ic} \tag{5.8}$$

where,

R_{ic} = Annual risk of a release from tank car specification 'i' for chemical 'c' ($)

For example, the risk estimates for all the tank cars used for benzene are presented in Table 5.4. For the purpose of this study, I assumed that car-miles are distributed proportional to the number of shipments in each specification; or in other words, shipment distance is independent of tank car specification.

Chemical	Tank Car Specification	Risk per Car-mile (r_{ic})	Annual Risk (R_{ic})
Benzene	111A100W1 – INS	16.82	436,777
	111A100W3	16.82	22,108
	111J100W3 -1/2 HS	15.51	2,702
	211A100W1 – INS	16.82	1,221
	105J100W -1/2 HS	8.54	62
Total			462,871

Table 5.4 Risk Estimates for Each Tank Car Specification used for Benzene

The risk per car-mile and annual risk values for all chemical – tank car combinations are stated in Appendix G.

5.2 Risk as a Metric for Rank Ordering Chemicals

5.2.1 Risk per Car-mile as a Metric for Rank Ordering Chemicals

Risk per car-mile is a metric that combines both the likelihood and consequence terms. The rank ordering based on this metric shown in Figure 5.2.

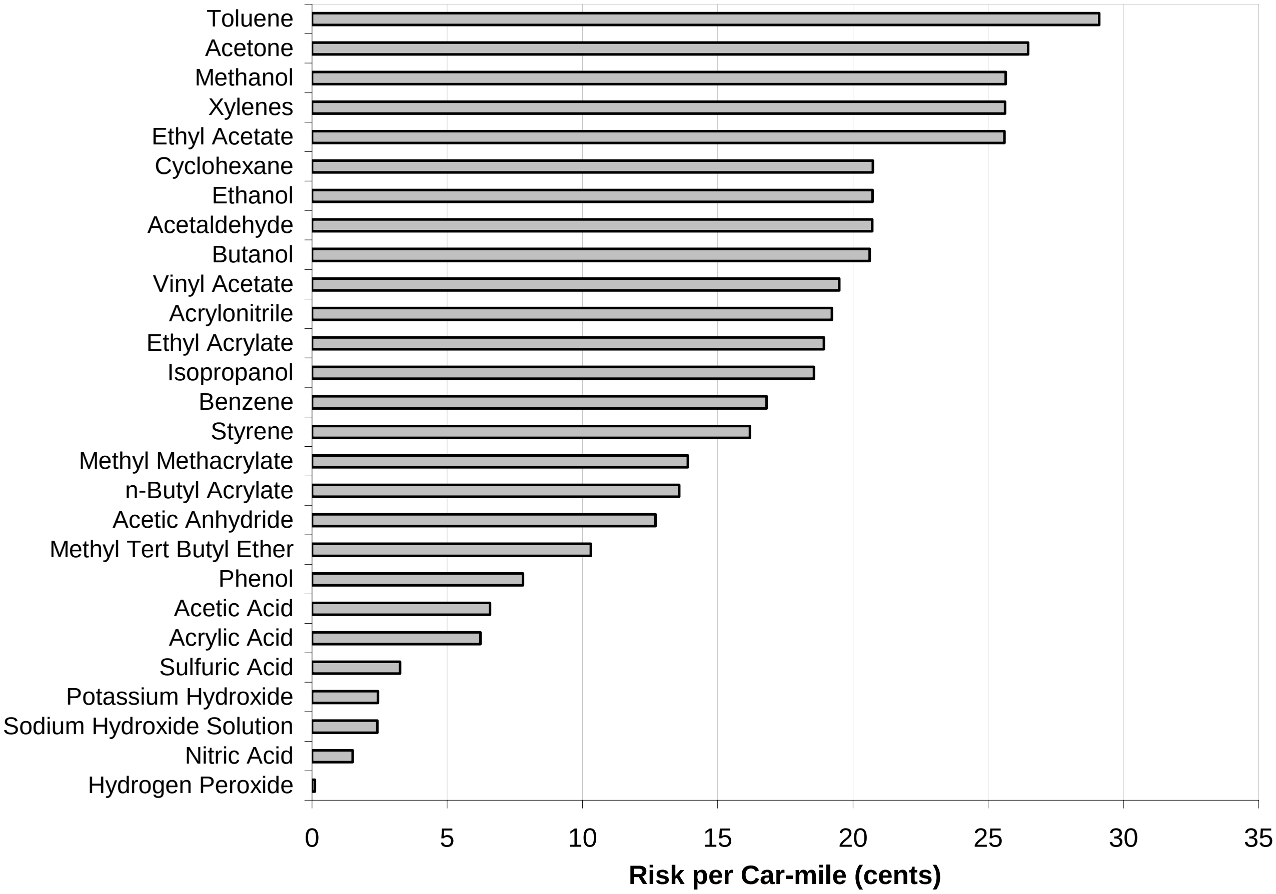


Figure 5.2 Rank Ordering of Chemicals Based on Risk per Car-mile

Toluene has the highest estimated risk per car-mile while hydrogen peroxide has the lowest. Different chemicals fall at various points along the spectrum for different metrics. For example, methyl tert butyl ether has the highest conditional probability of release (Figure 3.2), given derailment, because all its shipments, however small (Appendix A), are made in 111A100W1, but it incurs low remediation costs if spilled (Figure 4.17). The low remediation costs for methyl tert-butyl ether are attributable to the fact that the soil remaining after excavation of the first 20 ft. is assumed not to need treatment. On the other hand, acrylonitrile has the highest consequence term (Figure 4.17), but it has a low likelihood of release (Figure 3.2). The low probability of release for acrylonitrile is because about 49% of its shipments were in pressure cars, in the year 2004. But when we use the risk-per-car-mile metric, both methyl tert-butyl ether and acrylonitrile fall somewhere in the middle. Toluene, which has a high clean up cost as well as a high probability of release (transported primarily in non-insulated 111A100W1 cars), has the highest risk per car-mile. Acetone, methanol and xylenes, that have the second, third and the fourth highest risk-per-car-mile estimate, follow a trend similar to toluene. Hydrogen peroxide occupies the bottom of the scale, which is primarily due to its low remediation cost. I assumed that hydrogen peroxide spills generally require little if any treatment; with the only cost being for emergency response. Also, around 80% of its shipments are in alloy steel tank cars (though the other 20% are in aluminum cars), which also reduces its risk. In fact, only acrylic acid has a lower conditional probability of release than hydrogen peroxide (Figure 3.2), again, due to transportation in alloy cars. Benzene and styrene have a high consequence term but a release probability lower than many other products because they are transported in insulated cars, hence their lower risk-per-car-mile estimate. Another chemical that has a high consequence term but a moderate risk per car-mile is ethyl acrylate. Like acrylonitrile, around 46% of shipments of ethyl acrylate were transported in pressure cars in the year 2004, hence it has a low likelihood term and consequently a low risk-per-car-mile estimate.

The inorganic compounds, i.e., sodium hydroxide, potassium hydroxide, sulfuric acid and nitric acid, all have a very low consequence term, which is also the primary reason for their low risk-per-car-mile estimates. There are three reasons for this. The soil that is excavated is treated using neutralization, which is less expensive than soil treatment techniques for most other chemicals. The soil remaining after excavation of the upper 20 ft. is not subjected to in-situ treatment. And with the exception of nitric acid, ground water treatment would generally not be required for these chemicals.

5.2.2 Annual Risk as a Metric for Rank Ordering Chemicals

Annual risk combines the risk-per-car-mile estimates with the exposure term for these chemicals. The average shipment distance and annual carloads differ for each chemical. Consequently chemicals travel different numbers of car-miles annually. A chemical with a very high risk per car-mile might have a low annual risk if it has low exposure, and vice versa. Figure 5.3 shows the chemicals rank ordered based on their annual risk.

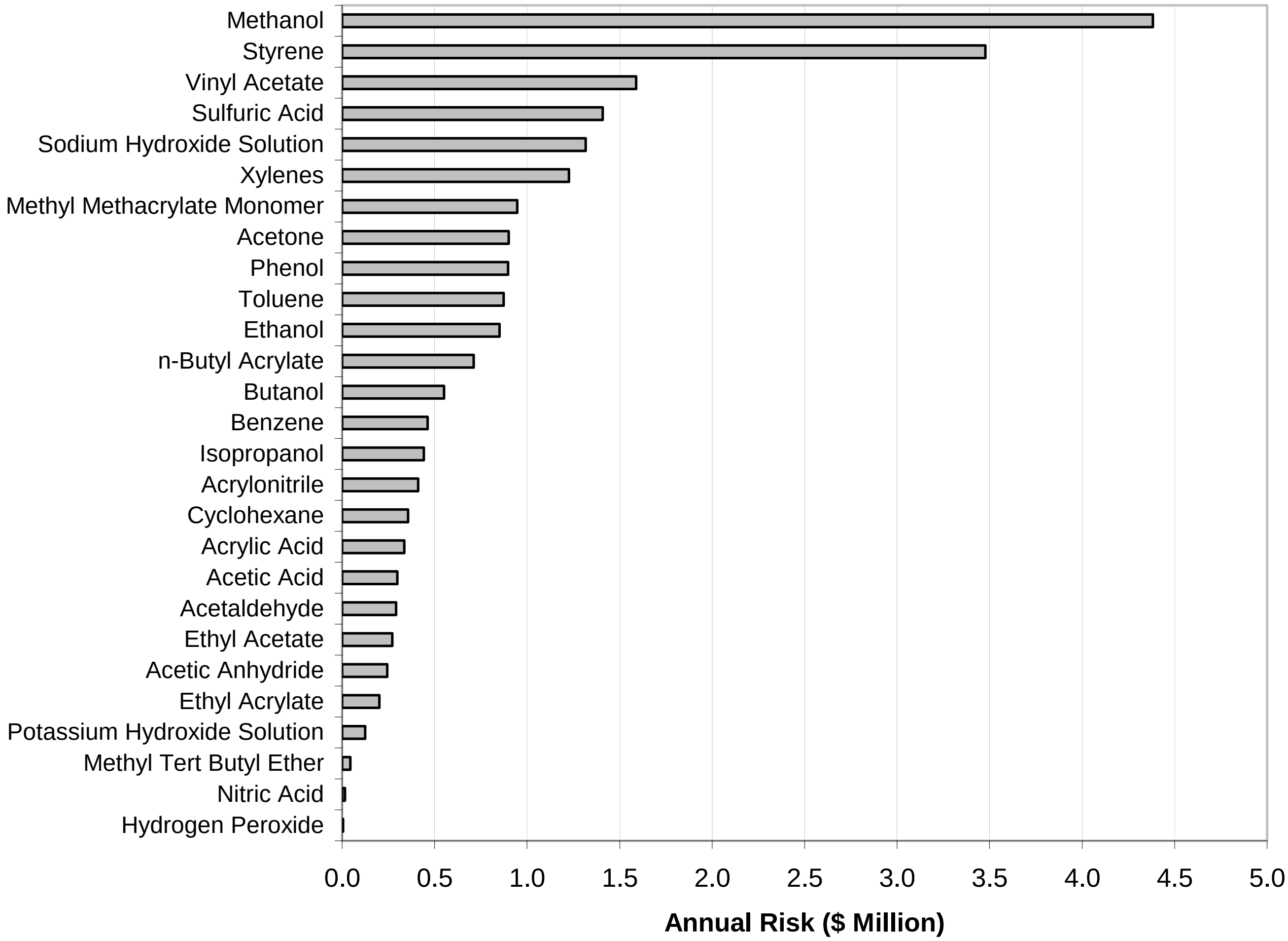


Figure 5.3 Rank Ordering of Chemicals Based on Annual Risk

Methanol and styrene have the highest annual risk. Methanol has a high risk per car-mile as well as high annual car-miles. Styrene was in the middle third of the risk-per-car-mile range but it has high annual number of car-miles traveled. A noticeable shift in rank is realized for sodium hydroxide and sulfuric acid. These two chemicals have very low risk-per-car-mile estimates (Figure 5.2) but the highest and the second highest annual number of car-miles (Figure 5.1), hence the annual risk incurred by these is quite high (Figure 5.3).

5.3 Risk Profiles

The metrics discussed above, i.e., the risk per car-mile and annual risk cover all possible spill scenarios to yield a single number and hence are good metrics for comparison and ranking purposes. But from the point of view of a risk manager it might also be appropriate to consider all possible consequences and their probabilities of occurrence together. Risk profiles, also known as "f-N" curves (f = frequency and N = number), are an effective method to show the full spectrum of risk,

"Risk profiles are a graphical means of depicting the relative and/or absolute likelihood of different levels of consequences." (Arthur D. Little Inc 1996b).

The risk profile typically has the various possible values of consequence severity on the horizontal axis, in this case the remediation costs for the 60 spill scenarios (three soil types x five groundwater depth ranges x four lading loss categories). The cumulative annual frequency of a spill incurring a remediation cost equal to or higher than a certain remediation cost is represented on the vertical axis. The annual release frequency for a scenario is calculated using Equations 5.9 and 5.10.

F_{cqjk} = Annual Car Derailment Rate x P_{cqjk} (5.9)

where,

F_{cqjk} = Annual frequency of a spill occurring in the lading loss category 'q' over a groundwater depth region 'j' on a soil type k' for a chemical 'c'

P_{cqjk} = Given derailment, probability of a spill occurring in the lading loss category 'q' over a groundwater depth region 'j' on a soil type k' for a chemical 'c'

Annual car derailment rate is simply the product of the car derailment rate per car mile with the annual car miles traveled by the chemical. Assuming that the probability of occurrence of a spill in a particular lading loss category for a chemical (P_{cq}) is independent of the probability of occurrence of a certain soil type – groundwater depth combination (P_{jk}), Equation 5.9 can be simplified to Equation 5.10.

$$F_{cqjk} = (F_{derail} d_c T_c)(P_{cq} P_{jk}) \tag{5.10}$$

and as defined earlier,

F_{derail} = Car derailment rate per car-mile

P_{cq} = Probability of release from a derailed tank car carrying chemical ‘c’, in lading loss category ‘q’

P_{jk} = Probability of occurrence of a groundwater depth region ‘j', on a soil type ‘k’, at spill location

Using the value of F_{derail} (= 1.26×10^{-7} cars derailed per car-miles) and information on d_c and T_c from Table 5.2, P_{cq} from Table 3.13 and the values of P_{jk} from Table 4.35, the release frequency is evaluated for each spill scenario using Equation 5.10. The consequence values are taken from Tables 4.22 through 4.33. A representative risk profile was generated for benzene (Table 5.5, Figure 5.4). Both annual release frequency and consequence values are tabulated in Table 5.5 in decreasing order of consequence.

Annual Release Frequency	Cumulative Annual Release Frequency (f)	Consequence ($) (N)
0.0014	0.0014	37,005,434
0.0022	0.0037	27,294,797
0.0013	0.0050	21,432,449
0.0004	0.0055	11,978,880
0.0061	0.0116	10,706,596
0.0037	0.0153	10,127,668
0.0012	0.0165	9,326,207
0.0026	0.0191	8,834,318
0.0018	0.0209	7,748,994
0.0024	0.0234	7,748,994
0.0039	0.0272	7,748,994
0.0009	0.0282	7,116,326
0.0000	0.0282	6,264,802
0.0000	0.0282	6,264,802
0.0008	0.0290	6,264,802
0.0000	0.0290	6,264,802
0.0016	0.0306	6,264,802
0.0009	0.0315	5,556,877
0.0011	0.0326	5,556,877
0.0015	0.0340	5,556,877
0.0023	0.0363	5,556,877
0.0000	0.0363	3,709,060
0.0000	0.0363	3,709,060
0.0005	0.0368	3,709,060
0.0000	0.0368	3,709,060
0.0010	0.0378	3,709,060
0.0014	0.0392	3,407,596
0.0009	0.0401	3,019,668
0.0003	0.0404	2,499,207
0.0049	0.0453	2,338,716
0.0006	0.0459	2,186,318
0.0027	0.0485	2,138,236
0.0029	0.0515	2,001,138
0.0016	0.0531	1,816,788
0.0003	0.0533	1,703,784
0.0004	0.0537	1,703,784
0.0005	0.0542	1,703,784
0.0008	0.0550	1,703,784
0.0010	0.0559	1,552,987
0.0005	0.0565	1,391,337
0.0030	0.0595	1,347,394
0.0021	0.0616	1,282,628
0.0018	0.0634	1,149,969
0.0011	0.0645	1,132,968
0.0000	0.0645	1,115,373
0.0000	0.0645	1,115,373

Annual Release Frequency	Cumulative Annual Release Frequency (f)	Consequence ($) (N)
0.0002	0.0647	1,115,373
0.0000	0.0647	1,115,373
0.0003	0.0650	1,115,373
0.0006	0.0656	887,539
0.0013	0.0669	715,966
0.0006	0.0675	481,382
0.0008	0.0683	481,382
0.0010	0.0693	481,382
0.0016	0.0710	481,382
0.0000	0.0710	295,568
0.0000	0.0710	295,568
0.0003	0.0713	295,568
0.0000	0.0713	295,568
0.0007	0.0720	295,568

Table 5.5 Probability and Consequence Values for the Risk Profile for Benzene

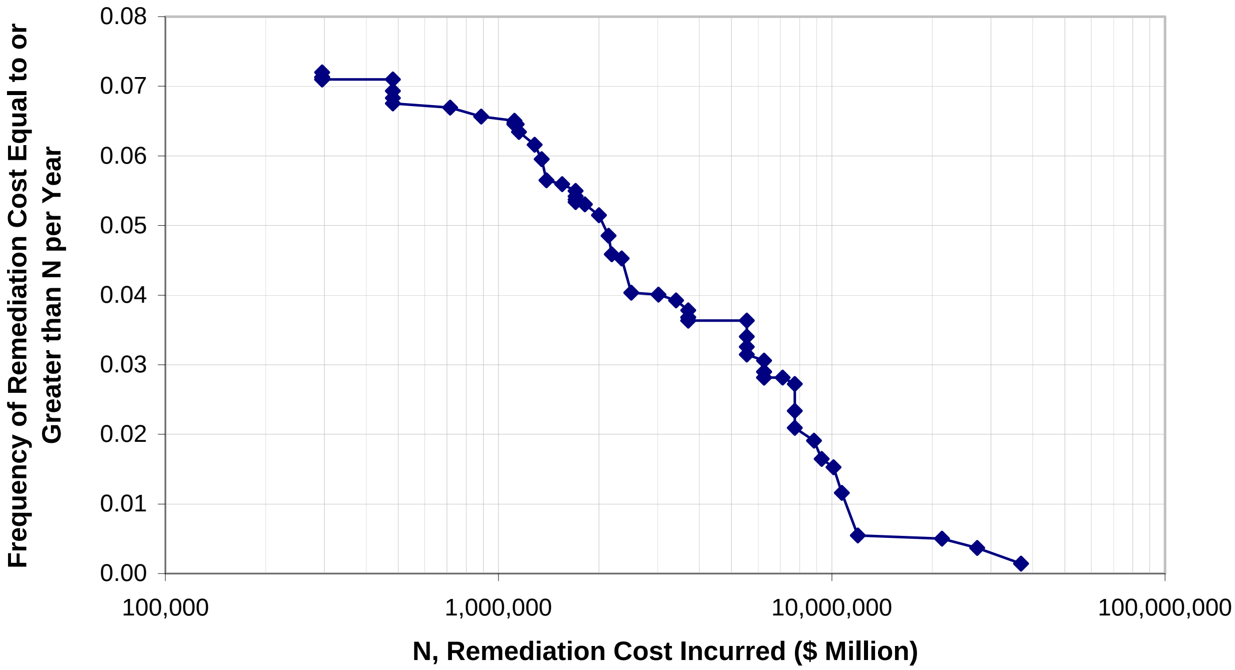


Figure 5.4 Risk Profile for Environmental Impact of Benzene

Risk profiles for other chemicals are presented in Appendix H. Use of risk profiles enriches the risk information available to decision makers and enables them to better understand various criteria for risk management and mitigation purposes. The risk profile in Figure 5.4 represents probability numbers weighted across all tank car specifications for a chemical. Risk profiles can also be developed for each individual tank car specification for each chemical by simplifying Equation 5.10 to Equation 5.11.

$$F_{ciqjk} = (F_{derail} d_c T_{ic})(P_{iq} P_{jk}) \qquad (5.11)$$

where,

F_{ciqjk} = Annual frequency of a spill occurring in the lading loss category ‘q’ over a groundwater depth region ‘j’ on a soil type k’ from a tank car specification ‘i’ transporting chemical ‘c’

and as defined earlier,

P_{iq} = Probability of release from a damaged tank car specification ‘i’ in the lading loss category ‘q’

5.4 Conclusions

Risk-per-car-mile and annual risk estimates were developed for each chemical for each tank car specification individually as well as weighted across all the tank car specifications. Chemicals were rank ordered based on weighted risk per car-mile as well as weighted annual risk. The rank ordering was compared with the rank ordering based on other metrics, i.e., weighted conditional probability of release and expected clean up cost. Chemicals that have a high probability of release might not have a high consequence and vice versa and hence have a low risk per car-mile. Similarly chemicals with a low risk per car-mile might have high annual car-miles traveled and consequently a high annual risk.

The risk data are also presented in the form of risk profiles (f-N curves) and an example is developed. These provide a useful way of viewing the entire spectrum of clean up costs and their frequency of occurrence. Overall, the choice of metric will depend on the purpose of the study.

CHAPTER 6

COST ANALYSIS

There are two key elements involved in analyzing the cost of replacing or retrofitting tank cars currently used for transportation of the hazardous materials under study, the capital cost and the operating expenses. The capital cost is the cost of the tank car. The cost of a tank car is affected in part by its damage resistance features. The greater thickness of the tank and the extra protective features, such as, head shields and the protective housing for top fittings, increase the material and construction expense for these cars. Therefore, costs differ with tank car specifications. The difference in the cost of various specifications of tank cars can range from one to tens of thousands of dollars. This variation in costs leads to one of the principal questions of this study: is it cost-effective to use an enhanced safety tank car, compared to continued use of the current tank car? In addition to specification, the value of a tank car is also affected by factors such as age and volumetric capacity.

The second key element of the cost is the operating expense. Railroad operating or variable expenses continue throughout the life of the tank car; and are grouped into four categories by the Interstate Commerce Commission (ICC) (now known as the Surface Transportation Board, STB) (Hay 1982):

1. Maintenance of way and structures
2. Maintenance of equipment
3. Transportation – rail line
4. General and administrative costs

When accounting for changes in operating expense these must be accounted for. The STB publishes commodity specific transportation cost figures that can be used for this purpose.

Operating expenses increase with traffic levels and replacement of current tank car specifications with more damage-resistant cars will generally result in an increase in traffic due to the lower capacity of these cars. Four-axle railcars in unrestricted interchange service are limited to a maximum GRL of 286,000 lbs (AAR 2004). However, US DOT regulations specify that tank cars in hazardous materials service built after November 30, 1970, cannot have a GRL greater than 263,000 lbs (49CFR179.13 2005, Barkan 2005). The GRL is defined as the total weight of the tank car and its lading. I assume that most tank cars used for transporting the chemicals in this study are operated at or near this maximum GRL of 263,000 lbs. The addition of most types of protective features will increase the tare (empty) weight of the car, and due to the maximum GRL constraint there will be a corresponding reduction in the capacity (Barkan et al 2005, Barkan 2005), (an exception being removal of bottom outlets, which does not lead to reduction in capacity). As a result more shipments of the alternative specification are required for the same amount of chemical transportation, thereby increasing the operating cost.

Decrease in capacity may also have a bearing on expenses in terms of capital costs. If the utilization rate of the cars remains constant, more cars of the alternative specification will be required to make up for the lost capacity of the alternative specification cars compared to the cars currently in use, thus further increasing the capital cost.

In this chapter, estimates of the capital cost are developed for the tank car specifications under consideration as well as estimates of unit variable cost.

6.1 Capital Cost

The AAR UMLER database contains data on a wide range of railcar attributes, including the cost of the car. Table 6.1 shows the fields of interest for the purpose of this research:

Car Initial
Car Number
Ledger Value
Gallon
Insulation Type
Shipping Spec
Original Cost
Cert of Const
Year Built

Table 6.1 Attributes of Interest from the UMLER Database for Tank Cars

The term “Shipping Spec” refers to the tank car specification (DOT/AAR specification) and the term “Cert of Const” refers to the certificate of construction (COC) number. The COC number indicates the order under which the tank car was constructed. Before a tank car is placed in service, its design needs to be approved by the AAR tank car committee (49CFR179.5 2005). The COC contains a summary of the principal engineering design features for each group of tank cars constructed for use on North American railroads. There were more than 30 different tank car specifications for which cost estimates were required (Table 3.8). The set of fields specified in Table 6.1 was extracted for all the tank car specifications under study.

6.1.1 Estimation of Tank Car Cost

I had to estimate what the current cost of tank cars built to various specifications would be today. Tank cars are long-lived assets, with lives typically in the range of 30-40 years. Because of inflation, the cost of a new car can be expected to have increased. According to car builders (Dalrymple 2005), size of the car is the other primary factor affecting cost due to the differential amount of material needed. Thus, within any given specification, it was surmised that age and volumetric capacity are the two variables likely to have the greatest effect on the cost of a tank car. Prices vary from year to year due to market factors and inflation. Therefore, the effect of the variable “year built” was considered. Analysis was conducted using year 2003 as the base year (or year 0) for calculation of a tank car’s age from the variable “year built”. Tank cars are built to various sizes for transporting different chemicals. Therefore “gallon capacity” (Table 6.1) was considered as one of the variables for analysis.

For each tank car specification, records were grouped by the COC number. This was done because tank cars built under a single COC are generally built at the same time and have the same, or similar, original cost and age. However, due to minor variations in construction, volumetric capacity for individual tank cars built under the same COC varies slightly from car to car. Therefore, average volumetric capacity for all the cars on each COC was calculated. Subsequently, a multiple linear regression (model indicated by Equation 6.1) was conducted on the data for each tank car specification to explore the underlying cost model. The significance of the regression model was tested at $\alpha = 0.05\%$.

$$Y = \beta_0 + \beta_1 X_1 + \beta_2 X_2 + \varepsilon \qquad (6.1)$$

where,

Y = Capital cost of a tank car specification under study

X_1 = Age of the tank car

X_2 = Capacity of the tank car

β_i = Regression coefficients

ε = Random error in the prediction model

Example data for one of the most common tank car specification, the insulated 111A100W1, are presented in Table 6.2. After grouping the records obtained from UMLER by the COC number, a total of 4,400 observations were obtained for insulated 111A100W1 tank cars. Using these 4,400 observations, the regression coefficients for volumetric capacity and age were significant at the 95% confidence level because the *t* *statistic* (Table 6.2) for both the contributing variables, i.e., age and capacity, fall in the rejection region ($\alpha = 0.05$, degrees of freedom (df) = 4,397,

$t_{age} = -118.86 > t_{0.025,\,df} = -1.96$ and $t_{capacity} = -4.00 > t_{0.025,\,df} = -1.96$).

Regression Statistics	
Multiple R	0.8795
R Square	0.7735
Adjusted R Square	0.7734
Standard Error	8,077.51
Observations	4,400

ANOVA	**df**	**SS**	**MS**	**F**	**Significance F**
Regression	2	9.80E+11	4.90E+11	7,507.01	0.0000
Residual	4,397	2.87E+11	6.52E+07		
Total	4,399	1.27E+12			

	Coefficients	**Standard Error**	**t Stat**	**P-value**
Intercept	74,364.40	771.58	96.38	0
Gallon Capacity	-0.13	0.03	-4.00	6.35E-05
Age	-1,342.17	11.29	-118.86	0

	Lower 95%	**Upper 95%**
Intercept	72,852	75,877
Gallon Capacity	-0.19	-0.07
Age	-1,364	-1,320

Table 6.2 Regression Statistics for Insulated 111A100W1 Tank Cars

It is worth mentioning that although the trend observed for cost with age of the tank car was as expected, i.e., the cost decreases with increase in age, that observed for cost with gallon capacity cannot be readily explained. It was expected that an increase in capacity of the tank car would lead to an increase in the cost of the tank car owing to a larger amount of material used for the construction of the car but the regression coefficient was negative (Table 6.2) (β_2 = -0.13) which implies that increase in capacity will lead to a decrease in the cost. Therefore, to further verify the results of the statistical analysis, the cost data were plotted against volumetric capacity and age and a simple linear regression was conducted on each of the two variables (Figures 6.1 and 6.2). The prediction models for cost of the tank car for each of the two variables are shown respectively in Equations 6.2 and 6.3.

$$Y_1 = \beta_{01} + \beta_{11}X_1 + \varepsilon_1 \tag{6.2}$$

where,

Y_1 = Capital cost of a tank car specification under study, using age as the independent variable

X_1 = Age of the tank car

β_{i1} = Regression coefficients for predicting cost using age of the tank car as the independent variable

ε_1 = Random error in the prediction model

$$Y_2 = \beta_{02} + \beta_{22}X_2 + \varepsilon_2 \tag{6.3}$$

where,

Y_2 = Capital cost of a tank car specification under study, using capacity as the independent variable

X_2 = Capacity of the tank car

β_{i2} = Regression coefficients for predicting cost using capacity of the tank car as the independent variable

ε_2 = Random error in the prediction model

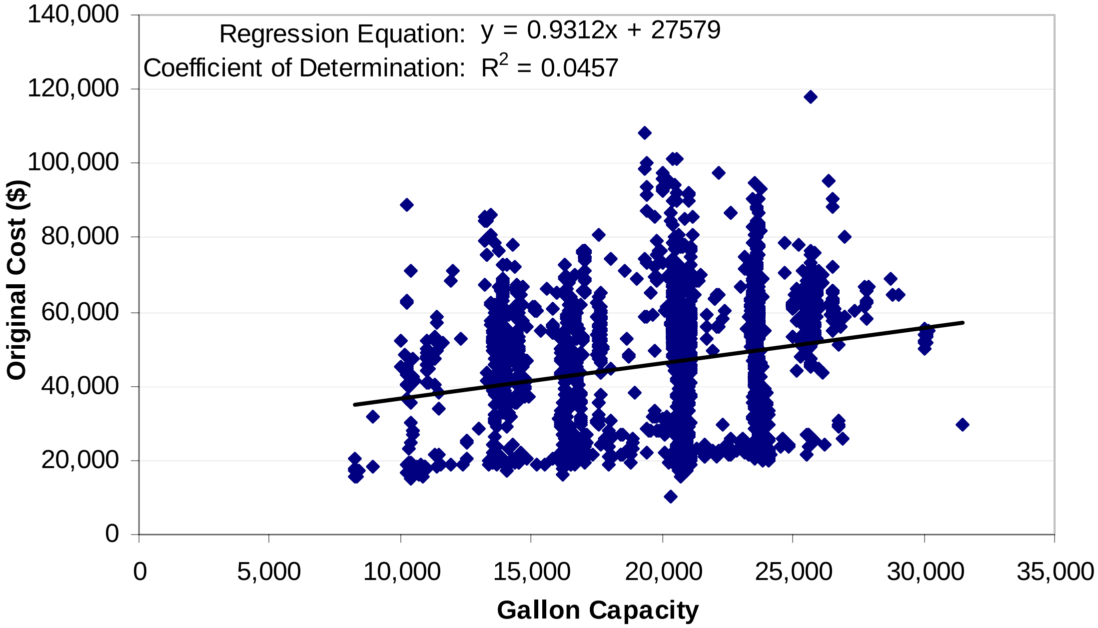


Figure 6.1 Relationship Between Gallon Capacity and Original Cost of Tank Cars

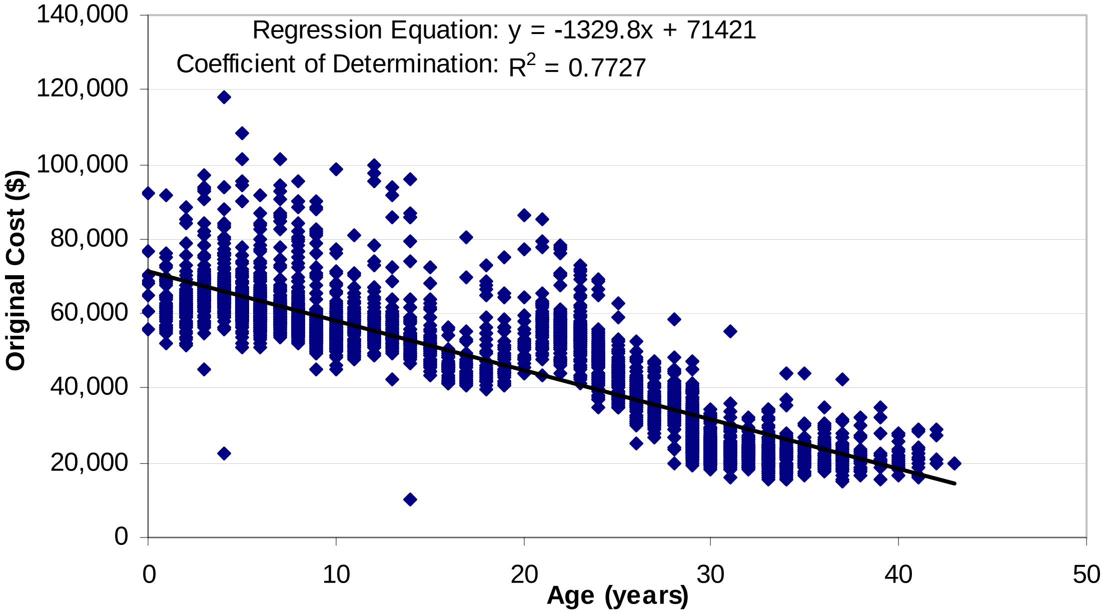


Figure 6.2 Relationship Between Age and Original Cost of Tank Cars

The plots and corresponding statistics indicated that age (R-squared value = 0.7727 or $\alpha = 0.05$, degrees of freedom (df) = 4,398, $t_{age} = -122.26 > t_{0.025,\ df} = -1.96$) was an important factor affecting cost of the tank car and the model obtained (Figure 6.2) was quite similar to that obtained using multiple regression. But the volumetric capacity did not come out to be an important factor (R-squared value = 0.0457) and the predicted model (Figure 6.1) was quite different from the one obtained using multiple linear regression. The regression coefficient for the volumetric capacity was positive which is in complete contradiction with the multiple regression model. Therefore, the analysis of the relation between capacity and cost of the tank car was inconclusive. There could be several possible reasons for this result, e.g., the model assumed for multiple regression might not be correct. A linear model was assumed to predict the relationship (Equation 6.1) whereas in reality the underlying model might have a different functional form.

There might also be other variables that affect the cost but were not included in the model, e.g., the presence of risk reduction options like a headshield increases the cost of the car but this field was not extracted as the UMLER database does not always have accurate information on presence of absence of the risk reduction options. Nonetheless, it was realized that this analysis required a more in-depth analysis that was beyond the scope of this study. Therefore it was assumed that tank car age is the primary parameter affecting tank car cost within each specification and volumetric capacity was dropped from further analysis.

For developing the most up-to-date tank car cost estimates, it was deemed reasonable that only the latest data be used for analysis. Therefore, simple linear regression was conducted on the last 5 years (1998-2003) data (Figure 6.3) for insulated 111A100W1 tank car, which included 703 records for different COC car groups.

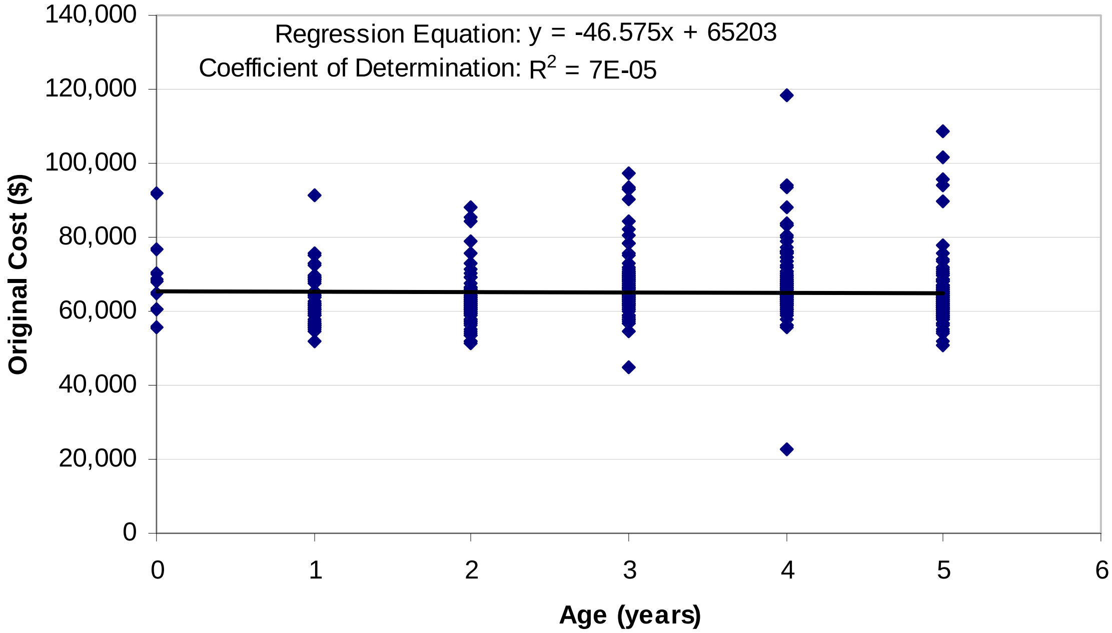


Figure 6.3 Relationship Between Age and Original Cost of Tank Cars based on Last 5 Years Data

There was no indication of a trend in car cost over the five-year time period (R-squared value ≈ 0); therefore, the average cost of cars over the interval, 1998-2003, was considered to be representative of the current cost for each tank car specification (Table 6.3; Figure 6.4).

Tank Car Specification	Average Cost ($)	Number of Certificates of Construction
105J100W – 1/2 HS	79,171	22
105J200W – 1/2 HS	75,599	4
105A300W	81,837	5
105J300W – 1/2 HS	80,509	95
105J400W – 1/2 HS	85,240	13
105A500W	92,996	14
105J500W – 1/2 HS	79,007	47
111A100W1 – NI	59,305	258
111A100W1 – INS	65,035	703
111A100W2 – NI	57,834	30
111A100W2 – INS	68,796	6
111A100W3	76,238	5
111A100W5 – NI	56,694	91
111A100W5 – INS	63,834	5
111A100W6 – NI	109,866	8
111A100W6 – INS	105,266	5
111S100W1 – INS, 1/2 HS	69,617	1
111S100W2 – INS, 1/2 HS	68,178	3
112S200W – NI, 1/2 HS	70,362	12
112J340W – 1/2 HS	78,597	119
211A100W1 – NI	63,847	27
211A100W1 – INS	66,440	283

Table 6.3 Average Cost of Tank Car Specifications of Interest
(Based on UMLER Data from 1998-2003)

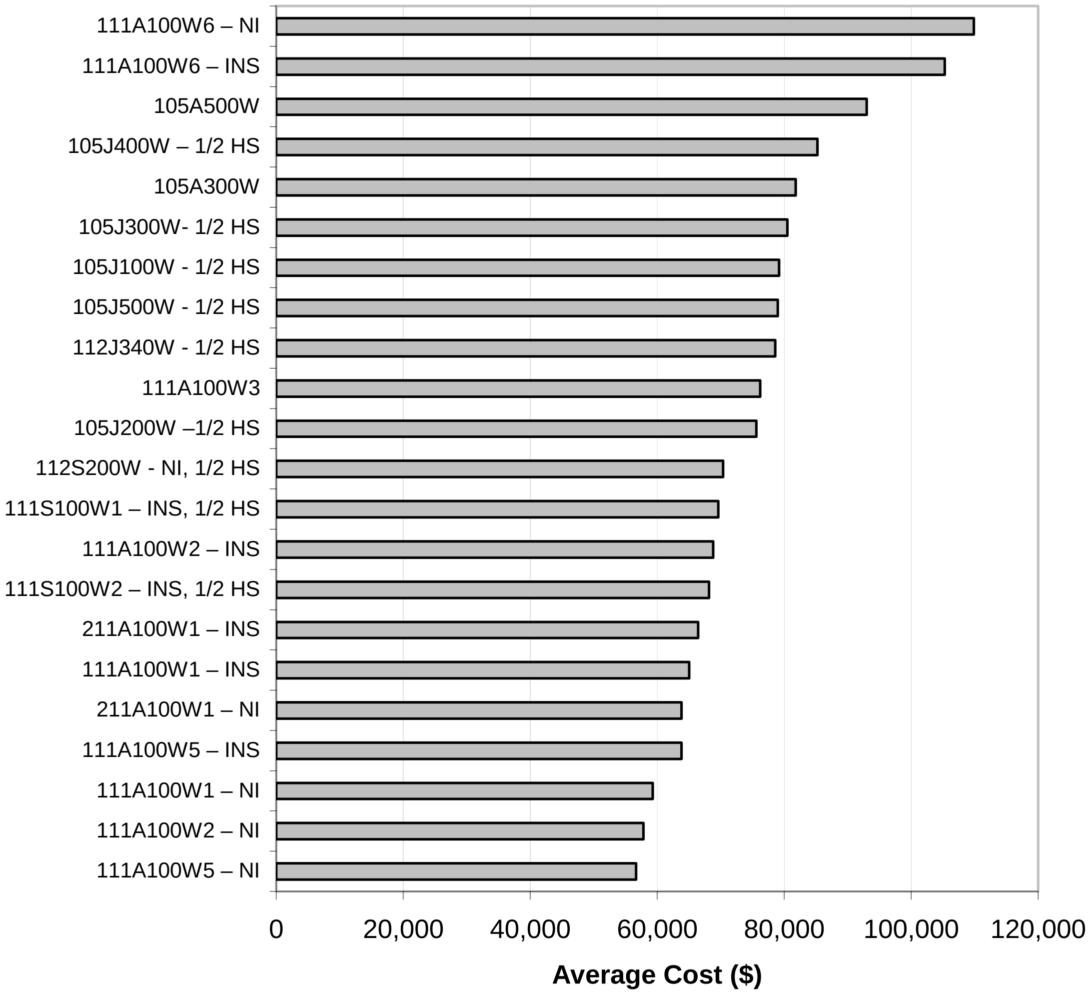


Figure 6.4 Estimated Current Cost of Various Tank Car Specifications
(Based on Recent UMLER Data)

Apart from developing an estimate of the cost of the tank car, it was also necessary to know the incremental cost of risk reduction options because the current car specification was also an option if it was equipped with one or more risk reduction options. A new tank car equipped with various risk reduction options differs in cost from a tank car that is retrofitted with the same enhancement. The cost of the same option retrofitted will be more expensive than if it is part of the original construction (Table 6.4). Estimates of the cost of various risk reduction options were determined based on discussion with railroad tank car, and chemical industry personnel.

Risk Reduction Option	New car	Retrofit
Half Head Shield	$2,000	$3,000
Full Head Shield	$4,000	$6,000
Jacket	$7,000	$21,000
Top Fittings Protection (TFP)	$4,000	$6,000

Table 6.4 Cost Estimates for Risk Reduction Options

There were several tank car specifications for which the last five years data were not available in UMLER, so direct cost estimates could not be developed for these. However, costs were estimated for these specifications by adding or subtracting the cost(s) of the applicable risk reduction options from the cost of the base tank car specification which is similar in configuration to the specification under study and for which the cost is available from UMLER (Table 6.3). Using the information in Tables 6.3 and 6.4, I estimated the cost for other tank car configurations (Table 6.5, Figure 6.5).

Tank Car Specification	Base Tank Car Specification	Cost Estimate ($)
105A100W	105J100W – 1/2 HS	77,171
105S100W – 1/2 HS	105J100W – 1/2 HS	79,171
105J100W – full HS	105J100W – 1/2 HS	81,171
105J300W – full HS	105J300W – 1/2 HS	82,509
105J500W – full HS	105J500W – 1/2 HS	81,007
111A100W1 – NI, 1/2 HS	111A100W1 – NI	61,305
111A100W1 – NI, full HS	111A100W1 – NI	63,305
111A100W1 – INS, 1/2 HS	111A100W1 – INS	67,035
111A100W1 – INS, full HS	111A100W1 – INS	69,035
111A100W2 – NI, 1/2 HS	111A100W2 – NI	59,834
111A100W2 – NI, full HS	111A100W2 – NI	61,834
111A100W2 – INS, 1/2 HS	111A100W2 – INS	70,796
111A100W2 – INS, full HS	111A100W2 – INS	72,796
111A100W3 – 1/2 HS	111A100W3	78,238
111A100W3 – full HS	111A100W3	80,238
111A100W4	111A100W2 – INS	68,796
111A100W4 – 1/2 HS	111A100W2 – INS	70,796
111A100W4 – full HS	111A100W2 – INS	72,796
111A100W5 – NI, 1/2 HS	111A100W5 – NI	58,694
111A100W5 – NI, full HS	111A100W5 – NI	60,694
111A100W5 – INS, 1/2 HS	111A100W5 – INS	65,834
111A100W5 – INS, full HS	111A100W5 – INS	67,834
111A100W7 – NI	111A100W6 – NI	109,866
111A100W7 – INS	111A100W6 – INS	105,266
111S100W1 – NI, 1/2 HS	111S100W1 – INS, 1/2 HS	62,617
111S100W2 – NI, 1/2 HS	111S100W2 – INS, 1/2 HS	61,178
111A60W1 – NI	111A100W1 – NI	59,305
111A60W1 – INS	111A100W1 – INS	65,035
112A200W – NI	112S200W – NI, 1/2 HS	68,362
112A200W – INS	112S200W – NI, 1/2 HS	75,362
112J200W – 1/2 HS	112S200W – NI, 1/2 HS	77,362
112S200W – INS, 1/2 HS	112S200W – NI, 1/2 HS	77,362
112S200W – NI, full HS	112S200W – NI, 1/2 HS	72,362
112T200W – NI, 1/2 HS	112S200W – NI, 1/2 HS	70,362
112T200W – INS, 1/2 HS	112S200W – NI, 1/2 HS	77,362
112A340W – NI	112J340W – 1/2 HS	69,597
112A340W – INS	112J340W – 1/2 HS	76,597
112J340W – full HS	112J340W – 1/2 HS	80,597
112S340W – NI, 1/2 HS	112J340W – 1/2 HS	71,597
112S340W – INS, 1/2 HS	112J340W – 1/2 HS	78,597
112S340W – NI, full HS	112J340W – 1/2 HS	71,597
112J400W – 1/2 HS	112J340W – 1/2 HS	78,597

Table 6.5 Cost Based on UMLER Data Supplemented by Risk Reduction Option Cost Data

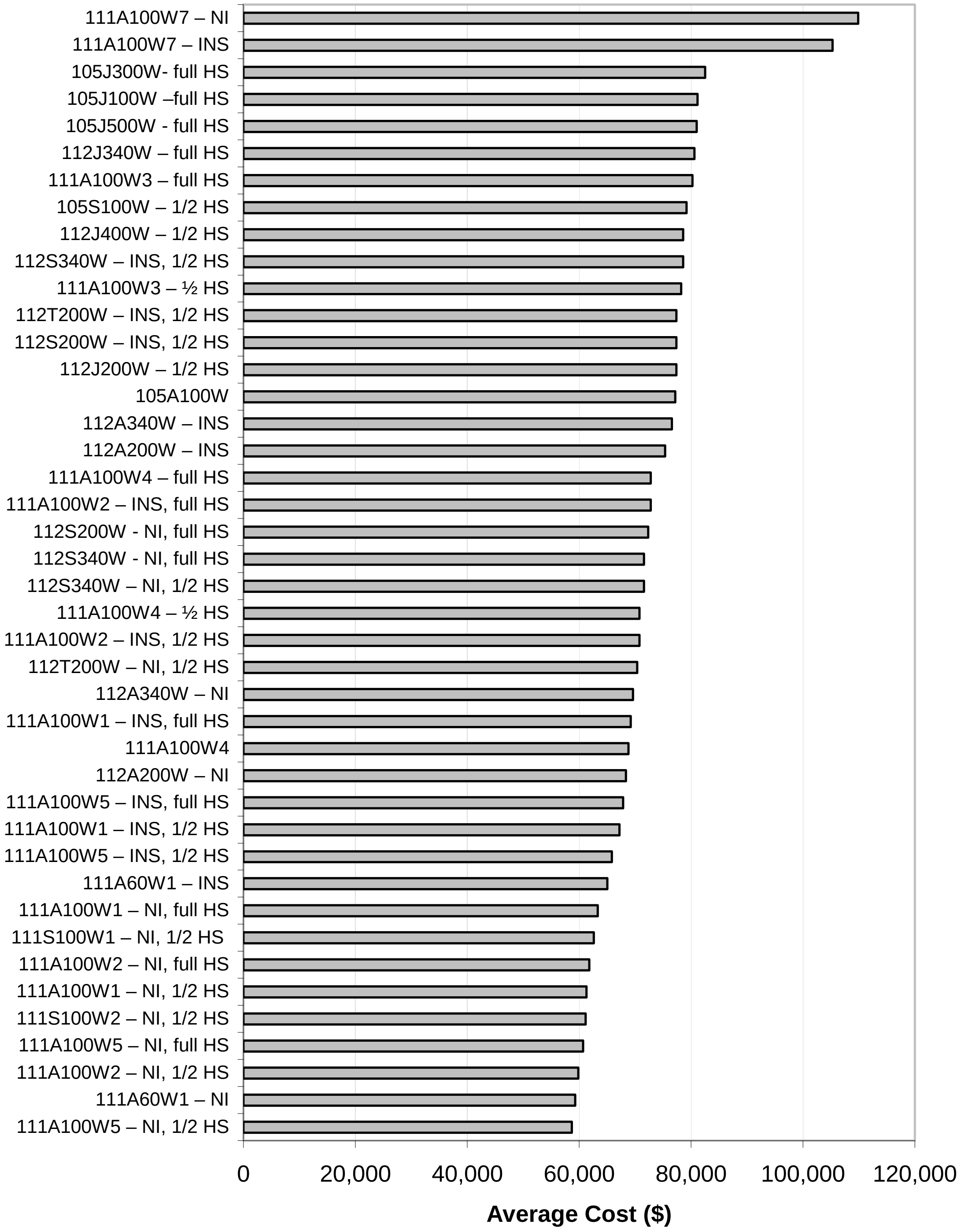


Figure 6.5 Cost Based on UMLER Data Supplemented by Risk Reduction Option Cost Data

6.2 Operating Cost

Operating cost is positively related to the amount of traffic. The number of shipments required to transport a certain quantity of a product depends on the lading capacity of the car. The lading capacity of the tank varies with the density of the lading and the different risk reduction options installed on the tank car.

6.2.1 Variation in Lading Capacity with the Density of the Lading

Depending on the density of the chemical, the same tank car specification is manufactured in different sizes such that the capacity of the tank car can be optimized with the constraint on the GRL. Tank car size does not have to vary with the density of the product, but if a tank car were available only in a single size then the capacity would be underutilized for higher density chemicals and would be insufficient for the lower density chemicals. Therefore, to maximize the efficiency, the size of the tank car is optimized to the product it transports. A tank car size optimization program, IlliTank (Saat & Chua 2004) was used for tank car capacity calculations.

6.2.1.1 Tank Car Size Optimization Program

This program calculates the optimal length of the tank car by minimizing the difference between the GRL and the sum of tare weight of the car and the weight of the lading. The tare weight of the car is determined using the inputs on internal diameter, head and shell thickness and details on insulation and other risk reduction options for the car (indicated in Table 6.6). The weight of the lading is determined using the product density which is also an input to the program (Table 6.6). Among the inputs, the GRL for the tank cars currently in use (Table 3.8) is always 263,000 lbs; but one of the alternatives considered is the enhanced safety 111 tank car with 286,000 lbs GRL. All pressure cars, e.g., 105 and 112, have top fittings protection. For insulated cars, 2” of ceramic fiber is assumed to be the insulating material with a density of 4.5lbs/cubic feet. The program has a default value of 33,000 lbs for the total weight of non tank components but allows the user to either specify another default value or to specify the detailed component weights. I used the default value of 33,000 lbs for all of the capacity calculations presented here.

Input Parameters	**Values**
Gross Rail Load (GRL) (pounds)	263,000 lbs/286,000 lbs
Product Density (pounds per gallon)	Depends on the product
Shell Thickness (inches)	Refer Table 3.9
Head Thickness (inches)	Refer Table 3.9
Tank Inside Diameter (inches)	110.25”
Insulation Thickness (inches)	2” (wherever applicable)
Insulation density (pounds per cubic feet)	4.5 lbs/cubic feet (wherever applicable)
Outage (%)	2%
Head shield Option	None/Half/Full
Head shield thickness (inches)	0.3804” (if tank jacket is present) 0.5” (if tank jacket is not present)
Top Fittings Protection Option	Yes/No
Tank Jacket Option	Yes/No
Tank Jacket Thickness (inches)	0.1196”
Detailed Component Weights Options	Not Selected
Lump-sum Detailed Component Weights (pounds)	33,000 lbs

Table 6.6 Inputs Required by the Tank Car Size Optimization Program (IlliTank)

Using Illitank I calculated the relationship between product density and the optimal size for one of the most commonly used tank car specifications, a non-insulated 111A100W1 (Figures 6.6 and 6.7). Typically, the volumetric capacity of the 111 tank car class ranges from about 13,000 gallons up to about 30,000 gallons (Barkan 2005, GATX 1994).

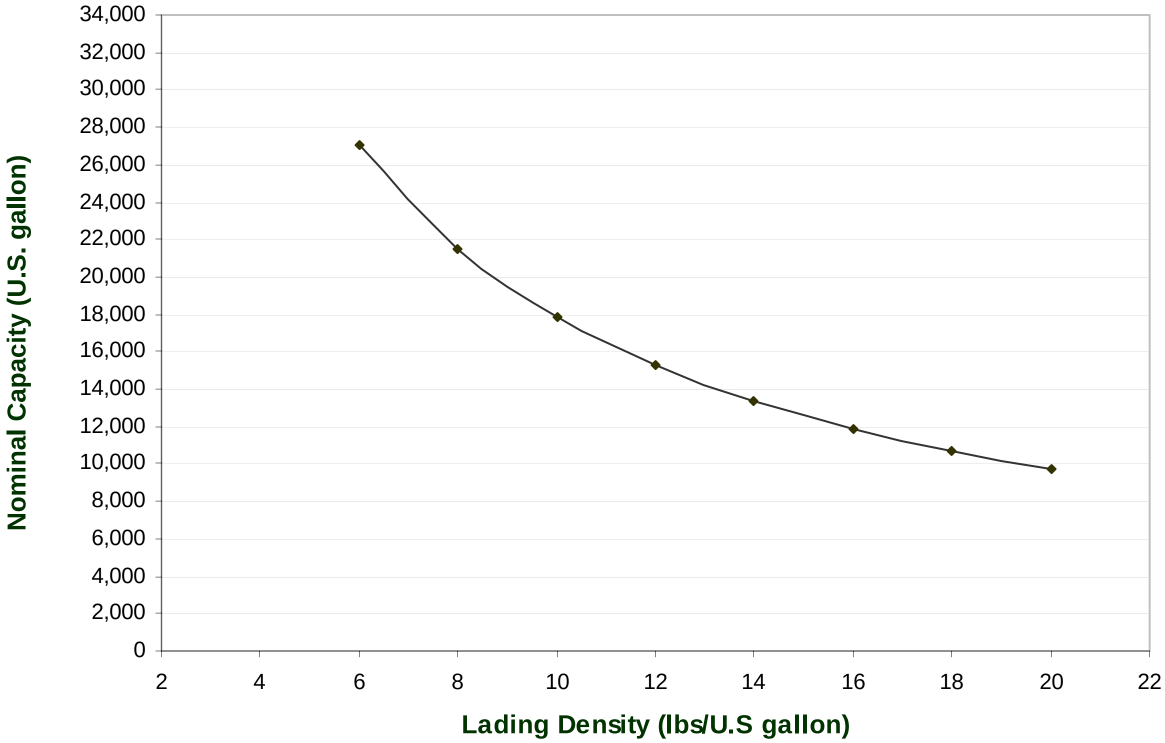


Figure 6.6 Variation in Tank Capacity (gal) with the Density of the Lading

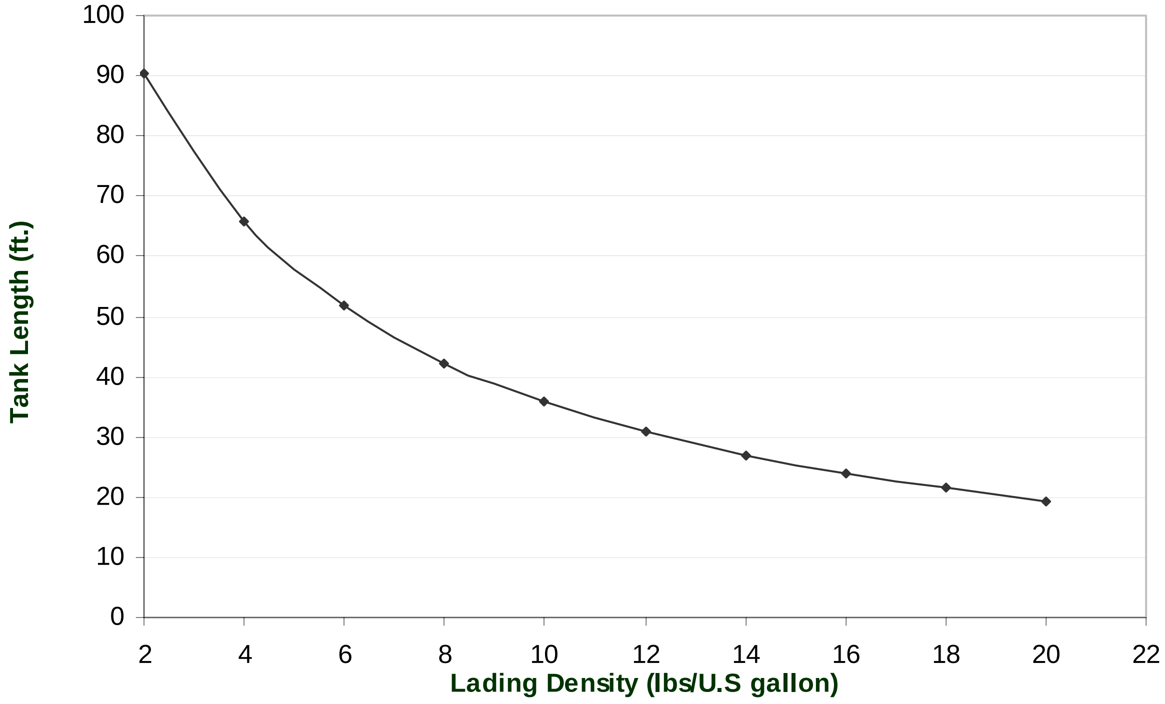


Figure 6.7 Variation in Tank Length with the Density (lbs/gal) of the Lading

The tank car size optimization program can be used for any basic carbon steel tank car class, as well as for cars with various risk reduction options. For each of the carbon steel cars considered in this study, the program was used to calculate the capacity of each tank car for every chemical (Appendix A). The density of stainless steel (501 lbs/ft^3) (Mcelwee 2005) is similar to the density of carbon steel (490 lbs/ft^3). Therefore capacity of alloy cars was calculated assuming the density of stainless steel as equal to that of carbon steel. The program cannot calculate capacities of aluminum tank cars.

6.2.1.2 Variation in Lading Capacity with Installation of Risk Reduction Features

In general, increasing the damage resistance of a car also increases its weight. The GRL of most tank cars currently permitted to transport hazardous materials is 263,000 lbs (263K) which is equal to the maximum GRL that a tank car can have without a DOT exemption (49CFR179.4 2005). Depending on whether the maximum GRL regulation is waived or not, following are three possible scenarios regarding how the extra weight of the risk reduction options could be accommodated:

- Changing to a more robust 263K car *(the weight penalty option)*: The alternative car, being equipped with damage resistant features, will have extra weight and because it has the same GRL as the current car, its lading capacity would be less than the current car. The number of shipments required, for a given quantity of lading, will increase, leading to a small increase in exposure to accidents, although the consequence of a carload spill will be slightly reduced due to the lower quantity of material involved. This approach increases the operating expenses as the number of shipments increases. In the cost benefit study conducted by Barkan et al (1991) this approach was used. As a result of this analysis, the 10 ESCs in that study (all halogenated hydrocarbons) were required to be transported in cars whose specifications matched or exceeded those of 105S200W or 112S200W, both specifications being more damage resistant than 111 tank cars but with lower lading capacity.

- Installing protective features on the current car without a constraint on the GRL *(no weight penalty option)*: The current car is made more damage resistant by retrofitting or building it with risk reduction features. In this scenario the GRL is permitted to exceed 263K by the amount of additional weight added by the risk reduction features. So, the lading capacity of the car remains the same and so do the number of shipments required for transportation, which in turn implies that the operating expenses do not change. Also, this approach leads to no changes in exposure and consequences. Also known as the 263K+ option, it has been exercised under waivers from the US DOT gross weight limitations, provided that the extra weight of the tank car is in the form of safety features. The first example of this was an exemption (E – 11241) granted by the US DOT to Rohm and Haas in March 1994 for 105J tank cars to transport butyl acrylate (DOT RSPA 2004, LaValle & Rader 2004). Since then various other shippers have requested and received similar exemptions.

- Changing to a 286K car *(weight advantage option)*: If the maximum GRL of the alternate cars is increased to 286K, the lading capacity will be higher than the capacity of the current car despite the additional weight of the enhanced safety features. This scenario enhances the damage resistance of the car and reduces exposure to accidents. However, if an accident does occur, the consequence from a carload of spill will potentially be higher due to a larger amount of lading involved. The reduction in shipments also means that the operating expense will decrease. This approach was used by the AAR tank car committee in developing the requirements for 286K tank cars (AAR 2004, Barkan 2005). To take the maximum safety advantage of the extra weight, a multi-attribute decision making

> analysis was used to determine which safety enhancements should be incorporated in the new 286,000 lbs tank car specification to most efficiently enhance its safety (Barkan 2005).

To calculate changes in operating cost, an estimate of the unit variable cost of transporting chemicals was needed.

6.2.2 Variable Cost of Transportation

Variable cost of transportation was obtained from the 2001 STB Costed Waybill database which contains cost and revenue information for a stratified sample of waybills for all rail carriers that terminated at least 4,500 revenue carloads, in any of the three preceding years (STB 2005). The cost is developed using the Uniform Rail Costing System (URCS) which is a general purpose costing system used by STB to calculate variable and total unit costs for U.S. Class I railroads (STB 2005). This database also consists of information regarding carloads, tons and ton-miles of a commodity transported each year. Using this information, the operating (or variable) cost per car-mile for a loaded average-weight tank car transporting ‘Chemicals or Allied Products’ is estimated to be $1.48. This figure was used in conjunction with the number of car-miles required for different chemicals and tank car specifications to determine the change in operating costs for various alternatives.

The underlying costing model for URCS does not include the risk cost associated with transporting the chemical. Quantification of environmental liability that the railroads incur in hazardous material transportation is one of the principal contributions of the current study. The risk-per-car-mile metric (Table 5.1) is an indicator of how much risk railroads incur when transporting a carload of a chemical.

Cost-benefit analysis requires the ability to calculate changes in operating cost that result due to changes in tank car design. With the unit variable cost estimate and the ability to calculate the capacity for any tank car specification, this could now be accomplished. Operating cost changes will be discussed in detail in Chapter 7 under cost-benefit analysis.

6.3 Conclusions

Cost Analysis involved estimation of capital cost and operating cost involved in transporting a commodity. The capital cost estimates for the tank cars were obtained using the UMLER database assuming that the age of the car is the principal factor affecting its capital cost. This cost might be more accurately estimated if a more in-depth statistical analysis was conducted that thoroughly investigated the effects of gallon capacity and any other variables affecting tank car cost.

Operating expense is a product of the unit variable cost for transporting chemicals and the traffic volume for the chemical. The unit variable cost estimate was obtained using the

STB Costed Waybill database. The traffic volume for every chemical was assessed using the AAR TRAIN II database but with changes in the tank car specification used for transporting a chemical, the traffic volume also changed due to the difference in capacity of the alternative tank car specification compared to the ones currently in use. Therefore, for assessing the changes in operating expense it was also necessary to calculate the change in capacity and hence the change in the number of carloads required for transporting equal quantities of a commodity using different tank car specifications. This was achieved using the tank car size optimization program, IlliTank. The next chapter discusses the cost benefit analysis that combines the risk results from Chapter 5 and the capital cost and variable cost results from this chapter to investigate which alternative tank car specifications would cost effectively reduce the transportation risk for the chemicals of interest.

CHAPTER 7

COST-BENEFIT ANALYSIS: REPLACEMENT SCHEDULES

In the year 2000, approximately 95% of the annual carload traffic of the chemicals considered in this study was transported in non-pressure cars. Among these non-pressure cars, the most commonly used were 111A100W1 tank cars, carrying about 54% of the annual carloads (Figure 7.1). Pressure cars transported only 4% of the traffic.

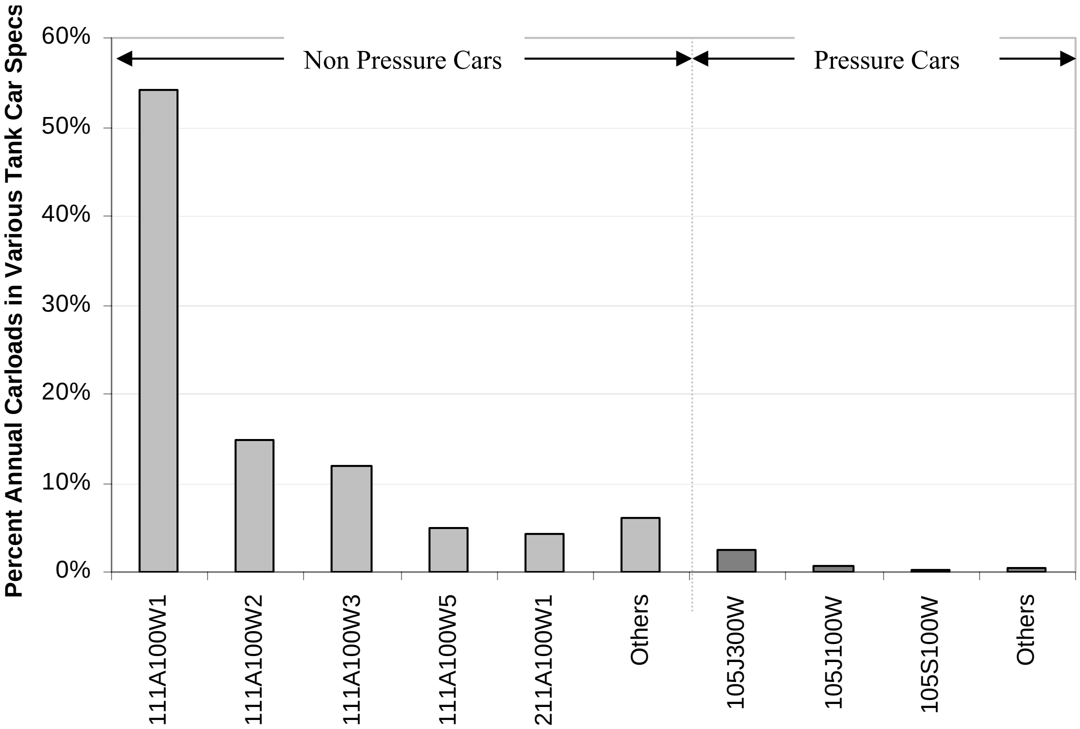


Figure 7.1 Percent Distribution of Carloads by Tank Car Specifications
(for 38 chemicals of interest for the year 2000)

Use of non-pressure cars is driven by economics and regulatory requirements, which do not require use of a more robust specification for these products. Non-pressure cars are more economical than the pressure cars because, in general, they have fewer risk reduction features and hence lesser material is used for their construction, which leads to:

- lower cost of the tank car, compared to a pressure car, and
- lower weight of the tank and hence a higher capacity than a pressure car with an equal maximum GRL. Due to their larger capacity, fewer non-pressure cars are required to carry the same amount of material than pressure cars. Consequently, this reduces both the operating and capital expense compared to pressure cars.

For example, the non insulated 111A100W1 has the lowest cost (Figure 5.3) and highest capacity for of the products of interest (Appendix A). On the other hand, it has the highest conditional probability of release among all the carbon steel cars (Figure 3.1); but it is the combination of cost and capacity that makes it the most economical car for transporting more than half the annual carload traffic of the chemicals of interest. While the economic efficiency of this car is desirable for transport of many products, spills of some products can lead to significant financial consequences. Use of a more robust car reduces the risk of these spills but incurs extra costs. Thus, the question: whether investment in more damage resistant cars is cost justified, i.e., whether the decrease in clean up risk, achieved by use of more damage resistant cars than are currently used, will offset the extra capital and operating costs incurred as a result of the process of replacement. Barkan et al (1991) conducted a net present value (NPV) analysis for assessing the cost effectiveness of replacing non-insulated 111A100W1 tank cars with

105A300W and 105A500W cars. They assumed that all ten of the halogenated hydrocarbons considered had the same risk and that the car replacement occurred in one year and found that the investment was cost beneficial.

In my analysis, I have extended and expanded upon the method used by Barkan et al (1991) to consider a variety of chemical risk levels and a much wider variety of car designs and replacement schedules. This analysis also uses the NPV approach. If the NPV is positive, the investment is considered to be cost effective. If the NPV is negative, the investment is not cost effective.

Whether a particular replacement is cost effective or not depends on:

- the chemical: Different chemicals pose different degrees of risk of environmental clean up risk. From Tables 5.1 and 5.3 it is evident that there is nearly an order of magnitude of difference among the chemicals considered in this study. If the risk is very low to begin with, then it is less likely to be cost-effective than if the risk is high.
- the current tank car specification and the alternative tank car specification: The differences in conditional release probability, capital cost and capacities are the parameters that affect the economics of the replacement. While the degree of improvement in conditional probability of release will affect the magnitude of benefit achieved in terms of reduced risk, the decrease in capacity will affect the number of carloads required to transport the same amount of chemical and hence the capital cost and operating costs associated with its transportation. Therefore,

the conditional release probability, cost and capacity together influence whether it would be economically feasible to use a particular specification in place of the current specification.

- the time span over which the replacement is scheduled. For a chemical with a high risk-per-car-mile value it might be cost effective to replace all the cars at once, whereas for a chemical that has an intermediate risk per car-mile, a slower replacement schedule might be cost effective.

I conducted cost-benefit analyses to determine the circumstances when it would or would not be economically rational to upgrade. The inputs required for this analysis were:

1.• List of Alternatives: An exhaustive list of tank cars considered for this study was presented in Table 3.8. The list of tank cars that are considered as alternatives is a subset of the above list and depends on the tank car specification being replaced. Any tank car specification (in Table 3.8) that has a lower release probability than the current tank car specification is considered as a possible alternative.

2.• Replacement Schedule: This indicates the time frame over which the current fleet gets replaced.

3.• Costs: Present value of the differential capital and operating costs of replacement incurred over the lifespan of the car.

4.• Benefits: Present value of the benefits that will accrue as a result of the replacement over the lifespan of the car.

7.1 Replacement Schedules

The rate at which the current cars are phased out of the fleet and replaced with more robust cars affects the economics of the replacement. This is because, depending on the replacement schedule, we might also have to account for the possible opportunity cost due to the reduced economic life of the current fleet. Depending on the replacement schedule, different cost and benefit terms must be considered.

Barkan et al (1991) assumed immediate replacement of the complete current fleet by the alternate tank car specifications, in their cost benefit analysis. Because of the unusually high cost of environmental clean up of spills of halogenated hydrocarbons, immediate replacement was a cost-beneficial option (Barkan 1991). However, the lower environmental risk of the chemicals considered in this study suggested that this might not be the case for them. Many, if not all, of these chemicals rank lower than the chlorinated solvents in terms of their hazards to the environment. Depending on the degree of risk posed by the chemical, three plausible scenarios might arise. A chemical can be so hazardous to the environment that immediate upgrade to an enhanced car is warranted, thus implying an immediate replacement scenario. By contrast, the hazard from a chemical may be so low that no change in tank car is warranted. Then there could be chemicals that pose an intermediate degree of risk, such that a slower replacement of the fleet could be called for. Consequently, I considered three replacement schedules that bounded the problem:

1. Immediate Replacement
2. Ten-year Retrofit/Replacement
3. Attrition-based Replacement

For chemicals for which the clean up cost risk is high, as in the case of the chlorinated solvents, immediate replacement might be more cost effective than a slower replacement schedule. I tested this by using the attrition-based replacement with data on halogenated hydrocarbons from Barkan et al (1991). The NPV was indeed lower than obtained using immediate replacement. The values obtained were \$44.43 million for the 105A500W and \$32.05 million for the 105A300W, compared to \$94.7 million and \$60.5 million, respectively, obtained by Barkan et al (1991) for the immediate replacement. Conversely for chemicals with a lower risk per car mile, attrition or ten-year retrofit schedule might be more cost-effective options.

This analysis also uses the NPV approach because, irrespective of the manner in which the replacement takes place, both the benefits and some of the costs will accrue for many years in the future. Therefore it is necessary to account for the time value of money over the entire period being analyzed.

7.1.1 Net Present Value

The net present value of an investment is the present (discounted) value of future cash inflows minus the present value of the investment and any associated future cash outflows (Anthes 2003).

NPV takes into account the time value of money. An investment A might yield more benefits over the lifetime of a project compared to investment B but B may still have a higher NPV if it returns the benefits in less time than investment A. The costs to be incurred or benefits to be obtained in the future are discounted to current dollars by using a discount factor for each year in the future. The discount factor is calculated using a constant discount rate. So, both benefits and costs incurred in the future are not valued as highly as they would if they were incurred today. The farther into the future, the higher the discounts.

The general form of NPV equation is:

$$\mathrm{NPV} = \sum_{n=0}^{N} \frac{B_n - C_n}{(1+d)^n} \tag{7.1}$$

where,

N = Time span over which NPV is calculated

B_n = Benefit from enhanced tank car in year n

C_n = Extra cost of enhanced tank car in year n

d = Discount rate

The discount factor for the n^{th} year is $1/(1+d)^n$.

In this analysis, NPV is calculated based on the nominal lifetime of a tank car, i.e., 30 years. If the status quo were maintained, this assumes that the tank car fleet would be renewed completely after 30 years. Tank cars sometimes operate longer than this but in fact the difference in costs and benefits accrued more than 20 years in the future are so small that they will have little effect on the outcome. Therefore, the NPV provides an economic comparison between the values of the various changes being considered with respect to the status quo.

7.1.1.1 Choice of Discount Rate for the Cost Benefit Analysis

Cost benefit analysis is conducted for projects that incur costs and generate benefits over a period of time. Often two or more projects compete for funding and often these projects will have cost and benefit streams spread over different time spans. Therefore, for the purpose of comparison and decision-making these streams should be consolidated into a single number, which is achieved by calculating the net present value of the project (Sassone & Schaeffer 1978). But to account for the time value of money, the future costs and benefits need to be discounted to current dollar terms (King County OMB 2005).

The cost effectiveness of a project depends critically on the discount rate selected for the project. The net present value of a project can be greater than or lower than zero depending on the chosen discount rate. A higher discount rate penalizes the projects that have costs incurred at the outset and benefits accruing later, whereas, a project where costs accrue all throughout the life of the project may actually benefit from a higher discount rate, hence its importance. Nevertheless, there is no single value that can be assigned to this parameter. In fact, not only the numerical value of the discount rate but the meaning of discount rate itself is a matter of some controversy. Some advocate the use of Social Time Preference Rate (STPR) theory that argues in favor of a value lower than the market rate (Sassone & Schaeffer 1978). But there are others that argue in favor of the Social Opportunity Cost of Capital (SOCC) that is based on the idea that public sector investment displaces a lot of capital away from private sector and hence a higher discount rate should be adopted (Sassone & Schaeffer 1978). There are various other schools of thought, e.g., some espouse the idea of a single long-term rate while others prefer using different rates for different periods (Preez 2004).

I reviewed the literature to find out the typical values in use for this parameter. There have been several studies that have considered this question and identify the values used by other countries or their agencies. The World Bank uses a rate of 10% per annum (Preez 2004) while the U.S. Forest Services use a much lower discount rate, e.g., 4% unlike some other government institutions like water related federal agencies (Preez 2004) that use a rate based on SOCC and hence is higher. The most typical value used for the discount rate in South Africa is 8% (Preez 2004) while the UK uses a 4% rate for long-term social projects (Evans & Sezer 2002). At the same time the Treasury in the UK prefers a 6% rate for public sector projects (Evans & Sezer 2002); the authors reflect that although the 6% value embraces both the SOCC and the STPR considerations, it is at the top of the range of 4-6%. But for projects with a span of 50 or more years, the Treasury recommends the lower end of the range. At the same time, Preez (2004) estimates a rate of 10.1% for the Working for Water Programme (WfWP), a public sector application, based on SOCC as well as STPR considerations.

The U.S. federal government recommends a real discount rate of 7% for public investments and regulatory programs (Circular A-94 1992). This is because the marginal pretax rate of return of an average investment in the private sector, in the recent years, is approximately 7%. The government bases its recommendation on the fact that public investment displaces private investment and consumption and therefore to simultaneously comply with both sides of the argument, the base case analysis should be done at 7% but a sensitivity analysis on discount rate should accompany these calculations. The circular also clarifies that the nominal and the real discount rate should never be mixed in an analysis where the nominal rate reflects expected inflation. The real discount rate is obtained by adjusting the nominal discount rate for expected inflation. An approximate value can be obtained for real rate by subtracting the inflation from the nominal discount rate (Circular A-94 1992). But a more accurate formula (Equation 7.2) is suggested in a proposal by the King County Office of Management and Budget (2005) for discount policy rate considerations. It also suggests using 7% as the real discount rate and that the use of rates lower than 3% and higher than 10% should be amply justified.

$$R_r = ((1 + R_{nom})/(1 + R_i)) - 1 \tag{7.2}$$

or,

$$1 + R_r = (1 + R_{nom})/(1 + R_i)$$

where,

R_r = Real discount rate

R_{nom} = Nominal discount rate

R_i = Rate of inflation

A real discount rate of 7% was used for this research. The rate of inflation being 3.38% (Financial Trend Forecaster 2005), the nominal discount rate value of 10.62% is obtained from Equation 7.2. Using the notation from Equation 7.2, Equation 7.1 can also be written thus:

$$\mathrm{NPV} = \sum_{n=0}^{N} \frac{B_n - C_n}{(1+R_r)^n} = \sum_{n=0}^{N} \frac{(B_n - C_n)(1+R_i)^n}{(1+R_{nom})^n} \tag{7.3}$$

Equation 7.3 is a general template that will be used here; the notations for the discount rate and rate of inflation will be followed throughout, but those for the benefits and cost terms will change, depending on the particular replacement schedule being addressed.

7.1.2 Attrition-based Replacement

In this schedule 1/30th of the fleet is replaced each year with new cars. Instead of replacing the old cars with new cars of the same specification, the fleet is replenished by new cars of the one of the alternative specifications considered. At the end of 30 years the fleet will be entirely composed of tank cars of the alternate specification. A fixed amount of capital will be required each year to buy enough cars to replace 1/30th of the fleet of new cars that I will refer to as the annual acquisition cost and will be incurred each year for 30 years. The transportation (operating) costs will also be incurred starting in the first year and increase each year by an amount proportional to the percentage of the total fleet that has been replaced as of year ‘n’. Similarly the benefits due to a change in 1/30th of the fleet will also be realized beginning in the first year and then accrue proportionally over 30 years. The accumulated benefit and operating cost will be realized thereafter. These costs and benefits are subject to inflation in future years. Equation 7.4 is the expression for calculation of NPV for this schedule.

$$\mathrm{NPV_T} = \sum_{n=1}^{N} \{(nb - nC_t - C_a)(1 + R_i)^n (1 + R_{nom})^{-n}\} \tag{7.4}$$

where,

T = Time period of replacement or retrofitting

= 30 years

N = Expected lifetime of a tank car (30 years)

b = Annual decrease in clean up cost risk due to replacing 1/T of the current fleet with the alternate tank car specification

C_t = Annual change in transportation cost due to replacing 1/T of the current fleet with the alternate tank car specification

C_a = Annual acquisition cost of replacing the current fleet with the alternate specification, 1/T every year

R_i = Rate of inflation (3.38%)

R_{nom} = Annual nominal discount rate (10.62%)

7.1.2.1 Acquisition Cost

The acquisition cost is the difference between the cost of replacing 1/30th of the fleet annually with tank cars of the alternate specification, and the cost of continuing to use the current tank car specification. Therefore the acquisition cost will accrue over a period of 30 years. Due to the difference in capacity of the two tank car specifications, I first need to know how many alternate tank cars are required to replace a single carload of the current tank car. Suppose the current specification (represented as ‘curr’) is replaced with alternate specification (represented as ‘alt’) leading to a percent tank capacity change of ‘δ’ with respect to the current specification.

Let,

V_{curr} = Tank capacity of a current tank car specification for a particular chemical

V_{alt} = Tank capacity of the alternate tank car specification for the same chemical

δ = Percent change in tank capacity, with respect to current specification

then,

$V_{alt} = V_{curr}(1+\delta/100)$, or

$V_{curr} = V_{alt}/(1+\delta/100)$

hence,

Number of carloads of alternate car equivalent to one carload of the current car

$= V_{curr}/V_{alt}$

$= (V_{alt}/(1+\delta/100))/V_{alt}$

$= 1/(1+\delta/100)$

Let,

α = Change in number of shipments when changing from the current to the alternate tank car specification, expressed as a fraction

$= (1/(1+ \delta /100)) -1$

If ‘δ’ is negative, it implies a decrease in capacity and hence an increase in number of shipments, i.e., positive α. If ‘δ’ is positive, an increase in capacity is implied and hence a decrease in number of shipments is obtained, i.e., negative α .

Let,

C_{curr} = Present cost of buying a new car of the currently used tank car specification

C_{alt} = Present cost of buying a new car of the alternative tank car specification

T_c^{curr} = Number of annual carloads of a chemical ‘c’ transported in the current tank car specification

To obtain the number of cars used in a year from the annual carload information we need to know the number of trips that a tank car makes each year. This statistic will be different for each chemical but in the absence of this information I have assumed an average of nine trips per year (based on figures used by the Railway Supply Institute) as the current car utilization rate for all commodities. However, as will be discussed later, a sensitivity analysis was conducted on this parameter to see the effect of its change on NPV. For this reason, I adopt a variable notation for car utilization rate to facilitate discussion of this effect.

Let,

R_{trip} = Trips per year made by a tank car for the chemicals of interest

Therefore, the number of tank cars of the current specification used to transport a chemical is assumed to be = T_c^{curr} / R_{trip}

In the sensitivity analyses, the net present value of R_{trip} was calculated at 5, 10, 15, 25 and 35 trips per year. For the sake of convenience, 10 trips per year represents the current car utilization rate (being close to the current average of nine trips per year).

7.1.2.1.1 Cost of Continuing to use the Current Tank Car Specification

The cost of continuing to use the current tank car specification is the cost of maintaining the status quo, wherein old cars are replaced by new cars of the same specification, 1/30th of the fleet every year. Therefore,

- There is no change in capacity.
- The capital cost is the present cost of buying the current tank car specification.
- Each of the cars displaced from service is assumed to yield a scrap value of 10 percent of the cost of a new tank car.

Number of cars displaced from service annually = $(T_c^{curr}/R_{trip})/30$

Annual cost of continuing to use the current specification

= Cost of buying $((T_c^{curr}/R_{trip})/30)$ new cars of the current specification minus scrap value obtained from $((T_c^{curr}/R_{trip})/30)$ old cars of the current specification

= $(C_{curr} - 0.1C_{curr})(T_c^{curr}/R_{trip})/30$

7.1.2.1.2 Cost of Replacing Current Tank Car Specification with Alternate Specification

- This is the cost of replacing old cars with new cars of the alternate specification, 1/30th of the fleet each year. Therefore, the capacity changes and hence the number of carloads and tank cars.
- The capital cost is the present cost of buying the alternate tank car specification.
- Each of the cars displaced from service is assumed to yield a scrap value of 10 percent of the current cost of the tank car.

Number of cars of the alternate specification required to replace the displaced cars

$= (1+\alpha)\ (T_c^{curr}/R_{trip})/30$

Annual cost of replacing the current specification with the alternate specification

= Cost of buying $((1+\alpha)(T_c^{curr} / R_{trip})/30)$ cars of the alternate specification minus scrap value obtained from $((T_c^{curr}/R_{trip})/30)$ old cars of the current specification

$= ((1+\alpha)C_{alt} - 0.1C_{curr})(T_c^{curr} / R_{trip})/30$

7.1.2.1.3 Acquisition Cost Calculation

Acquisition cost is the difference in the two scenarios, i.e., investing in the new cars vs. maintaining the status quo.

Let,

C_a = Acquisition cost for any year

= Annual cost of replacing the current specification with the alternate specification minus annual cost of continuing to use the current specification

= $((1+\alpha)C_{alt} - C_{curr})(T_c^{curr} / R_{trip})/30$

7.1.2.2 Transportation Cost

Due to differences in the capacity of various tank car specifications, the difference in transportation cost must be accounted for.

Let,

C_{var} = Variable cost of transportation of chemicals, per car-mile

d_c = Average shipment distance per carload for the chemical

Annual car-miles traveled by the current fleet for the chemical = $T_c^{curr} d_c$

Annual cost of transporting the chemical using the current specification = $C_{var} T_c^{curr} d_c$

If the whole fleet is replaced, the annual cost of transporting the chemical using the alternate specification = $C_{var} (1+\alpha) T_c^{curr} d_c$

As only 1/30th of the fleet is changed every year, let,

C_t = Annual incremental change in transportation cost due to replacing 1/30th of the fleet

= 1/30(Annual cost of transporting the chemical using the alternate specification minus annual cost of transporting a chemical using the current specification)

= $C_{var}\alpha T_c^{curr} d_c /30$

This change in transportation cost accumulates proportionally over the 30-year time period as the fleet is replaced until year 30 when the fleet will consist entirely of the alternate tank car specification.

For the n^{th} year after beginning the replacement schedule, the overall change in transportation cost with respect to the status-quo = nC_t

7.1.2.3 Benefit

Assuming that the probability of derailment is the same for any tank car involved in an accident, the probability of release from a tank car, given it is derailed, varies with the tank car specification. The alternate tank car specification has design features that result in a lower conditional probability of release than the current tank car specification.

A lower release probability reduces the probability of a clean up associated with the spill of a chemical; therefore, benefits are realized in terms of risk reduction. The benefit is the change realized in the annual clean up cost risk of transporting the chemical in the current tank cars vs. the alternate tank cars.

Let,

P_q^{curr} = Release probability for the current tank car specification, in lading loss category 'q', given a derailment

P_q^{alt} = Release probability for the alternate tank car specification, in lading loss category 'q', given a derailment

If the annual clean up cost risk incurred by the current fleet used for transporting the chemical = $R_c^{curr} = Fd_c T_c^{curr} \sum_{q=1}^{4} (P_q^{curr} C_{cq})$

then, the annual clean up cost risk incurred by the alternative car specification for transporting the same chemical is $R_c^{alt} = Fd_c (1+\alpha) T_c^{curr} \sum_{q=1}^{4} (P_q^{alt} C_{cq})$

As only 1/30th of the fleet is changed every year, let,

b = Annual benefit realized due to replacing 1/30th of the fleet

= 1/30(Annual clean up cost risk incurred by the current specification used for transporting the chemical minus annual clean up cost risk incurred by the alternative specification for transporting the same chemical)

= 1/30($R_c^{curr} - R_c^{alt}$)

This benefit accrues proportionally over the 30 year period until all of the current cars are replaced by the alternate car specification.

For the nth year after beginning the replacement schedule, the benefit realized with respect to the status-quo = nb

When the above costs and benefits are used in Equation 7.3 and inflation is accounted for, I obtain the NPV Equation 7.4 for this schedule.

7.1.3 Immediate Replacement

This replacement schedule implies that the complete fleet of the current tank car specification is replaced with the alternate tank car specification in a single year. This should be considered for chemicals that present a sufficiently high degree of hazard to the environment, e.g., the halogenated hydrocarbons. The chemicals in this analysis have a lower risk than halogenated hydrocarbons and it was considered unlikely that such a rapid replacement schedule would be found cost effective for most of the chemicals considered in this analysis. Nevertheless, this was considered primarily in congruence with the Barkan et al's (1991) results and also to bound the problem. Furthermore, it ignores the constraints of the North American tank car industry in their car building capacity.

In this schedule, the capital cost is incurred completely at the outset of replacement. The benefits and the operating cost changes also accrue immediately but are considered over the entire, anticipated 30-year life of the car. As is the case in the previous schedules, these costs and benefits will then be adjusted to their current dollar value. Equation 7.5 is used to calculate NPV for this schedule.

$$\mathrm{NPV} = \sum_{n=1}^{N} \{(b - C_t)(1 + R_i)^n (1 + R_{nom})^{-n}\} - C_a \qquad (7.5)$$

where,

N = Expected lifetime of a tank car (30 years)

b = Annual decrease in clean up cost risk due to replacing the complete current fleet with the alternate specification

C_t = Annual change in transportation cost due to replacing the complete current fleet with the alternate specification

C_a = Annual acquisition cost of replacing the current fleet with alternate the specification, all at once

7.1.3.1 Acquisition Cost

The acquisition cost is the difference between the cost of replacing the complete fleet with alternate specification tank cars all at once and the cost of continuing to use the current tank car specification. The definitions for C_{curr}, C_{alt}, T_c^{curr}, δ and α are the same as defined in Section 7.1.2.

7.1.3.1.1 Cost of Continuing to use the Current Tank Car Specification

The cost of continuing to use the current specification is the present value of the cost of replacing old tank cars of the current specification with new ones. As before, each of the cars displaced from service is assumed to yield a scrap value of 10 percent of the current cost of the tank car.

Number of cars displaced from service annually = $(T_c^{curr}/R_{trip})/30$

Annual cost of continuing to use the current specification

= Cost of buying $((T_c^{curr}/R_{trip})/30)$ new cars of the current specification minus scrap value obtained from $((T_c^{curr}/R_{trip})/30)$ old cars of the current specification

= $(C_{curr} - 0.1C_{curr})(T_c^{curr} / R_{trip})/30$

As the whole fleet is being replaced immediately with the alternate specification, the total cost associated with using the current fleet is calculated for the lifetime of the fleet, that is N(=30) years accounting for inflation, and discounted to the present value.

Total cost associated with continuing to use the current fleet =

$$\sum_{n=1}^{30}\{1/30(C_{curr}-0.1C_{curr})(T_c^{curr}/R_{trip})(1+R_i)^n(1+R_{nom})^{-n}\}$$

$$= {}^{tot}C_{cont}$$

7.1.3.1.2 Cost of Replacing Current Tank Car Specification with Alternate Specification

The cars in the current fleet can either be scrapped, or they can be sold or transferred into other services. If the cars are scrapped, a scrap value equal to 10 percent of the current cost of a new car of this specification is assumed. If the cars are transferred into another service then the replacement value for a 15-year-old car (average age of a tank car) is assumed for each car but the cost of cleaning the car is deducted from this value. Using the figures from Barkan et al (1991), the cost of cleaning is assumed to be $1,000 per car, while the replacement value for a 15-year old (111A100W) car is assumed to be $31,900 (based on AAR replacement value for a 15-year old car). It is assumed that the average age of the cars in the service will be 15 years (lifetime of the car being 30 years). Therefore, net replacement value of a tank car transferred into another service is $30,900. If all the current cars are scrapped, the annual cost of replacing the current fleet with the alternate specification

= Cost of buying ((1+α) T_c^{curr} / R_{trip}) cars of the alternate specification minus scrap value obtained from (T_c^{curr} / R_{trip}) old cars of the current specification

= $((1+\alpha)C_{alt} - 0.1C_{curr})\, T_c^{curr} / R_{trip}$

= $^{Sc}C_{alt}$

If all the current cars are transferred into a different service, the annual cost of replacing the current fleet with the alternate specification

= Cost of buying ((1+α) T_c^{curr} / R_{trip}) cars of the alternate specification minus replacement value obtained for (T_c^{curr} / R_{trip}) old cars of the current specification

= $((1+\alpha)C_{alt} – 30{,}900)\, T_c^{curr} / R_{trip}$

= $^{Tr}C_{alt}$

Assuming a 50% probability for the cars to get scrapped versus transferred, the average cost of replacement

= $(^{Sc}C_{alt} + {}^{Tr}C_{alt})/2$

= $^{avg}C_{alt}$

7.1.3.1.3 Acquisition Cost Calculation

Let,

C_a = Acquisition cost

= Cost of replacing the entire fleet of current specification cars with the alternate specification minus cost of continuing to use the current specification

= $^{avg}C_{alt}$ - $^{tot}C_{cont}$

7.1.3.2 Transportation Cost

The methodology to calculate transportation cost changes for this schedule is similar to that for the attrition-based schedule except that the entire fleet is changed at once. Therefore, keeping the definitions for C_{var} and d_c the same as before, I calculate the change in transportation cost as described below.

Let,

C_t = Change in transportation cost due to replacing the entire fleet

= Annual cost of transporting the chemical using the alternate specification minus annual cost of transporting a chemical using the current specification

$= C_{var}\,(1+\alpha)\,T_c^{curr}\ d_c - C_{var}\ T_c^{curr}\,d_c$

$= C_{var}\,\alpha\,T_c^{curr}\,d_c$

7.1.3.3 Benefit

The calculation of annual benefit follows the same procedure as that for the attrition-based schedule except that here it is calculated for the replacement of the entire fleet. The difference in annual risk is the benefit realized due to immediate replacement of the fleet. Keeping the definitions for P_q^{curr}, P_q^{alt}, R_c^{curr} and R_c^{alt} the same as before, the annual benefit is calculated in the following manner.

Let,

b = Annual benefit realized due to replacing the entire fleet

= Annual clean up cost risk incurred by the current specification used for transporting the chemical minus annual clean up cost risk incurred by the alternative specification for transporting the same chemical

$= R_c^{curr} - R_c^{alt}$

Substituting the above costs and benefits in Equation (7.3), and adjusting for inflation, I obtain the NPV Equation (7.5).

7.1.4 Ten-Year Retrofit/Replacement

Due to various AAR and US DOT requirements, tank cars receive a variety of inspections and tests on a ten-year cycle. Consequently, a replacement (or retrofit) schedule based on this interval meshes well with established industry practice. Every ten years each car in the fleet will undergo inspection and, in addition, approximately 1/30th of the fleet will be replaced each year due to attrition. The 1/10th of the fleet that is due for inspection each year will include some cars that are to be retired from service. These cars could be replaced with new cars of the same specification equipped with one or more protective fittings. The remaining 1/10th of the fleet could be retrofitted in conjunction with their shop visit for inspection. The 10-year retrofit schedule was designed with the idea of retrofitting existing cars as an alternative to replacing the cars. As discussed in Chapter 5, Section 5.1, retrofitting includes addition of protective features such as top fittings protection, half-height head shields, full head shields and/or a jacket and insulation. Instead of retrofitting, the cars could also be replaced with those of an alternative specification in which case this schedule is similar to the attrition-based schedule with the exception that 1/10th of the fleet changes every year instead of 1/30th. The latter is termed the 10-year replacement schedule and is not discussed here.

The ensuing discussion describes the derivation of the NPV terms for the 10-year retrofit schedule. At the end of 10 years the fleet will be composed of new cars and old retrofitted tank cars of the current specification. A fixed amount of capital will be required to retrofit 1/10th of the fleet each year. This is the annual acquisition cost and is incurred annually over the ten-year period. There is one unique difference between this and the other schedules discussed in this chapter. Within a period of ten years, 1/3 of the old fleet has been replaced with ‘new’ retrofitted cars. But the remaining 2/3 of the old fleet has been retrofitted and will reach the end of its service life within the next 20 years. So, starting in the 11th year there will also be a cost involved in continuing to use this retrofitted fleet that will be different from the cost of continuing to use the original fleet. The difference between the two also contributes to the acquisition cost term. The changes in transportation (operating) costs and benefits occur in the same fashion as for the attrition-based replacement except that it corresponds to 1/10th of the fleet change. As in the previous cases, these costs and benefits are subject to inflation in future years and then discounted to current dollars. Equation 7.4 can be used to calculate NPV for this schedule also with the following change in the values of the variables used in Equation 7.4.

T = Time period of replacement or retrofitting

= 10 years

7.1.4.1 Acquisition Cost

The acquisition cost in this case has different values depending on whether we are considering the initial 10 years of the retrofit schedule, or the latter 20 years after all the cars are retrofitted. The definitions for C_{curr}, C_{alt}, T_c^{curr}, δ and α are the same as defined in Section 7.1.2.

Let,

${}^{equip}C_{curr}$ = Current cost of buying a new car of the current specification equipped with a certain protective feature

C_{prot} = Cost of retrofitting a current specification tank car with that protective feature

7.1.4.1.1 Initial 10 Years *(since the outset of the schedule)*

The annual acquisition cost is the difference between the cost of retrofitting 1/10th of the fleet and the cost of continuing to use the current tank cars. Of the tank cars in the fleet, 1/10th are selected in a way that they include the 1/30th of the fleet that was to be retired in the particular year. The cost of continuing to use the current specification is the present value of the cost of replacing old tank cars of the current specification with new ones. Earlier assumptions for scrap value of the displaced car hold true in this case also.

Number of cars selected for inspection annually = (T_c^{curr} / R_{trip})/10

Number of cars displaced from service annually = (T_c^{curr} / R_{trip})/30

Annual cost of continuing to use the current fleet

= Cost of buying ((T_c^{curr} / R_{trip})/30) new cars of the current specification minus scrap value obtained from ((T_c^{curr} / R_{trip})/30) old cars of the current specification

= (C_{curr} - 0.1C_{curr})(T_c^{curr} / R_{trip})/30

These tank cars are to be replaced by new tank cars of the same specification but equipped with protective features.

Number of new equipped cars required to replace the retired cars = (1+α) (T_c^{curr} /R_{trip})30

Cost of replacing 1/30th of the current tank cars with equipped tank cars = Cost of buying ((1+α)(T_c^{curr} / R_{trip})/30) cars of the current specification with protective fittings minus scrap value obtained from ((T_c^{curr} /R_{trip})/30) old cars of the current specification

= ((1+α) $^{equip}C_{curr}$ - 0.1C_{curr})(T_c^{curr} / R_{trip})/30

The remaining ((T_c^{curr} /R_{trip})/10 – (T_c^{curr} /R_{trip})/30) tank cars will be retrofitted to equip them with protective fittings, and additional new cars bought to compensate for the decrease in capacity due to the retrofit.

Cost of retrofitting the remaining $(1/10)^{th} – (1/30)^{th}$ of the selected fleet

$= ((T_c^{curr}/R_{trip})/10 – (T_c^{curr}/R_{trip})/30)C_{prot}$

Number of new equipped cars required to compensate for the decrease in capacity of the $(1/10 – 1/30)^{th}$ of the fleet

$= \alpha((T_c^{curr}/R_{trip})/10 – (T_c^{curr}/R_{trip})/30)$

Cost of buying extra cars equipped with protective features to compensate for the decrease in capacity of the $(1/10 – 1/30)^{th}$ of the fleet

$= \alpha((T_c^{curr} / R_{trip})/10 – (T_c^{curr} / R_{trip})/30) \, {}^{equip}C_{curr}$

Annual cost of retrofitting $1/10^{th}$ of the fleet = Cost of replacing $1/30^{th}$ of the current tank cars with equipped tank cars plus the cost of retrofitting the remaining $(1/10 - 1/30)^{th}$ of the selected fleet plus the cost of buying extra cars equipped with protective fittings to compensate for the decrease in capacity of the (1/10 - 1/30) of the fleet

$= ((1+\alpha) \, {}^{equip}C_{curr} - 0.1C_{curr})(T_c^{curr} / R_{trip})/30 + ((T_c^{curr} / R_{trip})/10 – (T_c^{curr} / R_{trip})/30)C_{prot} +$
$\alpha((T_c^{curr} / R_{trip})/10 – (T_c^{curr} / R_{trip})/30) \, {}^{equip}C_{curr}$

$= ((T_c^{curr} / R_{trip})/10 – (T_c^{curr} / R_{trip})/30)C_{prot} + (\alpha(T_c^{curr} / R_{trip})/10 + (T_c^{curr} / R_{trip})/30) \, {}^{equip}C_{curr}$
$– 0.1C_{curr}(T_c^{curr} / R_{trip})/30$

Let,

C_a = Acquisition cost for any year = Annual cost of retrofitting $1/10^{th}$ of the fleet minus annual cost of continuing to use the current fleet

$= 1/ R_{trip} ((T_c^{curr} /10 - T_c^{curr} /30)C_{prot} + (\alpha\ T_c^{curr} /10 + T_c^{curr} /30)\ {}^{equip}C_{curr} - 0.1C_{curr}\ T_c^{curr} /30$

$- (C_{curr} - 0.1C_{curr})\ T_c^{curr} /30)$

$= 1/ R_{trip} ((T_c^{curr} /10 - T_c^{curr} /30)C_{prot} + (\alpha T_c^{curr} /10 + T_c^{curr} /30)\ {}^{equip}C_{curr} - C_{curr}\ T_c^{curr} /30)$

7.1.4.1.2 Later 20 Years *(after the completion of the schedule)*

The acquisition cost is the difference in the cost of continuing to use the equipped tank cars and the cost of continuing to use the original unequipped tank car fleet. For simplicity I have ignored the difference in the number of carloads and calculated it for T_c, number of annual carloads with the original fleet. The effect of this assumption on the final risk estimate is small.

Number of cars displaced from service annually = $((1+\alpha)\ T_c^{curr} / R_{trip})/30$

Annual cost of continuing to use the equipped fleet

= Cost of buying $(((1+\alpha)\ T_c^{curr} / R_{trip})/30)$ equipped tank cars minus scrap value obtained from $(((1+\alpha)\ T_c^{curr} / R_{trip})/30)$ equipped tank cars

$= ({}^{equip}C_{curr} - 0.1\ {}^{equip}C_{curr})(\ (1+\alpha)\ T_c^{curr} / R_{trip})/30$

C_a = Acquisition cost for any year

= Annual cost of continuing to use the equipped fleet minus annual cost of continuing to use the original unequipped fleet

$$= ({}^{equip}C_{curr} - 0.1\ {}^{equip}C_{curr})(\ (1+\alpha)\ T_c^{curr} / R_{trip})/30 - (C_{curr} - 0.1\ C_{curr})(\ T_c^{curr} / R_{trip})/30$$

$$= 0.9((1+\alpha)\ {}^{equip}C_{curr} - C_{curr})(\ T_c^{curr}\ / R_{trip})/30$$

7.1.4.2 Transportation Cost

The methodology to calculate transportation cost changes for this schedule is similar to that for the attrition-based schedule except that 1/10th of the fleet is retrofitted annually. Therefore, keeping the definitions for C_{var} and d_c the same as before, I calculate the change in transportation cost as described below.

Let,

C_t = Annual change in transportation cost due to retrofitting 1/10th of the fleet

= 1/10(Annual cost of transporting the chemical using the equipped fleet minus
annual cost of transporting a chemical using current unequipped fleet)

$= 1/10(C_{var}\ (1+\alpha)\ T_c^{curr}\ d_c -\ C_{var} T_c^{curr}\ d_c)$

$= C_{var}\alpha T_c^{curr}\ d_c /10$

This change in transportation cost increases proportionally over the ten-year interval until the fleet consists only of tank cars with protective fittings.

For the nth year after beginning of the replacement schedule, the change in transportation cost with respect to the status-quo = nC_t

After 10 years, the total change in operating cost accrued at the end of the 10 years is realized further on.

7.1.4.3 Benefit

Again, the calculation of annual benefit follows the same procedure as that for the attrition-based schedule except that here it is calculated for retrofitting 1/10th of the fleet annually. Keeping the definitions for P_q^{curr}, P_q^{alt}, R_c^{curr} and R_c^{alt} the same as before, the annual benefit is calculated in the following manner.

As only 1/10th of the fleet is retrofitted each year, let,

b = Annual benefit realized due to retrofitting 1/10th of the fleet

= 1/10(Annual clean up cost risk incurred by the current fleet used for transporting the chemical minus annual clean up cost risk incurred by the equipped fleet for transporting the same chemical)

= $1/10(R_c^{curr} - R_c^{alt})$

This benefit accrues proportionally over the years for 10 years when all the current cars are equipped with protective features. For the nth year after the beginning of the replacement schedule, the benefit realized with respect to the status-quo = nb

After 10 years, the total benefit accumulated at the end of the 10 years is realized further on. Costs and benefits summed, and accounted for inflation result in Equation 7.4.

7.2 Results and Discussion

The NPV was calculated for the 24 chemicals for the three replacement schedules. The results for the attrition-based schedule are shown for xylenes (Tables 7.1 and 7.2, Figures 7.2 and 7.3). The results are presented in the form of a sensitivity analysis on car utilization rate where NPVs are calculated for 5, 10, 15, 25 and 25 trips per year for a car. Most tank cars make somewhere between 5 and 10 trips per year and as discussed previously (Sec. 7.1.2.1), the RSI has used 9 trips per year as an approximate average. This utilization rate is considerably lower than for many other types of railcars, hence it is worthwhile to consider investigating the effect of this on the NPV results. There are certain alternatives that never become cost effective, regardless of car utilization rate, whereas some others are. There are some other alternatives that, even though they are not cost effective over the selected range of car utilization rate, do become cost effective at a higher rate. The value of utilization rate at which the NPV changes sign is also mentioned along with the NPV results (Tables 7.1 And 7.2). This value implies the value of utilization rate required for the NPV to become positive from negative, for most of the alternatives. Interestingly, there are a few alternatives for which the NPV actually decreases rather than increasing with utilization rate, hence, the utilization rate required for NPV to change sign should be interpreted as the value required for the NPV to turn negative from positive. Though the tables show the results for all the alternatives that were considered, the graphs show only the alternatives that are cost beneficial either within or outside the selected range of 5 to 35 trips per year. This rule is also followed for presenting the results for other schedules.

Tank Car Specification	Trips per year					Requisite Trips per year for NPV to Change Sign
	5	10	15	25	35	
105A100W	-7,128,547	-2,763,229	-1,308,123	-144,038	354,856	27
105A300W	-9,930,572	-4,282,810	-2,400,223	-894,153	-248,694	41
105A500W	-18,243,549	-8,875,387	-5,752,667	-3,254,490	-2,183,843	190
105J100W -1/2 HS	-8,139,124	-3,242,363	-1,610,109	-304,306	255,323	30
105J200W -1/2 HS	-6,611,670	-2,478,636	-1,100,958	1,184	473,531	25
105J300W- 1/2 HS	-9,544,882	-4,073,485	-2,249,686	-790,647	-165,344	39
105J400W -1/2 HS	-13,408,453	-6,294,970	-3,923,808	-2,026,880	-1,213,910	87
105J500W - 1/2 HS	-12,071,082	-5,804,873	-3,716,137	-2,045,148	-1,329,010	136
105S100W -1/2 HS	-8,139,124	-3,242,363	-1,610,109	-304,306	255,323	30
111A100W1 - INS	-1,935,843	-433,415	67,395	468,043	639,749	14
111A100W2 - INS	-3,061,516	-776,459	-14,773	594,575	855,725	15
111A100W2 - NI	1,097,364	798,953	699,483	619,907	585,803	
111A100W3	-6,598,320	-2,764,653	-1,486,764	-464,453	-26,319	36
111J100W3 -1/2 HS	-7,596,447	-3,244,263	-1,793,536	-632,954	-135,561	39
111S100W1 – INS, 1/2 HS	-3,985,997	-1,439,039	-590,052	89,136	380,217	23
111S100W2 - NI, 1/2 HS	249,513	457,247	526,491	581,887	605,628	3
112A200W - INS	-6,359,852	-2,378,881	-1,051,891	9,701	464,669	25
112A200W - NI	-3,497,649	-1,337,303	-617,187	-41,095	205,802	26
112A340W - INS	-8,474,631	-3,685,614	-2,089,276	-812,204	-264,888	43
112A340W - NI	-5,547,557	-2,582,862	-1,594,630	-804,044	-465,222	78
112J200W -1/2 HS	-7,365,562	-2,855,582	-1,352,255	-149,594	365,832	27
112J340W - 1/2 HS	-9,557,641	-4,219,411	-2,440,000	-1,016,472	-406,389	48
112S200W - INS, 1/2HS	-7,365,562	-2,855,582	-1,352,255	-149,594	365,832	27
112S200W - NI, 1/2HS	-4,368,515	-1,671,272	-772,190	-52,925	255,331	26
112S340W - INS, 1/2 HS	-9,557,641	-4,219,411	-2,440,000	-1,016,472	-406,389	48
112S340W - NI, 1/2 HS	-6,522,188	-2,997,157	-1,822,146	-882,138	-479,277	67
current spec + 1/2 HS	-873,323	-364,710	-195,173	-59,542	-1,415	35
current spec + full HS	-2,049,314	-1,023,603	-681,699	-408,176	-290,952	4,866
current spec + jacket	-2,464,393	-697,690	-108,788	362,333	564,242	17
current spec + TFP	-1,150,377	-288,117	-698	229,238	327,782	15
Enhanced Safety 111- 286K	2,109,530	2,482,345	2,606,616	2,706,033	2,748,641	1
Enhanced Safety INS 111- 286K	677,370	2,197,342	2,704,000	3,109,326	3,283,037	4

Table 7.1 NPV for Attrition-based Replacement of Non-Insulated 111A100W1 Cars for Xylenes

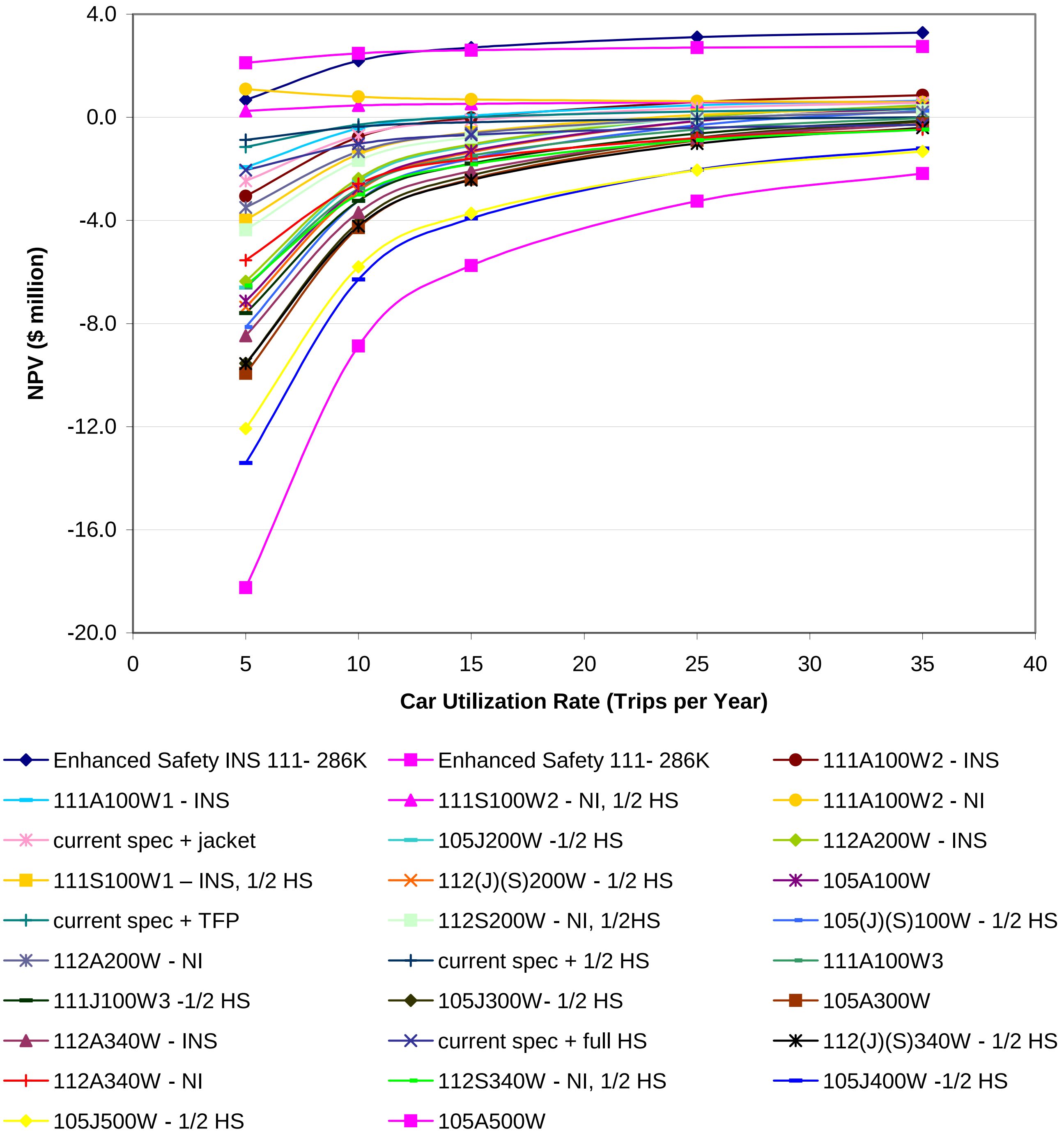


Figure 7.2 NPV for Attrition-based Replacement of Non-Insulated 111A100W1 Cars for Xylenes

	Trips per year					Requisite Trips per year for NPV to Change Sign
Tank Car Specification	**5**	**10**	**15**	**25**	**35**	
105A100W	-151,721	408	51,117	91,685	109,071	10
105A300W	-953,502	-434,410	-261,380	-122,956	-63,631	61
105A500W	-3,332,205	-1,748,546	-1,220,660	-798,351	-617,361	
105J100W -1/2 HS	-440,891	-136,694	-35,294	45,825	80,590	18
105J200W -1/2 HS	-3,820	81,842	110,396	133,239	143,029	5
105J300W- 1/2 HS	-843,139	-374,513	-218,305	-93,338	-39,781	50
105J400W -1/2 HS	-1,948,674	-1,010,177	-697,344	-447,078	-339,821	
105J500W - 1/2 HS	-1,565,994	-869,939	-637,920	-452,305	-372,756	
105S100W -1/2 HS	-440,891	-136,694	-35,294	45,825	80,590	18
111A100W1 - INS	1,334,137	667,068	444,712	266,827	190,591	
111A100W2 - INS	1,012,033	568,908	421,200	303,034	252,391	
111J100W3 -1/2 HS	-285,607	-137,237	-87,781	-48,215	-31,259	133
111S100W1 – INS, 1/2 HS	747,499	379,316	256,588	158,406	116,328	
112A200W - INS	68,236	110,386	124,436	135,676	140,493	3
112A340W - INS	-536,894	-263,527	-172,405	-99,507	-68,265	278
112A340W – NI	300,669	52,018	-30,865	-97,172	-125,589	13
112J200W -1/2 HS	-219,541	-26,019	38,489	90,095	112,212	12
112J340W - 1/2 HS	-846,790	-416,269	-272,762	-157,957	-108,754	302
112S200W – INS, 1/2HS	-219,541	-26,019	38,489	90,095	112,212	12
112S200W - NI, 1/2HS	638,044	312,864	204,470	117,756	80,592	264
112S340W – INS, 1/2 HS	-846,790	-416,269	-272,762	-157,957	-108,754	302
112S340W - NI, 1/2 HS	21,785	-66,529	-95,967	-119,518	-129,611	6
current spec + 1/2 HS	-285,607	-137,237	-87,781	-48,215	-31,259	133
current spec + full HS	-620,041	-321,426	-221,888	-142,257	-108,130	
current spec + TFP	-415,435	-158,294	-72,580	-4,010	25,378	26
Enhanced Safety INS 111- 286K	2,081,890	1,419,842	1,199,159	1,022,613	946,950	

Table 7.2 NPV for Attrition-based Replacement of 111A100W3 Cars for Xylenes

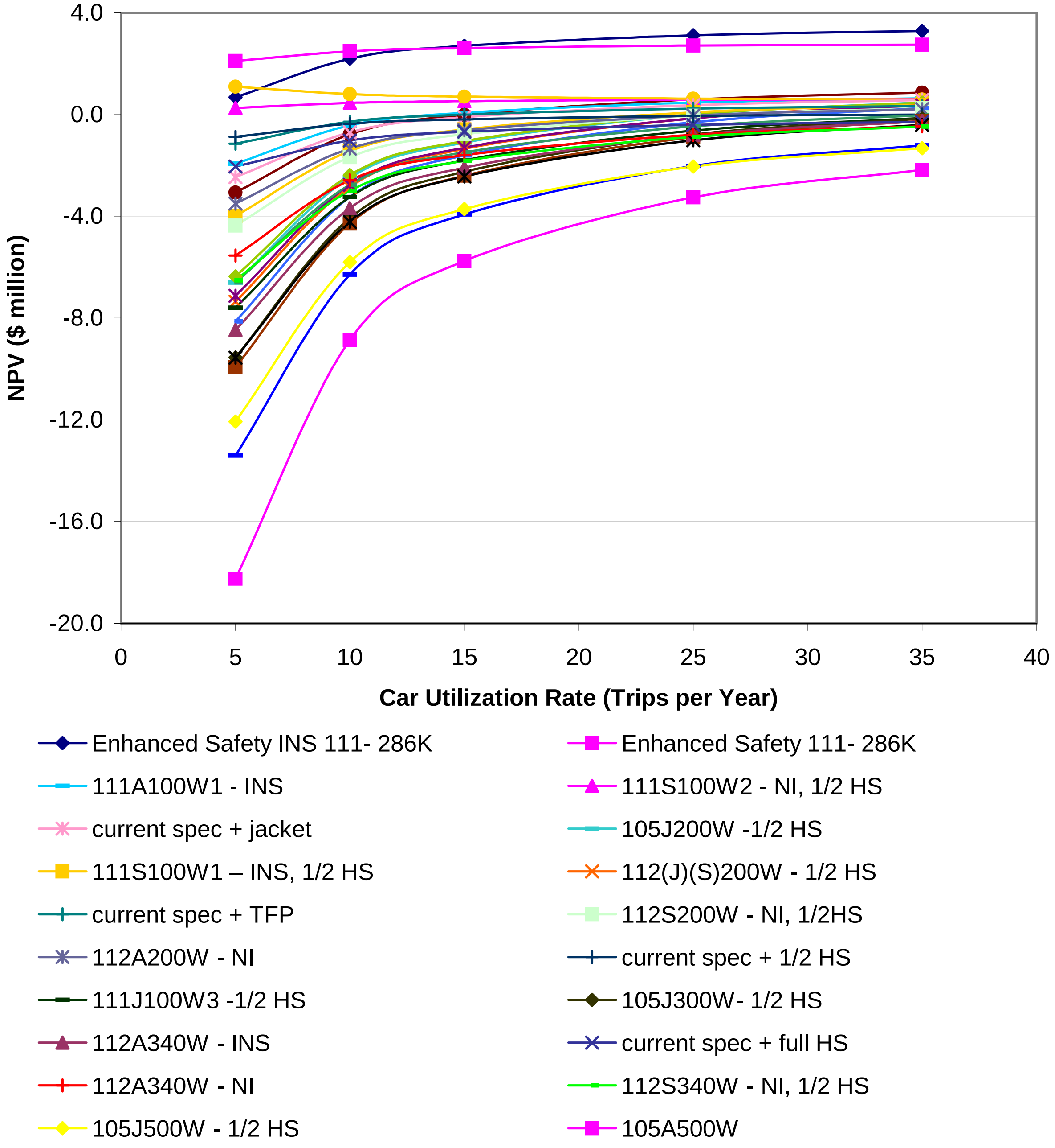


Figure 7.3 NPV for Attrition-based Replacement of 111A100W3 Cars for Xylenes

Table 7.3 shows the alternatives that are cost beneficial at the current car utilization rate of 10 trips per year for all the chemicals for each of the current tank car specifications in which they are transported.

Chemical	**Car being Replaced**	Alternatives	**NPV($)**
Acetaldehyde	111A100W1 NI	286K - 111 NI	761,271
		286K - 111 INS	709,125
		111A100W2 - NI	227,478
		111S100W2 - NI, 1/2 HS	129,302
	105J100W - 1/2 HS	105J200W – 1/2 HS	59,819
		112J200W -1/2 HS	30,295
		112S200W - INS, 1/2HS	30,295
Acetic Anhydride	111A100W1 INS	286K - 111 INS	375,578
Acetone	111A100W1 NI	286K - 111 NI	2,419,441
		286K - 111 INS	2,341,256
		111A100W2 - NI	728,522
		111S100W2 - NI, 1/2 HS	119,773
Acrylic Acid	111A100W1 INS	286K - 111 INS	236,121
Acrylonitrile	111A100W1 NI	286K - 111 NI	577,147
		286K - 111 INS	537,881
		111A100W2 - NI	189,060
		111S100W2 - NI, 1/2 HS	118,112
	105J300W – 1/2 HS	None	
	112A200W NI	286K - 111 INS	303,608
		111A100W1 - INS	78,761
		111A100W2 - INS	53,064
	111A100W3	286K - 111 INS	244,781
		111A100W1 - INS	113,494
		111A100W2 - INS	98,490
		111S100W1 – INS, 1/2 HS	65,216
		112S200W - NI, 1/2HS	52,565
		112A200W - INS	21,477
		105J200W -1/2 HS	17,287
		112A340W - NI	3,819
		105A100W	2,750
	105J300W – 1/2 HS	105J200W -1/2 HS	33,971
		112J200W -1/2 HS	17,204
		112S200W - INS, 1/2HS	17,204
Benzene	111A100W1 INS	286K - 111 INS	1,935,378
Butanol	111A100W1 NI	286K - 111 NI	1,771,825
		286K - 111 INS	1,757,196
		111A100W2 - NI	430,980
		111S100W2 - NI, 1/2 HS	260,807
n-Butyl Acrylate	111A100W1 NI	286K - 111 NI	1,750,983
		286K - 111 INS	1,746,584
	111A100W1 NI	111A100W2 - NI	421,082
		111S100W2 - NI, 1/2 HS	274,570
	105J300W – 1/2 HS	None	

Chemical	**Car being Replaced**	Alternatives	**NPV($)**
Cyclohexane	111A100W1 NI	286K - 111 NI	886,921
		111A100W2 - NI	470,960
		286K - 111 INS	167,008
		111S100W2 - NI, 1/2 HS	37,237
Ethanol	111A100W1 NI	286K - 111 NI	2,523,269
		286K - 111 INS	2,146,095
		111A100W2 - NI	753,149
		111S100W2 - NI, 1/2 HS	342,109
Ethyl Acetate	111A100W1 NI	286K - 111 NI	764,027
		286K - 111 INS	678,446
		111A100W2 - NI	230,777
		111S100W2 - NI, 1/2 HS	129,000
Ethyl Acrylate	111A100W1 NI	286K - 111 INS	529,813
		286K - 111 NI	443,930
		111A100W2 - NI	119,718
		111S100W2 - NI, 1/2 HS	98,018
		111A100W1 INS	40,465
		111A100W2 - INS	38,918
		current spec + TFP	14,633
		current spec + jacket	13,483
	105J300W – 1/2 HS	None	
Isopropanol	111A100W1 NI	286K - 111 NI	1,435,277
		286K - 111 INS	1,271,399
		111A100W2 - NI	384,188
		111S100W2 - NI, 1/2 HS	165,369
Methanol	111A100W1 NI	286K - 111 NI	11,917,051
		286K - 111 INS	10,769,125
		111A100W2 - NI	3,789,000
		111S100W2 - NI, 1/2 HS	298,622
Methyl Methacrylate Monomer	111A100W1 NI	286K - 111 NI	2,675,799
		286K - 111 INS	2,482,692
		111A100W2 - NI	1,330,573
		111S100W2 - NI, 1/2 HS	1,098,550
		current spec + TFP	750,807
		current spec + 1/2 HS	680,001
		111A100W1 - INS	531,818
		current spec + jacket	397,733
		111A100W2 - INS	358,926
		current spec + full HS	285,201
		112A200W - NI	102,448
	105J300W - 1/2 HS	112J340W - 1/2 HS	102,575
		112S340W - INS, 1/2 HS	102,575
Methyl tert Butyl Ether	111A100W1 NI	286K - 111 NI	204,677
		286K - 111 INS	138,707
		111A100W2 - NI	52,363

Chemical	**Car being Replaced**	Alternatives	**NPV($)**
Phenol	111A100W1 INS	286K - 111 INS	5,138,200
	111A100W3	286K - 111 INS	3,937,613
		111A100W2 - INS	1,362,650
		111S100W1 – INS, 1/2 HS	836,409
Potassium Hydroxide Solution	111A100W1 INS	286K - 111 INS	1,792,787
	111A100W3	286K - 111 INS	1,157,421
		111A100W2 - INS	420,892
		111S100W1 – INS, 1/2 HS	291,721
Sodium Hydroxide Solution	111A100W1 INS	286K - 111 INS	22,591,889
	111A100W3	286K - 111 INS	15,448,994
		111A100W2 - INS	5,957,752
		111S100W1 – INS, 1/2 HS	4,403,548
Styrene	111A100W1 INS	286K - 111 INS	16,048,361
Sulfuric Acid	111A100W2 NI	286K - 111 NI	13,842,809
Toluene	111A100W1 NI	286K - 111 NI	2,504,403
		286K - 111 INS	2,383,944
		111A100W2 - NI	646,136
		111S100W2 - NI, 1/2 HS	503,543
		111A100W1 - INS	120,014
		111A100W2 - INS	60,983
		current spec + TFP	22,370
Vinyl Acetate	111A100W1 NI	286K - 111 NI	5,204,625
		286K - 111 INS	4,980,801
		111A100W2 - NI	1,248,029
		111S100W2 - NI, 1/2 HS	728,124
Xylenes	111A100W1 NI	286K - 111 NI	2,509,668
		286K - 111 INS	2,221,528
		111A100W2 – NI	807,747
		111S100W2 - NI, 1/2 HS	462,279
	111A100W3	286K - 111 INS	1,419,842
		111A100W1 – INS	667,068
		111A100W2 – INS	568,908
		111S100W1 – INS, 1/2 HS	379,316
		112S200W - NI, 1/2HS	312,864
		112A200W - INS	110,386
		105J200W –1/2 HS	81,842
		112A340W - NI	52,018
		105A100W	408

Table 7.3 Cost Beneficial Alternatives for Attrition-based Replacement at 10 Trips per Year

The enhanced safety 286K 111 tank car is the cost beneficial alternative for replacing 111A100W1 or 111A100W2 (car used for sulfuric acid) for all the chemicals. Apart from the 286K 111 tank car, there are other alternatives, like 111S100W1 or 111S100W2, that are also cost beneficial. But while the 286K tank car is most often cost effective mainly because of its higher capacity coupled with moderate improvements in annual risk, the other alternatives are cost effective primarily because their capital cost is not very high. It should be noted that all alternatives, other than the 286K tank car, offer only slight improvements in risk but, their capital cost is also only slightly higher than the current tank car specification being replaced.

Other alternatives that present a moderate or high improvement in risk are invariably associated with a much higher capital cost and a decrease in capacity and hence are do not yield positive NPVs, at least at the current car utilization rate. As the highest fraction of traffic of the chemicals of interest is currently transported in the 111A100W1, the NPV for attrition-based replacement of the 111A100W1 (insulated or non insulated, as the case may be), with the enhanced safety 286K tank car is shown in Figure 7.4. For chemicals that must be shipped in insulated cars, only the insulated 286K 111 tank car can be considered (bottom portion of Figure 7.4). For the other chemicals the results are shown for replacement with both, the non insulated (represented as 286K – NI) and the insulated 286K (represented as 286K – INS) 111 tank cars. Also to be noted is, that, for sulfuric acid these results are for replacement of the current car, which is a 111A100W2 rather than a 111A100W1.

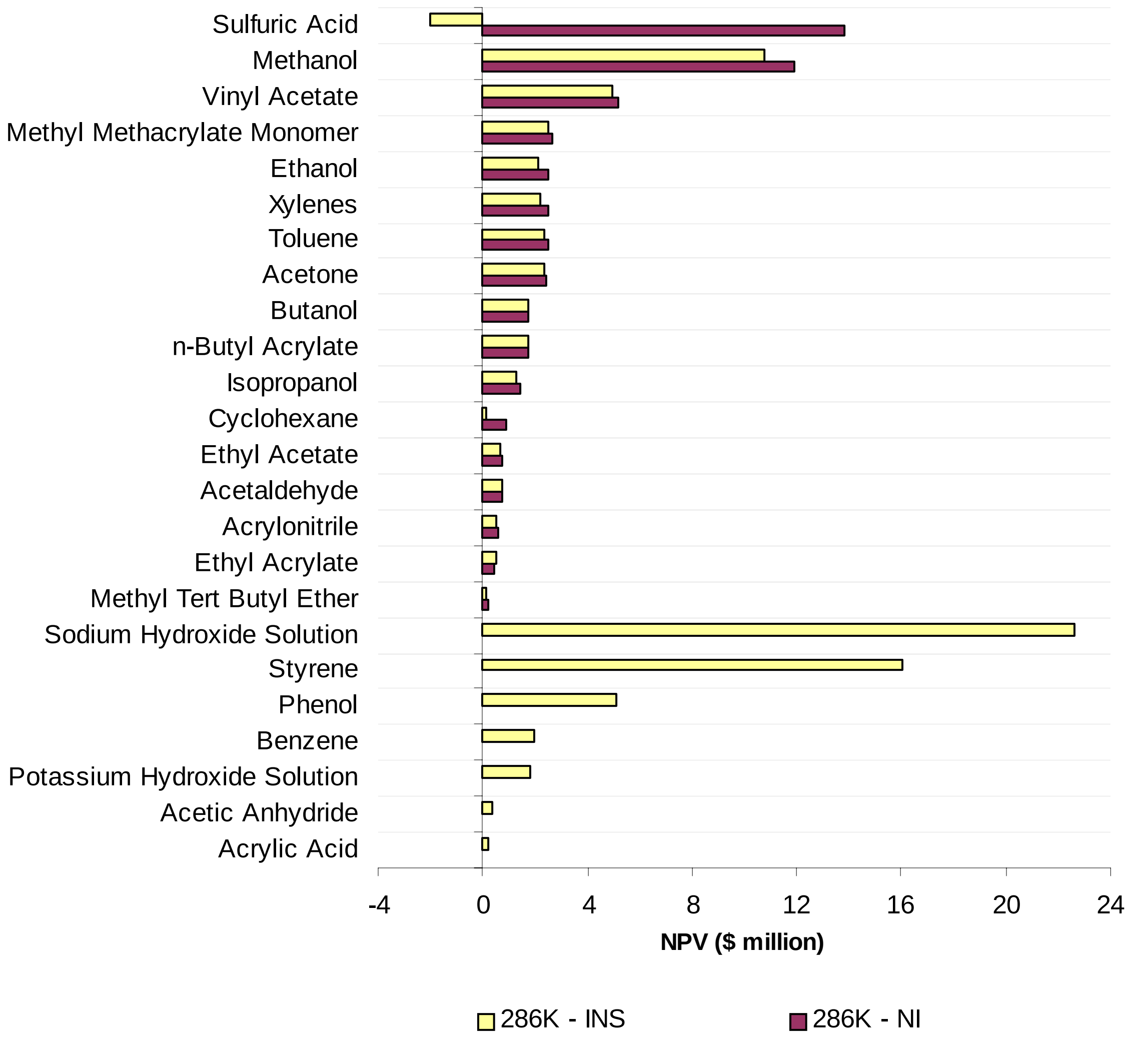


Figure 7.4 NPV for Attrition-based Replacement of 111A100W1/111A100W2 with 286K 111 Tank Car for the 24 Chemicals at 10 Trips per Year

The results for the immediate replacement schedule, presented again for the previous example chemical, xylenes (Tables 7.4 and 7.5, Figures 7.5 and 7.6), show that this schedule is not cost beneficial for either 111A1000W1 or 111A100W3 tank cars at the current car utilization rate for this chemical.

	Trips per year					Requisite Trips per year for NPV to Change Sign
Tank Car Specification	5	10	15	25	35	
105A100W	-35,107,499	-15,317,608	-8,720,977	-3,443,673	-1,181,971	44
105A300W	-41,972,375	-19,081,035	-11,450,588	-5,346,230	-2,730,077	60
105A500W	-62,401,847	-30,513,126	-19,883,553	-11,379,894	-7,735,468	232
105J100W -1/2 HS	-37,531,950	-16,456,823	-9,431,781	-3,811,747	-1,403,161	46
105J200W -1/2 HS	-33,837,969	-14,609,832	-8,200,454	-3,072,951	-875,449	42
105J300W- 1/2 HS	-41,027,326	-18,562,505	-11,074,232	-5,083,613	-2,516,205	58
105J400W -1/2 HS	-50,587,150	-24,151,121	-15,339,112	-8,289,504	-5,268,244	116
105J500W - 1/2 HS	-47,486,140	-23,099,154	-14,970,159	-8,466,963	-5,679,879	189
105S100W -1/2 HS	-37,531,950	-16,456,823	-9,431,781	-3,811,747	-1,403,161	46
111A100W1 - INS	-22,748,423	-9,882,118	-5,593,350	-2,162,335	-691,901	43
111A100W2 - INS	-25,306,714	-10,547,707	-5,628,039	-1,692,304	-5,560	35
111A100W2 - NI	-15,625,063	-7,113,890	-4,276,833	-2,007,187	-1,034,482	61
111A100W3	-34,024,114	-15,519,964	-9,351,914	-4,417,474	-2,302,714	62
111J100W3 -1/2 HS	-36,423,457	-16,665,332	-10,079,290	-4,810,457	-2,552,386	64
111S100W1 – INS, 1/2 HS	-27,691,978	-12,299,593	-7,168,797	-3,064,161	-1,305,031	50
111S100W2 - NI, 1/2 HS	-17,614,139	-7,878,913	-4,633,838	-2,037,777	-925,180	52
112A200W - INS	-33,248,494	-14,388,105	-8,101,309	-3,071,872	-916,399	42
112A200W – NI	-26,617,261	-12,159,854	-7,340,718	-3,485,410	-1,833,135	63
112A340W - INS	-38,548,936	-17,734,377	-10,796,191	-5,245,642	-2,866,835	68
112A340W – NI	-31,739,374	-15,336,736	-9,869,190	-5,495,154	-3,620,566	154
112J200W -1/2 HS	-35,661,174	-15,521,435	-8,808,189	-3,437,592	-1,135,907	44
112J340W - 1/2 HS	-41,162,325	-19,019,552	-11,638,627	-5,733,888	-3,203,285	71
112S200W - INS, 1/2HS	-35,661,174	-15,521,435	-8,808,189	-3,437,592	-1,135,907	44
112S200W – NI, 1/2HS	-28,647,635	-12,891,801	-7,639,856	-3,438,301	-1,637,634	55
112S340W - INS, 1/2 HS	-41,162,325	-19,019,552	-11,638,627	-5,733,888	-3,203,285	71
112S340W – NI, 1/2 HS	-34,041,918	-16,284,169	-10,364,920	-5,629,520	-3,600,063	121
current spec + 1/2 HS	-20,524,030	-10,061,161	-6,573,538	-3,783,439	-2,587,683	260
current spec + full HS	-23,420,946	-11,707,530	-7,803,059	-4,679,481	-3,340,805	19,904
current spec + jacket	-24,026,663	-10,521,238	-6,019,430	-2,417,984	-874,506	45
current spec + TFP	-21,033,515	-9,715,390	-5,942,681	-2,924,515	-1,631,015	71
Enhanced Safety 111- 286K	-12,298,645	-2,164,189	1,213,963	3,916,485	5,074,708	13
Enhanced Safety INS 111- 286K	-15,440,464	-2,531,731	1,771,180	5,213,508	6,688,792	12

Table 7.4 NPV for Immediate Replacement of Non-Insulated 111A100W1 for Xylenes

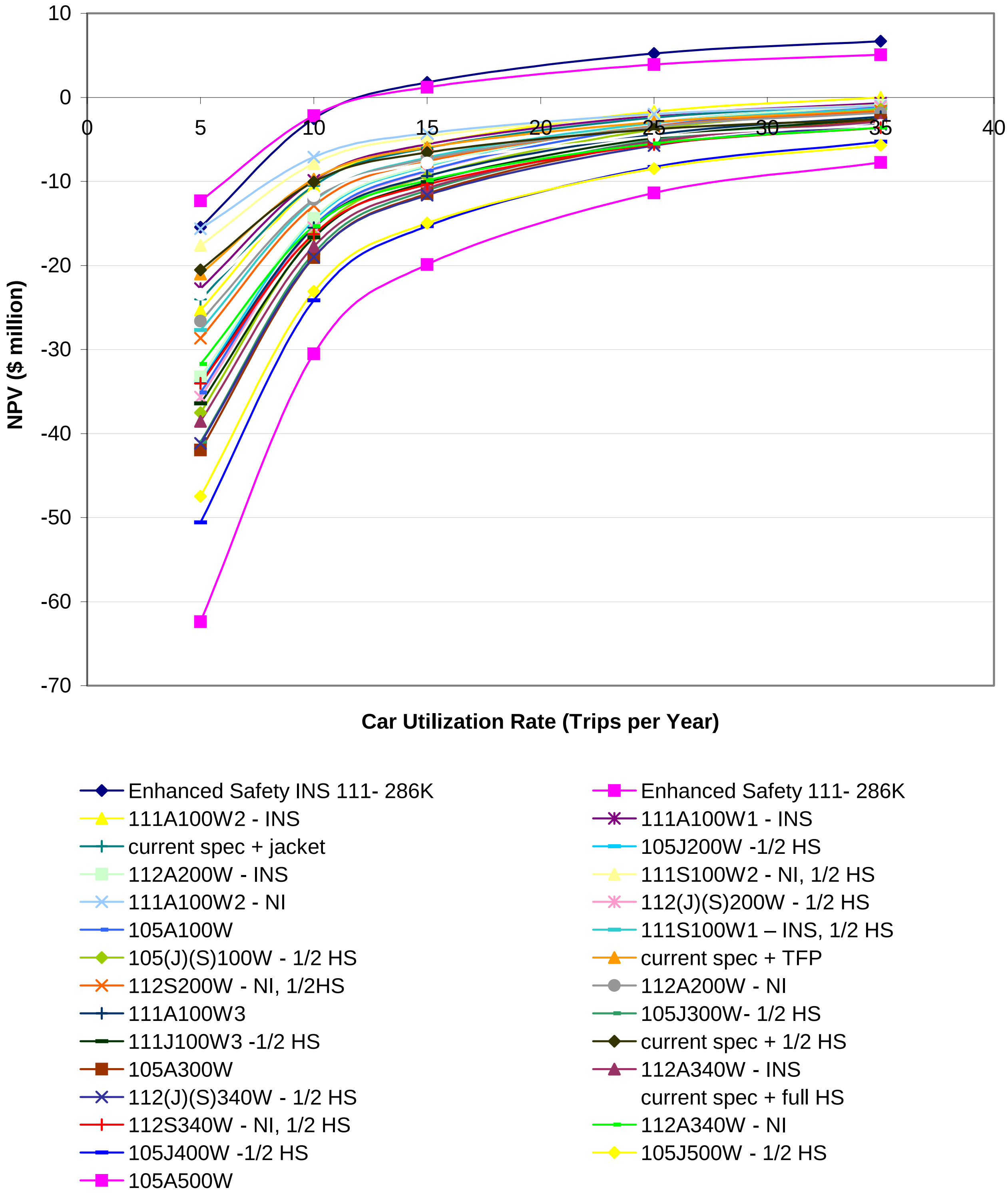


Figure 7.5 NPV for Immediate Replacement of Non-Insulated 111A100W1 for Xylenes

Tank Car Specification	Trips per year					Requisite Trips per year for NPV to Change Sign
	5	10	15	25	35	
105A100W	-8,548,030	-4,061,110	-2,565,471	-1,368,959	-856,168	105
105A300W	-10,512,369	-5,137,990	-3,346,530	-1,913,363	-1,299,148	227
105A500W	-16,358,126	-8,409,207	-5,759,567	-3,639,855	-2,731,407	
105J100W -1/2 HS	-9,241,771	-4,387,089	-2,768,862	-1,474,281	-919,460	104
105J200W -1/2 HS	-8,184,762	-3,858,585	-2,416,526	-1,262,879	-768,459	93
105J300W- 1/2 HS	-10,241,949	-4,989,616	-3,238,839	-1,838,217	-1,237,950	200
105J400W -1/2 HS	-12,977,429	-6,588,762	-4,459,206	-2,755,561	-2,025,428	
105J500W - 1/2 HS	-12,090,096	-6,287,748	-4,353,632	-2,806,340	-2,143,214	
105S100W -1/2 HS	-9,241,771	-4,387,089	-2,768,862	-1,474,281	-919,460	104
111A100W1 - INS	-5,011,563	-2,505,781	-1,670,521	-1,002,313	-715,938	
111A100W2 - INS	-5,743,601	-2,696,235	-1,680,447	-867,816	-519,546	87
111J100W3 -1/2 HS	-8,924,583	-4,446,753	-2,954,143	-1,760,055	-1,248,303	1,441
111S100W1 – INS, 1/2 HS	-6,426,128	-3,197,526	-2,121,325	-1,260,364	-891,381	1,039
112A200W - INS	-8,016,088	-3,795,140	-2,388,157	-1,262,570	-780,176	99
112A340W - INS	-9,532,774	-4,752,653	-3,159,279	-1,884,580	-1,338,280	1,740
112A340W – NI	-7,584,264	-4,066,584	-2,894,024	-1,955,976	-1,553,956	
112J200W -1/2 HS	-8,706,460	-4,119,434	-2,590,426	-1,367,219	-842,987	98
112J340W - 1/2 HS	-10,280,578	-5,120,397	-3,400,337	-2,024,288	-1,434,553	1,297
112S200W - INS, 1/2HS	-8,706,460	-4,119,434	-2,590,426	-1,367,219	-842,987	98
112S200W – NI, 1/2HS	-6,699,583	-3,366,982	-2,256,115	-1,367,421	-986,553	
112S340W - INS, 1/2 HS	-10,280,578	-5,120,397	-3,400,337	-2,024,288	-1,434,553	1,297
112S340W – NI, 1/2 HS	-8,243,121	-4,337,686	-3,035,874	-1,994,424	-1,548,089	
current spec + 1/2 HS	-8,924,583	-4,446,753	-2,954,143	-1,760,055	-1,248,303	1,441
current spec + full HS	-9,746,041	-4,904,859	-3,291,132	-2,000,151	-1,446,873	
current spec + TFP	-9,205,828	-4,464,947	-2,884,653	-1,620,418	-1,078,603	172
Enhanced Safety INS 111- 286K	-2,920,439	-402,517	436,790	1,108,236	1,395,998	12

Table 7.5 NPV for Immediate Replacement of 111A100W3 for Xylenes

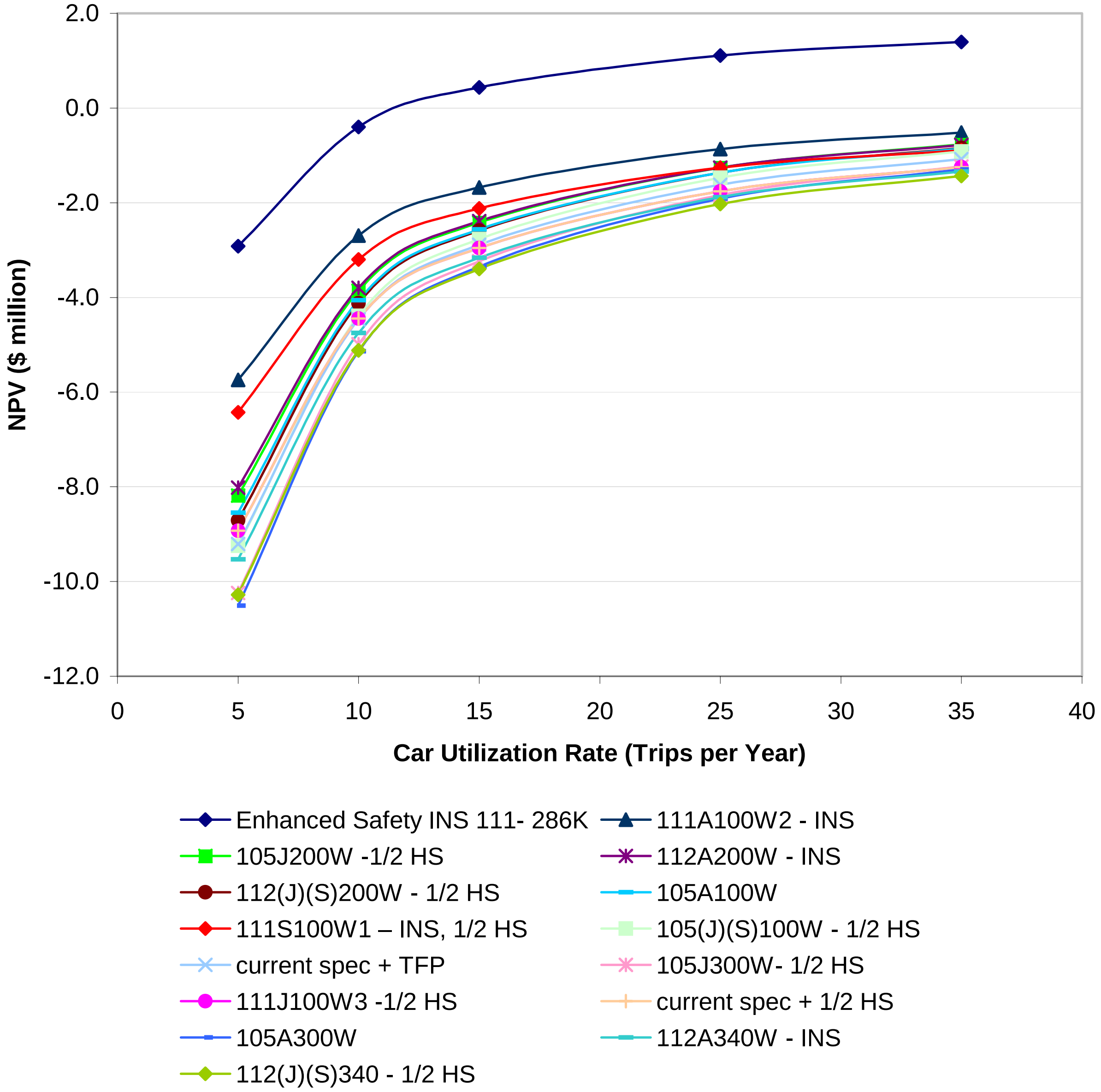


Figure 7.6 NPV for Immediate Replacement of 111A100W3 for Xylenes

There are only a few chemicals that yield a cost beneficial NPV for replacement of 111A100W1 at 10 trips per year (Figure 7.7), the alternative being the enhanced safety 286K 111 tank car, in all the cases. In Figure 7.7, styrene can only be transported in insulated tank cars and hence only the insulated 286K is considered for replacing the 111A100W1.

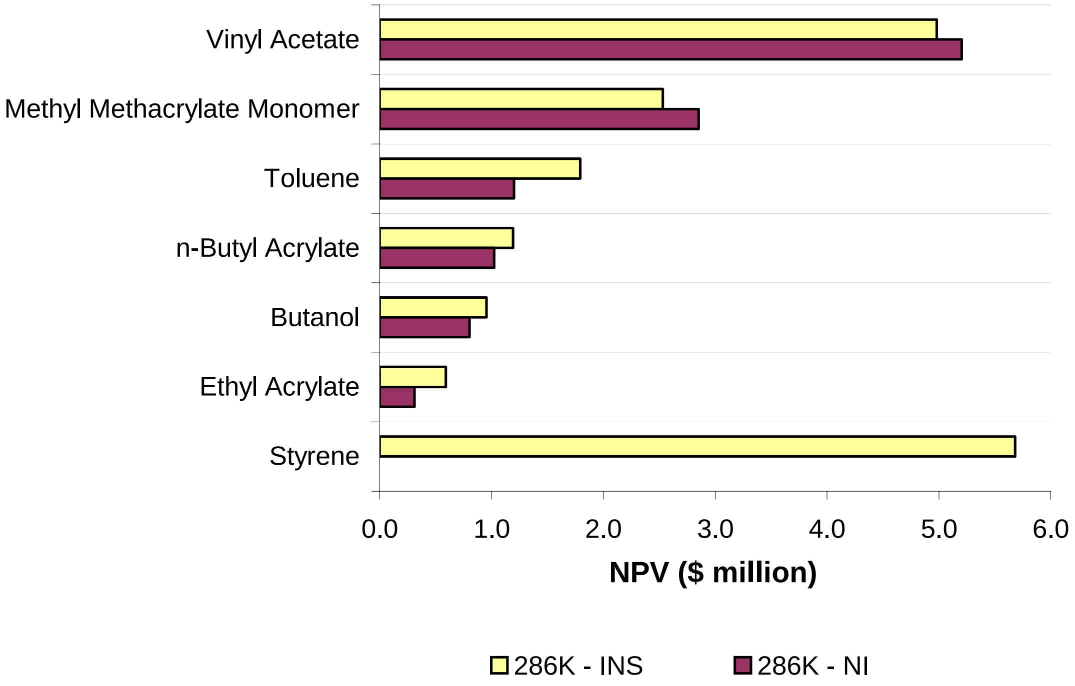


Figure 7.7 Cost Beneficial NPV for Immediate Replacement of 111A100W1 with 286K 111 Tank Car at 10 Trips per Year

The retrofit schedule does not turn out to be cost beneficial for any of the chemicals for any of the retrofit options considered at the current utilization rate. Results for xylenes are shown below (Tables 7.6 and 7.7, Figures 7.8 and 7.9). The reason for this trend is the high cost associated with retrofitting.

	Trips per year					Requisite Trips per year for NPV to Change Sign
Tank Car Specification	5	10	15	25	35	
current specification + TFP	-3,376,786	-1,116,313	-362,821	239,971	498,311	20
current specification + 1/2 HS	-2,297,398	-1,005,313	-574,618	-230,062	-82,395	45
current specification + full HS	-5,199,589	-2,597,694	-1,730,395	-1,036,557	-739,197	6,193
current specification + jacket	-11,681,435	-4,775,542	-2,473,578	-632,006	157,238	32

Table 7.6 NPV for 10-year Retrofit Schedule of Non-Insulated 111A100W1 for Xylenes

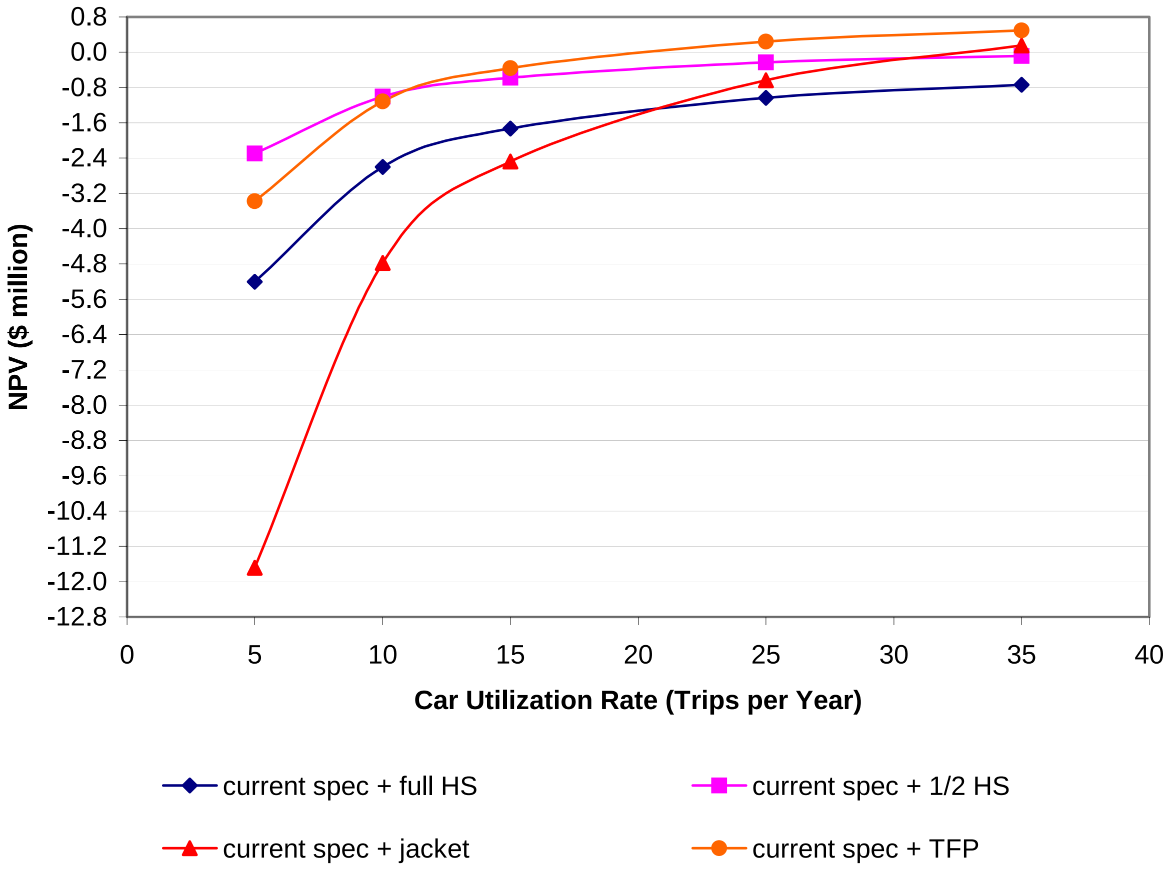


Figure 7.8 NPV for 10-year Retrofit Schedule for Non-Insulated 111A100W1 for Xylenes

	Trips per year					Requisite Trips per year for NPV to Change Sign
Tank Car Specification	**5**	**10**	**15**	**25**	**35**	
current specification + TFP	-1,146,925	-474,970	-250,986	-71,798	4,997	34
current specification + 1/2 HS	-732,484	-355,149	-229,371	-128,749	-85,625	170
current specification + full HS	-1,562,631	-804,045	-551,183	-348,893	-262,197	

Table 7.7 NPV for 10-year Retrofit Schedule of 111A100W3 for Xylenes

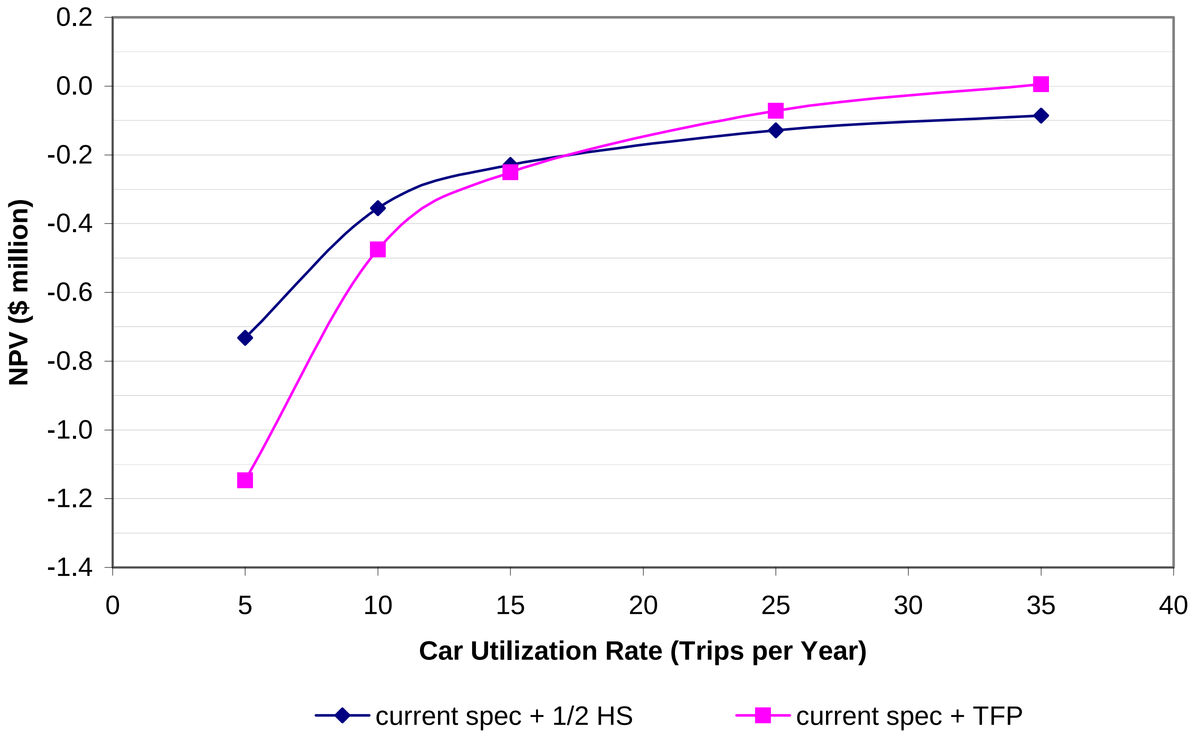


Figure 7.9 NPV for 10-year Retrofit Schedule for 111A100W3 for Xylenes

Whether the net present value of the investments considered here is positive or negative depends on three terms: the benefits, the change in operating costs and the capital cost. Each of these three terms can be positive or negative. In this section I consider each of the three terms in the context of the attrition-based replacement schedule. The other two schedules are not discussed.

7.2.1 Annual Benefit

The benefit term indicates the change in the risk cost when the current tank car is replaced by the alternative tank car. Whether the benefit is positive (i.e., the risk decreases as a result of the replacement) or negative (i.e., the risk increases as the result of the replacement) depends on the difference in the conditional release probability of the current car compared to the alternative car (P_q^{curr} , P_q^{alt}) and the fractional change in carloads as a result of the replacement (α). Let us look at the benefit equation again:

$$b = 1/30(R_c^{curr} - R_c^{alt})$$

$$= 1/30(Fd_c T_c^{curr} \sum_{q=1}^{4} (P_q^{curr} C_{cq})) - (Fd_c (1+\alpha) T_c^{curr} \sum_{q=1}^{4} (P_q^{alt} C_{cq})))$$

$$= \frac{Fd_c T_c^{curr}}{30} \sum_{q=1}^{4} ((P_q^{curr} - (1+\alpha) P_q^{alt}) C_{cq})$$

Therefore, the change in risk will be non-negative only if:

$$P_q^{curr} \geq (1+\alpha) P_q^{alt} \tag{7.6}$$

Whether the inequality in Equation 7.6 is positive or not depends on the conditional release probability and capacity of the alternative tank car specification vs. the current tank car specification. This leads to a consideration of what the alternatives are, given the current tank car specification.

7.2.1.1 Alternative Tank Car Specification List for a Current Tank Car Specification

The first step was to check whether the chemical must be transported in insulated cars. If this was the case then only insulated specifications were considered, otherwise non-insulated specifications were also considered as alternatives. Secondly only those tank car specifications that had a lower conditional release probability than the current tank car specification were considered. After a list of alternatives was chosen for each chemical-current tank car combination, the third and final step was to check, for each chemical-current tank car-alternative tank car combination, if the current annual risk was higher than or equal to the alternative annual risk, i.e., the inequality discussed above (Equation 7.6) holds true. Thus, only the combinations with a positive benefit term were considered for NPV analysis.

7.2.2 Annual Change in Transportation Cost

The change in transportation cost indicates how many more or less carloads are required to transport the same amount of material in an alternative tank car. Whether this change is positive (i.e., more carloads) or negative (i.e., fewer carloads) depends on the fractional change in carloads as a result of the replacement (α). Consider the equation for change in transportation cost:

$$C_t = C_{var} \alpha \, T_c^{curr} \, d_c / 30 \qquad (7.7)$$

All the alternatives except the 286K enhanced safety 111 car had a lower capacity for all considered combinations of alternative and current cars and hence a positive α. Thus, the change in transportation cost is positive for all other alternatives except the 286K car for which α is negative (i.e., the capacity of the alternative is higher than that of the current tank car). Therefore, the transportation cost decreases for this car and hence this term is negative. For example, for benzene, a 286K enhanced safety 111 tank car has a higher capacity (28,502 gallons) than an insulated 263K 111A100W1 (26,227 gallons). Therefore, because of its higher capacity the operating cost for a 286K car will always be lower than the 263K cars it replaces.

7.2.3 Acquisition Cost

The acquisition cost indicates the difference between the cost of replacing the current tank car specification and the cost of continuing to use the current tank car specification. Whether the acquisition cost is positive or negative depends on the fractional change in carloads as a result of the replacement (α) and the costs of buying a new car of the alternative tank car specification and the current tank car specification (C_{alt}, C_{curr}). Let us look at the equation for acquisition cost calculation again:

$$C_a = ((1+\alpha)C_{alt} - C_{curr})(T_c^{curr} / R_{trip})/30$$

Therefore, the acquisition cost is non-negative only if:

$$(1+\alpha)C_{alt} \geq C_{curr} \tag{7.8}$$

Generally, the alternative tank cars have more damage resistant features that cause them to require more material and higher weight, and hence these have a higher capital cost and a lower capacity (i.e., positive α). Thus, the inequality (Equation 7.8) will generally hold true. Hence, acquisition cost is almost always positive. But one exception worth mentioning is the 286K enhanced safety 111 tank car. This tank car specification has a higher capacity than all the current tank car specifications currently used for the 24 chemicals. Thus the fractional change in carloads (α) is negative. Its cost is higher than some of the current tank car specifications (e.g., non-insulated 111A100W1) but lower than other current tank car specifications (e.g., 111A100W3). Thus the acquisition cost for this car as an alternative may be either positive or negative, depending upon the tank car specification being replaced.

7.2.4 Net Present Value for Attrition-based Replacement

As discussed above, the net present value is a combination of the benefit and the cost terms. Their increase or decrease, as a result of the replacement and their relative magnitudes affect whether the investment will be favorable or not. As discussed above, the benefit term is always positive because by definition I only consider alternatives that are more damage resistant than the current specification. But the change in the transportation cost and acquisition cost may be either negative or positive, thus giving rise to four possible cases. Consider the equation for net present value for attrition-based schedule (Equation 7.4) again.

$$NPV_T = \sum_{n=1}^{N} \{(nb - nC_t - C_a)(1 + R_i)^n (1 + R_{nom})^{-n}\}$$

It is evident that whereas benefit (b) and transportation cost changes (C_t) increase linearly with each year, the acquisition cost (C_a) remains constant. Only acquisition cost depends on car utilization rate (Sec 7.1.2.1) and a sensitivity analysis on car utilization rate affects only acquisition cost and none of the other terms.

Hence let us focus on the following term in Equation 7.4, encompassing all three terms discussed above:

$$
\begin{aligned}
&(nb - nC_t - C_a) \\
&\qquad = n(b - C_t) - C_a \\
&\qquad = nA - B \qquad (7.9)
\end{aligned}
$$

where,

$A = b - C_t$

$B = C_a$

The annual benefit, annual change in transportation cost and the acquisition cost are affected by capacity, cost and the release probability characteristics of the current versus the alternate tank cars, and other extraneous parameters (e.g., derailment rate). The following discussion of the four cases considers only the effect of the tank car characteristics. The effect of other parameters is discussed later (Sec. 7.2.4.2).

7.2.4.1 Effect of Tank Car Parameters on the NPV for Attrition-based Replacement

The alternative car may have a higher or lower cost compared to the current car. The alternative may also have a capacity lower or higher than the current car. Furthermore, if the alternative has a lower capacity, implying an increase in transportation cost, the annual benefit achieved as a result of the replacement might or might not be higher than the annual increase in transportation cost. The conditions of interest with regard to these variables can be represented using a simple matrix (Figure 7.10).

		Capacity of an Alternative Compared to Current Car	
		Lower	Higher
Capital Cost of an Alternative Compared to Current Car	Higher	Case 1.1: $b<C_t$ Case 1.2: $b>C_t$	Case 3
	Lower	Case 2.1: $b<C_t$ Case 2.2: $b>C_t$	Case 4

Figure 7.10 All Possible Replacement Scenarios

Case 1: Alternative is a lower capacity car with a higher capital cost

This implies that α is positive and $C_{alt} > C_{curr}$. This is the most general case because a more robust car with the same GRL will generally have a higher price and because of the increased damage resistance its capacity will be lower. This implies that the change in transportation cost (C_t) is positive (Equation 7.7) and the inequality in Equation 7.8 holds true. Therefore, acquisition cost (C_a) is also positive. Therefore, the term B in Equation 7.9 is positive and so, the NPV will be negative if term A is negative, i.e., annual benefit is lower than the annual increase in transportation cost. For the NPV to be positive it is necessary but not sufficient that the term A is positive.

Case1.1: Annual benefit is lower than the annual increase in transportation cost

This means that if the benefit accrued in a year is insufficient to cover even the extra transportation costs incurred in that year, the investment is not cost-beneficial. Also to be noted is that even if term A is zero, the NPV will be negative because in that case the benefit would just be sufficient to cover the extra operating costs and the acquisition cost will not be recovered. Improvement in car utilization rate will only reduce the magnitude of the acquisition cost, not the sign. So, acquisition cost will remain positive and hence the NPV will be negative, irrespective of the car utilization rate. For example, replacement of a 111A100W3 for transporting xylenes with 105A500W, falls in this category (Tables 7.2, 7.8(a) and (b)).

Case1.2: Annual benefit is higher than the annual increase in transportation cost

This implies that the annual benefit not only covers the extra operating costs for that year but also contributes to the recovery of the difference in acquisition cost. This scenario will prove cost beneficial but not necessarily at the current car utilization rate. An improvement in car utilization rate will decrease the magnitude of the acquisition cost and hence increase the NPV. The particular rate at which the investment becomes cost beneficial may or may not be feasible. Taking the same example as in Case 1.1, if the 111A100W3 for xylenes is replaced with a 105J100W – 1/2 HS then the investment is cost beneficial at a car utilization rate of 18 but not at 10 (Table 7.2, Figure 7.3). A rate of 18 trips per year is technically feasible as evidenced by other railcar types that do experience this level of utilization; however, it would require a substantial change in the operation and use of tank cars. Another example that also falls in this category but has an infeasible car utilization rate is that of 111A100W3 tank car for xylenes replaced with a 105A300W car (Table 7.2, Figure 7.3). The investment only becomes cost beneficial if the car makes 61 or more trips per year (Tables 7.8(a) and (b)), which is an unreasonably high expectation for car utilization.

Case	Chemical	Current Car	Cost of Current Car ($)	Alternative Car	Cost of Alternative Car ($)	Percent Increase in Carloads (α)
Case 1.1	Xylenes	111A100W3	76,238	105A500W	92,996	10.58%
Case 1.2	Xylenes	111A100W3	76,238	105J100W – 1/2 HS	79,171	2.75%
Case 1.2	Xylenes	111A100W3	76,238	105A300W	81,837	3.81%

Table 7.8(a) Tank Car Cost and Capacity Comparison for Example Replacements of Case 1

Case	Annual Benefit	Annual Increase in Transportation Cost ($)	Term A	Acquisition Cost ($) (Term B)	NPV at 10 Trips per Year per Car ($)	Car Utilization Rate for Positive NPV (Trips per Year)
Case 1.1	3,813	5,050	-1,237	127,664	-1,748,546	Never
Case 1.2	2,568	1,312	1,256	24,522	-136,694	18
Case 1.2	2,454	1,819	635	41,846	-434,410	61

Table 7.8(b) Annual Benefit, Acquisition Cost and Annual Change in Transportation Cost for Example Replacements in Table 7.8(a)

Case 2: Alternative is a lower capacity car with a lower capital cost

This implies that α is positive but $C_{alt} < C_{curr}$. This is an unusual case but might occur when the alternative, with a lower conditional release probability, is not very different from the current car in terms of damage resistant features. In my analysis there are a few instances of this but they may be due to the capital cost calculations based on a sparse set of UMLER data for the particular specification, which provide an unreliable estimate. The change in transportation cost (C_t) is positive due to a positive α (Equation 7.7) but the inequality in Equation 7.8 might or might not hold true. Therefore, acquisition cost (C_a) might or might not be positive. By definition, a negative acquisition cost implies that it is more expensive to keep using the current tank car specifications than to buy alternate tank car specifications (Sec. 7.1.2.1.3). This gives rise to a counterintuitive situation that with increase in car utilization rate, the acquisition cost increases rather than decreasing (as was the case with a positive acquisition cost). This is because buying alternative cars reduces expenses so the more cars acquired, the greater the savings. Therefore, the higher the car utilization rate, the fewer new cars are needed and hence the lower the savings.

Case2.1: Annual benefit is lower than the annual increase in transportation cost

The acquisition cost, i.e., the term B in Equation 7.9, can be positive or negative but, as discussed in Case 1.1, the term A in Equation 7.9 is negative. If the term B is positive then the NPV will always be negative irrespective of the car utilization rate.

If term B is negative then the NPV can be positive. But with the improvement in the car utilization rate, the acquisition cost increases (i.e., becomes less and less negative) and so the expression in Equation 7.9 decreases. Hence the NPV decreases and can even become negative. For example, replacing a 111A100W3 for xylenes with a non-insulated 112A340W has a negative acquisition cost (Tables 7.9(a) and (b)). It is a cost beneficial replacement even at a car utilization rate of 5 trips per year but as the utilization rate increases from 5 to 35, the NPV decreases and becomes negative for utilization rates of 13 trips or more per year (Table 7.2, Figure 7.3).

Case2.2: Annual benefit is higher than the annual increase in transportation cost

The term B in Equation 7.9 can be positive or negative but, as discussed in Case 1.2, the term A is positive. If the acquisition cost is positive then the scenario is just like in Case 1.2 and will prove cost beneficial but not necessarily at the current car utilization rate. The acquisition cost decreases and the NPV increases with increase in the car utilization rate. For example, a 111A100W3 for xylenes replaced with an insulated 112A200W falls in this category (Tables 7.9(a) and (b)).

If the acquisition cost is negative then Equation 7.9 will be positive and hence the NPV will be positive irrespective of the car utilization rate. For example, a 111A100W3 being replaced by an insulated 111S100W1 – 1/2 HS for xylenes falls in this category. Again, because of the negative acquisition cost the NPV actually decreases with improvements in car utilization rate (Table 7.2, Figure 7.3).

Case	Chemical	Current Car	Cost of Current Car ($)	Alternative Car	Cost of Alternative Car ($)	Percent Increase in Carloads (α)
Case 2.1	Xylenes	111A100W3	76,238	112A340W – NI	69,597	3.54%
Case 2.2	Xylenes	111A100W3	76,238	112A200W – INS	75,362	2.10%
Case 2.2	Xylenes	111A100W3	76,238	111S100W1 – INS, 1/2 HS	69,617	0.63%

Table 7.9(a) Tank Car Cost and Capacity Comparison for Example Replacements of Case 2

Case	Annual Benefit	Annual Increase in Transportation Cost ($)	Term A	Acquisition Cost ($) (Term B)	NPV at 10 Trips per Year per Car ($)	Car Utilization Rate for Positive NPV (Trips per Year)
Case 2.1	216	1,691	-1,475	-20,044	52,018	13[*]
Case 2.2	2,147	1,003	1,144	3,398	110,386	3
Case 2.2	384	300	84	-29,680	379,316	Always

[*] The NPV decreases with increase in utilization rate and turns from positive to negative at the specified rate.

Table 7.9(b) Annual Benefit, Acquisition Cost and Annual Change in Transportation Cost for Example Replacements in Table 7.9(a)

Case 3: Alternative is a higher capacity car with a higher capital cost

This implies that α is negative and $C_{alt} > C_{curr}$. The 286K enhanced safety 111 car falls in this category because for any given chemical, its capacity is expected to be higher than the current tank car, and its cost would be higher as well. This implies that the change in transportation cost (C_t) is negative (Equation 7.7) and hence, the term A in Equation 7.9 will always be positive. The inequality in Equation 7.8 might or might not hold true. Therefore, acquisition cost (C_a) or the term B in Equation 7.9 can be negative or positive.

If the acquisition cost is positive then it becomes Case 1.2 and hence will be cost beneficial but not necessarily at the current car utilization rate. The acquisition cost will decrease with the increase in car utilization rate thus increasing the NPV. For example, replacement of a non insulated 111A100W1, for acrylonitrile, with an enhanced safety insulated 286K 111 car falls in this category (Tables 7.10(a) and (b)).

If the acquisition cost is negative then Equation 7.9 will be positive and hence the NPV will be positive irrespective of the car utilization rate. For example, replacing a non-insulated 112A200W car, for acrylonitrile, with an enhanced safety insulated 286K 111 car falls in this category (Tables 7.10(a) and (b)).

Case	Chemical	Current Car	Cost of Current Car ($)	Alternative Car	Cost of Alternative Car ($)	Percent Increase in Carloads (α)
Case 3	Acrylonitrile	111A100W1 - NI	59,305	286K – 111 INS	71,035	-5.95%
Case 3	Acrylonitrile	112A200W – NI	68,362	286K – 111 INS	71,035	-8.20%

Table 7.10(a) Tank Car Cost and Capacity Comparison for Example Replacements of Case 3

Case	Annual Benefit	Annual Increase in Transportation Cost ($)	Term A	Acquisition Cost ($) (Term B)	NPV at 10 Trips per Year per Car ($)	Car Utilization Rate for Positive NPV (Trips per Year)
Case 3	4,424	-2,185	6,609	27,660	537,881	4
Case 3	728	-1,140	1,868	-4,400	285,415	Always

Table 7.10(b) Annual Benefit, Acquisition Cost and Annual Change in Transportation Cost for Example Replacements in Table 7.10(a)

Case 4: Alternative is a higher capacity car with a lower capital cost

As discussed in Case 3, the 286K enhanced safety 111 car falls in this category too. While its capacity was always higher, its cost was not always higher than the tank car specifications considered for replacement. For example, a 111A100W3 has a higher cost than an enhanced safety, insulated, 286K 111 tank car (Table 7.11(a)). This is an unlikely scenario and the cases that fall in this category might actually be an artifact of the capital cost estimates, which were sometimes based on a sparse set of UMLER data points for some of the particular specifications.

The higher capacity of the alternate car implies that α is negative, which coupled with the inequality $C_{alt} < C_{curr}$, renders the inequality in Equation 7.8 true for all cases. Therefore, acquisition cost (C_a) or the term B in Equation 7.9 is always negative. The change in transportation cost (C_t) is negative (Equation 7.7) and hence, the term A in Equation 7.9 will always be positive. Hence, Equation 7.9 will be positive and hence the NPV will be positive irrespective of the car utilization rate. For example, replacing a 111A100W3, for xylenes, with an insulated 286K enhanced safety 111 car falls in this category (Tables 7.11(a) and (b)).

Case	Chemical	Current Car	Cost of Current Car ($)	Alternative Car	Cost of Alternative Car ($)	Percent Increase in Carloads
Case 4	Xylenes	111A100W3	76,238	286K – 111 INS	71,035	-8.33%

Table 7.11(a) Tank Car Cost and Capacity Comparison for Example Replacements of Case 4

Case	Annual Benefit	Term A	Annual Increase in Transportation Cost ($)	Acquisition Cost ($) (Term B)	NPV at 10 Trips per Year per Car ($)	Car Utilization Rate for Positive NPV (Trips per Year)
Case 4	1,709	-3,975	5,684	-53,370	1,419,842	Always

Table 7.11(b) Annual Benefit, Acquisition Cost and Annual Change in Transportation Cost for Example Replacements in Table 7.11(a)

7.2.4.2 Effect of Other Parameters on the NPV for Attrition-based Replacement

Derailment Rate (F_{derail}):

The car derailment rate (Sec. 3.1) has been held constant throughout this analysis (1.26E-07 car derailments per year). This parameter linearly affects the risk-per-car-mile estimate for a chemical (Equations 5.1 & 5.6). Any increase in car derailment rate will increase the risk per car-mile and the annual risk by the same factor. Thus, the annual benefit (b) increases linearly with an increase in car derailment rate (Sec. 7.1.2.3). This implies that the higher the derailment rate, the greater the benefit from switching to a more robust tank car. The transportation cost and the acquisition cost remain unaffected by any change in the derailment rate. Therefore, an increase in car derailment rate will always have the effect of improving the NPV, and vice versa.

Average Shipment Distance for a Chemical (d_c):

Any increase in average shipment distance will increase the annual risk (Equations 5.5 & 5.8) of the chemical by the same factor. Thus, the annual benefit (b) achieved as a result of the replacement will also increase correspondingly. An increase in average shipment distance will also increase the transportation cost. It is assumed that average shipment distance for the chemical does not change after replacement, even though the number of carloads may change. In reality this might or might not be true. Based on this assumption, the increase in average shipment distance will increase the transportation cost by the same factor for the current and alternate tank car specifications (Sec. 7.1.2.2). Hence the change in transportation cost (C_t), achieved as a result of the replacement, will also increase by the same factor, but only in magnitude not in sign. Whether the change in transportation cost is positive or negative is independent of the average shipment distance.

Both annual benefit and change in transportation cost increase with shipment distance, Therefore, the magnitude of term A in Equation 7.9, will increase by the same factor but its sign remains unchanged. The acquisition cost (term B in Equation 7.9) remains unaffected by average shipment distance. Therefore, increase in shipment distance may increase or decrease the NPV, depending on the characteristics of the particular replacement. For example, if the replacement falls under the category of case 1.1, the NPV will be reduced whereas if it falls under case 1.2, the NPV will improve.

Annual Carloads (T_c^{curr}*):*

An increase in annual carloads will affect the annual benefit (b) and the annual change in transportation cost (C_t) in exactly the same manner as does average shipment distance but the difference is that the change in annual carloads also affects the acquisition cost (C_a), unlike average distance. Increase in carloads implies an increase in the number of cars if car utilization rate remains constant. Thus, an increase in annual carloads increases the cost of replacing the current specification with the alternate specification and also the cost of continuing to use the current specification, by the same factor (Sec. 7.1.2.1.1 and Sec. 7.1.2.1.2). Therefore, the acquisition cost will increase in magnitude by the same factor (Sec. 7.1.2.1.3) but remains unchanged in sign.

As each of the three terms: annual benefit (b), annual change in transportation cost (C_t) and acquisition cost (C_a) all increase in magnitude by the same factor, the NPV also increases by a corresponding amount.

Operating Cost (C_{var}):

The operating cost (Sec. 6.2.2) has also been held constant throughout the analysis ($1.48 per car-mile). An increase in this cost has the direct effect of increasing the transportation cost for a chemical and vice versa. The effect on annual change in transportation cost (C_t) is the same as for the average shipment distance or annual carloads, i.e., the annual change in transportation cost (C_t), as a result of the replacement, will have its magnitude altered without any change in sign. For example, if the transportation cost decreases as a result of replacement (i.e., negative C_t) then an increase in operating cost will lead to a larger reduction in transportation cost. The acquisition cost and the annual benefit remain unaltered by changes in operating cost. Therefore, an increase in operating cost can have the effect of increasing or reducing NPV, depending on which of the four cases discussed above (Sec. 7.2.4.1), the replacement falls under.

Car Utilization Rate (R_{trip}):

The car utilization rate affects the number of cars required for a certain number of carloads. A higher car utilization rate implies fewer cars and vice versa (Sec. 7.1.2.1). An increase in car utilization rate will decrease the number of cars by the same factor. This leads to a reduction in both, the cost of replacing the current fleet of tank cars with an alternative specification, and also the cost of continuing to use the current tank car specification, by the same factor. Thus, the acquisition cost is reduced by the same factor, but only in magnitude (Sec. 7.1.2.3), the sign remains unaffected. If the acquisition cost is positive then this has the effect of improving the NPV whereas if the acquisition cost is negative, the effect is to reduce the NPV (as discussed in Case 2 in Sec. 7.2.4.1). The effect of car utilization rate has been explained in detail in the description of the four cases in Sec. 7.2.4.1.

Discount Rate (R_{nom}):

By definition, the effect of increasing the discount rate is to decrease the NPV. Though the above discussion has been confined to attrition-based replacement, it was more interesting to compare the three schedules in the context of discount rate.

In this analysis, there are three different schedules with different cost and benefit streams. The immediate replacement schedule has a very large initial cost (acquisition cost) unlike the attrition-based or 10-year retrofit schedule. In the attrition-based schedule, the acquisition cost is distributed uniformly (not accounting for discounting or inflation) over the life of the project whereas in the 10-year retrofit schedule, the major acquisition cost is incurred in the first 10 years, it is much lower in the later 20 years. Therefore, a higher discount rate might penalize the immediate and 10-year retrofit schedule more than the attrition-based schedule.

A sensitivity analysis was conducted on discount rate for all three schedules for replacement or retrofitting of 111A100W3 cars for transporting xylenes (this particular replacement was chosen because it portrays all the effects that need to be discussed). The alternative is 111A100W3 cars fitted with top fittings protection. At a utilization rate of 10 trips per year, the retrofit schedule is not cost beneficial irrespective of the discount rate, and hence it was not possible to compare the results. Therefore, a car utilization rate of 35 trips per year was selected and kept constant for this analysis. The net present values are presented below for the nominal discount rates varying from 4% (this yields a real discount rate around zero percent) to 14% (around ten percent in real discount rate terms) (Table 7.12, Figures 7.11 and 7.12).

	NPV at 35 Trips per Year		
Discount Rate	**Attrition-based Replacement**	**10-Year Retrofit Schedule**	**Immediate Replacement**
4%	143,427	191,721	663,782
6%	87,356	104,346	-97,848
8%	52,455	48,813	-619,789
10%	30,425	13,209	-987,232
10.62% (Base Case)	25,378	4,997	-1,078,603
12%	16,345	-9,724	-1,252,774
14%	7,250	-24,484	-1,449,552

Table 7.12 Variation of Net Present Values with Discount Rate for the Three Schedules for Replacement/Retrofit of 111A100W3 for Xylenes

(assuming car utilization rate of 35 trips per year)

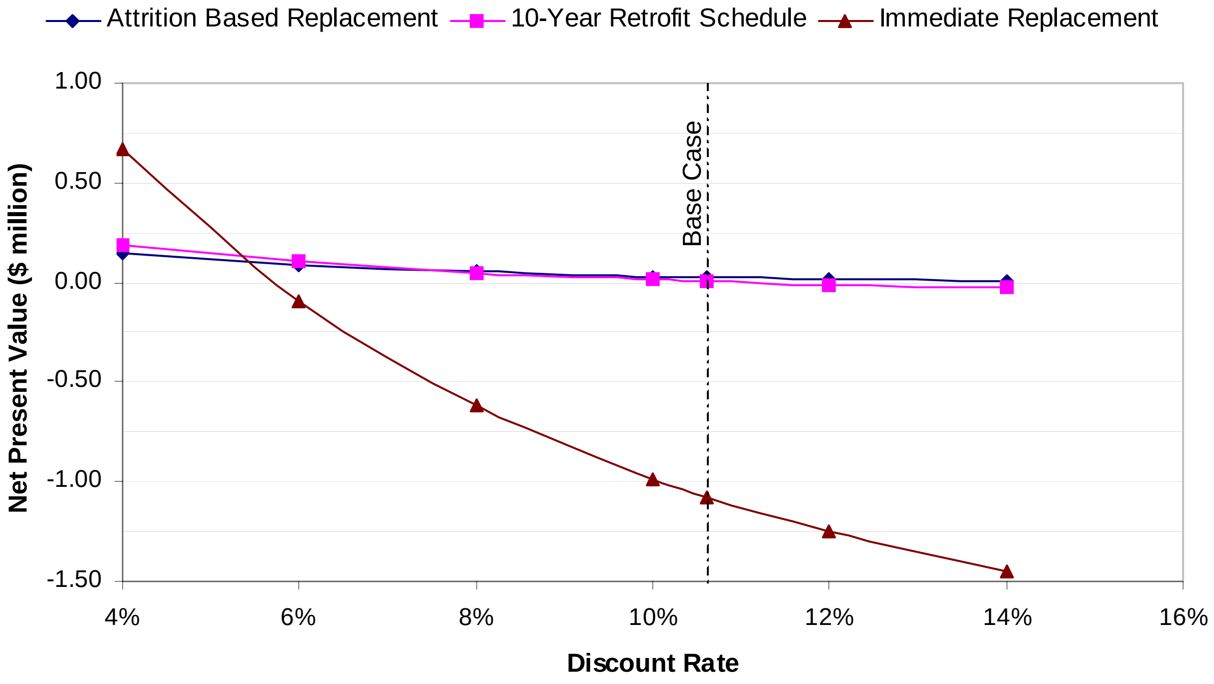


Figure 7.11 Sensitivity of the Three Schedules to Discount Rate

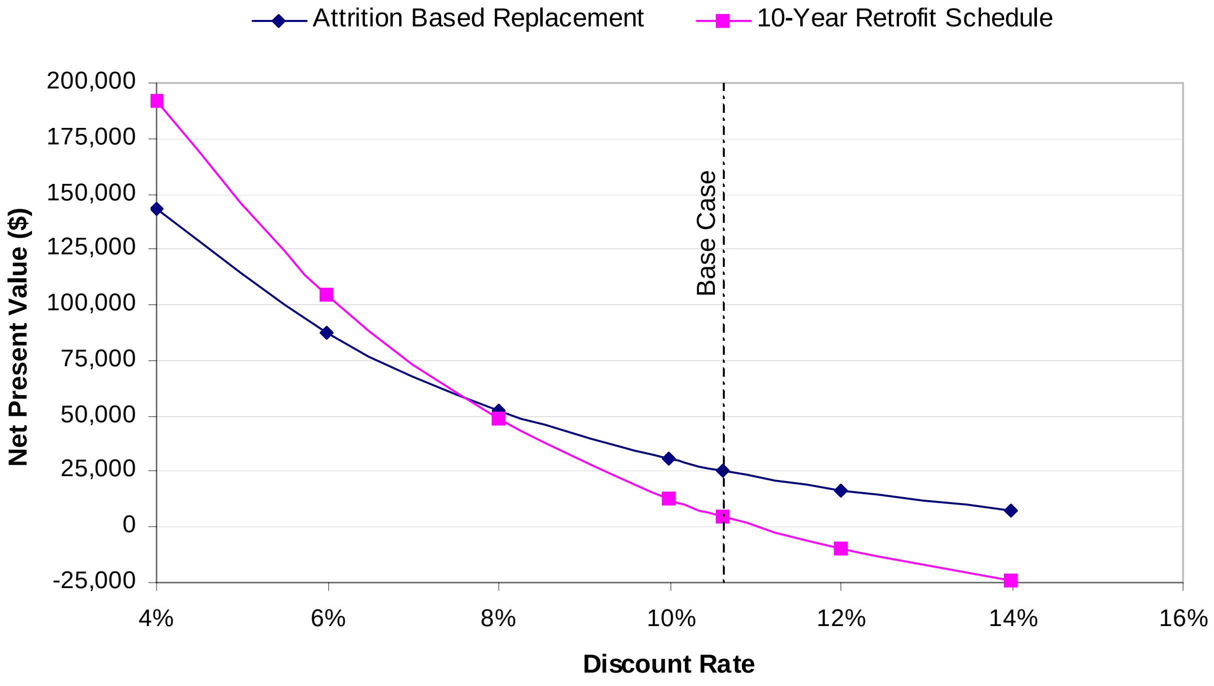


Figure 7.12 Sensitivity Analysis Graph of Figure 7.10, Without Immediate Replacement Schedule

It is evident from Figures 7.11 and 7.12 that as discount rate increases, the NPV values decrease for all schedules, but the immediate replacement schedule is the first to yield negative NPVs (Table 7.12) followed by the 10-year retrofit schedule. The attrition-based replacement continues to be positive till the end of the discount rate range selected for the sensitivity analysis. Therefore, higher discount rates have the greatest effect on the immediate replacement schedule. It is also seen that at lower discount rates, the NPV for the immediate replacement schedule is much higher than the other two schedules (Table 7.12). The 10-year retrofit schedule also yields somewhat higher NPVs than attrition-based replacement at lower rates (Table 7.12). Thus lower discount rates favor immediate replacement the most. But it should be noted that as much as immediate replacement turns out to be a better schedule than the attrition-based replacement, these results are calculated at 35 trips per year rate. The immediate replacement is not a cost beneficial schedule at the current car utilization rate of 10 trips per year for majority of the chemicals considered in this research.

7.3 Conclusions

This chapter uses the results of cost, capacity and benefit analyses discussed in earlier chapters and tests the cost effectiveness of using more robust tank cars using the NPV approach. Three different replacement schedules have been defined: immediate, attrition-based and 10-year retrofit schedule. There could be more variations of the above-defined schedules. For example, instead of the immediate replacement schedule we might consider an immediate retrofitting schedule. This has not been taken up in this study but is a feasible alternative to consider for future work on this topic. Enhanced safety 286K tank cars turn out to be a cost beneficial alternative for all of the 24 commodities under the attrition-based schedule, and for 7 of the 24 commodities under the immediate replacement schedule. This is due to its higher GRL which reduces transportation costs, and in some cases even acquisition cost. Among the 263K GRL cars, the alternatives that turn out to be cost beneficial at the current car utilization rate are 111A100W2, 111S100W1, and 111S100W2, which present a small improvement in release probability compared to the car being replaced, with a minor increase in cost per car. Other alternatives with more damage resistant features like a 105A300W do not prove cost beneficial because their combined capital cost and operating cost more than offsets the benefits accrued due to their better accident performance.

CHAPTER 8

CONCLUSIONS AND FUTURE WORK

This chapter presents a summary of the results of this research and presents recommendations on further work that can refine and expand the generality of the findings from this research.

8.1 Conclusions and Discussion

There are several important conclusions that result from the current research. These are discussed below in the context of the objectives stated at the beginning of the study (Sec. 1.3).

1. Evaluation of environmental risk for each chemical under study: This study presents the first, detailed step-by step methodology to quantitatively analyze the risk to the environment due to transportation of hazardous materials. This includes development of estimates of per car-mile and annual environmental risk (Figures 5.2 and 5.3) for the chemicals of interest. Risk calculation involved an in-depth analysis of the probability of release of these chemicals and the consequences of the release once the chemical has been spilled. Therefore, in the process of developing risk results, there are several other important results that are generated. The weighted conditional

probability of release for a chemical, given the distribution of tank cars used for the chemical (Figure 3.2) is one such result. Another result is the expected clean up cost for a chemical (Figure 4.17) given that a release has occurred. While expected clean up cost is a metric that indicates the environmental hazard associated with the chemical's spill regardless of its likelihood of release, the weighted conditional probability of release is an indicator of probability regardless of the consequence. Risk per car-mile takes into account both aspects and annual risk accounts for the traffic volume of the chemical, in other words the extent of exposure of the environment to the chemical. Each of these metrics has potential value, depending on the particular project and questions being considered by risk managers.

With the increased awareness of the impact of hazardous materials on environment, there was a need for a general yet exhaustive model that could quantify this impact. Perhaps the most significant aspect and contribution of the current research is the methodology that has been developed for carrying out this objective in terms of risk to soil and groundwater. More recently, natural resource damages such as impact on surface water bodies has emerged as an important additional factor affecting railroads' environmental risk but it falls beyond the scope of the current phase of research. As a risk analysis study this research has been novel in several aspects:

- This is the first attempt to calculate chemical-specific environmental risk. Barkan et al (1991) calculated environmental risk due to halogenated hydrocarbons for a combined group of ten chemicals. Modeling was used to initially identify the halogenated hydrocarbons as a group of chemicals of interest, but the risk values were developed empirically based on historic clean up costs and projected rates of inflation for these costs. Chemical specific properties, characteristics of spill sites, geographical distribution of spill sites and various other parameters were not taken into account in the Barkan et al (1991) research. The current study is the first attempt to bring together several elements required for quantitative environmental risk assessment of chemical transportation:

a. The annual shipment information for a chemical in terms of types of tank cars used and the annual number of carloads transported in each type for probability analysis and for determining the amount of exposure of the environment to the chemical.
b. The average shipment distance per carload for a chemical, again for evaluating the amount of exposure.
c. Chemical and soil property data, and the interaction of the two, for conducting simulations of spills using the quantitative risk assessment software for consequence analysis.
d. Exposure probability of various soil types and groundwater depths to chemical spills.
e. Thoroughly up-to-date train accident and car derailment rates combined with the latest statistical results on tank car safety performance, for probability analysis.

But while the use of chemical specific information for calculating risk is a strength of the study, these results are a function of various input parameters.

Their validity depends on the accuracy of the inputs. In fact, some of the inputs vary from one year to another. For example, the tank car distribution for a chemical varies from year to year, in terms of the tank car specifications used and the percent of carloads transported in each of the specifications, but more so in terms of the total annual carloads transported. Average shipment distance for various chemicals also changes from year to year. Both the annual number of carloads transported and the average shipment distance for a chemical affect the annual risk for the chemical. The changes in the tank car distribution affect the weighted conditional probability of release for the chemical (Equation 3.4) and hence the risk per car-mile (equation 5.1) but as long as a majority of the shipments are in the non pressure 111 cars, the weighted conditional probability will not vary much. The derailment rate (F_{derail}) may also vary but as discussed previously (Sec. 3.1), mainline derailment rates have remained nearly constant over the period, 1992-2001 (Anderson and Barkan 2004) and have not changed substantially since then (Barkan 2006). Therefore, unlike annual risk the risk-per-car-mile estimates generally do not vary much but only as long as there is no change in the consequence analysis procedure.

Ideally, the consequence analysis results i.e., remediation costs for chemicals should hold true if:

a. the properties of the chemical do not vary
b. the underlying model used for simulation does not change, and,

c. the treatment techniques employed for treating a chemical and the unit costs of treatment do not vary.

Although the basic chemical properties will not change it is quite possible that the cost of remediation will. Different factors can cause the cost to change in different directions. Inflation and more stringent cleanup requirements will tend to drive costs up. But this may be countered by increasing acceptance of risk-based cleanup standards and development of new remediation technologies that will reduce costs. This will change the consequence analysis results and hence the expected clean up cost and risk-per-car-mile estimates. The net effect of these over time is difficult to predict and there may be differential effects for different chemicals, thereby causing changes in the risk they pose relative to one another.

- This is the first time an environmental risk analysis incorporated an in-depth exposure analysis analogous to the population density categorization required for human health risk analysis. The exposure analysis work (Anand 2004, Anand and Barkan 2006) conducted in an earlier phase of this research was the first attempt to develop a nationwide estimate of the probability distribution of the exposure of two of the important elements affecting the risk to the environment from railroad spills of hazardous materials, soil type and depth to groundwater.

While the soil dataset used for the exposure analysis was an exhaustive GIS dataset called the State Soil Geographic database (STATSGO), from the Natural

Resources Conservation Service (NRCS), the real time groundwater well monitoring database of the United States Geological Survey (USGS) used for groundwater depth analysis was sparsely populated and hence presented the greatest limitation to a more refined estimate of the nationwide distribution of this parameter. Several assumptions were made regarding the distribution of groundwater depth regions in the country that could not be substantiated due to the small amount of data. The wells were assumed to be randomly scattered in the 48 states and rail line location was assumed to be independent of the groundwater depth distribution such that the distribution of groundwater depths near rail lines could be assumed to be the same as their distribution nationwide.

As discussed later in the section on future work, the exposure analysis for groundwater depth can be updated using a more extensive database also available from USGS. This could have the effect of changing the probability of occurrence of groundwater depth regions and hence might also affect the joint probability of occurrence of soil type and groundwater depth. This will change the expected clean up cost and risk-per-car-mile results for the chemicals.

The exposure analysis also does not account for the actual routings of hazardous materials shipments over the rail network. This will make a difference only if the distribution of critical environmental features along rail lines with hazardous materials traffic is substantially different than the rail network as a whole. One of the findings of the exposure analysis (Anand 2004) was that the nationwide percentage of soil types is not significantly different than the distribution beneath the rail network. This finding gives reason to believe that the distribution of environmental features along rail lines with a high volume of hazardous materials traffic is similar to their distribution along the entire rail network. However, the assumption can only be verified with certainty if the specific traffic data is flowed on a U.S. rail network map in a GIS compatible environment such that the hazardous material routes and traffic densities can be overlaid on soil maps and groundwater depth maps to evaluate the exposure of these environmental features along these specific routes. The section on future work discusses the possibility of conducting such an analysis in more detail.

2. Ascertain the cost-effectiveness of using more robust tank cars for each chemical:
   - This is the first study to conduct a comprehensive comparison of a variety of tank car replacement and retrofit options. The set of alternatives for a non insulated 111A100W1 (conditional release probability = 35.27%) included tank cars with a release probability anywhere from around 4% (105J500W) to around 32% (non insulated 111A100W1 with half-height head shields).

It was shown that the economics of the replacement were controlled by the combination of the annual benefits, change in transportation cost and the acquisition cost (which indicates the change in capital investment). It was found that among the alternative specifications with a 263K GRL, those with a much higher capital cost compared to the car being replaced do not turn out to be cost beneficial for replacing

111A100W1 or 111A100W2 tank cars for any of the chemicals at the current car utilization rate. The tank car specifications belonging to the 105 and 112 tank car classes fall in this category. These tank car specifications are more resistant to damage in accidents and hence present a large reduction in conditional release probability and risk-per-car-mile estimates; 105s decrease the conditional release probability by at least 67% and 112s reduce it by at least 36%. Nevertheless, the benefits accrued in terms of reduced risk are insufficient to compensate the increased cost, and in some cases do not even cover the increase in operating costs. The only cost effective options among the 263K GRL alternatives were those that had only a slightly higher capital cost compared to the current car and hence were invariably associated with only a minor improvement in conditional release probability, e.g., a 111A100W2 or a 111S100W2. Therefore, reduction in release probability is not sufficient to justify a replacement; it is the improvement in release probability in combination with the increase in cost that controls the economics.

Barkan (2005) used a similar concept involving release probability and weight, instead of cost, as part of the development of new specifications for 286K tank cars. Barkan (2005) analyzed 24 different combinations of 3 risk reduction options in terms of ‘the reduced release probability per unit increase in weight’ and generated a Pareto optimal set of combinations. This set consisted of 10 out of the 24 combinations that yielded the highest improvement in safety with the lowest increase in weight for any desired level of tank car weight increase.

Among the 286K GRL alternatives, both non insulated and insulated enhanced safety 111 tank cars are cost beneficial options for all transitions considered (except sulfuric acid for which the insulated 286K cars yield a negative NPV). The capital cost of these two alternatives ranges from being moderately higher to being lower than that of the current car. For example a non insulated 286K 111 tank car (capital cost approximately around $71,000) replacing a non insulated 111A100W1 tank car (capital cost of approximately $59,000) presents a moderately high cost replacement whereas if the car being replaced is a 111A100W3 (capital cost approximately around $76,000), the transition actually yields a negative acquisition cost.

The case for the use of 286K tank cars is primarily driven by the change in annual transportation costs. This tank car has a higher lading capacity when optimized for a chemical compared to a 111A100W1 and hence the carloads and the operating expenses decrease in the process. Therefore, one important conclusion from this research is that the 286K tank cars are clearly a cost beneficial option for transporting the chemicals of interest (Table 7.3, Figure 7.4). It should be remembered though that the usage of alternatives like 286K tank cars or 111A100W2 tank cars (i.e., cars without bottom fittings) may involve costs other than those directly associated with the buying and operating of the new tank car specifications (e.g., it might involve improvement in track quality or costs associated with changing the loading/unloading practices) that are not accounted for in this research.

Perhaps the weakest point of the cost benefit analysis is the estimation of costs of the tank cars of interest from the UMLER database. Age of the tank car and gallon capacity were recognized as the variables that should have a bearing on the cost of the tank car but even though the effect of age was realized (Figure 6.2), the results of multiple regression analysis for gallon capacity were contradictory to simple regression results for this variable. The results of a simple regression analysis of one of the most common car types indicated that the relation between cost and capacity was poor (R-squared value = 0.0457). In fact, when the gallon capacity for cars built in a single year was plotted against cost, no significant relationship between the two variables was found. On the contrary the multiple regression analysis model indicated that the effect of gallon capacity on cost was significant, but with a negative coefficient, i.e., the model predicted that an increase in capacity decreased the cost. This is illogical, the cost of a tank car should increase with the capacity of the car because of the greater amount of material required (Dalrymple 2005). Therefore, there remain some questions regarding this aspect of the research. There might be several reasons for the problem, such as other variables that affect tank car cost that were not accounted for in the multiple regression model, and/or a linear regression might not be applicable in this case. Nevertheless this aspect requires a more in-depth analysis of the cost database.

Though the methodology for cost estimation needs further work, the cost estimates presented for various tank car specifications in the research are not very far off from general values attached by the railroad industry to this parameter.

Another weak point in the study is that the consequence analysis simulations were run for the tank car capacity equal to a 111A100W1 (insulated or non insulated whatever the case might be). Therefore, when a replacement is considered, the new risk-per-car-mile estimate calculation involves the product of the conditional release probability value for the new car with the consequence values for a 111A100W1. This leads to an underestimation or overestimation of the benefit incurred for the 263K or 286K alternatives, respectively. However this effect is quite small and the results of the analysis are not substantially affected by this assumption. Recommendations for an improved approach to this are discussed in the future work section.

- Another novel contribution of the current research is the attempt to compare three different tank car replacement schedules. Although the immediate replacement schedule is not realistic because of the constraints on car building capacity, the cost beneficial results for replacement with 286K tank cars for seven of the chemicals of interest (Figure 7.7) strengthens the case for use of these higher capacity cars.

In theory there is infinite possible variation in the replacement schedules. The options chosen for analysis here are intended to bound the problem. It is possible that within these bounds, for certain combinations of risk levels and car types, there may exist optimal replacement schedules that maximize the cost effectiveness that have not been specifically identified in this research.

8.2 Future Work

As in every research work, I had to make certain assumptions or estimations due to unavailability of sufficient data or documentation, or to simplify certain processes to achieve results within the given resource and time constraints. In this chapter I discuss the areas in which further work could be conducted to address some of these.

Some of the proposed future work is dependent on data availability. The following areas can be improved upon in the future phases of the project.

- Shipping conditions for chemicals: The IIRSTF risk assessment model required shipment pressure and temperature for the chemicals. I assumed ambient conditions for most of the chemicals and subjectively adjusted the values for some chemicals (e.g., acetaldehyde) for which the model failed to run because of this assumption. There are no official industry standards that set the shipping conditions for most chemicals and the documentation maintained by the shippers is not easily accessible. One of the sources to obtain this information are the accident reporting systems but these are currently structured such that either we cannot obtain shipping conditions of the chemical that spilled (Chemtrec Data) or if the shipping conditions are available, the system does not contain the name of the corresponding chemical that spilled (BNSF spill data). Revision of the data input processes would make more precise treatment of this variable possible.

- Property data for materials of concern: I did not find data for 21 out of 59 materials that were authorized for transport in the non pressure tank cars by the

CFR. This included all 19 mixtures under study. The amount of property data required by the IIRSTF model to run is difficult to obtain for mixtures and a different approach is required. One approach might be to study the major constituents of a mixture separately and obtain consequence estimates for each and then calculate a weighted average consequence estimate. This might be applied to certain mixtures for which the composition is well-defined, e.g., spent sulfuric acid, denatured alcohol (if the grade is specified); but even with well defined composition data, availability for individual constituents is essential. Some of the properties for such mixtures can also be calculated by use of certain software available, e.g., Prode Properties (Prode 2005), Cranium (Cranium 2006), etc. There are other mixtures for which the composition is not well defined, e.g., cleaning liquid compounds, elevated temperature liquid, N.O.S. One possible method to analyze consequences for such materials might be an empirical approach in which the expenses incurred for clean up of past spills of these materials is used.

Apart from mixtures I also could not find data suitable for the IIRSTF model for chemicals transported in solution. So, I used the data for the corresponding pure chemical form, whenever available. The methodologies suggested above for mixtures could be applied to solutions too.

- Limitations of the risk assessment model: The IIRSTF model is currently the only model that can simulate a tank car spill, trace the material's path into the soil and groundwater and calculate remediation costs. As much as the model fits our research needs to a large degree, it still has some limitations. The model could not handle solids, e.g., hexamethylenediamine and maleic anhydride, although as solids they are unlikely to pose much risk of contamination to soil or groundwater.

There are gaps in the model's documentation of the algorithm for tracing the material into the groundwater and calculating the volume of groundwater contaminated. The equations used to calculate plume width have variables that are either ambiguously defined or not defined at all. The clean up cost formulae for groundwater are also incompletely documented with gaps in definitions of variables. Thus it is not possible to verify the results of the groundwater recovery module. In this respect the model was sort of a black box and hence possibly the weakest area in this analysis. In a follow on project to the research described here, a new groundwater model for transport and fate of contaminant in groundwater is being developed at the University of Illinois with funding from the AAR. This model will incorporate modeling advances and new information developed over the past 15 years since the IIRSTF model was developed, as well as input from the railroad environmental clean up experts (Clark 2005, Williams 2005).

- Probability analysis for aluminum and alloy tank cars: I made certain assumptions to update the conditional probability values for the aluminum and alloy tank cars. Still I was not able to conduct a detailed analysis due to lack of updated information on the lading loss probabilities of these cars. Alloy steel cars have lower conditional release probabilities (e.g., 111A100W6) than their carbon steel counterparts (111A100W1) due to greater tensile strength of the tank. Conversely aluminum cars are lighter and have a higher conditional release probability than similar carbon steel cars. The effect of installing various risk reduction options on these cars is likely to be different from carbon steel cars. However, incomplete information on the effect of different RROs on the conditional release probabilities of the alloy and aluminum cars prevented me from performing a cost benefit analysis for these cars. An analysis of these cars similar to that for carbon steel tank cars conducted by Treichel et al (2006) should be developed.

- Capacity analysis for aluminum tank cars: The tank car optimization program, IlliTank, is capable of calculating the optimal capacity of a carbon steel tank car for a chemical. Currently it cannot accommodate aluminum cars. It is suggested that this feature be added to the model. In the future, if the model is updated to incorporate this feature in future, then it would be possible to calculate the change in transportation cost as a result of replacement of these cars. Also, if a more comprehensive probability analysis is conducted for the aluminum and alloy tank cars, as suggested above, then, in addition with the updated capacity estimation model, it would be possible to complete the cost-benefit analysis of the chemicals primarily transported in these cars.

While the future work proposed above could not be completed in the current research due to data constraints or the limitations of the model used, the following improvements suggest a more in-depth analysis for certain aspects of the study that would yield more accurate results.

- Consequence Analysis Simulations: One of the inputs required by the consequence analysis simulations conducted using the IIRSTF model was the quantity of the material transported in a tank car. The quantity transported will differ by the tank car specification in which the material is transported because of different capacities of the tank. But in this analysis, the quantity transported is calculated based on the tank capacity of a 111A100W1 tank car for all the chemicals. As described previously (Sec. 4.2.2.2.1), simulations were conducted for 2.5%, 12.5%, 50% and 90% of the tank capacity spilled and expected clean up cost (C_{cq}) calculated for each lading loss category ‘q’ for each chemical ‘c’. These expected clean up cost values once calculated (Equation 4.6) are kept constant for each chemical and used for risk-per-car-mile calculations for all the tank car specifications used for transporting the chemical (Equation 5.6).

  The 111A100W1 will generally have a higher capacity for a chemical than any of the other tank car specifications when optimized for that chemical. This will have the effect of overestimating the quantity spilled and hence the consequence results (i.e., cost of clean up). This leads to a modest overestimation of expected clean up cost and the risk-per-car-mile estimates, weighted over all tank car specifications. This also increases the risk per car-mile incurred from each individual tank car specification for a chemical (except 286K tank cars for which the risk-per-car-mile estimates will be somewhat of an underestimate of the actual estimates).

To obtain more accurate results, consequence runs need to be conducted separately for each of the current tank car specification that is being considered for replacement and each of the alternate tank car specification that is a candidate for replacing the current cars. Given the current data input capability of the IIRSTF model this would be a very cumbersome and time intensive procedure. The new environmental consequence model should be developed so that this can be easily accommodated when it is run.

- Tank Car Cost Analysis: The tank car cost analysis only addresses the effect of age on the cost of the tank car. Though it was speculated that the volumetric capacity of the tank should also affect the cost of the car due to differences in amount of material required for construction, I found only a weak relationship. As no definitive conclusion could be obtained, the effect of tank capacity on tank car cost was not accounted for in this study. The possible effect of variables other than age and tank capacity might also be checked using stepwise regression. The unaccounted for variability in the tank car costs will probably not substantially affect the results, but use of more sophisticated statistical analysis of tank car costs would enable greater precision and confidence in the cost-benefit analysis of tank cars for individual chemicals.

- Exposure analysis: I had to make a number of assumptions regarding the groundwater data for exposure analysis that are extensively discussed in my master's thesis (Anand 2004). An important assumption was that the groundwater data were representative of the nationwide groundwater characteristics. This could not be substantiated because of the sparse nature of the groundwater dataset. It is evident that the sampling wells in the real time groundwater database of the United States Geological Survey (USGS) are not randomly and independently distributed around the nation.

In the future work section of my master's work (Anand 2004) I stated that information on more wells could be obtained by using discrete data instead of real time data, also available from the USGS groundwater website, containing groundwater measurements from the early 1900s up to the present. At that time it was thought that these well records could not be selected or sorted on the start or end date of the measurement done for a site. However, I recently discovered that there is indeed a query based form on the groundwater website that could be used to capture the well records for a particular period for any state. Even with this tool, the task can be cumbersome because of the constraints on the data retrieval capacity of the database system. If this task is undertaken in the future, several questions should be addressed including, geographic location of wells, how large a sample to achieve a desired degree of confidence and how long a period should be considered to capture enough records. One possible solution is to start with a time span of one year, starting with the most recent year (relative to when the analysis is conducted). The retrieved records should be plotted on the U.S. rail network map presented in Anand (2004) to determine if they are randomly scattered and dense enough to carry out any further GIS buffering analyses with the rail network to determine their distribution in relationship to the rail network. Depending on the plot, the analysis might be extended to obtain records from additional years, as necessary. I found that the depth values did not significantly differ when I compared two seasons (Anand 2004) but if a time span of more than one year is used then it might be prudent to test for differences in depth data. The final dataset should be corrected for geographical bias using the methodology in Anand (2004). A well record may have more than one measurement, when this happens, the most recent measurement should be used to avoid double counting the well.

- Hazardous Material Routes: In my previous work on exposure analysis of soil and groundwater to hazardous material spills (Anand 2004) I made an assumption that the distribution of environmental features, i.e., soil types and groundwater depths along hazardous material routes is no different than that along rail lines in general. The hazardous material transportation data available from the STB Waybill database could be integrated in a GIS analysis of the rail network. I found that the distribution of soil types along rail lines was not significantly different than the overall distribution of soil types in the U.S.. However the analysis described above would help validate that assumption.

Use of such an approach would also enable development of a traffic route map for any chemical of concern and conduct exposure analysis along that route. This might or might not yield significantly different distributions than the distributions developed for the lower 48 states. But if the distribution is different, this will yield more accurate results of risk per car-mile, annual risk and consequently cost-benefit analysis for the particular chemical.

Other receptors of interest: Over the past decade or so, natural resource damages such as impact on surface water bodies has emerged as an important additional factor affecting railroads' environmental risk. This impact did not fall within the scope of the current research but should be addressed in future studies of the environmental risk of hazardous material transport.

This summarizes the suggested areas for future work on this topic. This research was taken up with the objective of quantifying the risk of release of hazardous materials on soil and groundwater. I developed risk estimates for 27 chemicals and conducted cost benefit analysis for 24 of those chemicals. The risk per car-mile varied from 1/10th of a cent to around 29 cents. The higher capacity 286K 111 tank car specification turns out to be the cost beneficial for all the chemicals for an attrition-based replacement schedule. Among 263K GRL cars, the specifications with certain improvements, that don’t generally affect costs, e.g., 111A100W2, 111S100W1 or 111S100W2 turn out to be cost beneficial .

The 27 chemicals of interest are among the 125 hazardous materials that have the highest rail transportation volume, hence any changes in their packaging practices will lead to a stronger impact or risk than other, lower volume chemicals. In general, the methodology developed in this research can be applied to other chemicals as the need arises. The risk estimates for chemicals impart a better understanding of the liability incurred by the railroads from an environmental standpoint. Cost benefit analysis puts the risk estimates in perspective by investigating if the risk warrants replacement or retrofit of the currently used tank cars with more damage-resistant tank cars for the chemicals studied. The current research serves a two-fold purpose: using the results from this research railroads and shippers will be able to make a better-informed decisions about the packaging practices of the chemicals considered in this study. Second, this research provides the tools necessary to extend the analysis to other chemicals.

REFERENCES

Association of American Railroads (AAR). (2001). *Railroad Facts: 2001 Edition.* Washington D.C.: Policy and Economics Department, Association of American Railroads.

Association of American Railroads (AAR). (2004). *Manual of Standards and Recommended Practices, Section C-III - Specifications for Tank Cars, M-1002.* Washington D.C.: Association of American Railroads.

Anand, P. (2004). Quantitative Assessment of the Exposure of Environmental Characteristics to Railroad Spills of Hazardous Materials. *Master's Thesis.* University of Illinois Urbana-Champaign.

Anand, P., & Barkan, C.P.L. (2006). A Geographic Information System Analysis of the Exposure of Soil and Groundwater to Spills Of Hazardous Materials Transported by Rail. *Accepted Transportation Research Record - Journal of the Transportation Research Board.*

Anderson, R. T. (2005). Quantitative Analysis of Factors Affecting Railroad Accident Probability and Severity. *Master's Thesis.* University of Illinois Urbana-Champaign.

Anderson, R. T., & Barkan, C. P. L. (2004). Railroad Accident Rates for Use in Transportation Risk Analysis. *Transportation Research Record: Journal of the Transportation Research Board, 1863:* 88-98.

Anthes, G. H. (2003). ROI Guide: Net Present Value. News Story on the Computerworld, Inc. Website. Accessed in 2003. http://www.computerworld.com/managementtopics/roi/story/0,10801,78530,00.html

Arthur D. Little, Inc. (1996a). *Rail Transportation Risk Screening Model: Reference Guide and Users Manual*. Cambridge, Massachusetts: InterIndustry Rail Safety Task Force (IIRSTF). Reference 64865.

Arthur D. Little, Inc. (1996b). *Risk Assessment for the Transportation of Hazardous Materials by Rail: Reference Manual*. Cambridge, Massachusetts: InterIndustry Rail Safety Task Force (IIRSTF). Reference 64865.

Arthur D. Little, Inc. (1996c). *Risk Assessment for the Transportation of Hazardous Materials by Rail: Users Manual*. Cambridge, Massachusetts: InterIndustry Rail Safety Task Force (IIRSTF). Reference 64865.

Barkan, C. P. L. (2005). Improving the Design of Higher Capacity Tank Cars: Optimizing the Trade-off between Weight and Safety. *Accepted with revisions in Journal of Hazardous Materials.*

Barkan, C. P. L. (2006). Associate Professor and Director of Railroad Engineering Program, University of Illinois at Urbana-Champaign. Personal Communication.

Barkan, C. P. L., Dick, C. T., & Anderson, R. (2003). Railroad Derailment Factors Affecting Hazardous Materials Transportation Risk. *Transportation Research Record: Journal of the Transportation Board, 1825:* 64-74.

Barkan, C. P. L., Glickman, T. S., & Harvey, A. E. (1991). Benefit-Cost Evaluation of using Different Specification Tank Cars to Reduce the Risk of Transporting Environmentally Sensitive Chemicals. *Transportation Research Record: Journal of the Transportation Research Board, 1313:* 33-43.

Barkan, C. P. L., Treichel, T. T., & Widell, G. W. (2000). Reducing Hazardous Materials Releases from Railroad Tank Car Safety Vents. *Transportation Research Record: Journal of the Transportation Research Board, 1707:* 27-34.

Barkan, C. P. L., Ukkusuri, S., & Waller, S. T. (2005). Optimizing Railroad Tank Cars for Safety: The Tradeoff Between Damage Resistance and Probability of Accident Involvement. *Published electronically, paper copy in press Special Hazardous Materials Issue of Computers and Operations Research.*

Batta, R., & Chiu, S. S. (1988). Optimal obnoxious paths on a network: Transportation of hazardous materials. *Operations Research, 36:* 84-92.

Borselli, L. (1999). Segmentation of Soil Roughness Profiles. *Earth Surface Processes and Landforms, 2:* 71-90.

Bureau of Explosives (BOE). (2000). *Annual Report of Hazardous Materials Transported by Rail, Calendar Year 1999*. Pueblo, Colorado: Association of American Railroads: Bureau of Explosives. Report BOE 99-1.

Bureau of Explosives (BOE). (2005). *Annual Report of Hazardous Materials Transported by Rail, Calendar Year 2003*. Pueblo, Colorado: Association of American Railroads: Bureau of Explosives. Report BOE 03-1.

Cambridgesoft Corporation. (2002). Chemfinder.com Database and Internet Searching Website. Accessed in 2002. http://chemfinder.cambridgesoft.com/

Center for Chemical Process Safety (CCPS). (1994). *Guidelines for Chemical Transportation Risk Analysis.* New York: American Institute of Chemical Engineers.

Choudhury, B. J., Schmugge, T. J., Chang, A. & Newton, R. W. (1979). Effect of Surface Roughness on the Microwave Emission from Soils. *Journal of Geophysical Research, 84:* 5699-5706.

Circular No. A-94 (1992). Guidelines and Discount Rates for Benefit-Cost Analysis of Federal Programs. Downloaded in 2005, from http://www.whitehouse.gov/omb/circulars/a094/a094.html

Clark, D. (2002). Director of Environmental Remediation, Burlington Northern Santa Fe Railway. Personal Communication.

Clark, D. (2005). Director of Environmental Remediation, Burlington Northern Santa Fe Railway. Personal Communication.

Code of Federal Regulations (CFR). (1997). Title 40—Protection of Environment Part 268—Land Disposal Restrictions. Office of the Federal Register. http://ecfr.gpoaccess.gov/cgi/t/text/text-idx?c=ecfr&tpl=/ecfrbrowse/Title40/40cfr268_main_02.tpl

Code of Federal Regulations (CFR). (2001). Title 49—Transportation, §172.101. Office of the Federal Register. http://www.access.gpo.gov/nara/cfr/waisidx_01/49cfr172_01.html

Code of Federal Regulations (CFR). (2005). Title 49—Transportation, §171.8. Office of the Federal Register. http://www.access.gpo.gov/nara/cfr/waisidx_05/49cfr171_05.html

Code of Federal Regulations (CFR). (2005). Title 49—Transportation, §179.4. Office of the Federal Register. http://www.access.gpo.gov/nara/cfr/waisidx_05/49cfr179_05.html

Code of Federal Regulations (CFR). (2005). Title 49—Transportation, §179.5. Office of the Federal Register. http://www.access.gpo.gov/nara/cfr/waisidx_05/49cfr179_05.html

Code of Federal Regulations (CFR). (2005). Title 49—Transportation, §179.13. Office of the Federal Register. http://www.access.gpo.gov/nara/cfr/waisidx_05/49cfr179_05.html

Comprehensive Environmental Response Compensation and Liability Act (CERCLA). (1986). 42 USC §9656 et seq., 1986.

Cranium – Physical Property Estimation Software. (2006). Bedford, New Hampshire: Molecular Knowledge Systems, Inc.

Dalrymple, T. (2003). *T72.10-98-286k Tank Cars-Task Force Proposal to TCC Subcommittee.* Memorandum to the 286k Tank Car Task Force.

Dalrymple, T. (2005). Vice President – Tank Car Engineering, Trinity Rail. Personal Communication.

Darboux, F., & Huang, C. H. (2005). Does Soil Surface Roughness Increase or Decrease Water and Particle Transfers? *Soil Science Society of America Journal. vol. 69,* 748-756.

Davis, G. A., Swanson, M., & Jones, S. (1994). *Comparative Evaluation of Chemical Ranking and Scoring Methodologies*. Tennessee: University of Tennessee, Center for Clean Products and Clean Technologies. EPA Order No. 3N-3545-NAEX.

Dennis, S. M. (1996). Estimating Risk Costs per Unit of Exposure for Hazardous Materials Transported by Rail. *Logistics and Transportation Review, 32 (4):* 351-375. Design Institute for Physical Properties (DIPPR). (2001). Student Chemical Database Website. Accessed in 2001. http://dippr.byu.edu/students/chemsearch.asp

Dennis, S. M. (2002). Changes in Railroad Track Accident Rates. *Transportation Quarterly, 56:* 161-174.

Department of Transportation, Research and Special Programs Administration (DOT RSPA). (2004). DOT-E 11241 (Ninth Revision). Downloaded in June, 2004, from http://hazmat.dot.gov/exemptions/E11241.pdf

Eder Associates Consulting Engineers, P. C. (1992). *CSX Transportation Inc.: Hazardous Materials Risk Assessment.* Jacksonville, Florida.

Elliott, H. R., & Mitchell, R. T. (2002). Development of a Non Accident-Release Risk Index. *Transportation Research Record: Journal of the Transportation Research Board, 1790:* 52-65.

Environmental Protection Agency (EPA). (2003). Remediation and Characterization Innovation Technologies (REACH IT) Website. Accessed in 2003. http://www.epareachit.org/

Environmental Risk Sciences, Inc. (1994). *Reference Manual for the Evaluation of the Environmental Hazards of Chemicals* (Technical Report). Washington, D.C.: InterIndustry Rail Safety Task Force (IIRSTF).

Evans, D., & Sezer, H. (2002). A Time Preference Measure of the Social Discount Rate for the UK. *Applied Economics, 34:* 1925-1934.

Federal Remediation Technologies Roundtable (FRTR). (2003). FRTR Screening Matrix Website. Accessed in 2003. http://www.frtr.gov/site/

Financial Trend Forecaster. (2005). Inflation Rates for Jan 2000 – Present. Accessed in October 2005. http://inflationdata.com/inflation/inflation_rate/CurrentInflation.asp

Freeze, R. A., & Cherry, J. A. (1979). *Groundwater.* Englewood, New Jersey: Prentice Hall Inc.

General American Transportation Corporation (GATX). (1994). *Tank and Freight Car Manual, 6th Edition.* Chicago, Illinois.

Glickman, T. S. (1988). Benchmark Estimates of Release Accident Rates in Hazardous Materials Transportation by Rail and Truck. *Transportation Research Record, 1193:* 22-28.

Glickman, T. S. (1991). An Expeditious Risk Assessment of the Highway Transportation of Flammable Liquids in Bulk. *Transportation Science, 25(2):* 115-123.

Glickman, T. S., & Gough, M. (Eds.) (1990). *Readings in Risk.* Washington D.C.: Resources for the Future.

Glickman, T. S., & Raj, P. K. (1993). A Comparison of Theoretical and Actual Consequences in Two Fatal Ammonia Incidents. In Saccomanno, F. F., & Cassidy, K. (Eds.*), Transportation of Dangerous Goods: Assessing the Risks* (pp. 511-529). Waterloo, Ontario: Institute for Risk Research: University of Waterloo, Canada. Proceedings of the First International Consensus Conference on the Risks of Transporting Dangerous Goods, held April 6-8, 1992, in Toronto--T.p. verso.

Glickman, T. S., & Rosenfield, D. B. (1984). Derailments and Release of Hazardous Materials. *Management Science, 30:* 257-277.

Griger, G. J., & Phillips, E. A. (1992). *Bottom Discontinuity Protection Effectiveness on DOT 111A Stub Sill Tank Cars. Report RA-09-7-60 (AAR R-815).* Chicago, Illinois: RPI-AAR Railroad Tank Car Safety Research and Test Project, Transportation Technology Center.

Hansen, B., Schjonning, P., & Sibbesen, E. (1999). Roughness Indices for Estimation of Depression Storage Capacity of Tilled Soil Surfaces. *Soil and Tillage Research*, *52:* 103-111.

Harvey, A. E., Conlon, P. C., & Glickman, T. S. (1987). *Statistical Trends in Railroad Hazardous Materials Transportation Safety*. Washington D. C.: Association of American Railroads. Report R-640.

Hay, W. W. (1982). *Railroad Engineering* (Second ed.). New York: John Wiley & Sons, Inc.

Helander, M. E., & Melachrinoudis, E. (1997). Facility Location and Reliable Route Planning in Hazardous Material Transportation. *Transportation Science, 31 (3):* 216-226.

Heller, F. J. (1981). *Memorandum to the Association of American Railroads (AAR) Tank Car Committee (March 17, 1981).* Ad Hoc Committee on Bottom Outlets. Docket T10.7-71.

Indiana Clean Manufacturing Technology & Safe Materials Institute (CMTI). (2002). Indiana Relative Chemical Hazard Score (IRCHS) Website. Accessed in 2003. http://www.ecn.purdue.edu/CMTI/IRCHS/

Jin, H., & Batta, R. (1997). Objectives Derived from Viewing Hazmat Shipments as a Sequence of Independent Bernoulli Trials. *Transportation Science, 31 (3):* 252-261.

Kamphorst, E. C., Jetten, V., Guerif, J., Pitkanen, J., Iverson, B. V., Douglas, J. T., et al. (2000). Predicting Depressional Storage from Soil Surface Roughness. *Soil Science Society of America Journal, 64:* 1749-1758.

Kempe, T. F., & Grondin, L. (1993). Risk Assessment of Transportation for the Canadian Nuclear Waste Management Program. In Saccomanno, F. F., & Cassidy, K. (Eds.), *Transportation of Dangerous Goods: Assessing the Risks* (pp. 183-210). Waterloo, Ontario: Institute for Risk Research: University of Waterloo, Canada. Proceedings of the First International Consensus Conference on the Risks of Transporting Dangerous Goods, held April 6-8, 1992, in Toronto--T.p. verso.

King County Office of Management and Budget (OMB) (2005). Discount Rate Policy. Proposal for Executive Policy Consideration. Downloaded in June, 2005, from http://www.metrokc.gov/budget/econ/Discount.pdf

Kuhlmeier, P. (2002). Director – Remediation Environmental Quality, Kansas City Southern. Personal Communication.

LaValle, D., Transportation Specialist, US DOT RSPA and Rader, J., Vice President Technical Support Group. (2004). AllTranstek e-mail messages regarding original issuance of RSPA exemption DOT-E 11241, 19 July 2004.

Leonelli, P., Bonvicini, S., & Spadoni, G. (2000). Hazardous Materials Transportation: A Risk Analysis-Based Routing Methodology. *Journal of Hazardous Materials, 71:* 283-300.

List, G. F., & Mirchandani, P. B. (1991). Integrated Network/Planar Multiobjective Model for Routing and Siting for Hazardous Materials and Wastes. *Transportation Science, 25:* 146-156.

List, G. F., Mirchandani, P. B., Turnquist, M. A., & Zografos, K. G. (1991). Modeling and Analysis for Hazardous Materials Transportation: Risk Analysis, Routing/Scheduling and Facility Location. *Transportation Science, 25:* 100-114.

Lowenbach, W. (2003). Arcadis G&M, Inc. Personal Communication.

Marcus Materials Co. (2005). Densities of Various Materials. Accessed in September 2005. http://www.mcelwee.net/html/densities_of_various_materials.html

McKone, T. E. (1993). *CalTOX, A MultiMedia Total Exposure Model for Hazardous-Waste Sites, Part I: Executive Summary*. Sacramento, California: The Office of Scientific Affairs, Department of Toxic Substances Control, California Environmental Protection Agency.

National Institute of Standards and Technology (NIST) Standard Reference Data Program. (1994). Design Institute for Physical Properties (DIPPR) Data Compilation of Pure Compound Properties, Ver. 9.0.

National Transportation Safety Board (NTSB). (1995). Tank car failure and release of arsenic acid in Chattanooga, Tennessee, on June 6, 1994. Hazardous Materials Accident Report, NTSB/HZM-95/01. Washington, DC.

Nayak, P. R., Rosenfield, D. B., & Hagopian, J. H. (1983). *Event Probabilities and Impact Zones for Hazardous Materials Accidents on Railroads.* Washington D.C.: Federal Railroad Administration, U.S. Department of Transportation. Report DOT/FRA/ORD-83/20.

Nelson, R. (1978). Evaluating the Environmental Consequences of Groundwater Contamination. *Water Resources Research, 14(3):* 409.

Phillips, E. A. (1990). *Analysis of Aluminum Tank Cars Damaged in Accidents 1965 Through 1986*. Chicago, Illinois: RPI-AAR Railroad Tank Car Safety Research and Test Project, Association of American Railroads. Report RA-20-1-57 (AAR R-749).

Phillips, E. A., & Role, H. (1989). *Effectiveness of Shelf Couplers, Head Shields and Thermal Shields on DOT 112(114) and 105 Tank Cars. Report (AAR R-610).* Chicago, Illinois: RPI-AAR Railroad Tank Car Safety Research and Test Project, Association of American Railroads.

Phillips, E. A., Treichel, T. T., & Barkan, C. P. L. (1995). *Probability of Lading Loss from Tank Cars Damaged in Accidents*. Chicago, Illinois: RPI-AAR Railroad Tank Car Safety Research and Test Project, Association of American Railroad. Report RA-02-7-61 (AAR R-867).

Powers, S. E., Abriola, L. M., & Weber, W. J. J. (1992). An Experimental Investigation of Non aqueous Phase Liquid Dissolution in Saturated Subsurface Systems: Steady State Mass Transfer Rates. *Water Resources Research, 28(10):* 2691-2705.

Preez, M. D. (2004). The Discount Rate for Public Sector Conservation Projects in South Africa. Blackwell Publishing Ltd.: African Development Bank, 456-471.

Prode Properties. (2005). Milan, Italy: Prode.

Purdy, G. (1993). Risk analysis of the transportation of dangerous goods by road and rail. *Journal of Hazardous Materials, 33 (2):* 229-259.

Rader, J. H., & Gagnon, J. P. (1999). *Maximizing Safety and Weight: A White Paper on 263K+ Tank Cars (Revision A: September, 99).* Washington, DC: Federal Railroad Administration. Downloaded in September, 2003, from http://www.fra.dot.gov/downloads/safety/Maximizing Safety and Weight.pdf

Raj, P. K., & Pritchard, E. W. (2000). Hazardous Materials Transportation on U.S. Railroads: Application of Risk Analysis Methods to Decision Making in Development of Regulations. *Transportation Research Record: Journal of the Transportation Research Record (1707),* 22-26.

Rhyne, W. R. (1994). *Hazardous Materials Transportation Risk Analysis: Quantitative Approaches for Truck and Train*. New York: Van Nostrand Reinhold.

Richardson, K. (2002). AMEC - Earth & Environmental. Personal Communication.

Riley, N. (1993). A Novel Risk Assessment Methodology for the Transport of Explosives. In Saccomanno, F. F., & Cassidy, K. (Eds.*), Transportation of Dangerous Goods: Assessing the Risks* (pp. 47-74). Waterloo, Ontario: Institute for Risk Research: University of Waterloo, Canada. Proceedings of the First International Consensus Conference on the Risks of Transporting Dangerous Goods, held April 6-8, 1992, in Toronto--T.p. verso.

Russell, S. B., & Kempe, T. F. (1993). Methodology for Assessing the Public Risk from Transporting Hydrogen Sulfide. In Saccomanno, F. F., & Cassidy, K. (Eds.), *Transportation of Dangerous Goods: Assessing the Risks* (pp. 121-151). Waterloo, Ontario: Institute for Risk Research: University of Waterloo, Canada. Proceedings of the First International Consensus Conference on the Risks of Transporting Dangerous Goods, held April 6-8, 1992, in Toronto--T.p. verso.

Saat, M. R., & Barkan, C. P. L. (2005). Release Risk and Optimization of Railroad Tank Car Safety Design. *Transportation Research Record: Journal of the Transportation Research Board (1916),* 78-87.

Saat, R. M., & Chua Z. Z. (2004). *Illini Tank Capacity: Railroad Tank Car Weight and Capacity Program.* University of Illinois at Urbana-Champaign, Illinois.

Saccomanno, F. F., & Shortreed, J. H. (1993). Hazmat Transport Risks: Societal and Individual Perspectives. *Journal of Transportation Engineering, 119 (2):* 177-188.

Saccomanno, F. F., Van Aerde, M., & Queen, D. (1987). Interactive Selection of Minimum Risk Routes for Dangerous Goods Shipments. *Transportation Research Record, 1148:* 9-17.

Sassone, P. G., & Schaeffer, W. A. (1978). *Cost-Benefit Analysis – A Handbook*. New York: Academic Press, Inc.

Sax, N. I. (1975). *Dangerous Properties of Industrial Materials* (Fourth ed.). New York: Van Nostrand Reinhold.

Sherali, H. D., Brizendine, L. D., Glickman, T. S., & Subramanian, S. (1997). Low Probability-High Consequence Considerations in Routing Hazardous Material Shipments. *Transportation Science, 31 (3),* 237-251.

Shi, J., Wang, J., Hsu, A.Y., O'Neill, P. E., Engman, E. T. (1997). Estimation of Bare Surface Soil Moisture and Surface Roughness Parameter Using L-band SAR Image Data. *IEEE Transactions on Geoscience and Remote Sensing, 35(5):* 1254-1266.

Sivakumar, R. A., Batta, R., & Karawan, M. H. (1993). Establishing Credible Risk Criteria for Transporting Extremely Dangerous Hazardous Materials. In Saccomanno, F. F., & Cassidy, K. (Eds.), *Transportation of Dangerous Goods: Assessing the Risks* (pp. 335-342). Waterloo, Ontario: Institute for Risk Research: University of Waterloo, Canada. Proceedings of the First International Consensus Conference on the Risks of Transporting Dangerous Goods, held April 6-8, 1992, in Toronto-T.p. verso.

Steichen, J. M. (1984). Infiltration and Random Roughness of a Tilled and Untilled Claypan Soil. *Soil and Tillage Research, 4:* 251-262.

Stjerman, G. (1993). The Need and Value of Routing of Dangerous Goods Transports. In Saccomanno, F. F., & Cassidy, K. (Eds.), *Transportation of Dangerous Goods: Assessing the Risks* (pp. 315-333). Waterloo, Ontario: Institute for Risk Research: University of Waterloo, Canada. Proceedings of the First International Consensus Conference on the Risks of Transporting Dangerous Goods, held April 6-8, 1992, in Toronto--T.p. verso.

Student, P. J. (2003, March). Director – Hazardous Material Management Safety, Union Pacific Railroad. Personal Communication.

Surface Transportation Board (STB). (2005). Section of Frequently Asked Questions. Accessed in December 2005. http://www.stb.dot.gov/stb/faqs.html

Treichel, T. T. (1996). Analysis of Tank Car Accident and Incident Statistics in the Railroad Industry. In *Ensuring Tank Car Safety: A Government and Industry Partnership*. Downloaded in October, 2003, from http://www.fra.dot.gov/safety/hazmat/pdf/program.pdf

Treichel, T. T., Hughes, J. P., Barkan, C. P. L., Sims, R. D., Phillips, E. A., & Saat, M. R. (2006). *Safety Performance of Tank Cars in Accidents: Probability of Lading.* Chicago, Illinois: RPI-AAR Railroad Tank Car Safety Research and Test Project, Association of American Railroads. Report RA-05-02.

Union Tank Car Company (UTC). (1996). *Union Tank Car Blue Book: Tank and Hopper Car Specifications.* Chicago, Illinois.

United States Department of Transportation (US DOT). (1992, 5 November), Research and Special Programs Administration. *Marine Pollutants,* 49 CFR Parts 171, 172, 173, 174 and 176. HM-211, Federal Register 57 (215), 52930-52940.

United States Department of Transportation (US DOT). (1995, 21 September). Research and Special Programs Administration. *Crashworthiness Protection Requirements for Tank Cars; Detection and Repair of Cracks, Pits, Corrosion, Lining Flaws, Thermal Protection Flaws and Other Defects of Tank Car Tanks,* 49 CFR HM-175A and HM-201, Federal Register 60 (183), 49048-49083.

Verschueren, K. (1983). *Handbook on Environmental Data on Organic Chemicals* (Second ed.). New York: Van Nostrand Reinhold.

Williams, B. (2005). Geotechnical Engineer, GeoEngineers, Inc. Personal Communication.

Zeman, J. (2005). Surface Roughness of Soil. *Literature Review as an Undergraduate Study.*

Zero Waste Alliance. (2003). Chemical Assessment and Ranking System (CARS) Brochure. Accessed in 2003. http://www.zerowaste.org/cars/CARSBrochure.pdf

Zografos, K. G., & Davis, C. F. (1989). Multi-Objective Programming Approach for Routing Hazardous Materials. *Journal of Transportation Engineering, 115 (6):* 661-673.

APPENDIX A: TYPES OF TANK CAR SPECIFICATIONS USED AND TANK CAPACITIES FOR CHEMICALS UNDER STUDY

APPENDIX B: PRORATING CONDITIONAL RELEASE PROBABILITIES FOR ALUMINUM AND ALLOY CARS FROM PHILLIPS (1990) TO TREICHEL ET AL (2006)

S_N = Steel Non-Ins S/S Tank Car

S_I = Steel Non-Ins S/S Tank Car

Al_N = Aluminum Non-Ins Tank Car

Al_I = Aluminum Non-Ins Tank Car

A_N = Alloy Non-Ins S/S Tank Car

i = Car Type (S_N, S_I, Al_N, Al_I, A_N)

P(H(i)) = Probability of release from a damaged tank car due to head puncture for car ‘i’

P(S(i)) = Probability of release from a damaged tank car due to shell puncture for car ‘i’

P(T(i)) = Probability of release from a damaged tank car due to top fittings damage for car ‘i’

P(B(i)) = Probability of release from a damaged tank car due to bottom fittings damage for car ‘i’

P(M(i)) = Probability of release from a damaged tank car due to multiple causes for car ‘i’

	Non-Insulated Steel[1]	**Insulated Steel[1]**	**Non-Insulated Aluminum[2]**	**Insulated Aluminum[2]**	**Alloy[3]**
P(H)	4.91%	2.07%	8.50%	4.40%	1.04%
P(S)	3.92%	2.19%	9.90%	7.00%	2.08%

[1] Values taken from Table 3 of Phillips (1990) report for 111A non insulated and insulated non pressure S/S steel welded cars.

[2] Values taken from Table 4 of Phillips (1990) report for 100 ton non insulated and insulated aluminum cars.

[3] Values taken from Table 3 of Phillips (1990) report for the group of cars labeled “Misc. (Alloy, Riveted, etc.)”.

Table B-1: Probability of Release due to Head and Shell Punctures from Phillips (1990)

		Non-Insulated Steel[4]	Insulated Steel[4]	Aluminum[5]	Alloy[6]
Number of Damaged Cars		5,360	7,161	682	3,650
Top Fittings Damage	Mechanical Damage	132	71	16	16
	Fire Damage	2	4	1	1
	No Damage (Loose)	182	138	17	13
	Details Unknown	13	5	4	10
	Total	329	218	38	40
P(T)		329/5,360 = 6.14%	218/7,161 = 3.04%	38/682 = 5.57%	40/3,650 = 1.10%
Bottom Fittings Damage		188	165	20	24
P(B)		188/5,360 = 3.51%	165/7,161 = 2.30%	20/682 = 2.93%	24/3,650 = 0.66%
More than One Cause		183	137	23	31
P(M)		183/5,360 = 3.41%	137/7,161 = 1.91%	23/682 = 3.37%	31/3,650 = 0.85%

[4] Values taken from Figure 1 of Phillips (1990) report for non insulated and insulated S/S non pressure steel welded cars.

[5] Values taken from Figure 1 of Phillips (1990) report for aluminum cars.

[6] Values taken from Figure 1 of Phillips (1990) report for the group of cars labeled "Misc. (Alloy, Riveted, etc.)".

Table B-2: Probability of Release due to Damage to Top Fittings, Bottom Fittings and Multiple Causes from Phillips (1990)

Step 1: P(T), P(B) and P(M) are assumed to be equal for car types Al_N and Al_I.

Step 2: Distribute the probability due to multiple causes (M) equally between head (H), shell (S), top fittings damage (T) and bottom fittings damage (B) using Equation Set B1.

$$\left.\begin{aligned} P(H'(i)) &= P(H(i)) + P(M(i))/4 \\ P(S'(i)) &= P(S(i)) + P(M(i))/4 \\ P(T'(i)) &= P(T(i)) + P(M(i))/4 \\ P(B'(i)) &= P(B(i)) + P(M(i))/4 \end{aligned}\right\} \text{Equation B1}$$

The new values are shown in Table B-3.

	Non-Insulated Steel	**Insulated Steel**	**Non-Insulated Aluminum**	**Insulated Aluminum**	**Alloy**
P(H′)	5.76%	2.55%	9.34%	5.24%	1.25%
P(S′)	4.77%	2.67%	10.74%	7.84%	2.29%
P(T′)	6.99%	3.52%	6.41%	6.41%	1.31%
P(B′)	4.36%	2.78%	3.78%	3.78%	0.87%

Table B-3: Probability of Release from Phillips (1990) after Adjusting for Probability for Multiple Causes

Step 3: Assume all steel car data from Phillips (1990) to be applicable for steel cars with bottom fittings.

	Non-Insulated Steel[7]	**Insulated Steel**[8]
P(H″)	7.99%	3.49%
P(S″)	10.92%	6.36%
P(T″)	15.77%	8.19%
P(B″)	6.25%	4.46%

[7] Values taken from Table 2 of Treichel et al (2006) for 111A100W1 (Tank Thickness = 0.4375 inches).
[8] Values taken from Table 4 of Treichel et al (2006) for 111A100W1 (Tank Thickness = 0.4375 inches).

Table B-4: Probability of Release of Steel Cars from Treichel et al (2006)

Step 4: Assume alloy car data from Phillips (1990) to be applicable only to non insulated alloy cars.

Step 5: Ratio of conditional release probability data available from Treichel et al (2006) and Phillips (1990) for steel cars is used for prorating. Prorate data for Aluminum and Alloy cars from Phillips (1990) using Equation Set B2.

$$
\left.
\begin{aligned}
P(H''(i)) &= \frac{P(H'(i)) \times P(H''(j))}{P(H'(j))} \\[2ex]
P(S''(i)) &= \frac{P(S'(i)) \times P(S''(j))}{P(S'(j))} \\[2ex]
P(T''(i)) &= \frac{P(T'(i)) \times P(T''(j))}{P(T'(j))} \\[2ex]
P(B''(i)) &= \frac{P(B'(i)) \times P(B''(j))}{P(B'(j))}
\end{aligned}
\right\} \text{Equation B2}
$$

where,

$j = S_N$ if $i = Al_N$ or A_N

and

$j = S_I$ if $i = Al_I$

	Non-Insulated Aluminum	Insulated Aluminum	Alloy
P(H′′)	12.95%	7.18%	1.74%
P(S′′)	24.58%	18.69%	5.24%
P(T′′)	14.47%	14.91%	2.95%
P(B′′)	5.41%	6.05%	1.25%

Table B-5: Probability of Release from Head, Shell, Top and Bottom Fittings for Aluminum and Alloy Cars Prorated

Step 5: Calculate conditional probability of release for aluminum and alloy cars using the Equation B3 (equation taken from Treichel et al (2006), Page 13).

$$\mathrm{P(i)} = 1 - \left[(1 - \mathrm{P(H''(i))}) \times (1 - \mathrm{P(S''(i))}) \times (1 - \mathrm{P(T''(i))}) \times (1 - \mathrm{P(B''(i))})\right]$$

Equation B3

where,

P(i) = Conditional Probability of Release from Car Type ‘i’

	Non-Insulated Steel	Insulated Steel	Non-Insulated Aluminum	Insulated Aluminum	Alloy
P(i)	35.28%	20.73%	46.88%	39.67%	10.76%

Table B-6: Overall Probability of Release for Aluminum and Alloy Cars Prorated

APPENDIX C: CONSTANT PROPERTY DATA FOR CHEMICALS UNDER STUDY

APPENDIX D: TEMPERATURE DEPENDENT PROPERTY DATA FOR CHEMICALS UNDER STUDY

APPENDIX E : PHYSICAL STATE OF THE COMMODITIES OF CONCERN DURING TRANSIT

Commodity Name	Physical State during Transit	Shipping Temperature (F)	Shipping Pressure (psia)
Acetaldehyde	liquid: 25 lbs of N2	70	14.7
Acetic Acid, Glacial	aqueous: 90% solution	70	14.7
Acetic Anhydride	liquid		
Acetone	liquid	70	14.7
Acrylonitrile, stabilized	liquid	70	14.7
Acyrlic Acid, stabilized	liquid	60	14.7
Ammonium Nitrate, Liquid	aqueous: 192% solution at 20 C	70	14.7
Benzene	liquid	70	14.7
Butanols	liquid	70	14.7
Butyl Acrylates, stabilized	liquid	70	14.7
Cyclohexane	liquid	70	14.7
Ethanol	aqueous: 95% solution	70	14.7
Ethyl Acetate	liquid	70	14.7
Ethyl Acrylate, stabilized	liquid	70	14.7
Formaldehyde, Solutions	aqueous: 37% solution at ambient	70	14.7
Hexamethylenediamine, Solid	solid form transported in covered hopper also transported as a saturated solution	70	14.7
Hydrochloric Acid	aqueous: 37% solution in water and methanol at ambient	70	14.7
Hydrogen Peroxide, Stabilized	aqueous: 70% solution	70	14.7
Isopropanol	liquid	70	14.7
Maleic Anhydride	molten	140	14.7
Methanol	liquid	70	14.7
Methyl Methacrylate Monomer, stabilized	liquid	70	14.7
Methyl Tert Butyl Ether	liquid	70	14.7
Nitric Acid	aqueous: lab concentration	70	14.7
Phenol, Molten	liquid	115-120	14.7
Phosphoric Acid	aqueous: 85% solution at ambient green phosphoric acid: 85% solution below ambient	>70	14.7
Phosphorus, White, Dry	molten: keep it under water with N2		
Potassium Hydroxide, Solution	aqueous	70	14.7
Propylene Oxide	liquid: with N2 Padding (MP = -73 C)		
Sodium Chlorate, Aqeous Solution	aqueous: 96% solution at 20C	70	14.7
Sodium Hydroxide Solution	aqueous: 50% solution	70	14.7
Styrene Monomer, stabilized	liquid	60	14.7
Sulfur Molten	liquid (mp = 44.1 C)		
Sulfuric Acid	aqueous: 98% solution	70	14.7

Commodity Name	Physical State during Transit	Shipping Temperature (F)	Shipping Pressure (psia)
Sulfuric Acid, Spent	fuming sulfuric acid: < 30% solution transported in non-pressure cars > 30% solution tranported in pressure cars		
Toluene	liquid	70	14.7
Toulene Diisocynate	molten	70	14.7
Vinyl Acetate, stabilized	liquid	70	14.7
Xylenes	liquid: a mixture of ortho and meta isomers	70	14.7

APPENDIX F: QUALITY CODE DESCRIPTIONS

Two digits quality codes descriptions:

0	Missing value
1	Error <= 1 Percent
2	Error <= 2 Percent
3	Error <= 5 Percent
4	Error <= 10 Percent
5	Error <= 15 Percent
6	Error <= 25 Percent
7	Error <= 50 Percent
8	Error <= 75 Percent
9	Error >= 75 Percent
10	Unknown accuracy
11	Calculated
12	Inappropriate

Five digits quality codes descriptions:

First digit: (type of data)

0- Missing
1- Experimental
2- Predicted
3- Smoothed
4- Unknown
5- Calculated

Second digit: (nature of data source)

0- Predicted
1- Critically Evaluated Data
2- Unevaluated Data

Third digit: (accuracy of data)

0- Predicted
1- Error <= 1 Percent
2- Error <= 3 Percent
3- Error <= 5 Percent
4- Error <= 10 Percent
5- Error <= 25 Percent
6- Error <= 50 Percent
7- Error <= 100 Percent
8- Error > 100 Percent
9- Unknown accuracy

Fourth digit: (data evaluation nature)

0- General Knowledge
1- Assigned by Expert Staff
2- Assigned by Original Author
3- Assigned by Author/Staff

Fifth digit: (Unused)

0- Reserved

APPENDIX G: CLEAN UP COST AND RISK STATISTICS FOR ALL TANK CAR SPECIFICATIONS FOR CHEMICALS UNDER STUDY

APPENDIX H: RISK PROFILES

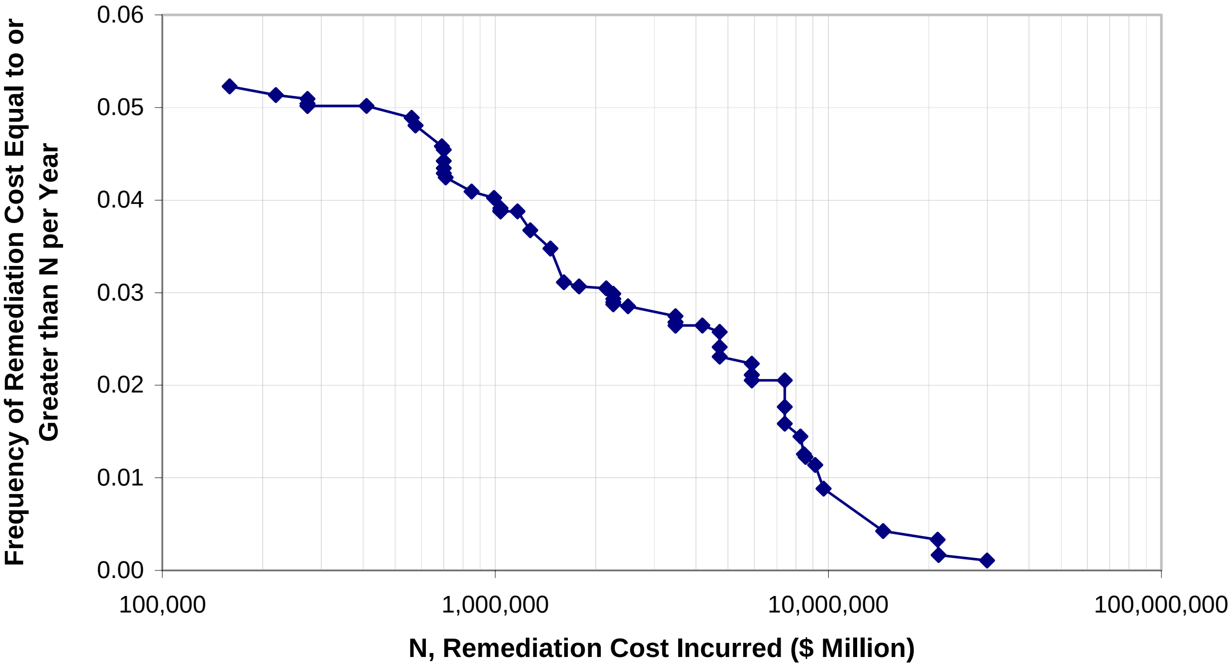


Figure H-1 Risk Profile for Environmental Impact of Acetaldehyde

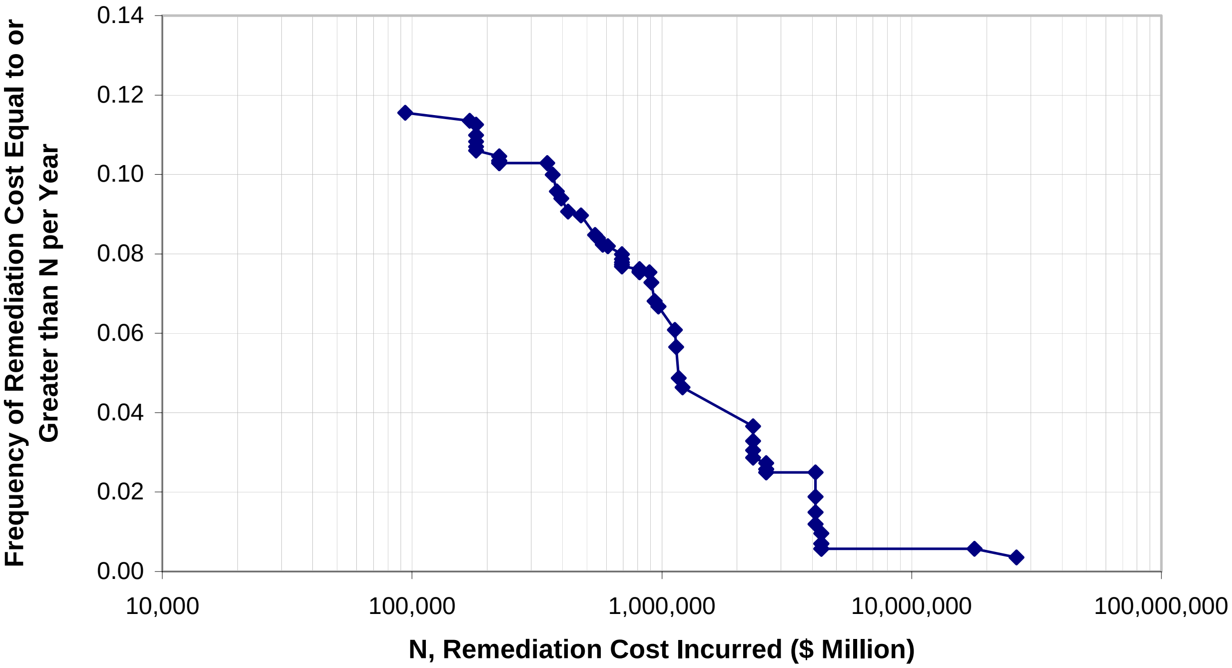


Figure H-2 Risk Profile for Environmental Impact of Acetic Acid

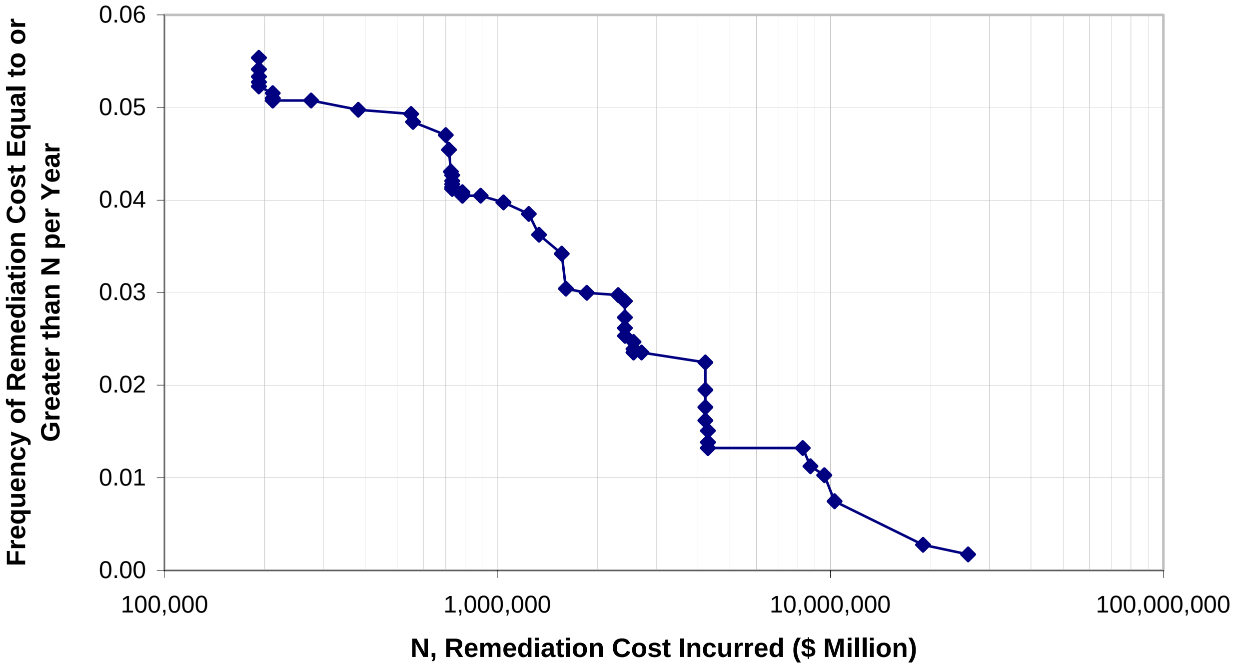


Figure H-3 Risk Profile for Environmental Impact of Acetic Anhydride

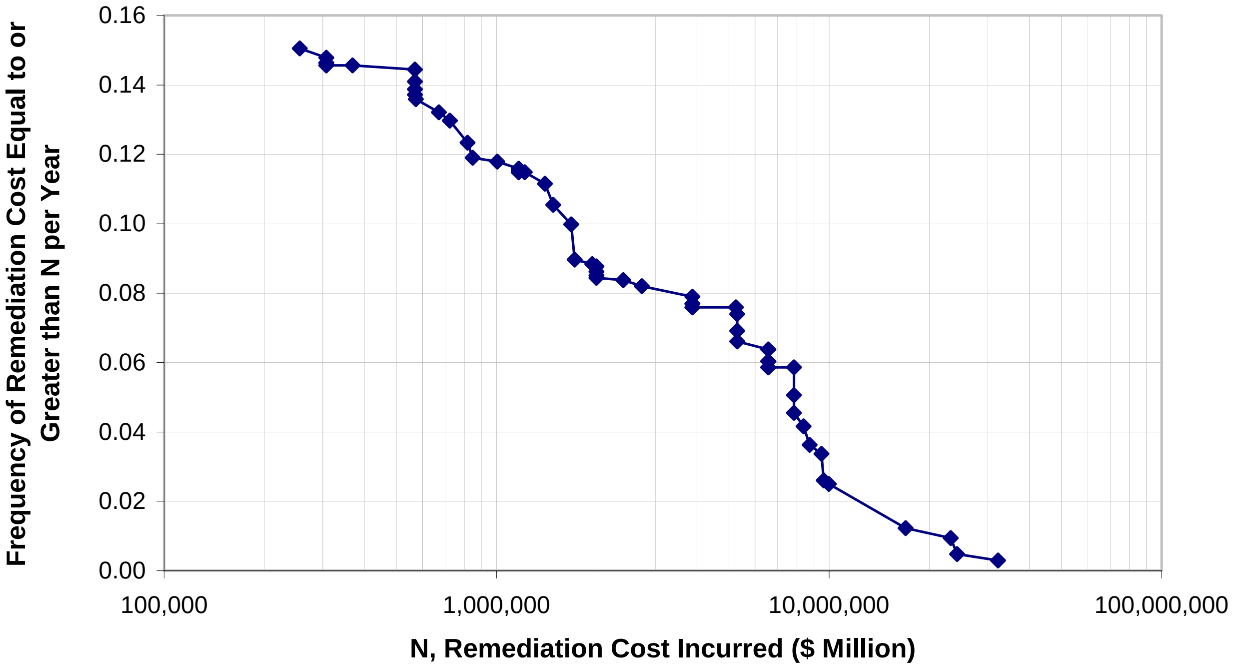


Figure H-4 Risk Profile for Environmental Impact of Acetone

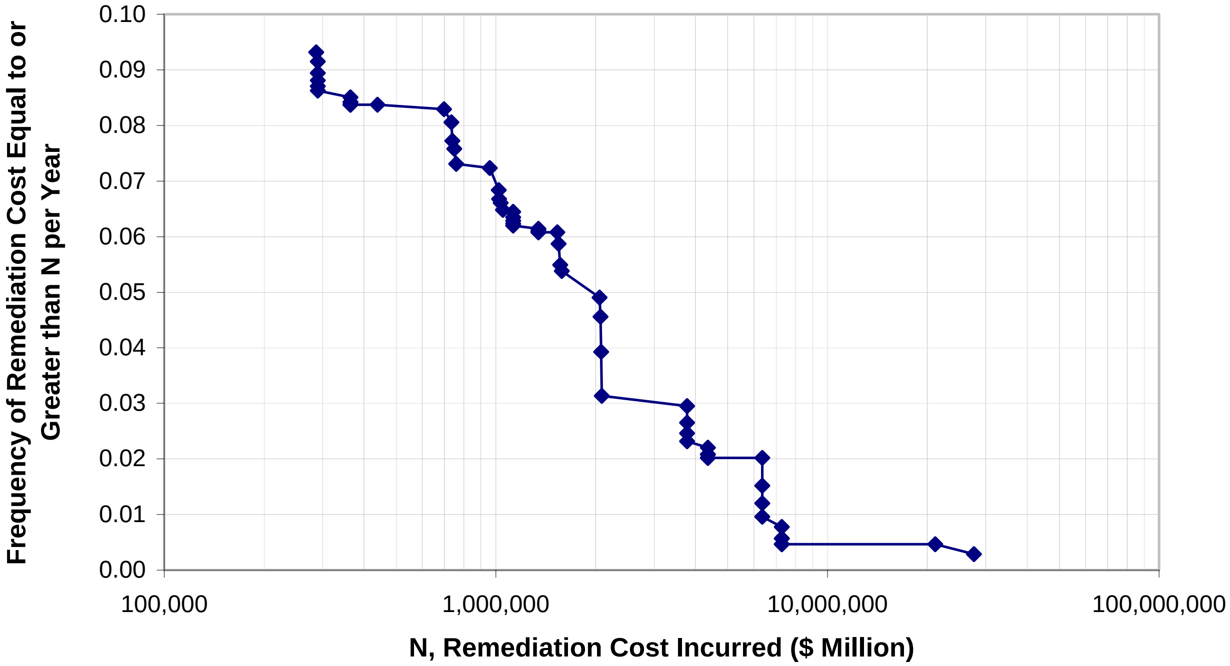


Figure H-5 Risk Profile for Environmental Impact of Acrylic Acid

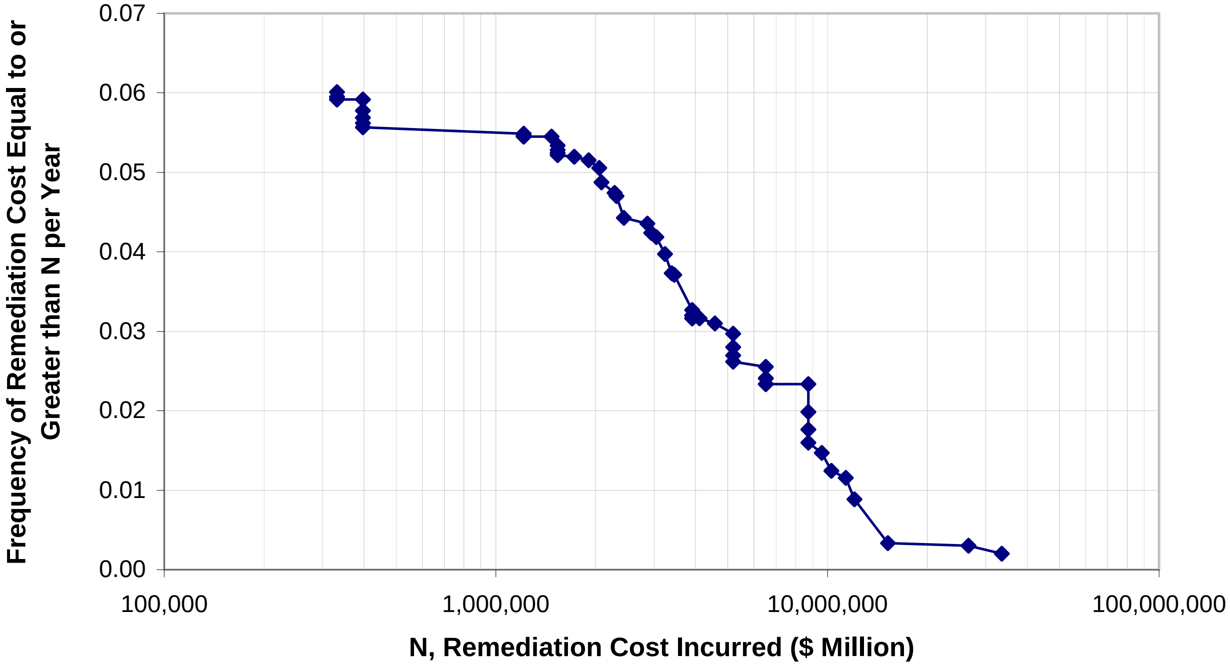


Figure H-6 Risk Profile for Environmental Impact of Acrylonitrile

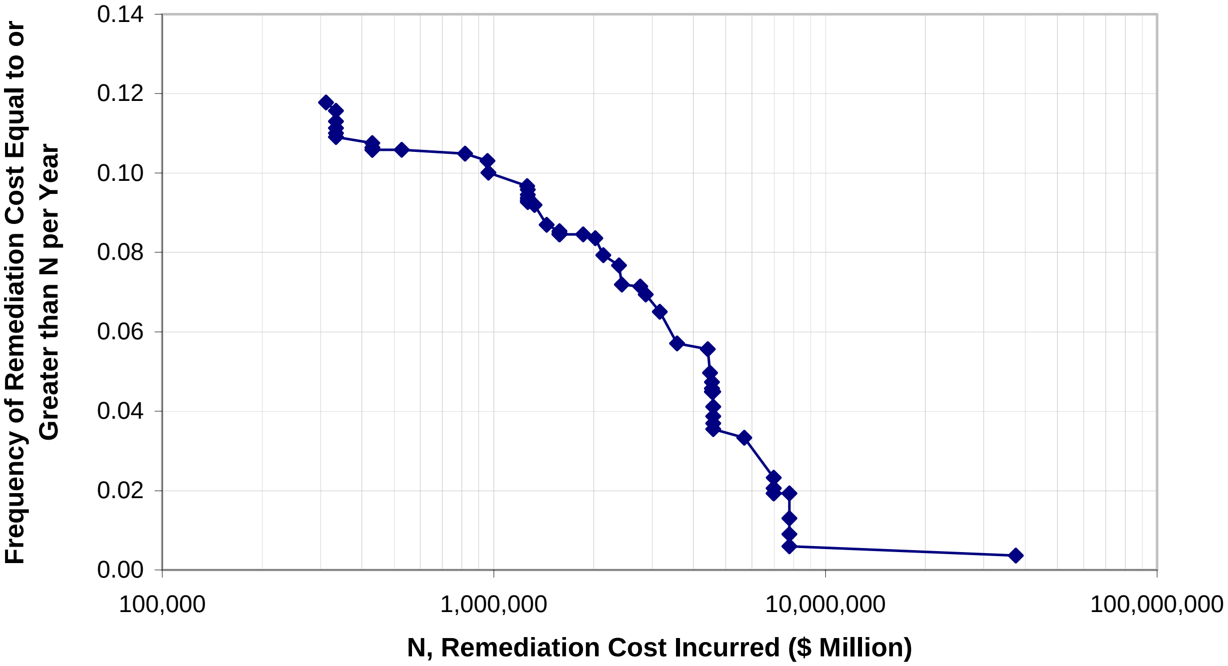


Figure H-7 Risk Profile for Environmental Impact of Butanol

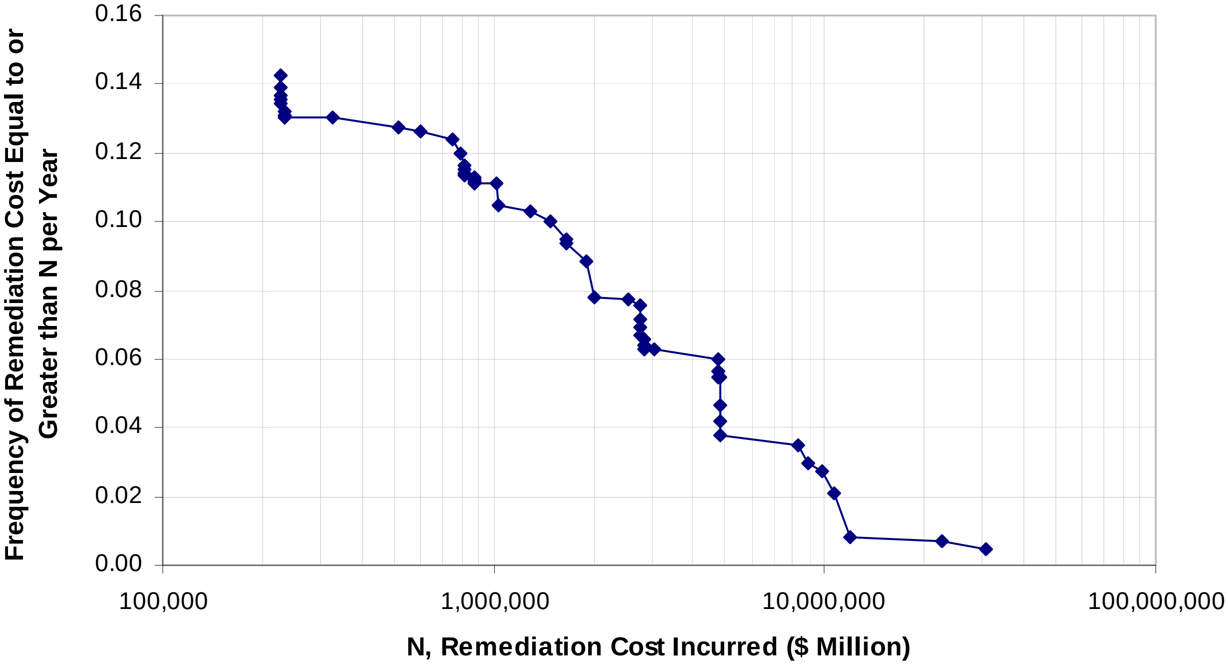


Figure H-8 Risk Profile for Environmental Impact of n-Butyl Acrylate

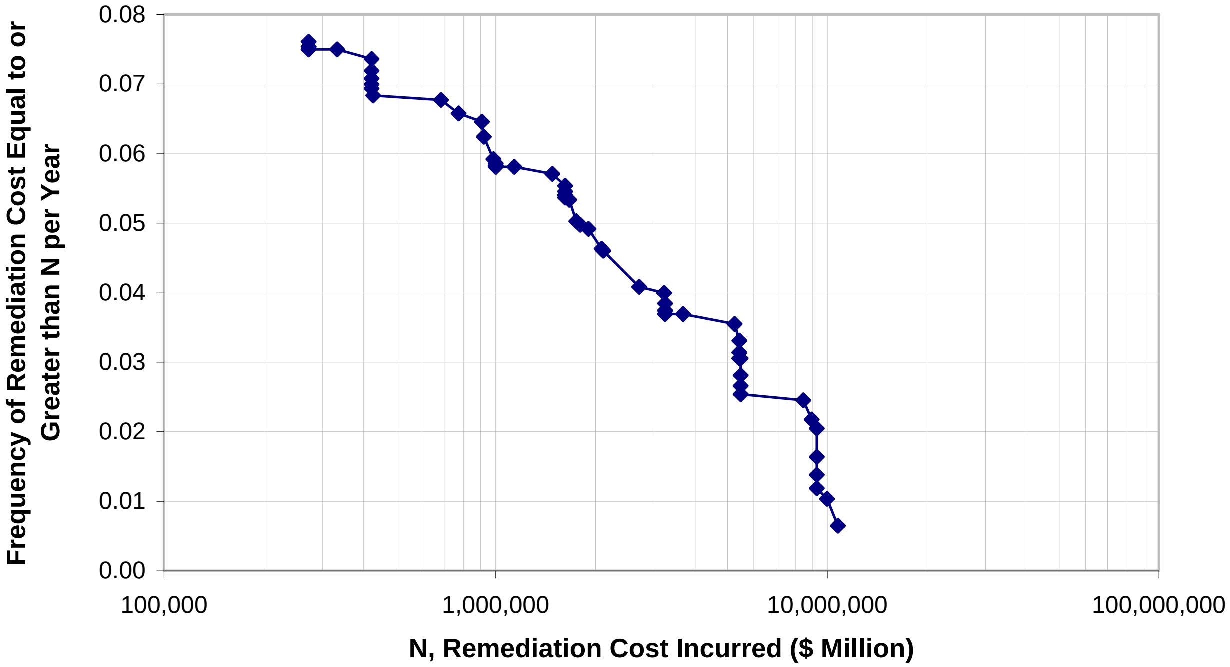


Figure H-9 Risk Profile for Environmental Impact of Cyclohexane

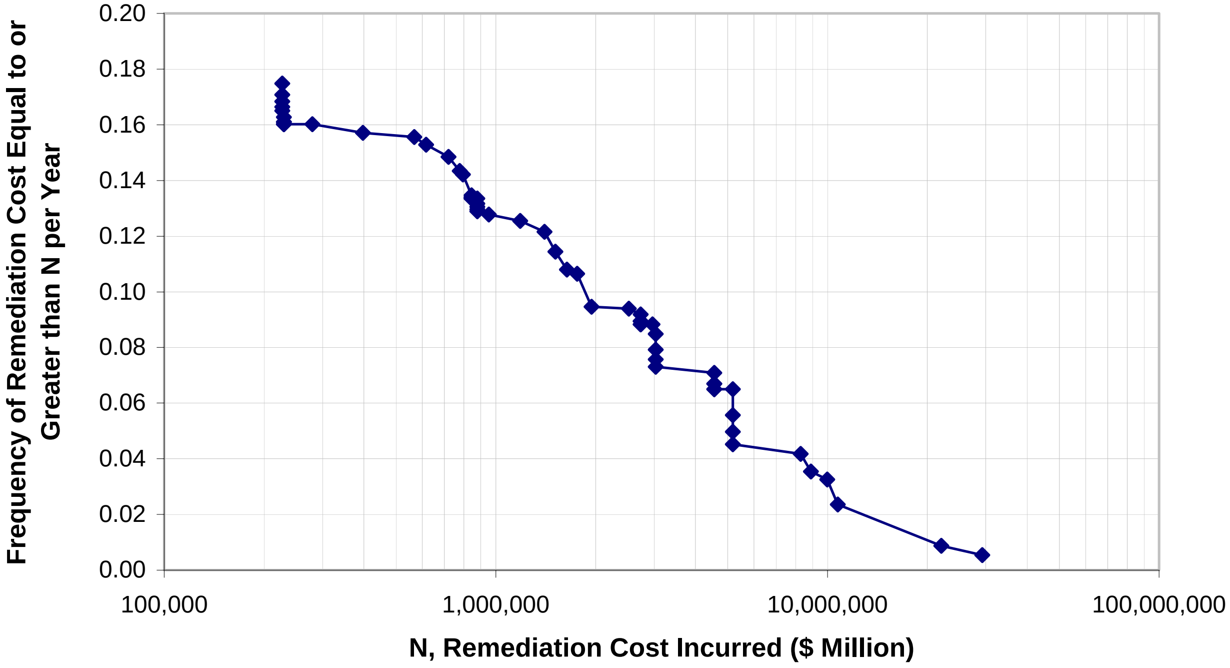


Figure H-10 Risk Profile for Environmental Impact of Ethanol

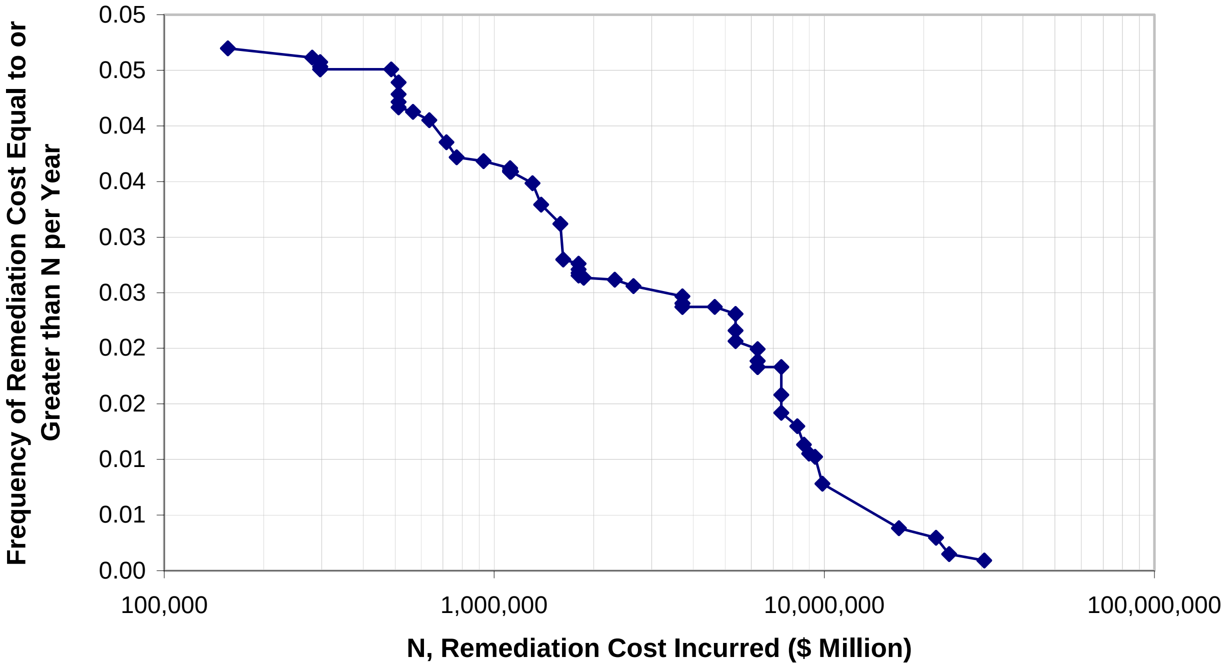


Figure H-11 Risk Profile for Environmental Impact of Ethyl Acetate

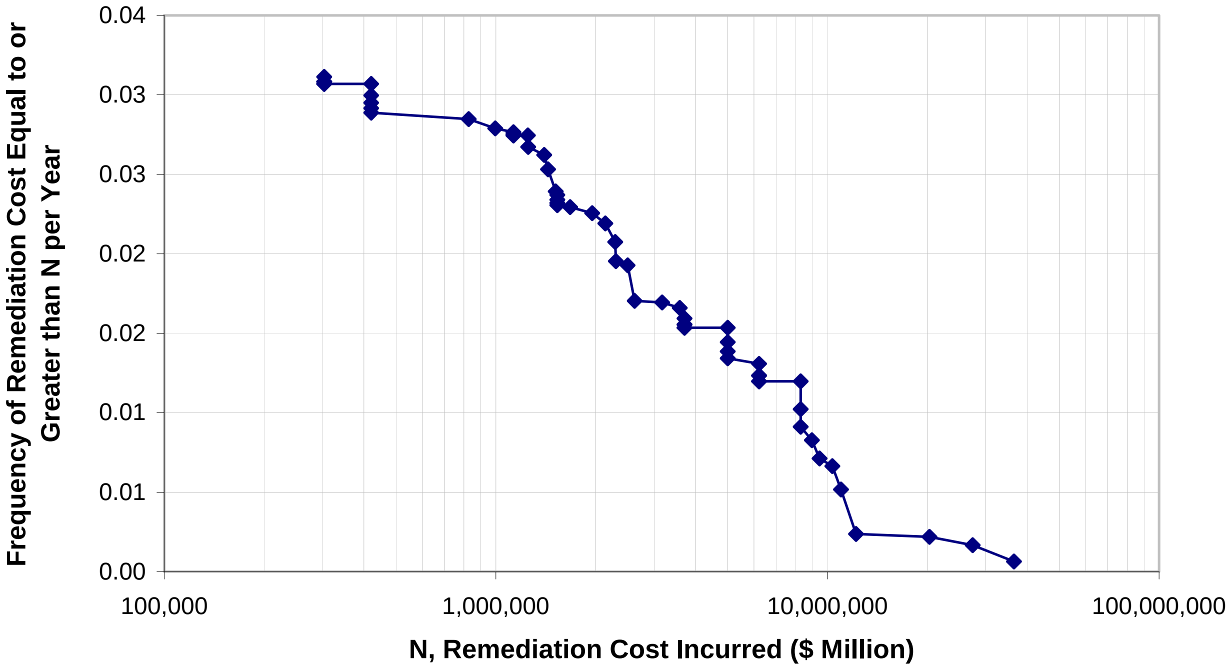


Figure H-12 Risk Profile for Environmental Impact of Ethyl Acrylate

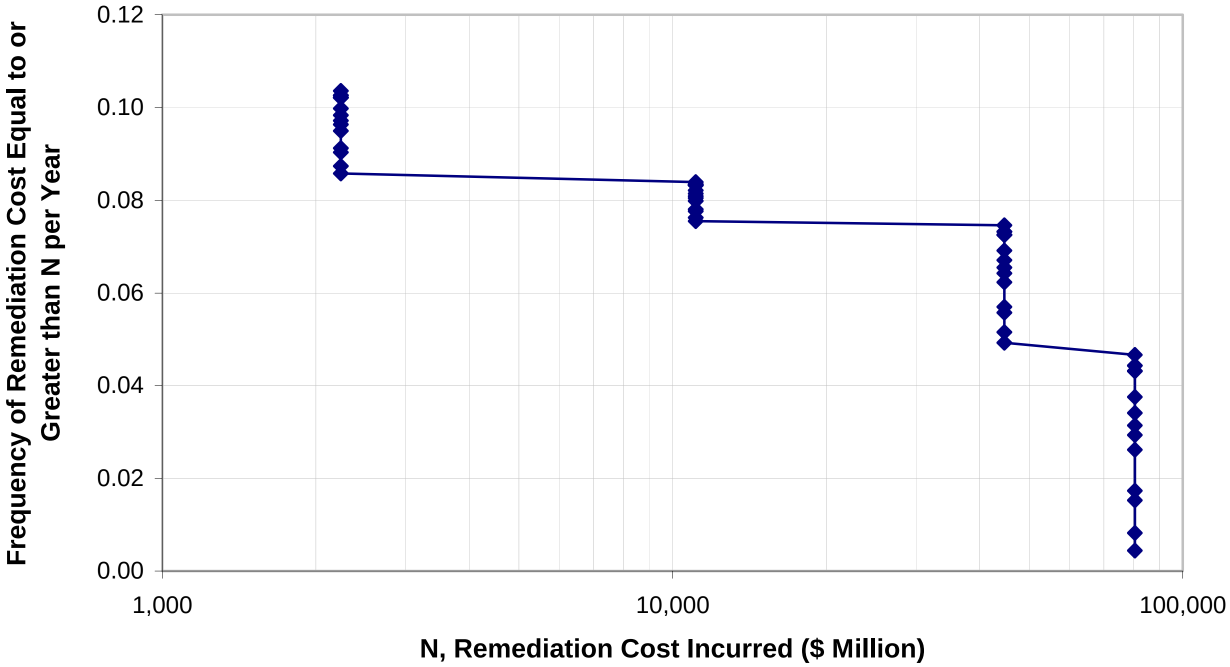


Figure H-13 Risk Profile for Environmental Impact of Hydrogen Peroxide

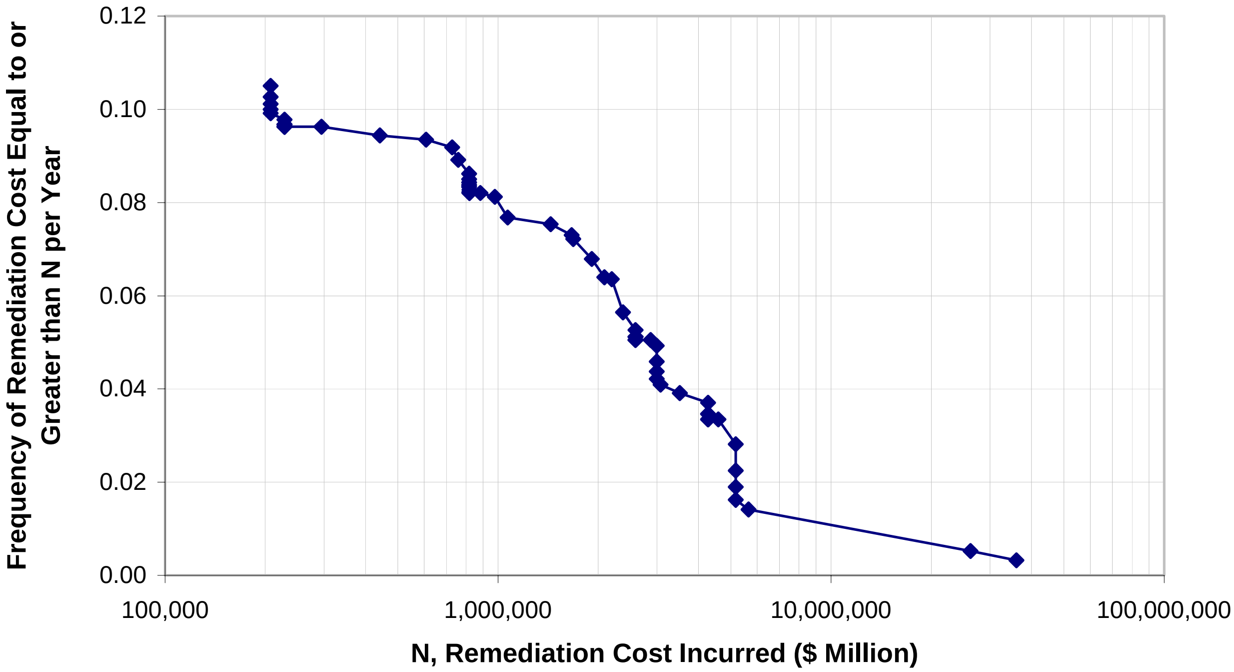


Figure H-14 Risk Profile for Environmental Impact of Isopropanol

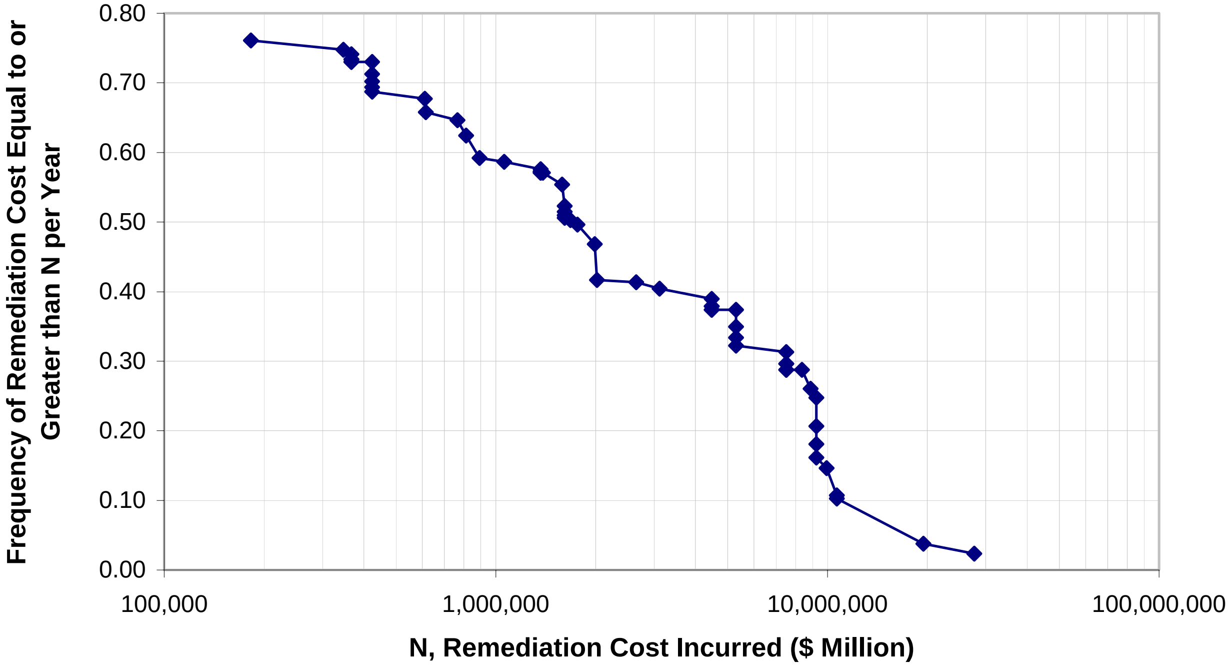


Figure H-15 Risk Profile for Environmental Impact of Methanol

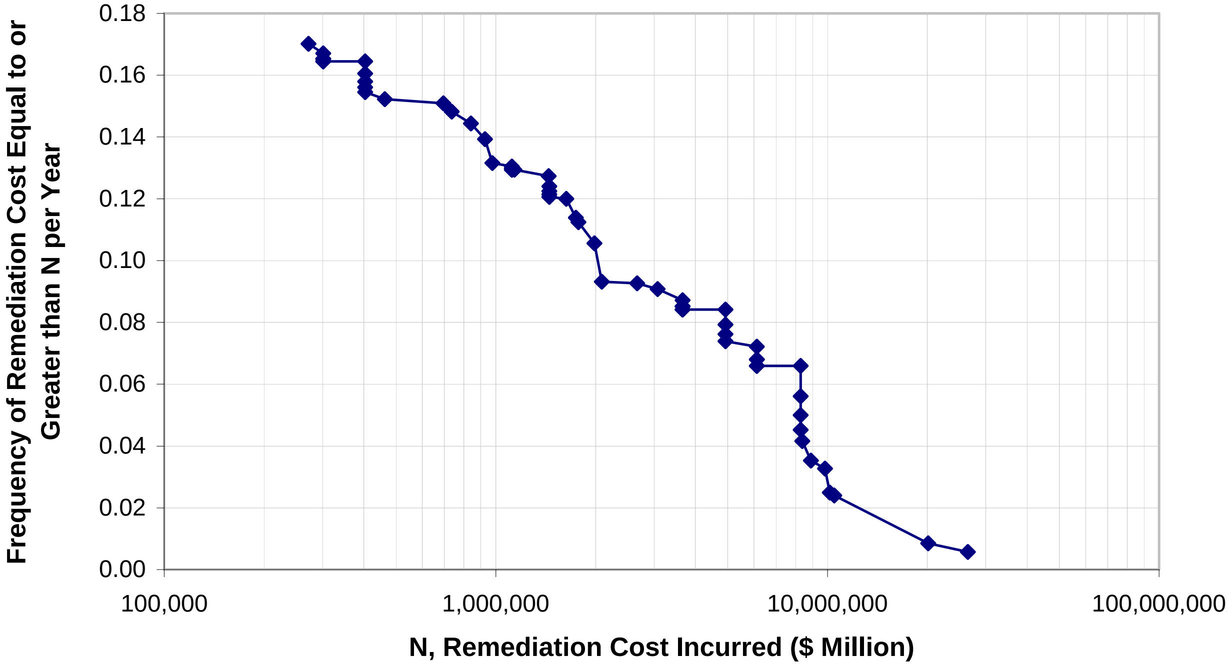


Figure H-16 Risk Profile for Environmental Impact of Methyl Methacrylate

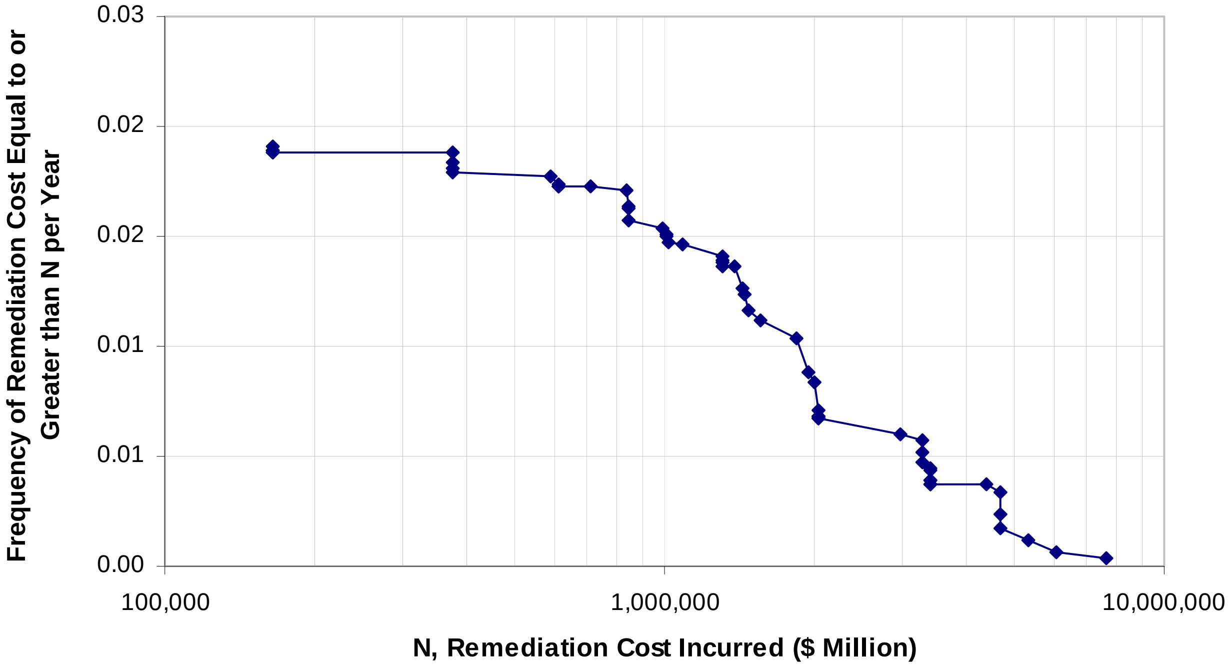


Figure H-17 Risk Profile for Environmental Impact of Methyl tert Butyl Ether

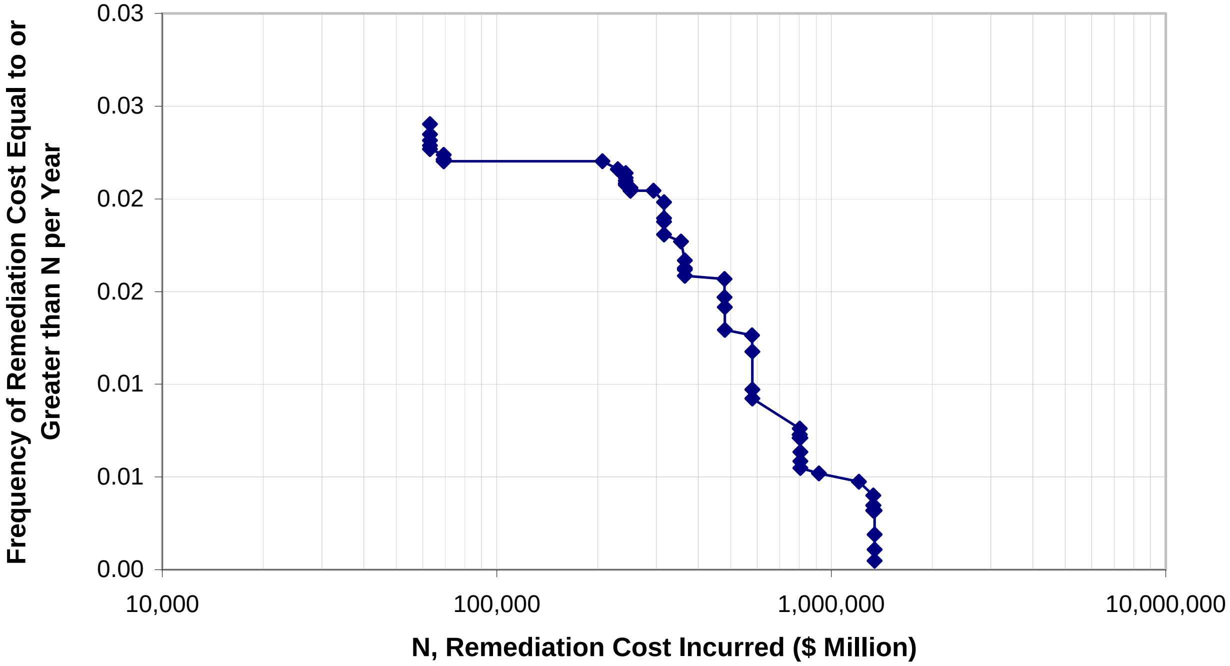


Figure H-18 Risk Profile for Environmental Impact of Nitric Acid

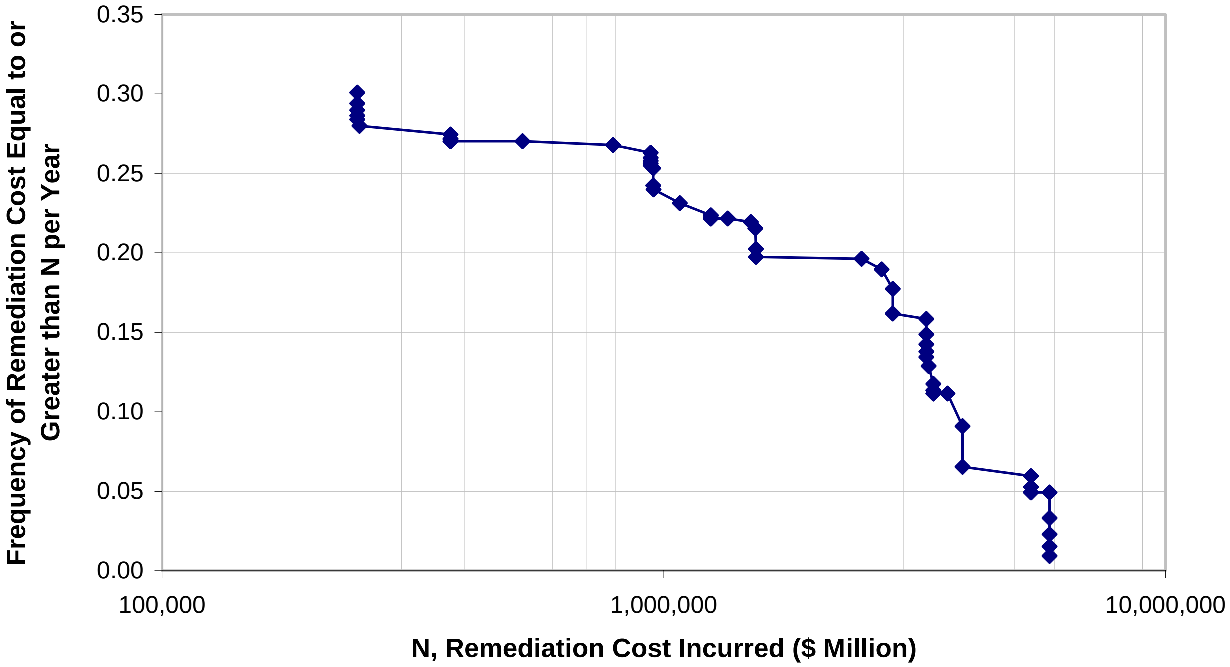


Figure H-19 Risk Profile for Environmental Impact of Phenol

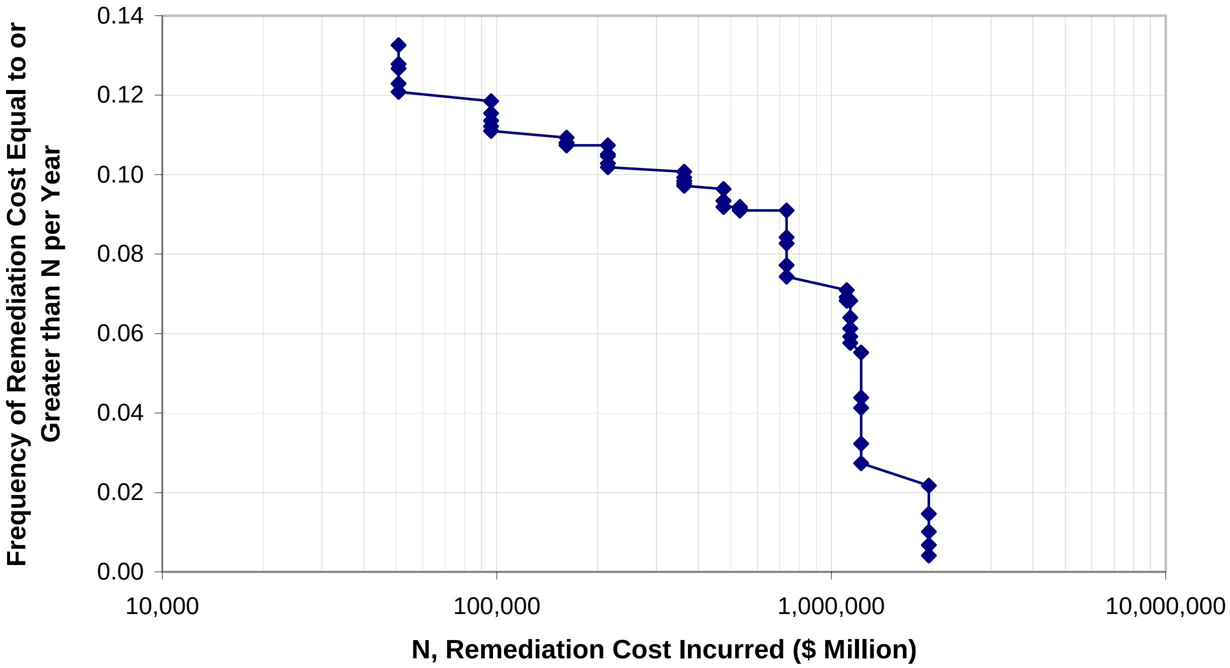


Figure H-20 Risk Profile for Environmental Impact of Potassium Hydroxide

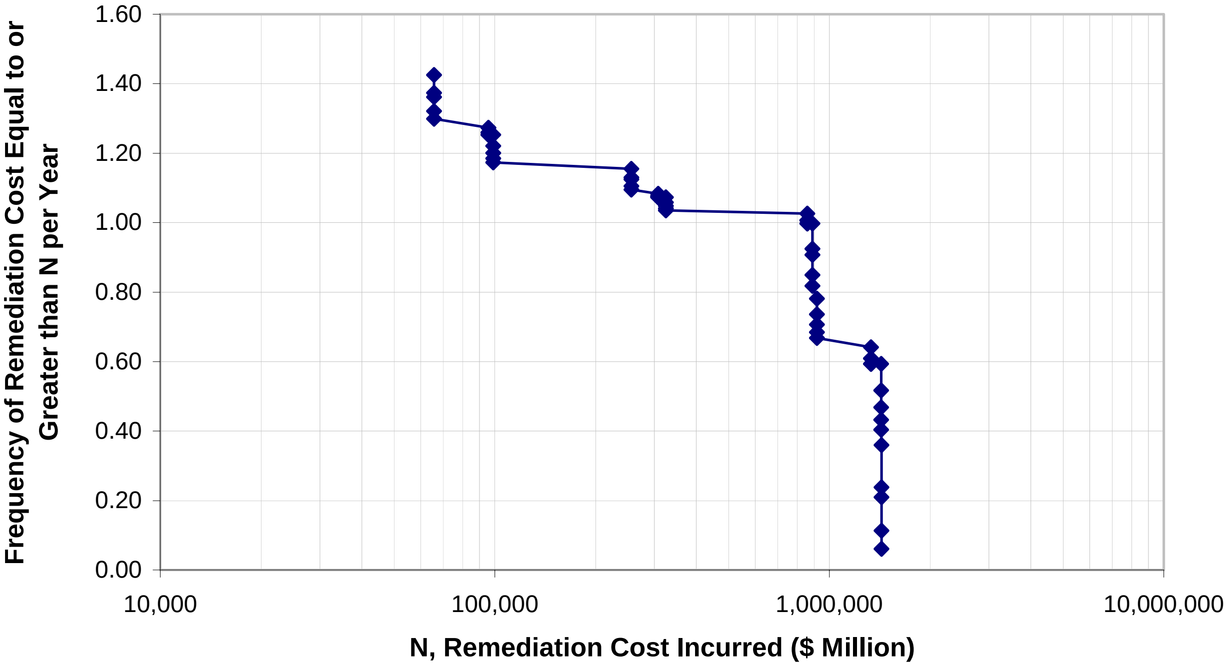


Figure H-21 Risk Profile for Environmental Impact of Sodium Hydroxide

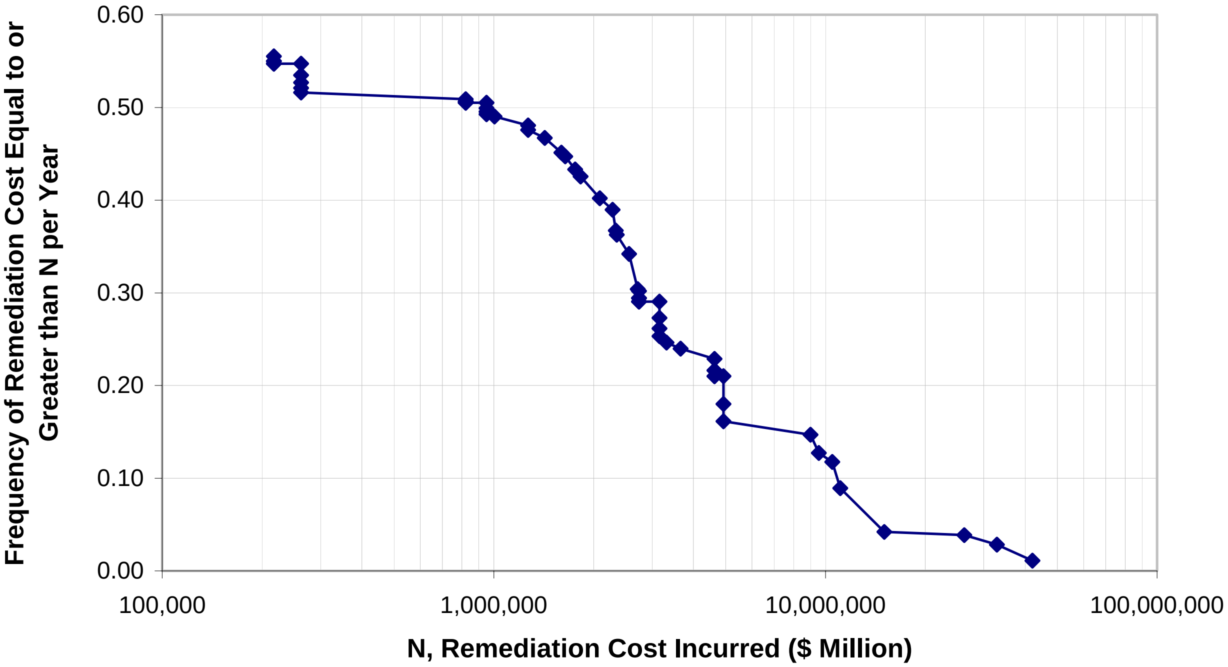


Figure H-22 Risk Profile for Environmental Impact of Styrene

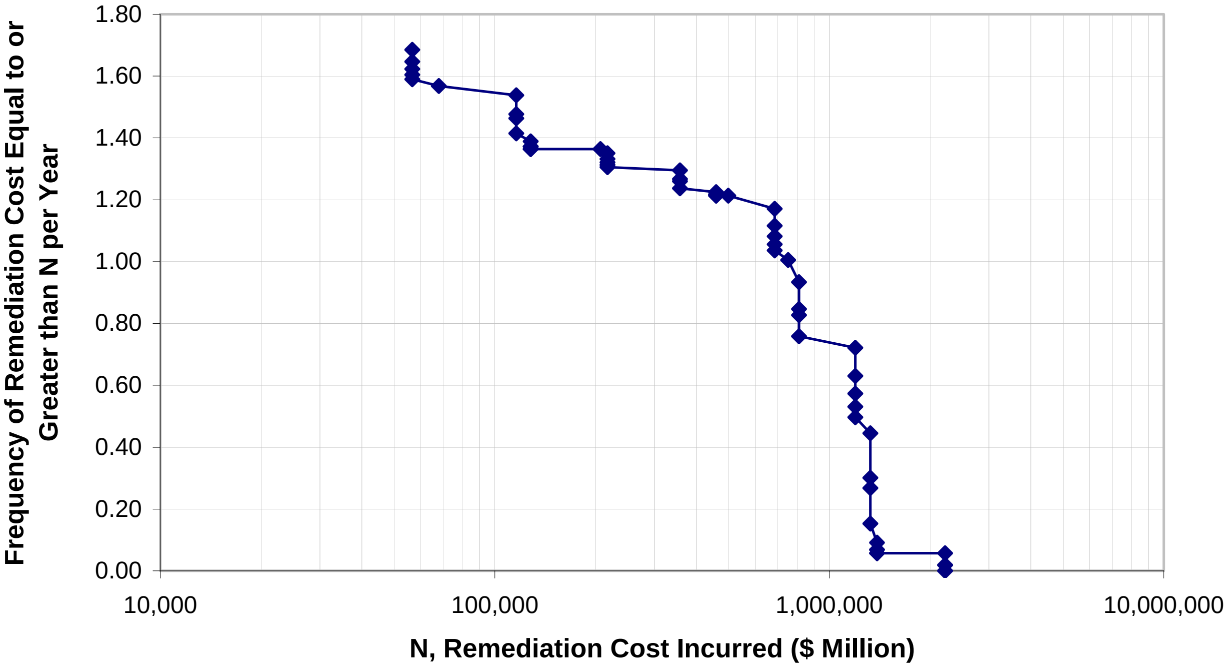


Figure H-23 Risk Profile for Environmental Impact of Sulfuric Acid

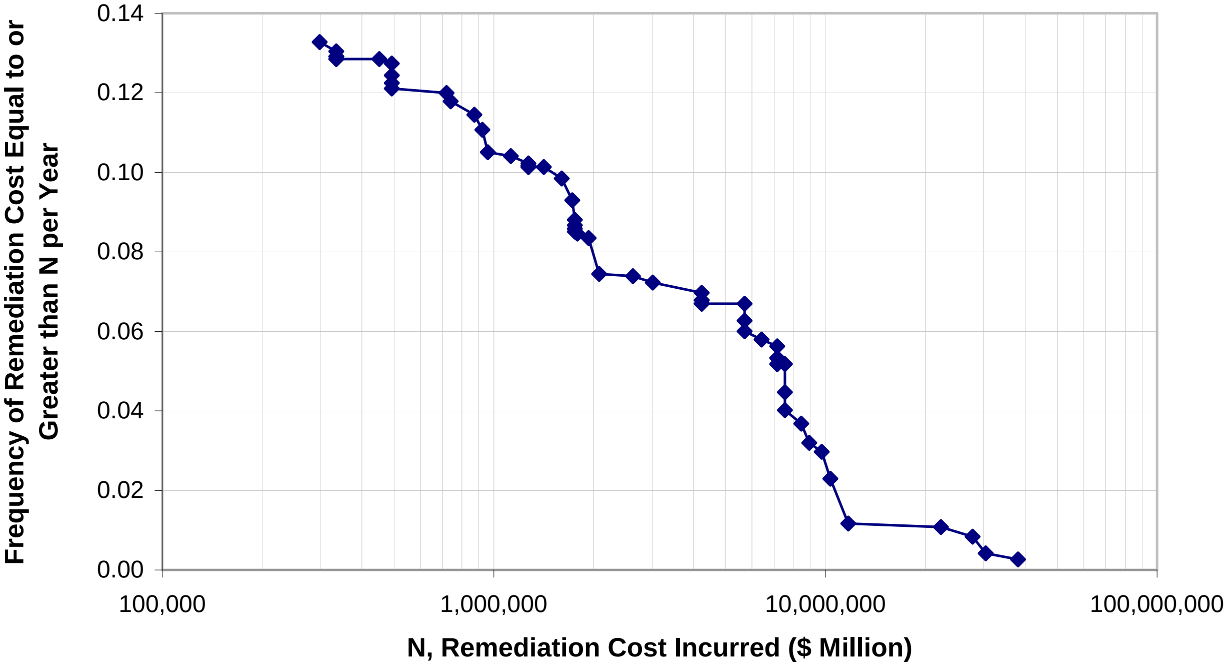


Figure H-24 Risk Profile for Environmental Impact of Toluene

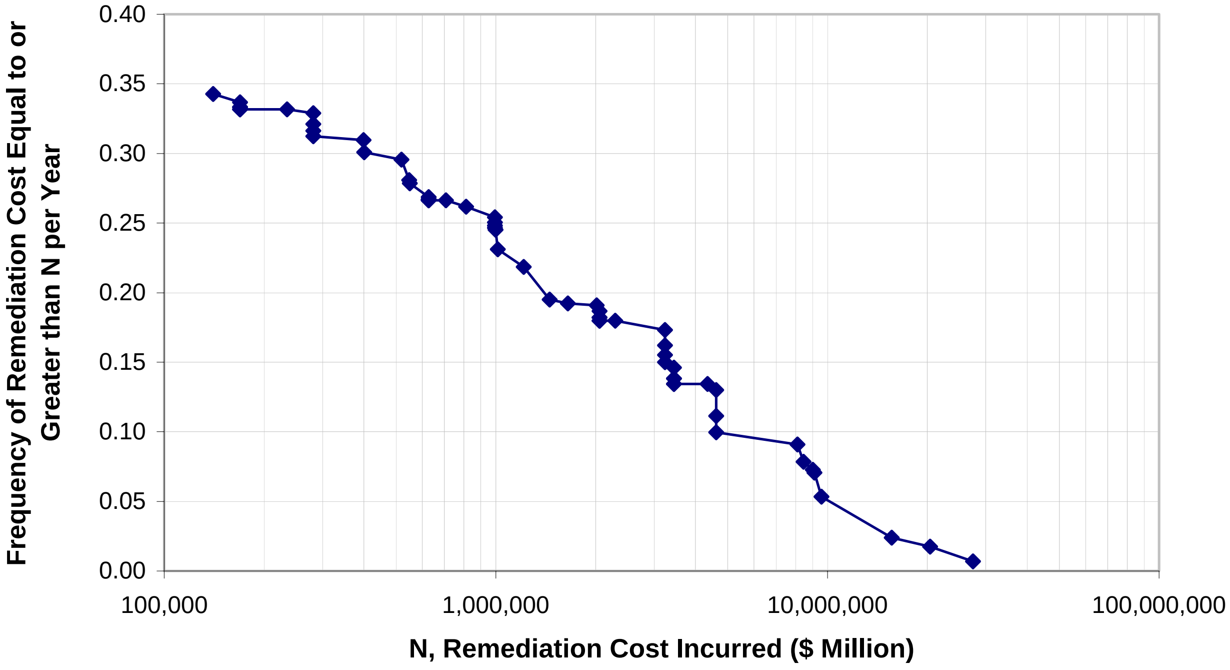


Figure H-25 Risk Profile for Environmental Impact of Vinyl Acetate

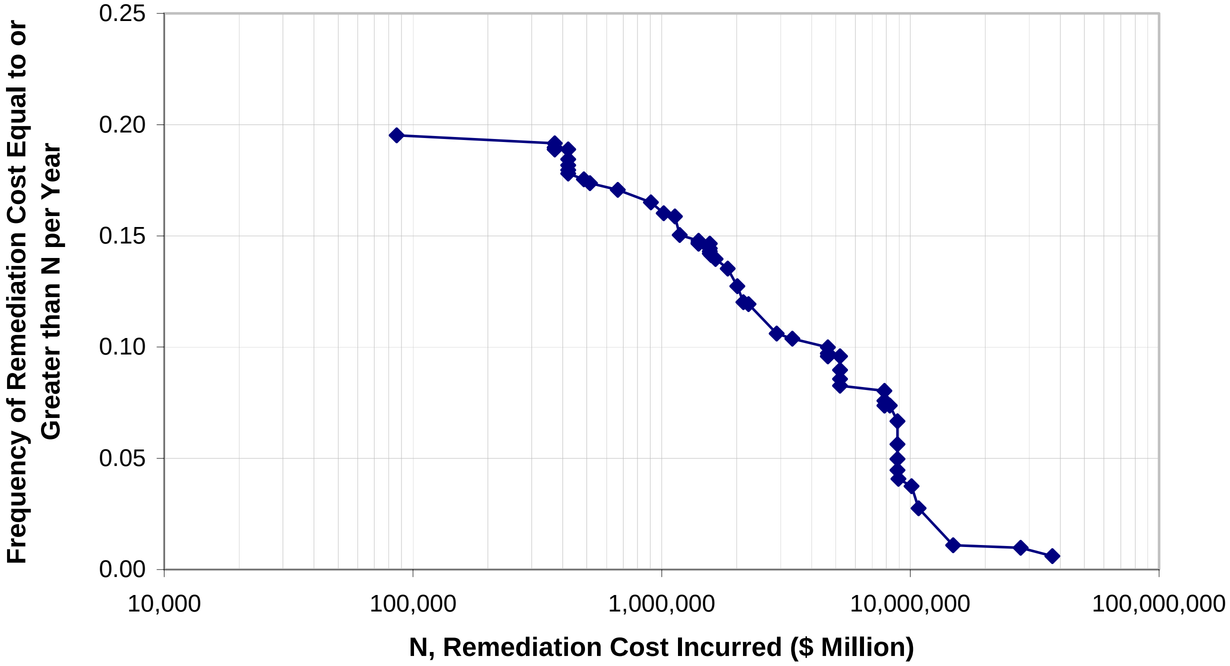


Figure H-26 Risk Profile for Environmental Impact of Xylenes

AUTHOR'S BIOGRAPHY

Pooja Anand was born in Kanpur, India. She graduated from Indian Institute of Technology (IIT), Kanpur, in 2000 with a baccalaureate degree in Civil Engineering. She worked as a software engineer with Infosys Technologies Ltd. in Bangalore, India for an year before joing the University of Illinois at Urbana-Champaign (UIUC) to start her graduate program. She worked as a research assistant in the Railroad Engineering Program in the Department of Civil and Environmental Engineering at UIUC. She completed a Master of Science degree in Civil and Environmental Engineering from the UIUC in 2004 .