OPTIMIZING RAILROAD TANK CAR SAFETY DESIGN TO REDUCE HAZARDOUS MATERIALS TRANSPORTATION RISK

BY

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DISSERTATION

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ABSTRACT

OPTIMIZING RAILROAD TANK CAR SAFETY DESIGN TO REDUCE HAZARDOUS MATERIALS TRANSPORTATION RISK

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The design of railroad tank cars is subject to structural and performance requirements and constrained by weight. They can be made safer by increasing tank thickness and adding various protective features, but these increase the weight and cost of the car and reduce its capacity and consequent transportation efficiency. Aircraft, automobiles and other vehicles are subject to a conceptually related set of problems and formal optimization techniques have been used to develop optimized design solutions using various objective functions. These general techniques can be adapted to solve a variety of tank car safety design optimization problems in which the tradeoff between safety and transportation efficiency is formally considered.

Hazardous materials are substances or materials capable of posing an unreasonable risk to health, safety, and property when transported in commerce. However, within this broad, general definition, the hazard posed by these materials varies widely in terms of both the nature and magnitude of the hazard. Consequently, the benefit derived from measures intended to prevent hazardous material releases also varies considerably. Efficient allocation of safety resources requires quantitative understanding of the risks and benefits associated with different hazardous materials and various approaches to enhance safety. Addressing these questions in the context of railroad tank car safety design optimization is the principal focus of this dissertation.

I develop a modeling approach in which tank car safety design optimization is considered as a two-phase process. The first phase addresses the tradeoff between safety and transportation efficiency by using Pareto optimization to identify the most efficient design combinations to improve safety while minimizing incremental weight. The second phase involves estimation of chemical-specific hazard levels and calculation of the consequent benefits and costs to determine the optimal level of protection for tank cars transporting different hazardous materials. This modeling approach is applied to two different current tank car safety design problems; consideration of tank car safety design enhancements to reduce the risk of transporting toxic inhalation hazard materials, and a group of chemicals that pose risk to the environment. The framework presented in this dissertation is can be used to assist industry and government policy makers to make better-informed decisions for safer transportation of hazardous materials.

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TABLE OF CONTENTS

LIST OF ABBREVIATIONS AND ACRONYMS

ACC	American Chemistry Council
ASLRR	American Short Line and Regional Railroad Association
CFR	Code of Federal Regulations
CI	Chlorine Institute
CPC	Casualty Prevention Circular
CPR	Conditional Probability of Release
DOT	U.S. Department of Transportation
ERG	Emergency Response Guidebook
FPR	Free Product Recovery
FRA	Federal Railroad Administration
GAC	Granulated Activated Carbon
GAMS	General Algebraic Modeling System
GIS	Geographic Information Systems
GRL	Gross Rail Load
HMTECM	Hazardous Materials Transportation Environmental Consequence Model
LNAPL	Light, Non-Aqueous-Phase Liquid
MACRS	Modified Accelerated Cost Recovery System
MBR	Membrane Bioreactor
MGT	Million Gross Tonnage
NAPL	Non-Aqueous-Phase Liquid
NPRM	Notice of Proposed Rulemaking
NPV	Net Present Value
NTSB	National Transportation Safety Board
NVH	Noise, Vibration, Harshness
NWIS	USGS National Water Information System
O-D	Origination and Destination
PHMSA	U.S. DOT Pipeline and Hazardous Materials Safety Administration
R&D	Research and Development
RRO	Risk Reduction Option
RSI	Railway Supply Institute
STATSGO	USDA State Soil Geographic Database
STB	Surface Transportation Board
SVE	Soil Vapor Extraction
TIH	Toxic Inhalation Hazard
TRAIN II	Tele Rail Automated Information Network II
USDA	U.S. Department of Agriculture
USGS	United States Geological Survey
VBA	Visual-Basic-in-Application

CHAPTER 1

INTRODUCTION

1.1. INTRODUCTION

Chemical production and use in manufacturing are crucial for industrial society. While people derive significant benefits from chemical use, there are also certain associated safety and economic risks that must be managed and to the extent feasible, minimized. This tradeoff is particularly relevant in the context of transportation of chemicals classified as hazardous materials. In the U.S., a hazardous material is defined by 49 Code of Federal Regulations (CFR 2009) as a substance or material that the Secretary of Transportation has determined is capable of posing an unreasonable risk to health, safety, and property when transported in commerce, and has designated as hazardous under section 5103 of Federal hazardous materials transportation law (49 U.S.C. 5103).

However within this broad and general definition, the actual hazard posed by these materials varies widely in terms of both the nature and magnitude of the hazard. Consequently, the benefit derived from measures intended to prevent hazardous material releases varies considerably. In order to allocate safety enhancement resources in the most efficient manner possible requires quantitative understanding of the consequent risks and benefits. Addressing these questions in the context of railroad tank car safety design is the focus of my dissertation.

Enhancing the safety of hazardous materials transportation has been the subject of a great deal of attention over the past three decades. Improvements have focused on all aspects including packaging of the materials, loading and unloading practices, transportation operations, routing of shipments, emergency response practices and hazardous materials shipment information (TRB 1980; Glickman and Rosenfield 1984; Harvey et al. 1987; Saccomanno et al. 1987; Glickman 1988; Abkowitz et al. 1989; Phillips and Role 1989; Barkan et al. 1991; Saccomanno and Cassidy 1992; Purdy 1993; TRB 1993, 1994; Rhyne 1994; CCPS 1995; Erkut and Verter 1995; FRA 1996; Barkan et al. 2000; Raj and Pritchard 2000; Elliott and Mitchell 2002; AAR 2003; BOE 2003; Barkan et al. 2007; Barkan 2008; CCPS 2008).

In North America, rail offers the safest and generally the most economical means of transporting many of these materials. Nevertheless, in the event of train accidents releases of hazardous chemicals can pose substantial risk to human health, property or the environment (Dennis 2002). Since 1982, the rate of railroad accident-caused releases has been reduced by about 93% (Barkan et al. 2000; BOE 2009) due to prevention of both accidents and of spills from railcars involved in accidents (Harvey et al. 1987; Barkan et al. 1991; Gallamore 1999; Barkan et al. 2000; Barkan 2008; BOE 2009).

The principal objective of my dissertation research is to improve our understanding of how to reduce the risk of transporting hazardous materials by rail through development and application of operations research and decision analysis techniques to evaluate the most efficient strategies to improve tank car safety design. The main contribution of my dissertation research is in the development of a new, quantitative model to optimize tank car safety design using a two-phase process. The first phase addresses the tradeoff between safety and transportation efficiency, while the second phase accounts for chemical-specific hazard levels and the consequent benefits and costs. Chapters in my dissertation focus on development of models to assess the effects of changes in tank car safety design on transportation efficiency and safety and to identify optimal designs for specific hazardous materials. The chapters build upon each other by addressing a series of inquiries as follows:

- What are the factors affecting railroad hazardous materials transportation risk?
- How tank car safety designs affect the risk?
- What are the options or design variables to improve tank car safety?
- What tradeoffs are involved in optimizing tank car safety design?
- What optimization techniques are available to address the tradeoffs?
- What are the risks from transporting toxic inhalation hazard (TIH) materials in railroad tank cars, and how to assess them?
- What are the optimal tank car safety designs to reduce the risk of transporting TIH materials?
- How to incorporate material hazard and the consequent risk in tank car safety design optimization?
- How to quantify the benefit and cost from tank car safety design enhancements?
- What decision criteria can be used to identify the optimal tank car safety design?
- What are the risks from railroad transportation of materials that pose hazard to the environment, and how to assess them?
- Is it cost-effective to replace tank cars transporting materials that pose risk to the environment?

In the following discussion, I provide a background on optimization of vehicle structural design, its history and applications in other fields including aircraft and aerospace systems, automotive, and use of multicriteria optimization methods as a tool in these fields. I develop the parallel between this research and my own, and consider how they relate to the first chapter of my dissertation. I also discuss the background of railroad tank car safety design optimization. In addition, I give an overview of hazardous material transportation risk that serves as an introduction to the remaining chapters in this dissertation.

1.1.1. Structural Optimization in Vehicle Design

The first analytical work in structural optimization can be traced back to research by Maxwell (1869) in which the basic theory for optimal layout of minimum-weight theoretical trusses under an ideal, single load condition was presented. Early research related to vehicle design was done by Cox and Smith (1943) and Zahorski (1944) who applied structural optimization techniques to identify the minimum-weight, optimal design of basic aircraft structural components.

Vehicle structural designs are generally subject to both performance requirements such as strength and stiffness, and to cost constraints like weight. For aircraft and most other aerospace systems, conceptual design optimization has typically been based on achieving efficient aerodynamics while minimizing weight configuration subject to structural requirements (Schmit 1981; AIAA 1991; Sobieszczanski-Sobieski and Haftka 1997; Bartholomew 1998). With regard to automotive design, crashworthiness criteria to maximize vehicle structural integrity for occupant safety in the event of a crash has been considered together with the objectives to minimize noise, vibration, harshness (NVH), and weight or other cost constraints (Sobieszczanski-Sobieski et al. 2001; Redhe and

Nilsson 2004; Kodiyalam et al. 2004; Hou et al. 2008). There are similar conflicting criteria in tank car safety design optimization. Tank cars can be made safer by increasing tank thickness and adding various protective features, but these increase the weight and cost of the car and reduce its capacity and consequent transportation efficiency. Formal consideration of this tradeoff between tank car safety and transportation efficiency, and use of optimization techniques to address these questions are addressed in the first phase of the tank car safety design optimization process in my dissertation.

Historically, the need to account for the tradeoff between structural weight and structural integrity in aerospace applications has been the factor behind the development of optimum design methods in structural optimization (Schmit 1981). A typical multicriteria design optimization method used in the field is to convert the multi-objective optimization to a single-objective problem. Using this approach, a primary criterion is selected as an objective function while other, less significant criteria are used as functional constraints (Sobieszczanski-Sobieski et al. 2001; Redhe and Nilsson 2004; Hou et al. 2008). Another typical approach is to consider multiple design criteria simultaneously as the objectives for optimization. In this multi-objective optimization framework, the decision space is searched for a set of Pareto optimal solutions, from which the final design is chosen from. This approach has its roots in mathematical consumer economics as considered by Pareto (1896) and this type of optimization has been used extensively in vehicle safety and crashworthiness design problems (Kasprzak et al. 1998; Andersson and Redhe 2003; Hamza and Saitou 2005; Lee et al. 2006; Cristello and Kim 2007; Sinha 2007; Sinha et al. 2007).

1.1.1.1. Tank Car Safety Design Optimization

Evolution of tank car safety and efficiency has been underway for over a century (Heller 1970; Dalrymple 1997; Barkan 2008). Development of new and more robust safety standards has been due to technology improvements in materials, manufacturing processes and car components, and influenced by changes in the railroad operating environment, and new safety expectations from industry, government and the public (Barkan 2008). Optimality techniques were first applied to tank car safety design by Barkan et al. (2007) who used minimization of conditional probability of release as the objective function to calculate the optimal thickness of a tank. Their model took into account the tradeoff between improved damage resistance of the tank versus the increased accident exposure due to the reduced capacity of the car and the consequent exposure of other elements such as fittings to damage in an accident. Saat and Barkan (2005) extended this work by considering the effect of damage to different parts of a tank car and developed the concept of "release risk" that combines accident-caused release probability with average amount spilled to develop an expected value of quantity lost.

Barkan (2008) developed a goal programming approach that was used to assist North American railroads in their development of specifications for higher capacity tank cars for transportation of hazardous materials. A group of tank car safety design features or "risk reduction options" (RROs) were analyzed with regard to their effect on the conditional probability of release in an accident, and their incremental effect on tank car weight. The Pareto-optimal set of options that provided the greatest improvement in safety with the least amount of additional weight for any desired level of tank car weight increase was identified. The model developed by Barkan (2008) considered a particular set of RRO combinations addressing certain objectives defined by the railroad and tank car industries regarding design attributes of 286,000 lb. maximum gross rail load (GRL), non-pressure tank cars. Chapter 2 of my dissertation builds on this work by improving our understanding and by developing a general model that can be applied to any type of tank car or set of RROs.

1.1.2. Hazardous Materials Transportation Risk

Precursors to contemporary risk analysis can be traced as far back as ancient Mesopotamia (Oppenheim 1977), but it was not until Pascal introduced probability theory in 1657 that the intellectual tools for quantitative risk analysis became available (Covello and Mumpower 1985). The first framework of modern quantitative risk assessment was presented by Laplace in 1792 in his analysis of the probability of death with and without smallpox vaccination (Laplace 1812).

In the context of hazardous materials transportation, the history of quantitative risk analysis dates back to 1971 when the National Transportation Safety Board (NTSB) proposed the need for a risk-based approach to develop hazardous material transportation safety regulations (NTSB 1971). In the late 1970s, Ang et al. (1979) introduced a general framework for transportation risk analysis that includes identifying probabilities, level of exposure and consequences from an undesirable event. Philipson and Napadensky (1982) provided an overview of the general risk assessment problem, presented a structured review of the types of risk estimation methodologies, and reviewed the procedures available for risk evaluation and mitigation. Early attention focused on rerouting as a means of managing hazardous materials transport risk. Glickman (1983) developed a model for network-level analysis of rerouting traffic and Abkowitz et al. (1989) were among the first to use Geographic Information Systems (GIS) to address risk and routing questions. List et al. (1991) presented a comprehensive survey of early research on hazardous materials transportation risk analysis.

Tank car safety design has also been studied in the context of risk analysis. Barkan et al. (1991) conducted a risk analysis of a group of chemicals with the potential to cause substantial soil and groundwater cleanup expense and calculated the costs and benefits of using more damage-resistant cars. Dennis (1996) extended their work by using cost data from U.S. Class 1 railroads to estimate the risk costs per unit of exposure due to hazardous materials transportation. Saat and Barkan (2005) developed a release risk approach to estimate the expected quantity of release from different tank car designs if they were involved in an accident. My dissertation Chapters 3 and 5 describe two types of risk due to rail transportation of hazardous materials. In Chapter 4 I present the second phase of the tank car safety design optimization process that accounts for chemical-specific hazard and consequent benefits and costs, and in Chapter 6 I apply that model to a group of hazardous materials.

1.2. DISSERTATION ORGANIZATION

This dissertation is organized as a series of individual, publishable papers, plus an introductory chapter and a discussion of future research needs in the final chapter.

Chapter 1: Introduction

This chapter presents the objectives of my dissertation, background on optimization of vehicle structural design and multicriteria optimization applications in the field, a brief overview of hazardous material transportation risk analysis, and a description of each chapter.

Chapter 2: A Generalized Bicriteria Model for Optimizing Railroad Tank Car Safety Design

In this chapter I present the first phase of the tank car safety design optimization process by using a Pareto-optimization method similar to those discussed above to develop a generalized model to quantitatively evaluate the tradeoff between weight and tank car conditional probability of release, which essentially represents the tradeoff between transportation efficiency and safety. I develop a new, modular approach in which I extend and generalize the optimization techniques used by Barkan (2008). The model enables evaluation of all of the current elements of tank car safety design, independently and in combination. I also introduce a more detailed tank car sizing program to quantify the changes in tank car weight and capacity, consider a wider range and finer increments of tank head and shell thicknesses, and incorporate the latest statistical model of tank car release probability (Treichel et al. 2006).

Chapter 3: Risk Analysis of Toxic Inhalation Hazard (TIH) Materials' Transportation on U.S. Railroad Mainlines

This chapter presents a nationwide analysis of the risk of transporting a group of TIH materials by rail. This work was used to support the Association of American Railroads (AAR')s initiative to develop new tank car design specifications for TIH materials. Initially, the Pareto-optimization technique described in Chapter 2 is combined with a utopia-point method to identify the most efficient approach to enhance the safety design of tank cars and thereby reduce the risk. Tank car derailment rate from Anderson and Barkan (2004) and a statistical model developed by Treichel et al. (2006) are used to estimate the conditional probability of release from a tank car involved in an accident. These probability estimates are combined with a hazard consequence model and a spatial analysis of the chemical-specific rail routes using geographic information system (GIS) data and software to estimate population exposure along the routes.

Chapter 4: Risk-Based Railroad Tank Car Safety Design Optimization

In Chapter 4 I present the second phase of the tank car safety design optimization process that combines the optimization method from Chapter 2 with a benefit-cost approach to determine what the optimal design tank car should be, based on maximizing the net present value (NPV) as the objective function. The model enables incorporation of chemical-specific hazard and risk to objectively determine the optimal tank car safety design for each material.

Chapter 5: Environmental Risk Analysis of Rail Transport of Hazardous Materials

In Chapter 5, I describe a quantitative, environmental risk analysis of rail transportation of a group of light, non-aqueous-phase liquid (LNAPL) chemicals commonly transported in railroad tank cars in North America. The Hazardous Materials Transportation Environmental Consequence Model (HMTECM) (Yoon et al. 2009; Hridaya 2008; Schaeffer et al. 2008) is used in conjunction with a geographic information system (GIS) analysis of environmental characteristics to develop probabilistic estimates of exposure to different spill scenarios along the North American rail network. The risk analysis incorporates the estimated cleanup cost developed using the HMTECM, route-specific probability distributions of soil type and depth to groundwater, annual traffic volume, railcar accident rate, and tank car safety features, to estimate the nationwide annual risk of transporting each product. Other release consequences including population exposure and train delay costs are also considered.

Chapter 6: Tank Car Safety Design Optimization to Reduce the Environmental Risk of Transporting Hazardous Materials

In Chapter 6, I use the risk analysis results from Chapter 5, and apply the risk-based tank car safety design optimization model from Chapter 4 to identify possible enhanced-design tank cars to reduce the risk of transporting a group of LNAPL chemicals. A generalized tank car life-cycle cost model is presented to enable a comprehensive tank car capital cost analysis to be used in tandem with the tank car fleet financial cost model in Chapter 4. I then present a benefit-cost analysis and consider maximizing the net present value (NPV) to identify possible optimal, enhanced tank car safety designs to transport the chemicals of interest.

Chapter 7: Future Research

This chapter presents additional research needs based on the findings and limitations addressed in my dissertation, and the next logical steps to expand the body of knowledge presented in this dissertation.

1.3. CONCLUSIONS

Tank car safety design optimization is presented in this dissertation as a two-phase process. The first phase addresses the tradeoff between safety and transportation efficiency by using Pareto optimization to identify the most efficient non-dominated design combinations of safety performance and weight. The second phase involves incorporating chemical-specific hazard level and the consequent benefit and cost to determine the optimal level of protection for different hazardous materials. My dissertation research provides decision tools and parametric models to assess hazardous materials transportation risk, identify optimal tank car safety design, and estimate potential risk reduction options and their associated benefit and cost. The framework presented in this dissertation is intended to assist industry and government policy makers to make better-informed decisions for safer transportation of hazardous materials.

1.4. REFERENCES

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CHAPTER 2

A GENERALIZED BICRITERIA MODEL FOR OPTIMIZING RAILROAD TANK CAR SAFETY DESIGN

2.1. INTRODUCTION

In 2007, there were approximately 2 million rail shipments of hazardous materials in the U.S. and Canada, and approximately 72% of these were transported in tank cars (BOE 2009). For the past several years, the rate of railroad accident-caused releases of hazardous materials has been fluctuating between 15 and 23 incidents per million carloads (BOE 2009). Although significantly lower than the rate of about 200 release incidents per million carloads in 1982 (Barkan et al. 2000), further reduction of accident-caused hazardous material releases remains an important objective.

Two of the principal elements affecting reduction of railroad hazardous material transportation risk are prevention of accidents and prevention of spills from railcars involved in accidents (Barkan et al. 1991). Due to improvements in track design and maintenance, as well as improvements in equipment and training, train accidents declined substantially in the 1980s and more gradually in the 1990s (Gallamore 1999; Dennis 2002). The result is that the annual accident rate, excluding grade-crossing accidents, has been reduced from approximately 12 accidents per million-train miles in 1980 (Harvey et al. 1987) to about 4 accidents per million-train miles in 2002 (Anderson and Barkan 2004).

Changes in tank car design to increase resistance to damage in accidents have also contributed to this improvement in safety (Barkan et al. 2000). Refinement of our understanding of the degree of hazard posed by different products is ongoing, but in general higher hazard materials are shipped in more robustly designed tank cars with tanks constructed of thicker and stronger steels, and in many cases, head shields, thermal protection and more damage-resistant top fittings protection designs.

Improving tank car safety design should be done in such a way that safety performance is maximized while minimizing additional weight and cost. Each of the safety design enhancements mentioned above has a unique functional relationship between its incremental safety benefit and its effect on weight. This tradeoff must be accounted for when optimizing the safety performance of a tank car.

Optimizing tank car safety design has certain parallels with other vehicle structural designs in which there is a tradeoff between performance requirements such as strength and stiffness, and cost constraints like weight. For aircraft and most other aerospace systems, conceptual design optimization has typically been based on achieving efficient aerodynamics while minimizing weight configuration subject to structural requirements (Schmit 1981; AIAA 1991; Sobieszczanski-Sobieski and Haftka 1997; Bartholomew 1998). With regard to automotive design, crashworthiness criteria to maximize vehicle structural integrity for occupant safety in the event of a crash has been considered together with the objectives to minimize noise, vibration, harshness (NVH), and weight or other cost constraints (Sobieszczanski-Sobieski et al. 2001; Redhe and Nilsson 2004; Kodiyalam et al. 2004; Hou et al. 2008).

Optimality techniques were first applied to tank car safety design by Barkan et al. (2007) who used minimization of conditional probability of release as the objective function to calculate the optimal thickness of a tank. Their model took into account the tradeoff between improved damage resistance of the tank versus the increased accident exposure due to the reduced capacity of the car and the consequent exposure of other elements such as fittings to damage in an accident. Saat and Barkan (2005) extended this work by considering the effect of damage to different parts of a tank car and developed the concept of "release risk" that combines accident-caused release probability with average amount spilled to develop an expected value of quantity lost.

Barkan (2008) described a goal programming approach that was used to assist North American railroads in their development of specifications for higher capacity tank cars for transportation of hazardous materials. A group of tank car safety design features or "risk reduction options" (RROs) were analyzed with regard to their effect on the conditional probability of release in an accident, and their incremental effect on tank car weight. The Pareto-optimal set of options that provided the greatest improvement in safety with the least amount of additional weight for any desired level of tank car weight increase was identified. Barkan's model considered a limited number of RRO combinations addressing a specific set of objectives defined by the railroad and tank car industries regarding design attributes of 286,000 lb. maximum gross rail load (GRL), non-pressure tank cars.

In this Chapter I develop a generalized model to quantitatively evaluate the tradeoff between tank car weight and conditional probability of release, which essentially represents the tradeoff between transportation efficiency and safety. I develop a new, modular approach in which I extend and generalize the optimization techniques used by Barkan (2008). The model enables evaluation of all of the current elements of tank car safety design, independently and in combination. I also introduce a more detailed tank car sizing program to quantify the changes in tank car weight and capacity, consider a wider range and finer increments of tank head and shell thicknesses, and incorporate the latest statistical model of tank car release probability (Treichel et al. 2006). I illustrate the generalized bicriteria tank car safety design optimization model by identifying a set of Pareto-optimal solutions for a baseline tank car design in a multi-attribute decision problem.

2.2. TANK CAR WEIGHT & CAPACITY MODEL

The volumetric capacity of tank cars is often optimized for the density of the specific product they are intended to transport. The light or empty weight of a car consists of the weight of its running gear and fittings, which are relatively constant, and the weight of the tank that varies with its size. The maximum allowable operating weight of railcars in North America is referred to as the maximum gross rail load (GRL). It is currently 263,000 lbs for a four-axle car, although 286,000-lb cars are now permitted if they comply with a set of specifications defined by the Association of American Railroads (AAR) (2003a). The GRL is the sum of the light or empty weight of a tank car plus its lading capacity.

$$\mathrm{GRL} = \mathrm{LW} + \mathrm{Cap} \quad (2.1)$$

where:

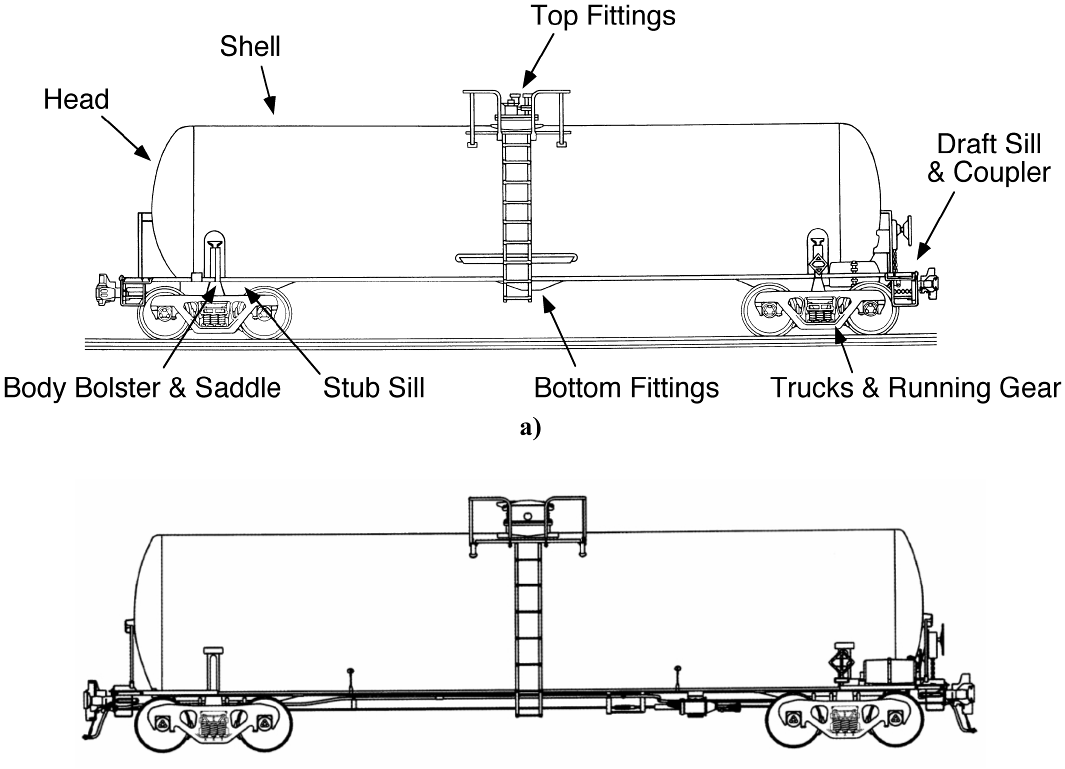
GRL = maximum total rail car weight in unrestricted interchange service
LW = tank car light weight
Cap = tank car maximum lading capacity

The maximum GRL for cars in unrestricted interchange is fixed, so any increase in a car's light weight reduces its capacity. Employing more robust safety designs or RROs to make a tank car less susceptible to damage in an accident will generally increase the weight of the tank, thereby reducing its capacity. Consequently, more shipments and more car-miles are required to transport the same quantity of lading over the same distance, exposing it to greater likelihood of being involved in an accident. This can affect the risk and should be accounted for when evaluating the effect of changes in tank car safety design (Barkan et al. 2007).

Saat (2003) developed *IlliTank*, a tank car weight and capacity model, in a Visual-Basic-in-Application (VBA) environment. The model presented in this Chapter is an extension of *IlliTank* in a more formal mathematical environment to offer a parameterized system that can be coupled with tank car safety performance, risk and cost models as part of an integrated tank car optimization formulation.

2.2.1. Tank Car Components

General components of a tank car include the tank head, tank shell, top and bottom fittings, running gear and other non-tank components (Fig. 2.1a). Some cars, including pressure cars that transport liquefied, pressurized gasses, are also equipped with insulation and an external steel jacket (Fig. 2.1b). Some designs have special thermal protection material between the tank and jacket, and some also have a half-, or full-height head shield integral to the jacket head.



a)

b)

Fig. 2.1. Diagrams of a) a typical non-jacketed North American railroad non-pressure tank car and, b) a typical jacketed North American railroad pressure tank car

2.2.2. Model Formulation

The general formulation for *IlliTank* is expressed by Equation (2.2) and requires a set of input values to run (Table 2. 1). Based on the input, *IlliTank* optimizes the size of a tank car by identifying the optimal length of the tank shell to maximize capacity while staying within the GRL limit and other clearance or tank diameter constraints. *IlliTank* assumes a basic cylindrical tank with no slope and a two-to-one ellipsoidal head at each end. Tank car builders typically have one or more design variations and corresponding tank size and weight models that account for more complicated tank geometries. Individual builders can incorporate their own models, but *IlliTank* is satisfactory to illustrate the generalized tank car safety design optimization model presented here.

$$\text{Cap} + \text{LW} \leq \text{GRL} \quad (2.2)$$

where:

GRL = maximum rail car weight in unrestricted interchange service, currently at 263,000 lbs
Cap = tank car maximum lading capacity in lbs
LW = tank car empty weight
= tank head and shell assembly + head shields + insulation + jacket + top fittings protection + bottom fittings + non-tank components + additional miscellaneous weight

Table 2.1
Variables for user-defined input in *IlliTank*

Variable	Description	Input Range	Unit
GRL	maximum gross rail load	Positive number, typically 263,000	lbs
productDensity	product density	Positive decimals	lbs/gallon
outage	tank outage	Positive number, typically 2 or 5	%
insideDia	tank inside diameter	Positive decimals	in.
headThick	tank head thickness	Positive decimals	in.
shellThick	tank shell thickness	Positive decimals	in.
insulate1Thick	ceramic fiber insulation thickness	Positive decimals	in.
insulate2Thick	fiberglass insulation thickness	Positive decimals	in.
jacket	tank jacket constant	0 = none, 1 = jacketed	-
headShield	head shield constant	0 = none, 1 = half-height, 2 = full-height	-
bottomFit	bottom fittings constant	0 = none, 1 = equipped	-
topFitProtect	top fittings protection constant	0 = none, 1 = equipped	-
addWeight	additional weight increase/reduction	Positive/negative number	lbs

A detailed *IlliTank* model was developed using the General Algebraic Modeling System (GAMS), and the optimization problem was solved with CPLEX 9.0, one of the integrated solvers incorporated in GAMS (Appendix A).

2.3. TANK CAR SAFETY PERFORMANCE MODEL

2.3.1. Tank Car Accident Database

Since the early 1970's, tank car companies and railroads have been collaborating to record data for tank cars damaged in accidents under the auspices of the Railway Supply Institute (RSI)-Association of American Railroads (AAR) Railroad Tank Car Safety Research and Test Project. The resultant database now has more than 40,000 damaged tank car records. It enables robust statistical analysis of the accident performance of each of the principal tank car components (Treichel et al. 2006) and permits development of probabilistic estimates of transportation risk for tank cars in accidents (CCPS 1995; Barkan and Pasternak 1999*)*. Statistics from Treichel et al. (2006) can be used to develop an accident-caused release rate metric to estimate the frequency of accident-caused release incidents for tank cars with specific safety designs.

2.3.2. Accident-Caused Release Rate

This Chapter focuses on Federal Railroad Administration (FRA) reportable incidents on U.S. railroad mainlines. The FRA database and reporting threshold[1] provides a standard baseline accident rate upon which to base consistent risk estimates. Railroads are required to report all accidents that exceed the FRA monetary threshold for damages to track, equipment and structures (FRA 2003). Non-FRA-reportable accidents are by definition limited in the extent of damage incurred, and rarely involve a release, and thus pose little risk. As such, the regression model used by Treichel et al. (2006) to estimate the

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[1] The threshold is equal to $8,900 in 2009

probability of release is conditional on a tank car being damaged in an FRA-reportable accident. This Chapter does not consider yard accidents because they are a relatively minor source of risk for the types of tank cars being considered. However, the benefits of a safer tank car can be expected to accrue for yard accidents as well as non-FRA-reportable, mainline accidents. Throughout this Chapter, all derailment and accident terms refer to FRA-reportable accidents.

The estimated rate of release for a tank car is defined as a product of the accident rate and the conditional probability of release given that the car is derailed in an FRA-reportable accident as follows:

$$P_R = P_{R|A} Z \qquad (2.3)$$

where:

P_R = tank car accident-caused release rate

$P_{R|A}$ = conditional probability of a tank car release given the car is derailed in an FRA-reportable accident

Z = accident frequency or exposure to accident

$= P_A M$

where:

P_A = tank car derailment rate per car-mile

M = number of car miles

2.3.2.1. Conditional Probability of Release

The source-specific conditional probabilities of release are calculated using the logistic regression model developed in Treichel et al. (2006). The model takes the form:

$$P_{R_i|A} = \varphi[e^{L(i)} / (1 + e^{L(i)})] \qquad (2.4)$$

where φ is the mainline or yard multiplier used to normalize the conditional probability for tank cars damaged to only include FRA-reportable accidents. This multiplier is equal to

0.533 for mainline and 0.245 for yard accidents (Treichel et al. 2006). L(*i*) is a linear combination of *n* statistically significant factors affecting release probability from source *i*, tank head (*H*), tank shell (*S*), top fittings (*T*) and bottom fittings (*B*), each with its own regression coefficient:

$$L(i) = b_0 + b_1 x_1 + b_2 x_2 + \ldots + +b_n x_n$$

The regression equations for the four release sources for a mainline accident-caused release are as follows:

$$L(H) = -0.4492 - 1.1672HST - 1.9863HMT - 0.9240JKT - 0.4176SHELF$$

(0.2523) (0.3650) (0.4609) (0.0914) (0.0948) (standard error)

$$L(S) = 0.4425 - 0.6427JKT - 4.1101STS$$

(0.2336) (0.0838) (0.4595) (standard error)

$$L(T) = -1.0483 - \alpha PRESS - 0.8388JKT + 0.1809SHELF$$

(0.0559) (0.0876) (0.0704) (0.0070) (standard error)

$$L(B) = -1.4399 - 0.3758JKT - 0.5789SHELF$$

(0.0767) (0.1002) (0.1101) (standard error)

where:

HST = head shield type = 1 for full-height, 0.75 for half-height, 0 for none
HMT = head thickness, in inches
JKT = jacket/insulation identifier = 1 for jacketed, 0 for unjacketed
SHELF = shelf couplers identifier = 1 if equipped, 0 if unequipped
STS = shell thickness, in inches
α = top-fittings-protection style factor = -1.6991 for chlorine-car style, else -0.8354
PRESS = pressure car identifier = 1 if pressure car, 0 if non-pressure

The total conditional probability of release given a tank car is derailed in an FRA-reportable accident is calculated as follows:

$$P_{R|A} = 1 - [(1 - P_{R_H|A})(1 - P_{R_S|A})(1 - P_{R_T|A})(1 - P_{R_B|A})] \qquad (2.5)$$

Appendix B provides coefficients of correlation tables for these regressions and a summary of the procedures needed to calculate the standard errors and (1-α)100% confidence intervals.

2.3.2.2. Relationship between Tank Car Safety Designs, Capacity, and Number of Shipments

Changes in tank car safety design affect a tank car's volumetric capacity. This can potentially influence the overall risk because of the change in the number of shipments and consequently the total car-miles required to transport the same quantity of lading over the same distance.

Over the range of feasible tank car thicknesses, the relationship between reduction in tank car capacity and the number of shipments can be approximated by a linear function with a coefficient termed K in Barkan et al. (2007). K is an estimate of the proportional increase in the number of shipments required as tank capacity is reduced due to changes in design that affect its weight or maximum gross rail load. Consequently, K is unique for a car's product density, the GRL, and tank car light weight (Barkan et al. 2007).

In this Chapter, instead of using K to approximate the tradeoff between a design's performance and number of shipments, I directly compared the capacity of a baseline tank car with alternate-designs using the estimated weight and capacity from *IlliTank*. This approach provides greater precision and enhances the generality of the model. As a result, the accident exposure term, previously defined in (2.3), is modified as follows:

$$Z = P_A M S \qquad (2.6)$$

where:

S = shipment multiplier = Cap/Cap'

Cap = nominal volumetric capacity of a baseline tank car
Cap' = nominal volumetric capacity of an alternate-design tank car

With all elements in the release rate metric defined, the equation to evaluate a tank car with a specific safety design can be summarized as follows:

$$P_R = P_{R|A} P_A M Cap / Cap' \qquad (2.7)$$

Appendix C illustrates the calculations of the standard errors and (1-α)100% confidence intervals for P_R.

2.3.2.3. Tank Car Derailment Rate

Anderson and Barkan (2004) developed estimates of Class 1 railroad mainline freight train and car accident rates based on the FRA safety statistics. In the analyses described here I used their estimate of average railcar derailment rate per car-mile for P_A:

$$P_A = 1.28 \times 10^{-7} \text{ (s.e. } = 6.6327 \times 10^{-8}\text{).}$$

Risk estimates for other, more route- or track-specific operations can be developed using the approach described in Anderson and Barkan (2004).

2.3.2.4. Uncertainty

The statistically derived metric presented in this section is subject to error and some uncertainty, primarily in the accident rate, P_A, from Anderson and Barkan (2004) and the conditional probability of release from a tank car derailed in an accident $P_{R|A}$ (Treichel et al. 2006).

P_A equals the accident rate, and is calculated by dividing the total number of freight cars derailed by the total freight car miles operated between 1992 and 2001 (Anderson and Barkan 2004). Subsequent changes in capital investment in infrastructure, safety technologies, maintenance schedules, other safety initiatives or changes in freight traffic volume compared to the aforementioned period may introduce a bias in P_A.

For the $P_{R|A}$ estimation, the method is based on regression analyses in Treichel et al. (2006). Confidence intervals can be constructed around the estimates of $P_{R|A}$ and P_R as shown in Appendices B and C using estimated variances. Wider confidence interval indicates lesser precision in estimating the true value of $P_{R|A}$ or $P_{R.}$

2.4. BICRITERIA TANK CAR SAFETY DESIGN OPTIMIZATION

In this section, I formulate a multi-attribute decision problem in which I consider RROs that can reduce the likelihood of accident-caused releases from the principal release sources of tank cars involved in accidents (Treichel et al. 2006). The weight and capacity model presented in Section 2.1 is incorporated to estimate the relationship between changes in a tank car's light weight due to changes in its design. The conditional probability of release, $P_{R|A}$, in Section 2.2 is used to estimate tank car safety performance in an accident. Although P_R incorporates the change in weight and accident exposure implicitly, $P_{R|A}$ offers an objective metric to evaluate tank car safety performance with various changes in design, independent of the change in weight.

2.4.1. Tank Car Risk Reduction Options

The primary sources of release for a tank car involved in an accident are the tank head, tank shell, top fittings and bottom fittings (Fig. 2.1). The nature of damage to these components is distinct, and different approaches are used to enhance different components. There is a unique functional relationship between incremental safety benefit and weight for each approach and this must be accounted for when optimizing the safety performance of a tank car. The usual approach to enhance damage resistance to the tank head and shell is to increase the strength of these components and by using tank head protection, and/or application of a tank jacket. Additionally, the tank material properties may be improved by use of higher tensile strength and/or normalized steel. Enhancing damage resistance of the fittings includes enclosing top fittings in a protective housing (AAR 2007b), adding bottom fittings protection (Griger and Phillips 1992), and/or removing bottom fittings completely (Barkan et al. 1991, 2007).

The set of tank car safety design features or "risk reduction options" to enhance tank car safety design includes:

- Increasing tank head thickness (H)
- Increasing tank shell thickness (S)
- Adding an 11-gage (0.1196") steel jacket and insulation (JKT)
- Adding either half- or full-height head shields to the tank head (HHP or FHP)
- Adding top fittings protection for non-pressure tank cars (TFP)
- Using enhanced top fittings protection for pressure tank cars (E-TFP)
- Removing bottom fittings for non-pressure tank cars (BFR)
- Combinations of any of the above

The feasibility of each RRO depends on the baseline design of a tank car under consideration for improvement, and also the scope of the options specified by stakeholders interested in a specific risk analysis.

2.4.2. Identification of Pareto-Optimal Tank Car Safety Designs

To illustrate the bicriteria tank car safety design optimization model, a typical baseline general-purpose, non-insulated, non-pressure tank car was evaluated for enhancement. The car has a 20,000-gallon capacity, has 0.4375" head and shell thicknesses, is equipped with several top and bottom fittings and has a maximum gross rail load of 263,000 lbs.

Fig. 2.2 shows a decision tree framework illustrating possible combinations of RROs (for simplicity, only one branch is expanded at each decision node). For bottom fittings removal and jacket options, the choices are binary; "yes" or "no". For top fittings protection, three options are considered; none, typical i.e., similar to the designs currently in service, and enhanced i.e., any relatively new design that conforms to the latest amendment to the Hazardous Materials Regulations (74 FR 1769)[2]. For head shields, three options are considered; none, half- or full-height. The next two RROs, increasing tank head and shell thicknesses are considered independently and are represented by a two-dimensional matrix in which thickness of each is increased from the baseline thickness of 0.4375" to 1.5", in 0.0625-inch increments. Collectively, this figure represents a total of 11,664 (2 × 2 × 3 × 3 × 18 × 18) unique tank car safety designs.

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[2] The amendment requires top fittings protection to withstand a rollover accident at a speed of 9 miles per hour. An analysis of a new design developed by TrinityRail (authorized under U.S. DOT Special Permit 14167) found that the rollover velocity that caused top-fittings failure was 2.6 times higher for the enhanced-design fittings compared to the baseline chlorine car design for top-fittings protection. I assumed any enhanced design would reduce the probability of release from top fittings by 50%.

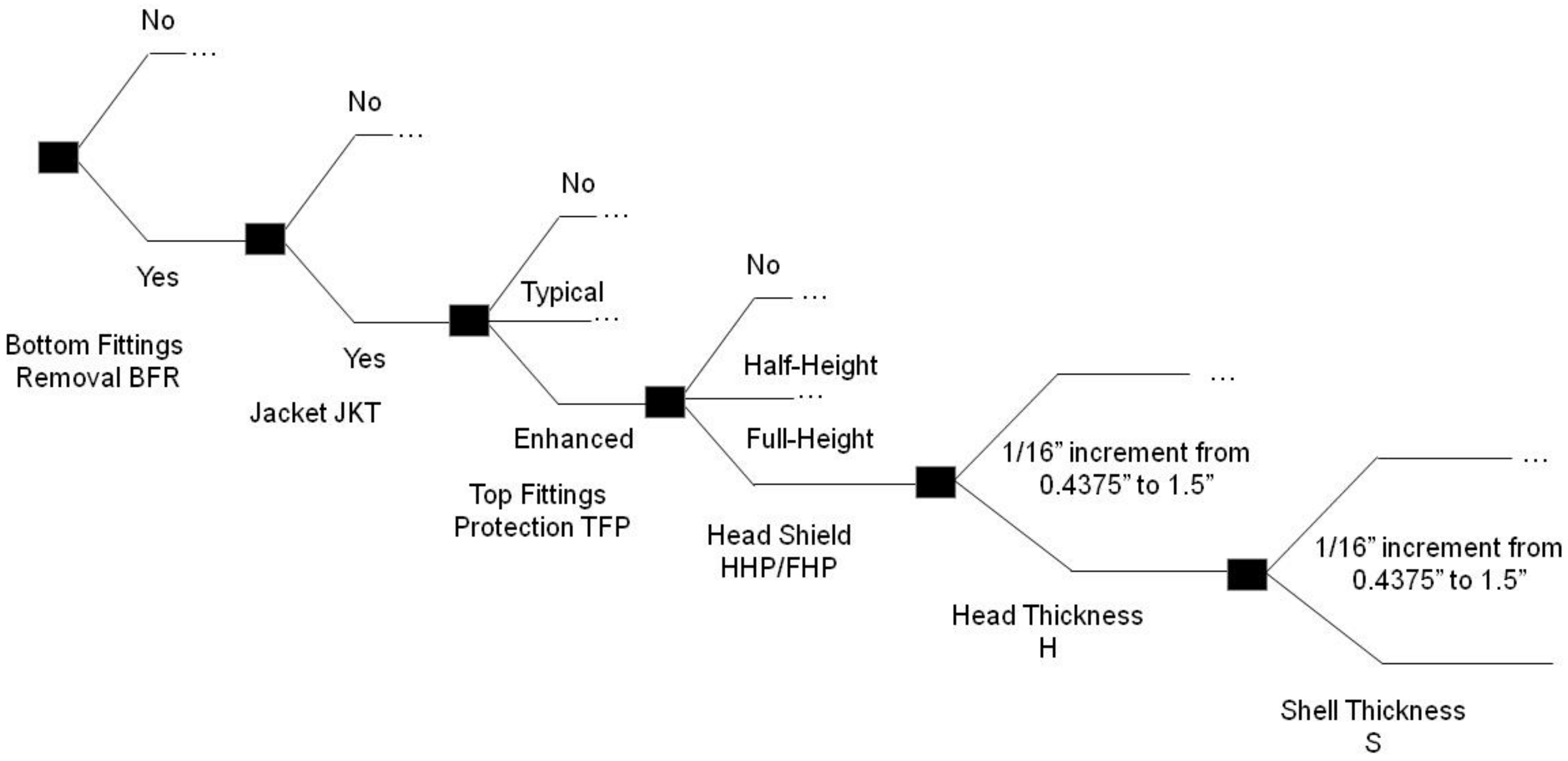

Fig. 2.2. Decision tree framework of possible RRO combinations

In general, implementing any RRO increases light weight, with the exception of bottom fittings removal, which slightly reduces the weight. Each RRO has its own characteristic relationship between changing light weight and conditional probability of release given a tank car is involved in an accident, $P_{R|A}$ (Fig. 2.3). The specific functional relationship is also affected by the particular baseline car. Employing each of the individual RROs gives different reductions in the conditional probability of release per unit weight (Fig. 2.4). Instead of considering implementation of each RRO independently, the generalized tank car safety design optimization model characterizes the weight and $P_{R|A}$ for all possible RRO combinations, and identifies a set of solutions that will provide the most efficient reduction in the $P_{R|A}$ with the increase in the light weight, similar to the approach presented in Barkan (2008).

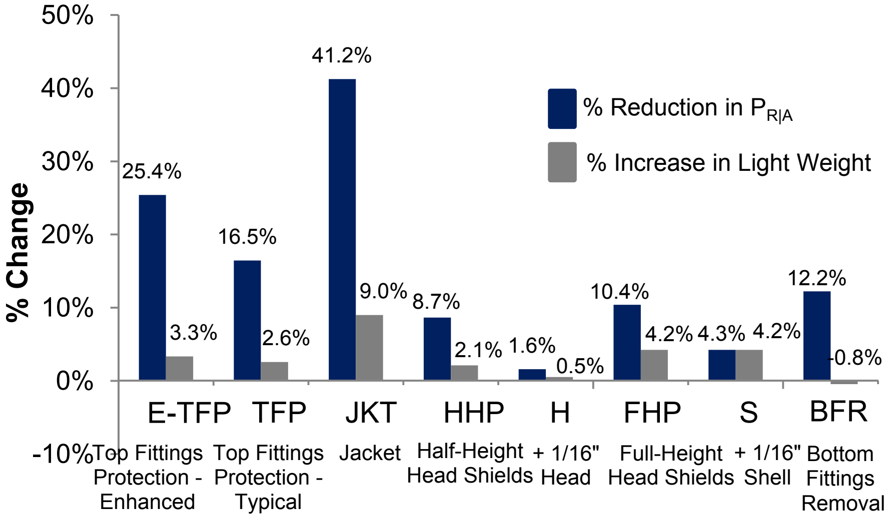

Fig. 2.3. The change in light weight and the $P_{R|A}$ for each RRO for a specific size of baseline general-purpose tank car

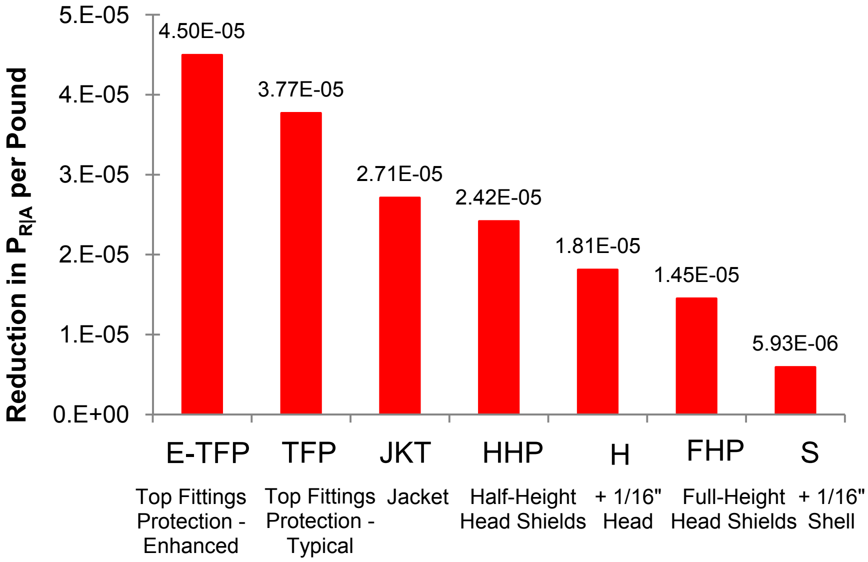

Fig. 2.4. Reduction in $P_{R|A}$ per unit weight for each RRO except bottom fittings removal (BFR) for a specific size of baseline general-purpose tank car

2.4.2.1. Light Weight and $P_{R|A}$ Enumerations

Let **RRO** be the set of all possible RRO combinations (Fig. 2.3). Each subset of **RRO** represents any combination of each of the RROs in Fig. 2.3 except increasing the head and shell thicknesses, $\mathbf{h_0}$ is the baseline head thickness, $\mathbf{h_1}$ is the first increment of the head thickness, $\mathbf{h_2}$ the second, and so on. Similarly, $\mathbf{s_0}$ is the baseline shell thickness, $\mathbf{s_1}$ is the first increment of shell thickness, and so on. For each pair-wise combination of head and shell thickness, the car light weight, **W**, and conditional probability of release, $\mathbf{P_{R|A}}$ were enumerated (Tables 2.2 and 2.3). $\mathbf{W_0}$ and $\mathbf{P_{R|A0}}$ are the baseline light weight and conditional probability of release, respectively. Percentage change in light weight, $\mathbf{\Delta W}$, for all solutions i were calculated as follows:

$$\mathbf{\Delta W}_i = 100 \times (\mathbf{W}_i - \mathbf{W_0}) / \mathbf{W_0}$$

Table 2. 2
Tank car light weight (W) enumeration for each RRO combination

	s_0	s_1	s_2	…
h_0	$W(h_0, s_0)$	$W(h_0, s_1)$	$W(h_0, s_2)$	…
h_1	$W(h_1, s_0)$	$W(h_1, s_1)$	$W(h_1, s_2)$	…
h_2	$W(h_2, s_0)$	$W(h_2, s_1)$	$W(h_2, s_2)$	…
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Table 2. 3
Tank car conditional probability of release ($P_{R|A}$) enumeration for each RRO combination

	s_0	s_1	s_2	…
h_0	$P_{R|A}(h_0, s_0)$	$P_{R|A}(h_0, s_1)$	$P_{R|A}(h_0, s_2)$	…
h_1	$P_{R|A}(h_1, s_0)$	$P_{R|A}(h_1, s_1)$	$P_{R|A}(h_1, s_2)$	…
h_2	$P_{R|A}(h_2, s_0)$	$P_{R|A}(h_2, s_1)$	$P_{R|A}(h_2, s_2)$	…
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2.4.2.2. Analytical Solutions

A set of Pareto-optimal or non-dominated solutions was determined from the enumerated $P_{R|A}$ and light weight. By definition, a feasible solution, $x* \in X$, is Pareto-optimal if there does not exist another point, $x \in X$, such that $F(x) \leq F(x*)$, and $F_i(x) < F_i(x*)$ for at least one objective function (Marler and Arora 2004). In other words, a feasible set of solutions is called Pareto optimal if there is no other feasible solution that would improve some objective function without causing a simultaneous decline in at least one other objective function.

The calculated $\mathbf{P_{R|A}}$ and $\mathbf{\Delta W}$ were used in a stepwise decision process to determine the Pareto-optimal (non-dominated) solutions. The decision criteria can be implemented using an updated algorithm originally from Barkan (2008):

1) Compute $\mathbf{W}$, $\mathbf{P_{R|A}}$ and $\mathbf{\Delta W}$ for all $\mathbf{RRO}_i$; set $i = 0$ (base case); initialize the set of Pareto-optimal solutions, $\mathbf{S} = \{\varnothing\}$
2) From $\mathbf{RRO}_i$**,** find **RRO** with the closest $\mathbf{\Delta W}$ and lower $\mathbf{P_{R|A}}$ than current $\mathbf{P_{R|A}}_i$
3) Insert solution $\mathbf{RRO}_{i+1}$ that has the minimum $\mathbf{P_{R|A}}$ among **RRO** identified in step 2 to the set of Pareto-optimal solutions, **S**
4) Repeat steps 2 and 3 until i =11,663 (total number of RRO combinations minus 1)

2.4.2.3. Graphical Solutions

Fig. 2.5 shows the decision space for a complete enumeration of percent change in light weight and the $P_{R|A}$ for all RRO combinations and the identified Pareto-optimal solutions for the baseline general-purpose tank car under consideration. From 11,664 enumerated solutions, 161 solutions were identified as Pareto-optimal. All non-dominated solutions correspond to designs with no bottom fittings (BFR). This strategy reduces the overall probability of release while offering a slight increase in capacity with reduced light weight. The predominant non-dominated solutions correspond to designs with no bottom fittings, equipped with enhanced top fittings protection, jacket and either the half-height or full-height head shields. These solutions are labeled in Fig. 2.6 as “H S BFR E-TFP JKT HHP” or “H S BFR E-TFP JKT FHP.”

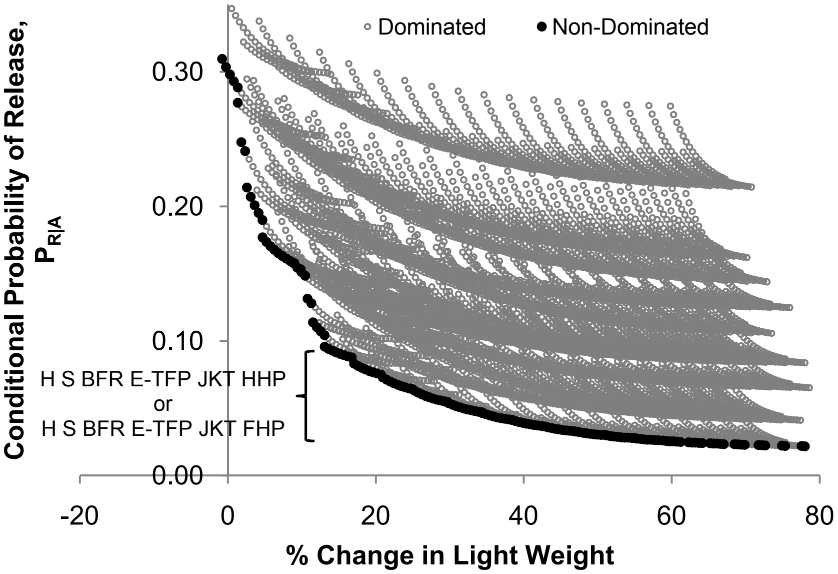


Fig. 2.5. Decision space for the $P_{R|A}$ vs. the light weight for all RRO combinations

Fig. 2.6 shows the initial set of non-dominated solutions. Figs. 2.6 a) and b) show different part of the same graph in Fig. 2.5. The BFR strategy was followed by the strategy with the least increase in the car's light weight while reducing the probability of release - increasing tank head thickness. This corresponds to the first five solutions in Fig. 2.6a. As the net weight of increasing the head thickness exceeded the net weight of adding half-height head shields, the latter RRO entered the Pareto-optimal set. The next-most efficient strategy was to use a typical top fittings protection followed by the use of enhanced top fittings protection (Fig. 2.6a). Strategies to increase shell thickness and adding a jacket enter the Pareto-optimal set in Fig. 2.6b.

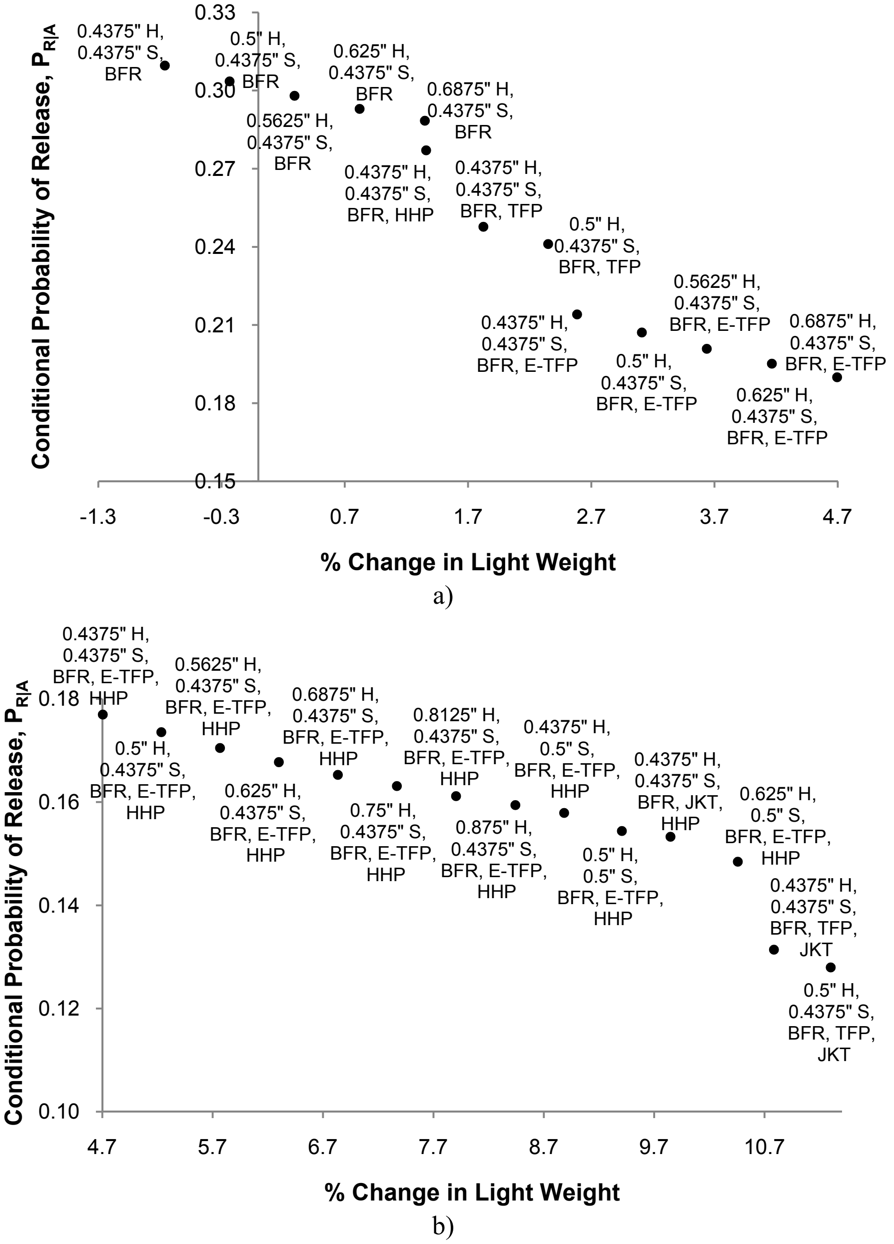


Fig. 2.6. Initial subset of non-dominated solutions for the baseline general-purpose tank car from a) -1.3 to 4.7, and b) 4.7 to 11 percentage change in light weight

2.4.2.4. Sensitivity Analysis of the Effect of Baseline Tank Car Size

The effect of tank car safety design enhancements on a car's light weight is affected by tank car size. I varied the capacity of the baseline tank car presented above from 20,000 gallons to 13,000 and 30,000 gallons to compare the Pareto-optimal sets. Both variations showed the same shape of dominated and non-dominated solutions as the 20,000-gallon baseline case (Figs. 2.7 and 2.8). Further observations on the initial subset of the Pareto-optimal solutions for both 13,000- and 30,000-gallon cases (Figs. 2.9 and 2.10) show that the sequence of each individual RRO entering the Pareto-optimal set was consistent with the 20,000-gallon baseline case.

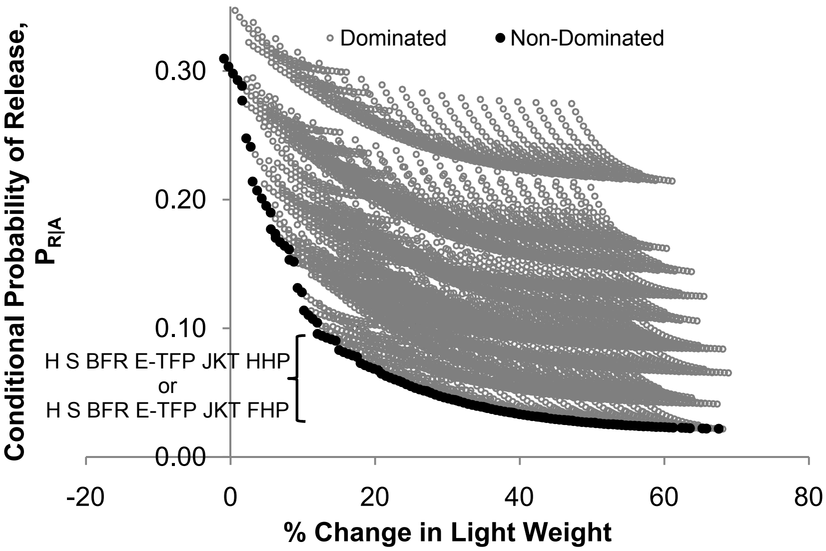


Fig. 2.7. Decision space for the $P_{R|A}$ vs. the light weight for all RRO combinations for the 13,000-gallon capacity general-purpose tank car

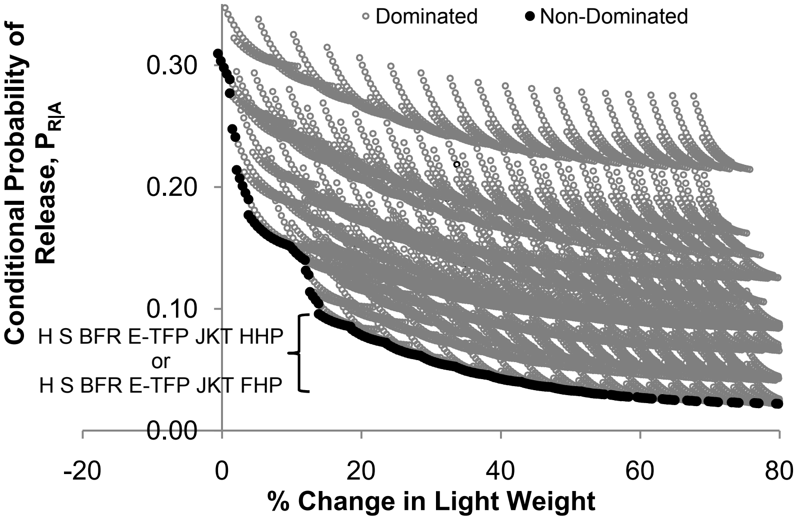
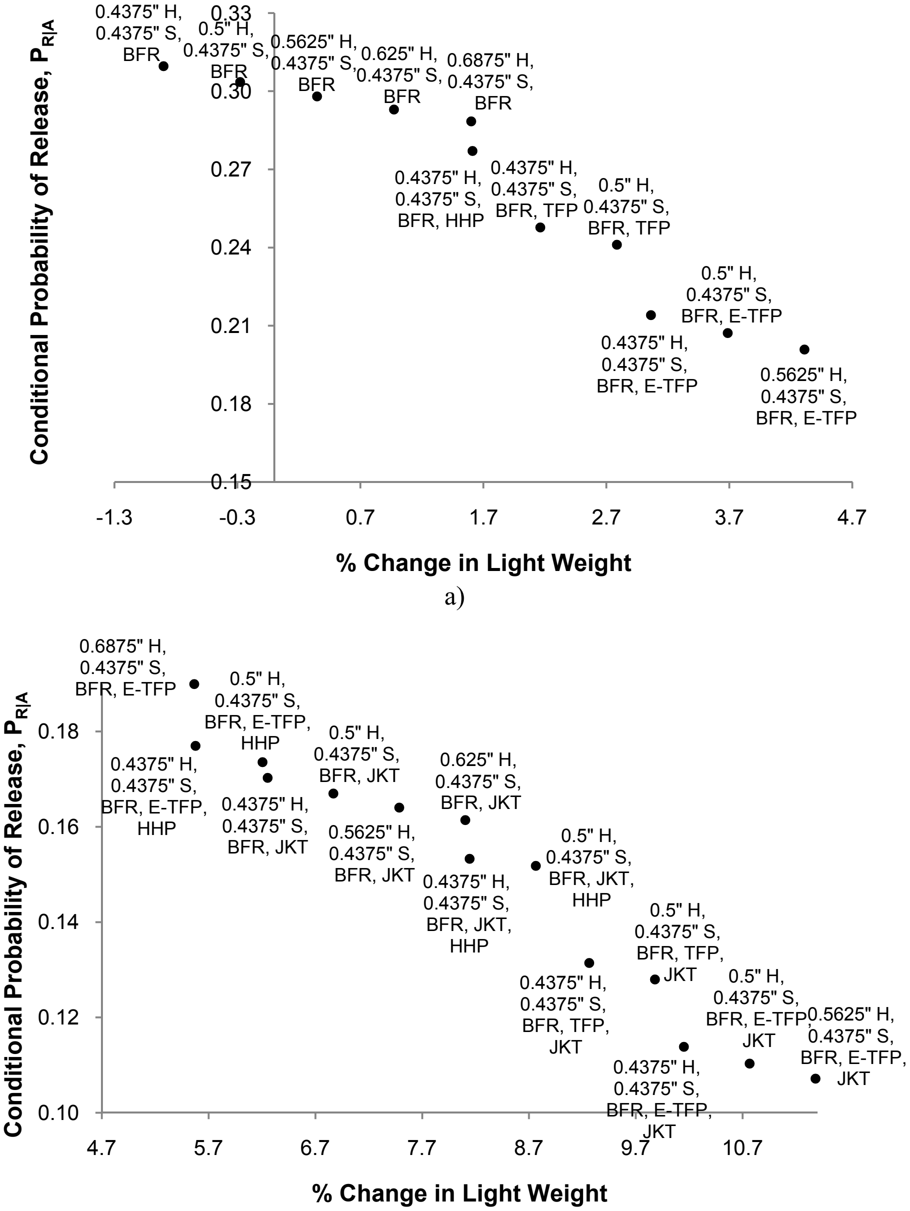


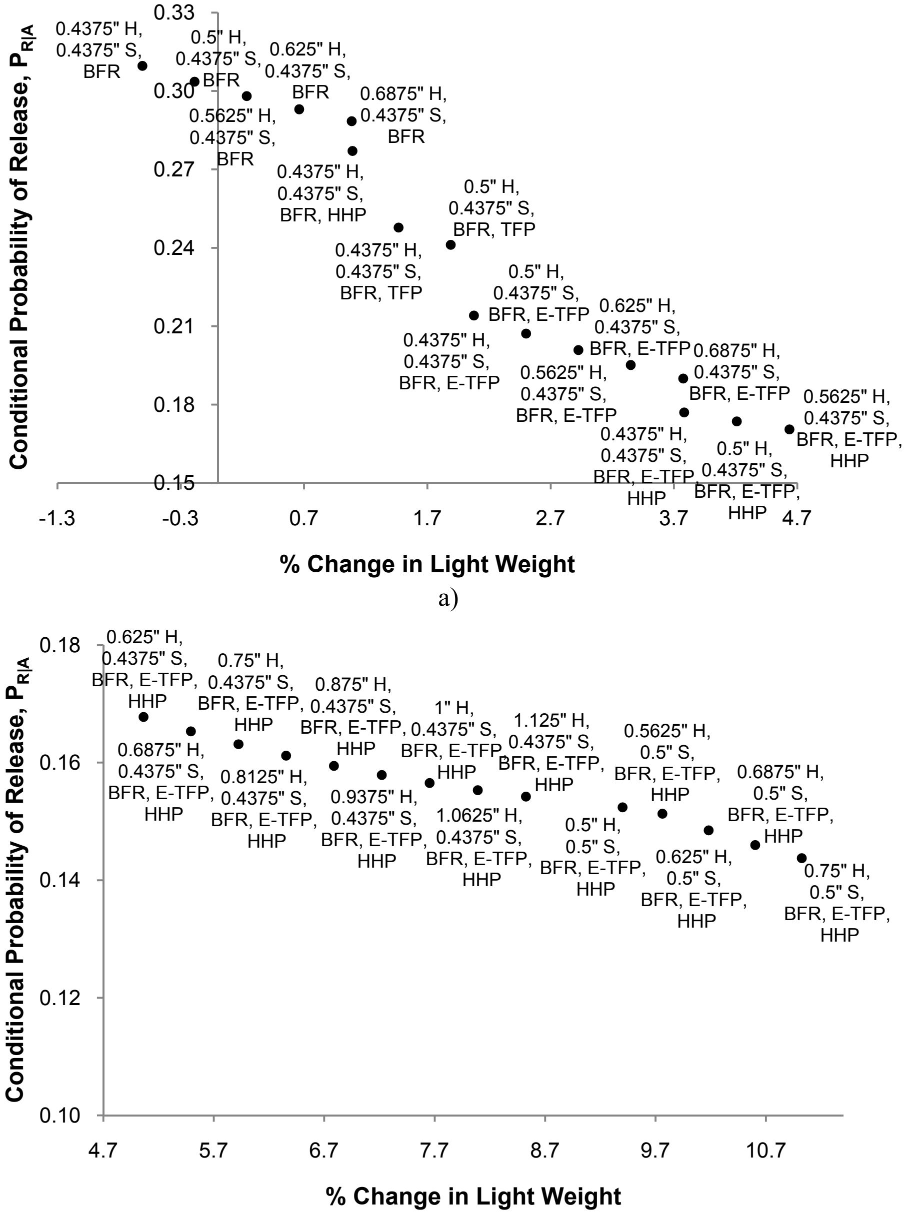
Fig. 2.8. Decision space for the $P_{R|A}$ vs. the light weight for all RRO combinations for the 30,000-gallon capacity general-purpose tank car



a)

b)

Fig. 2.9. Initial subset of the non-dominated solutions for the 13,000-gallon capacity general-purpose tank car from a) -1.3 to 4.7, and b) 4.7 to 11 percent change in light weight



a)

b)

Fig. 2.10. Initial subset of the non-dominated solutions for the 30,000-gallon capacity general-purpose tank car from a) -1.3 to 4.7, and b) 4.7 to 11 percent change in light weight

2.4.2.5. Sensitivity Analysis of the Effect of Higher Gross Rail Load (GRL)

I varied the GRL of the 20,000-gallon baseline tank car presented above from 263,000 to 286,000 lbs to compare the Pareto-optimal sets. The shape of dominated and non-dominated solutions, and the sequence of each individual RRO entering the Pareto-optimal set were consistent with the 263,000-lb GRL case (Fig. 2.11 and Fig. 2.12.)

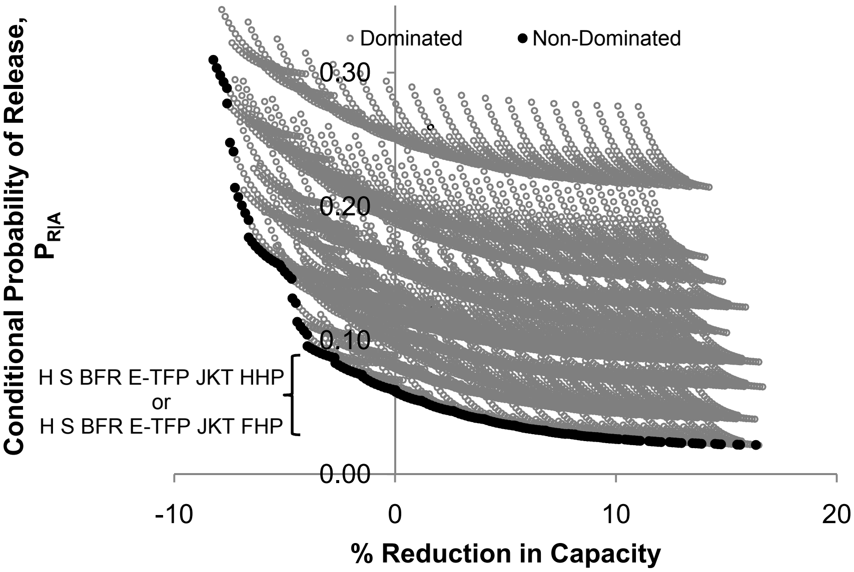
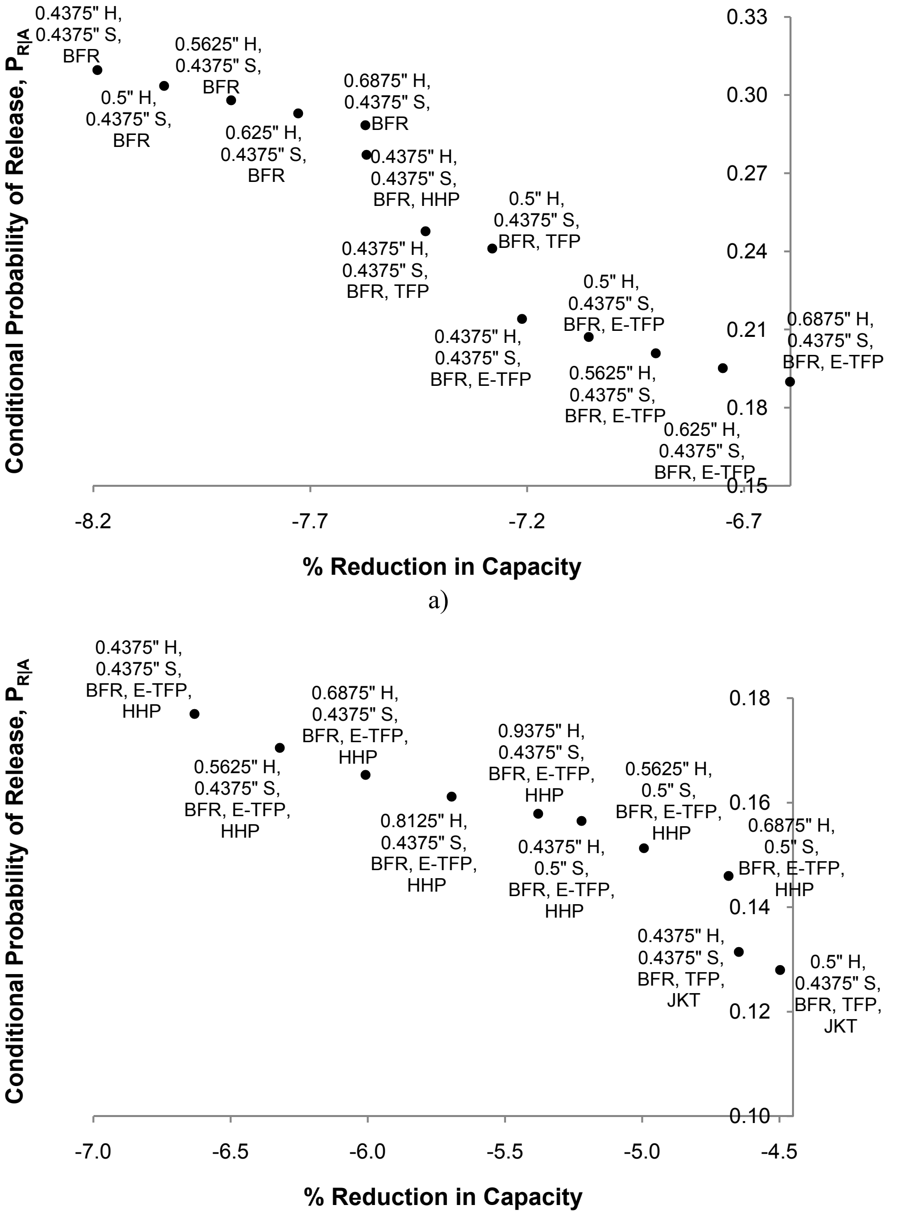


Fig. 2.11. Decision space for the $P_{R|A}$ vs. percent reduction in capacity for all RRO combinations for 286,000-lb GRL



a)

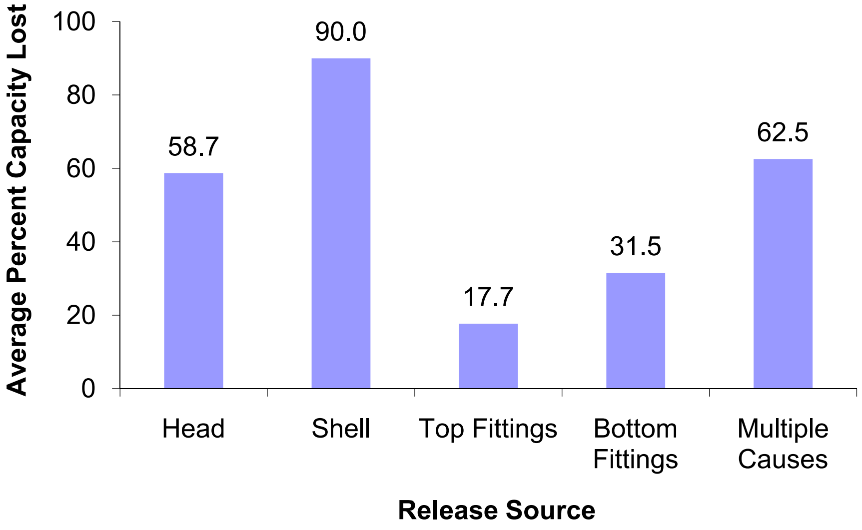
b)

Fig. 2.12. Initial subset of non-dominated solutions for 286,000-lb GRL from a) -8.2 to -7, and b) -7 to -4.5 percent change in light weight

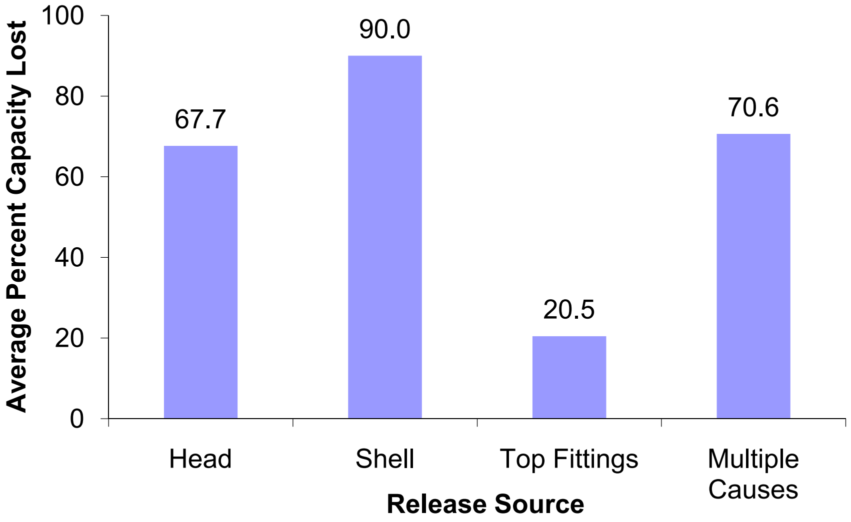
2.4.2.6. Conditional Probability of Release versus Expected Quantity of Lost

The Pareto-optimal set identification was presented in the context of the conditional probability of release given that a tank car is derailed in an accident. Also of interest is the fact that damage to different parts of tank cars results in different average quantity lost. Fig.

2.13 shows the mutually-exclusive, average percentage of tank capacity lost from each release source for two typical tank car configurations: non-insulated non-pressure cars, and insulated pressure tank cars (Treichel et al. 2006) (Note that pressure tank cars are rarely equipped with bottom fittings. So that source of loss is not included in Fig. 2.13b).



a)



b)

Fig. 2.13. Average percent tank capacity lost distribution for a) non-insulated non-pressure tank cars, b) insulated pressure tank cars

A larger release will generally result in a larger exposure area and greater impact on people, property and the environment, and incur higher costs. Therefore, when evaluating the benefit of applying various risk reduction options to tank cars, it may also be beneficial to consider the amount lost from different parts of the car. Saat and Barkan (2005) develop the concept of release risk, which is essentially the expected quantity lost from a tank car involved in an accident. In this section, I considered the tradeoff between the expected quantity lost, given a tank car is derailed in an accident (Eqn. 2.9), and weight. I identified the Pareto-optimal set for the 20,000-gallon baseline tank car in the same manner as for the conditional release probability versus weight.

$$\mathrm{E}_{\mathrm{Gal}_\mathrm{R}} = \mathrm{Cap} \ \textstyle\sum_{\mathrm{i}}\left(\overline{\mathrm{P}}_{\mathrm{R_i|A}} \times \mathrm{Q_i}\right) \qquad (2.9)$$

where:

$\mathrm{E}_{\mathrm{Gal}_\mathrm{R}}$= expected volumetric capacity lost given a tank car is derailed in an accident

Cap = tank car volumetric capacity

$\overline{\mathrm{P}}_{\mathrm{R_i|A}}$ = mutually-exclusive and collectively-exhaustive conditional probability of release from source i given a tank car is derailed in an accident

Q_i = average percent tank capacity lost from source i

i = tank head (H), tank shell (S), top fittings (T), bottom fittings (B) and multiple causes (M)

Each RRO has its own characteristic relationship between changing light weight and the expected quantity lost given a tank car is involved in an accident (Fig. 2.14). Employing each of the individual RROs gives different reductions in the expected quantity lost per unit weight (Fig. 2.15).

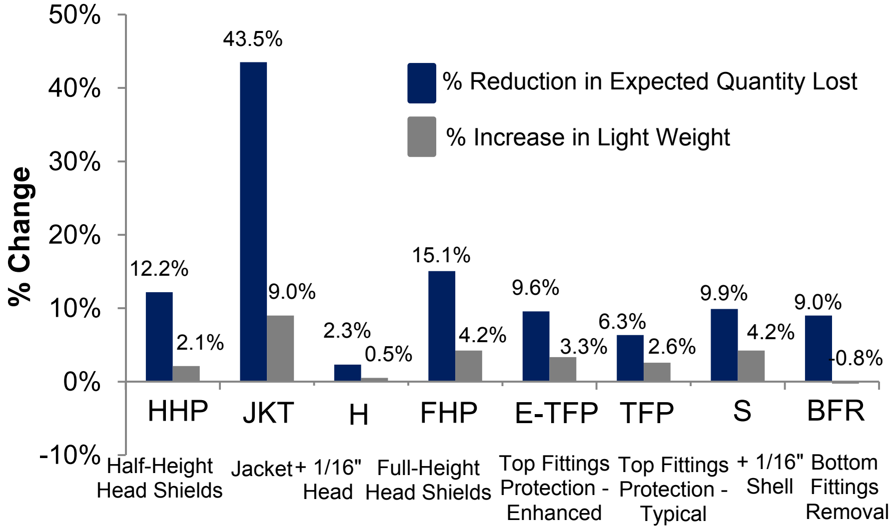


Fig. 2.14. The change in light weight and the expected quantity lost for each RRO for a specific size of baseline general-purpose tank car

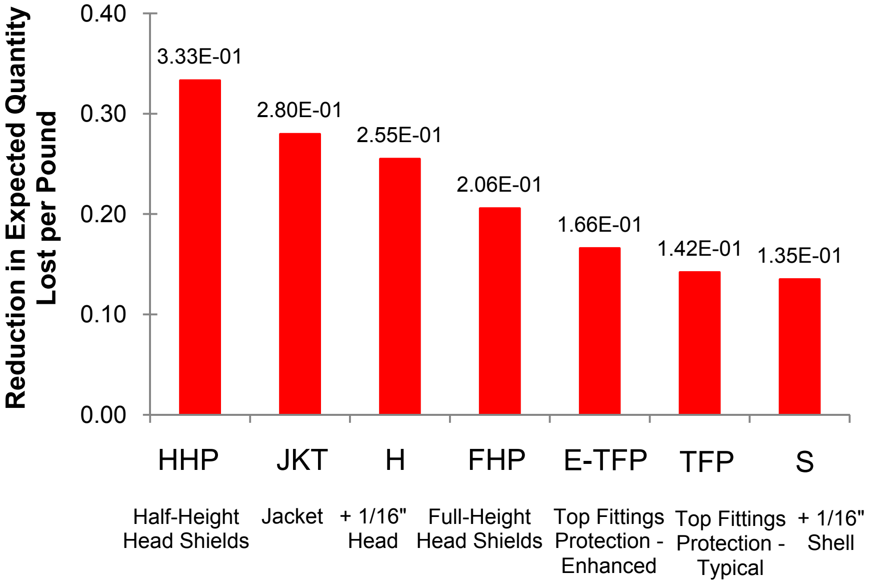


Fig. 2.15. Reduction in the expected quantity lost per unit weight for each RRO except bottom fittings removal (BFR) for the baseline general-purpose tank car

Comparisons of Figs. 2.4 and 2.15 show that when the expected quantity lost is considered, the RRO top fittings protection changes from among the most efficient, in terms of reducing the probability of release per pound, to among the least efficient in reducing the expected quantity lost per pound. This is because release quantity from top fittings averages much less than from the tank head or shell (Fig. 2.13).

When all the individual RROs are considered simultaneously, the results are generally similar to when the probability of release was considered. Fig. 2.16 shows the decision space with complete enumeration of the expected quantity lost and weight for the baseline 20,000-gallon tank car. The predominant non-dominated solutions correspond to designs with no bottom fittings, equipped with enhanced top fittings protection, jacket and either half-height or full-height head shields. In addition, the sequence of each individual RRO entering the Pareto-optimal set was consistent with the case when the probability of release versus weight was considered (Fig. 2.17). However, the specific non-dominated solution at a certain level of weight increase is different. This is due to the different efficiencies in RRO-specific reduction of conditional probability of release compared to expected quantity of release (Figs. 2.4 and 2.15).

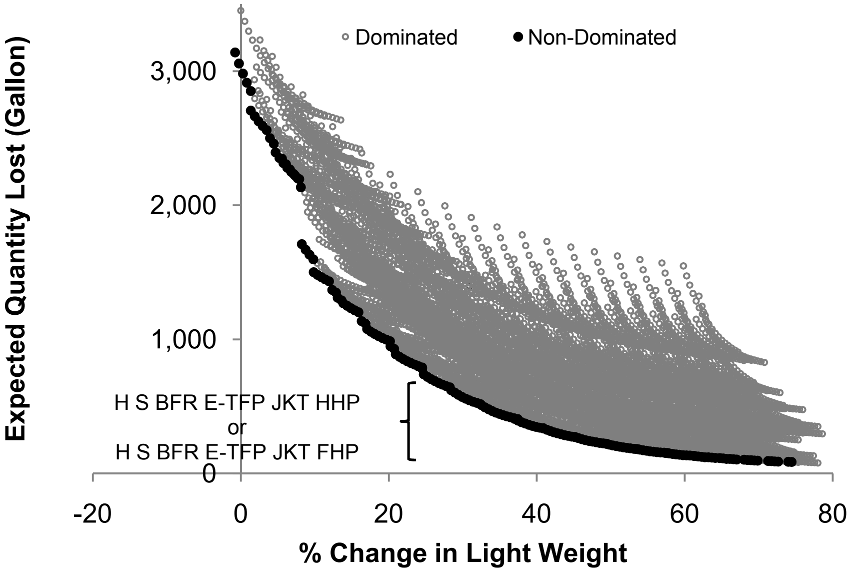
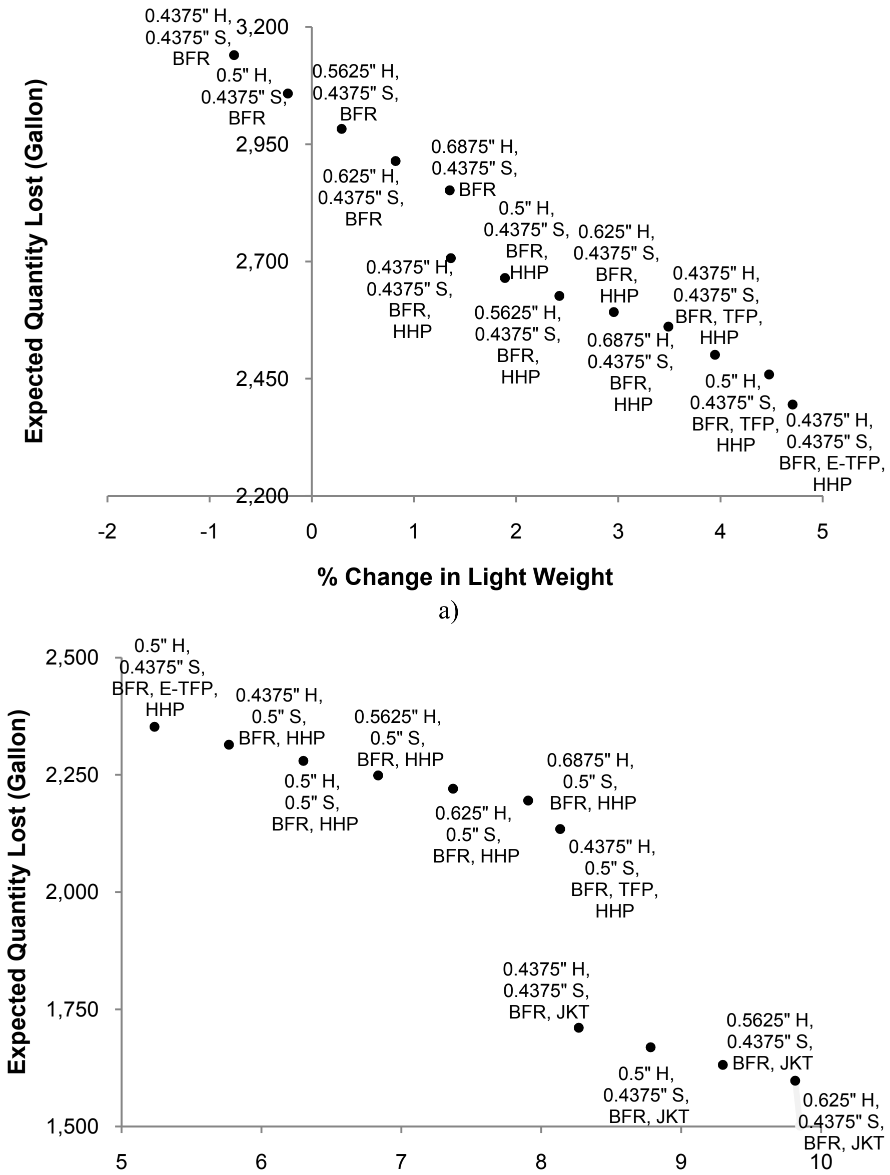


Fig. 2.16. Decision space for the expected quantity lost vs. the light weight for all RRO combinations for the baseline 20,000-gallon capacity general-purpose tank car



a)

b)

Fig. 2.17. Initial subset of non-dominated solutions for the baseline general-purpose tank car (expected quantity lost) from a) -2 to 5, and b) 5 to 10 percent change in light weight

2.5. DISCUSSION

2.5.1. Implications for Current Packaging Practices

Tank car safety design has evolved and improved based on over 100 years of industry operating and engineering experience (Heller 1970; Dalrymple 1997; Barkan 2008). The

U.S. Department of Transportation (DOT) and Transport Canada regulate transportation of materials that are flammable, corrosive, poisonous, or pose environmental or other hazards in North America. All regulated materials are not equally hazardous and tank car safety specifications and packaging requirements are intended to be commensurate with the degree of risk posed by the product (Barkan et al. 1991; CFR 2009). The model presented here provides general insight on the relative impact of various changes in tank car safety design. Furthermore it allows considerably better precision in understanding the tradeoffs involved in improving tank car design and provides a basis for quantitative evaluation of optimal, commodity-specific tank car designs. In the following sections I will discuss several potential applications of the model.

2.5.1.1. Bottom Fittings

Bottom fittings removal is an unusual example of an option that reduces both weight and release probability. This causes it to be included in the optimal set of solutions. However, it requires significant investment to retrofit terminals and tank cars for unloading from top fittings (Barkan et al. 1991). These costs are external to the tank car itself so additional benefit-cost analysis would be necessary to determine circumstances when bottom-fittings removal is cost-effective. The model developed here can be used to identify the Pareto-optimal set of tank car designs, both with and without bottom-fitting removal as an option, thereby facilitating such an analysis.

2.5.1.2. Higher Gross Rail Load Tank Cars

This model can be used to consider tank car designs with a GRL higher than the normal DOT maximum of 263,000 lbs. Construction of such cars offers the opportunity to increase tank car capacity and efficiency while at the same time using some of the extra allowable weight to enhance the safety design of these cars. This provides an incentive to use safer tank cars without incurring a weight penalty. Barkan (2008) developed a specific version of the model described here and applied that to a particular type of car. This was used in an analysis for the AAR Tank Car Committee to help it establish the safety design requirements for cars exceeding this limit. The model presented here enables a finer grained, comprehensive approach to addressing related questions for the design requirements for such cars that encompasses all feasible combinations.

2.5.1.3. Tank Cars for Toxic Inhalation Hazard Materials

In the wake of several fatal tank car accidents involving the release of toxic inhalation hazard (TIH) materials, the AAR initiated development of new requirements for tank cars transporting these products (AAR 2008). I used a variation of the model described here to identify the most effective designs for such cars. More recently the U.S. Department of Transportation issued an interim final rule (74 FR 1769) with requirements for TIH tank cars based on the AAR's earlier proposal. Both the AAR and the DOT rules give tank car builders flexibility in complying with the requirements. The model presented here can be used for this purpose to help tank car designers achieve the specified safety performance objectives in the most efficient manner possible. In particular, the model can be used to evaluate the best combination of parameters for tank head and shell thicknesses, full-height head shields and enhanced top fittings protection for tank cars transporting TIH materials.

2.5.1.4. Implications for New Tank Car Design Concepts

The same incidents that motivated the development of new standards for TIH tank cars also inspired research and development investigating new tank car safety design concepts. This work is intended to identify designs with considerably better safety performance to weight ratios than are possible using conventional steel tank car designs. In addition to consideration of new and stronger steels, this research is also developing and evaluating new composite materials and corrugated metal structures that are intended to absorb the energy of an object impacting a tank car before it penetrates the tank itself (Ward et al. 2007; Tyrell et al. 2007a, b; Kirkpatrick 2009; Jeong et al. 2009). New valve designs are also being evaluated that will substantially reduce the likelihood of release in an accident (Midland Manufacturing 2009). One of the challenges associated with this work is that in the absence of statistical estimates of the performance of these designs in a variety of accident scenarios, it is difficult to quantify their performance as accurately as can be done for more conventional designs for which there is an abundance of statistical data. Nevertheless, if accident performance and weight data can be developed for these new design concepts, the generalized tank car optimization model described in this Chapter can be used to consider them and help identify the optimal combination of design features.

2.5.1.5. Incorporating Expected Quantity Lost

Releases from the head and shell have much higher average percentage losses compared to those from top and bottom fittings. One reason for this disparity is that in accidents in which fittings develop a leak, it may often be small and stopped relatively quickly by response personnel. Conversely, a hole in the tank head or shell is often the result of impact damage from a rail or another railcar that punctures or tears open the tank. These may be more likely to be large and difficult to plug before a large portion of the tank's contents have been lost.

The use of the expected quantity lost metric offers a useful means to consider the explicit benefit in terms of reduction in the component-specific release quantity with enhancement in each tank car release source - the head, shell, top and bottom fittings. Since quantity lost is an important contributor of the level of risk in a hazardous material release accident, it is worthwhile to consider whether use of release risk as the objective function affects the optimal solution, compared to use of conditional probability of release.

The results in Section 2.3.2.6 show that the resultant set of Pareto-optimal design solutions is similar in terms of the members of the set, but different in terms of the level of specific percentage change in light weight when each member is entering the set. As such, the use of the conditional probability of release or the expected quantity lost may result in different optimal solutions when certain criteria or weight constraints are considered. The use of the conditional probability of release offers a simpler and more concise metric in evaluating the improvement in the likelihood of release from a tank car with the use of different RROs. The expected quantity lost, on the other hand, offers a more detailed and explicit consideration of risk in evaluating the tradeoff between safety and transport efficiency. Expected quantity lost is the metric used in Chapter 4 in conjunction with chemical-specific hazard to develop a risk-based tank car safety design optimization model.

2.5.2. Incorporating Chemical-Specific Hazard in Optimizing Tank Car Safety Design

Hazardous material risk is also affected by the physicochemical properties of the product involved in a release incident and its interaction with various characteristics of the environment in which it is released. As discussed above tank car safety design is intended to be commensurate with risk, but no formal optimization method has previously been applied to the process of matching safety design features with product hazard. Historically, the nominal burst pressure of the tank has been used as a proxy variable for tank car damage resistance (TRB 1994). Higher pressure tanks require a thicker shell and head, but for most products the higher pressure rating was determined by the physical properties of the material being transported instead of its hazard characteristic.

Controlling tank thickness using the nominal burst pressure rating in the DOT tank specification is consistent with the general objective of matching hazard to tank car damage resistance; however, it is inexact because other factors affecting tank thickness are not considered. A more direct means would be to determine the level of damage resistance desired for a particular hazardous material, and engineer the car to achieve this level of performance. The model here enables comprehensive evaluation of all elements of tank car design that affect safety performance. It facilitates rational consideration and selection of the design combination that maximizes safety for any level of weight or cost increase. Furthermore, if additional information is available that allows quantification of the cost of tank car fleet replacement with enhanced-design cars, and the value of the associated benefit, designs can be optimized on a product specific level.

2.5.3. Implications for Other Strategies to Reduce Risk

In the larger context of hazardous materials transportation safety and risk, tank car design is just one of several important factors. Others that can be evaluated and potentially modified to affect risk are accident likelihood and severity, operational practices and routing. There are a variety of changes in practices that may offer opportunities to reduce risk (Kawprasert and Barkan 2008, 2009). A major challenge is to understand the inter-relationships among different factors, that is, how changes in one affect another (Saat and Barkan 2006). Additionally, the cost-effectiveness of addressing these different factors will vary, relative to the others at both a system and scenario-specific level.

Ultimately all of these strategies and inter-related factors must be considered to determine the optimal approach to risk reduction; however, development of such a comprehensive approach is a major undertaking. The model presented here is the first step in such an analysis. By isolating the number of possible tank car designs to those that represent the most efficient combination of safety performance and weight, the problem of selecting among them is simplified. The generalized tank car optimization model presented here offers the first phase in a three-level hierarchical process to most efficiently reduce the risk of rail transport of hazardous materials. The second phase involves incorporating chemical-specific hazard level to determine the optimal level of protection for different materials. The third phase will involve risk-based tank car safety design combined with simultaneous consideration of other strategies to reduce risk. This model enables local identification of the optimal solution regarding tank car safety design that can ultimately be incorporated into a global optimization model to reduce overall hazardous materials transportation risk.

2.6. CONCLUSIONS

In this Chapter, I develop a generalized tank car safety design optimization model that consists of two sub-models, tank car weight and safety performance. This model enables quantitative evaluation of nearly all of the tank car safety design enhancement options currently in use by North American tank car manufacturers. Each option is systematically considered alone, and in combination with every other feasible option to calculate the effect on tank car weight and on the probability of release in an accident. The model thus permits estimation of the effect on transport efficiency and risk. For most options there is a tradeoff between these two parameters so the problem is developed as a bi-criteria, multi-attribute model. The model provides a methodology to identify a set of Pareto-optimal solutions to compare enhanced tank car safety designs to any specific baseline design.

The model presented in this Chapter is intended to provide guidance in identifying the Pareto optimal set of tank car safety designs for general-purpose non-pressure tank cars and can also be applied to decisions regarding pressure specification cars. Different options offer different efficiencies for safety improvement, but I found that designs with no bottom fittings, enhanced top fittings protection, a jacket and either half-height or full-height head shields represented the majority of the solutions identified in the optimal set. This was the case when minimization of either probability of release or expected quantity lost was used as the objective function in the optimization model, indicating the robustness of the result.

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CHAPTER 3

RISK ANALYSIS OF TOXIC INHALATION HAZARD (TIH) MATERIALS' TRANSPORTATION ON U.S. RAILROAD MAINLINES

3.1. INTRODUCTION

Chemical production and use in manufacturing are crucial for industrial society. While people derive significant benefits from chemical use, there are also certain associated safety and economic risks that must be managed and to the extent feasible, minimized. In the event of train accidents, releases of hazardous chemicals may pose substantial risk to human health, property or the environment (Dennis 2002). In North America, rail offers the safest and generally the most economical means of transporting many of these materials. Since 1982, the rate of railroad accident-caused releases has been reduced by about 93% (Barkan et al. 2000; BOE 2009) due to effective prevention of accidents, and prevention of spills from railcars involved in accidents (Harvey et al. 1987; Barkan et al. 1991; Gallamore 1999; Dennis 2002; Barkan 2008; BOE 2009).

In spite of continuous improvements in railroad safety, there were several accidents in the early to mid 2000s that resulted in fatalities due to releases of TIH materials. These placed industry and government under scrutiny to further reduce the risk associated with rail transport of these materials (NTSB 2004, 2005, 2006). In addition to ongoing infrastructure and train control improvement efforts to reduce the likelihood of accidents, the railroad industry via its standard setting organization, the Association of American Railroads (AAR), initiated development of new, safer tank car design specifications for transportation of TIH materials in 2006 (AAR 2008a). The objective was to develop new tank car standards that would reduce the likelihood of a release if a tank car was involved in an accident. However, a critical question facing the industry was what combination of enhancements to TIH tank car design would most effectively improve their safety?

The first part of this Chapter presents the results of an optimization analysis in which I use the technique described in Chapter 2 to identify the most efficient combination of design enhancements to improve TIH tank car safety design. The second part of this Chapter presents a risk analysis that was conducted to estimate the potential reduction in risk through use of safer tank cars. The results of the risk analysis are illustrated by comparing the risk associated with the baseline tank car designs currently used for transportation of TIH materials, with the new, enhanced specifications adopted by the AAR.

Quantitative risk analysis of hazardous materials transportation in the U.S. dates back to as early as 1971 when the National Transportation Surface Board (NTSB) proposed the need for a risk-based approach in developing hazardous material transportation safety regulations (NTSB 1971). In the late 1970s, Ang et al. (1979) introduced a general framework for transportation risk analysis that includes identifying probabilities, level of exposure and consequences from an undesirable event. Philipson and Napadensky (1982) provided an overview of the general risk assessment problem, presented a structured review of the four general types of risk estimation methodologies involving statistical inference, fault tree modeling, analytical or simulation modeling and expert knowledge assessment, and reviewed the procedures available for risk evaluation and mitigation. Early attention was focused on rerouting as a means of managing hazardous materials transport risk. Glickman (1983) developed a model for network level analysis of rerouting traffic and Abkowitz et al. (1989) were among the first to use Geographic Information Systems (GIS) to address risk and routing questions. List et al. (1991) presented a comprehensive, survey of early research on hazardous materials transportation risk analysis.

Due to their substantial potential consequences, there has been particular interest in toxic inhalation hazard (TIH) materials, especially chlorine and ammonia because of the large volumes transported and several fatal accidents in the 1970s (NTSB 1978a, 1978b). Brockhoff et al. (1992) developed a simple consequence model for chlorine and ammonia releases based on a fatality index approach. Others introduced more detailed models to estimate the transportation risks of chlorine and other hazardous materials (Purdy et al. 1988; Purdy 1993; Saccomanno and Shortreed 1993).

Tank car safety design has also been studied in the context of risk analysis. Barkan et al. (1991) conducted a risk analysis of a group of chemicals with the potential to cause substantial soil and groundwater cleanup expense and calculated the costs and benefits of using more damage-resistant cars. Dennis (1996) extended their work by using cost data from U.S. Class 1 railroads to estimate the risk costs per unit of exposure due to hazardous materials transportation. Saat and Barkan (2005) developed a release risk approach to estimate the expected quantity released from different tank car designs if they were involved in an accident.

Hwang et al. (2001) presented a quantitative risk analysis of transporting TIH materials on highways and railroads. However accident rates and conditional release probabilities were combined into a single, composite incident probability, so their risk assessment method could not be adapted to assess the effects of changes in railroad operating practices or packaging.

In this Chapter, I adapted elements of each of these to conduct a nation-wide estimate of the risk of transporting a group of TIH materials by rail (Table 1). I used a new method described in Chapter 2 to identify the most efficient approach to enhance the safety design of tank cars and thereby reduce the risk. I used tank car derailment rate from Anderson and Barkan (2004) and a statistical model developed by Treichel et al. (2006) to estimate the conditional probability of release from a tank car involved in an accident. These probability estimates were combined with a hazard consequence model and a spatial analysis of the chemical-specific rail routes using geographic information system (GIS) data and software to estimate population exposure along the routes.

Table 3.1
TIH materials shipped by railroad tank car in 2007[3].

Commodity Name	Hazardous Material Code	UN Number	U.S. Annual Tank Car Shipments
Chlorine	4920523	UN1017	31,324
Ammonia, Anhydrous	4904210 4920359	UN1005	29,336
Ethylene Oxide	4920353	UN1040	7,512
Hydrogen Fluoride	4930024	UN1052	3,062
Methyl Mercaptan	4920355	UN1064	1,182
Sulfuric Acid, Fuming	4930030	UN1831	874
Acetone Cyanohydrin	4921401	UN1541	828
Hydrogen Chloride	4920504	UN2186	599
Sulfur Trioxide	4930050	UN1829	493
Sulfur Dioxide	4920508	UN1079	492
Titanium Tetrachloride	4932385	UN1838	438
Phosphorus Trichloride	4921016	UN1809	227
Chlorosulfonic Acid	4930204	UN1754	223
Methyl Bromide	4920518	UN1062	162
Dimethyl Sulfate	4921405	UN1595	128
Hydrogen Cyanide	4927014	UN1051	85
Bromine	4936110	UN1744	80
Allyl Alcohol	4921019	UN1098	70
Hexachlorocyclopentadiene	4921722	UN2646	27
Ethyl Chloroformate	4921020	UN1182	20

3.2. OVERVIEW OF RISK ANALYSIS FRAMEWORK

Risk in general can be defined as the product of the probability and the consequences of an event. In the context of railroad hazardous materials transportation, a simplified definition of risk is as follows:

$$R=P_R\times P_C\times C \qquad (3.1)$$

where:

R = risk of transporting a hazardous material
P_R = accident-caused release rate
P_C = probability of a particular release scenario occurring
C = consequence level

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[3] The list of TIH chemicals under consideration and the number of annual U.S. shipments in tank cars were determined by crosschecking the list of TIH chemicals in the AAR's Circular OT-55-I (AAR 2006) with waybill shipment data from the AAR's railcar movement database, TRAIN II, for the year 2007 (TRAIN II 2008).

The decision analysis framework to evaluate approaches to reducing hazardous materials transportation risk can be summarized using a decision diagram (Fig. 3.1). This diagram provides an overview of the principal inputs affecting risk calculation, and the relationships between them (Howard 1968, 2007). The rectangles represent three options or decision variables that affect risk. This Chapter focused on the “Car Design” variable. Oval nodes in the diagram represent specific uncertainty events while double oval nodes correspond to deterministic or functional values for each step in the risk analysis.

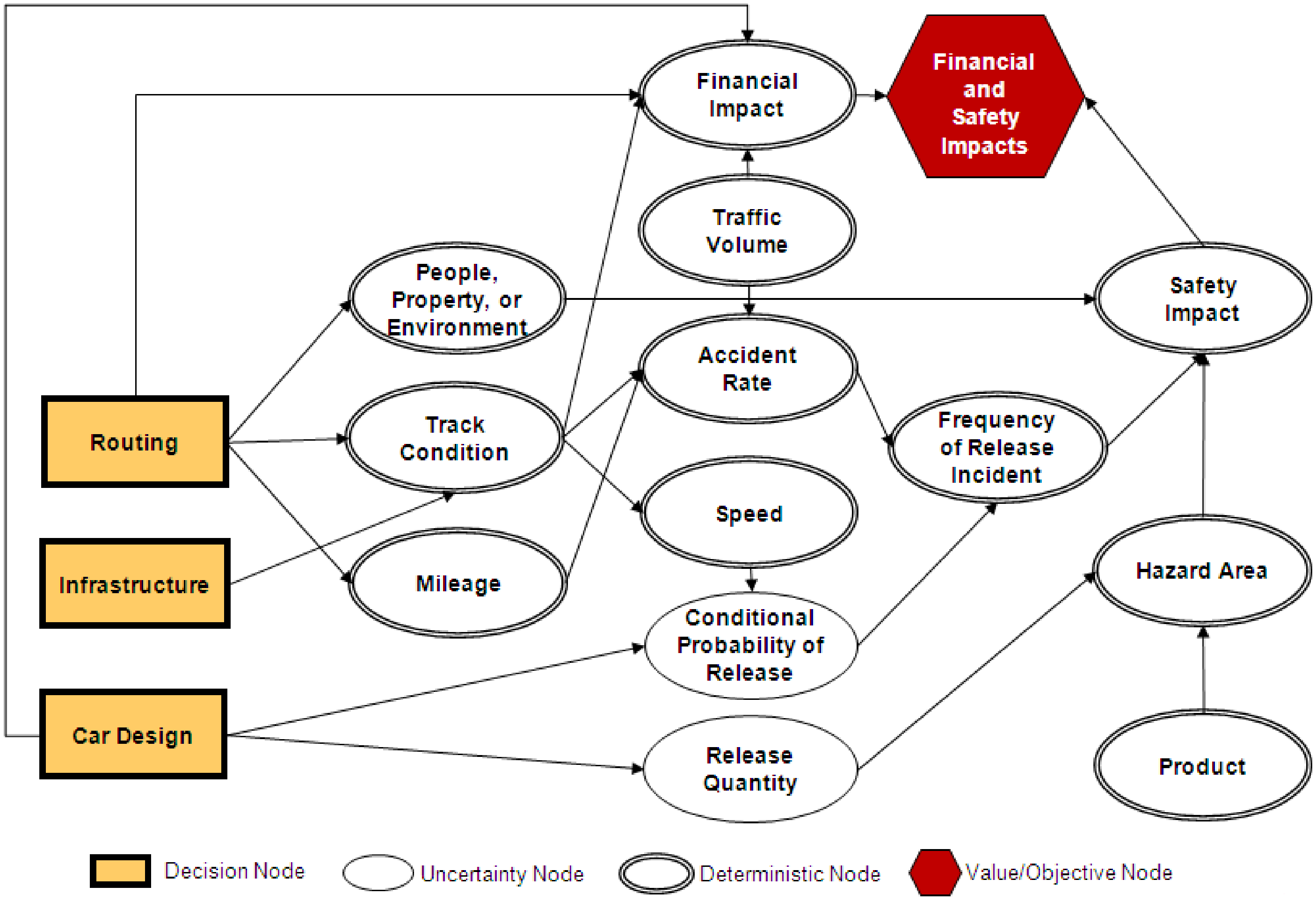

Fig. 3.1. Decision diagram for consideration of alternate tank car designs

The conditional probability of release and the quantity released given a tank car is involved in an accident are directly influenced by tank car design. The frequency of release incidents is affected by track condition, which affects railcar accident rate. Tank car conditional probability of release and the number of shipments, which determines the total accident exposure in terms of total car miles and ton miles, also affect the frequency of release incidents.

Release quantity and atmospheric condition (as approximated by time of day) affect the consequence level per the model used in this analysis (U.S. DOT 2008). These two variables affect the size of the exposure area as indicated by a double-oval node in Fig. 3.1 with arrows from the release quantity and atmospheric condition uncertainty nodes. When multiplied by the population density distribution, the hazard area determines the level of consequences in terms of number of people affected. The frequency of a release incident is multiplied by possible consequences or outcomes to estimate risk.

The decision diagram also indicates that there is a cost associated with replacing the current baseline tank car design. The octagon denotes the overall decision objectives where safety is considered along with cost. The risk reduction benefits due to the use of enhanced tank car designs are expressed in terms of the reduction in the number of people affected (this risk metric is discussed in more detailed in Section 3.3).

Although a decision diagram (Fig. 3.1) is shown to provide a general overview of the overall decisions and related factors in railroad hazardous materials transportation risk, a decision analytic approach was not used to identify the optimal tank car safety design in this Chapter. In the following section, it will be shown that there are a large number of decision alternatives or possible tank car safety designs. A decision analytic approach would require significant time to consider each possible tank car design alternative. In addition, it would require an assessment of a decision maker's value or utility function. In this case the "decision-maker" was a committee along with a number of individuals and organizations operating on an expedited schedule. Consequently the decision analytic approach was not feasible in the time frame available.

3.3. TANK CAR SAFETY DESIGN OPTIMIZATION

The overall objective of enhancing tank car safety design is to reduce risk. The weight of a fully loaded railcar in North America is constrained to not exceed what is referred to as the maximum gross rail load (GRL), which for tank cars is affected by both federal regulations and rail industry interchange standards (CFR 2009; AAR 2007). Most conventional tank car safety enhancements increase the weight of the car, thereby reducing its capacity and consequent transport efficiency due to the limit on the maximum GRL. This tradeoff must be accounted for when optimizing the safety design of a tank car. I used the generalized tank car safety design optimization model described in Chapter 2 to identify a set of Pareto-optimal designs for each of the TIH materials under consideration. I defined the baseline tank car designs for each TIH and then compared these to a set of alternate, enhanced safety tank car designs. Once a set of Pareto-optimal designs was identified, I used the utopia point method to identify a design that balanced the benefit from the reduction in the probability of release versus the reduction in capacity.

3.3.1. Baseline Tank Car Designs

The baseline tank car designs (Table 3.2) were defined based on the minimum requirements specified in 49 Code of Federal Regulations (CFR 2009). The conditional probability of release given that a car is derailed in an accident, $P_{R|A}$ was calculated for each baseline design by using the statistical model in Treichel et al. (2006). Tank car weight and capacity were estimated using *IlliTank*, a tank car weight and sizing program from Saat (2003) and Chapter 2, and reviewed by tank car builders and experts at the AAR.

3.3.2. Enhanced Tank Car Designs

There are three principal sources of release from tank cars in TIH service: the tank head, shell, and top fittings (Fig. 3.2). Consequently, these locations were candidates for design enhancements to reduce the likelihood of release if a car is derailed in an accident. For the tank head and shell, I considered increasing its thicknesses and for the tank head I also evaluated use of full-height head shields, which are additional ½-inch steel plates that protect the heads from impacts in accidents (Philips and Role 1989). I used the regression equations from Treichel et al. (2006) to quantify the effects of each of these changes in tank head and shell on tank car conditional probability of release.

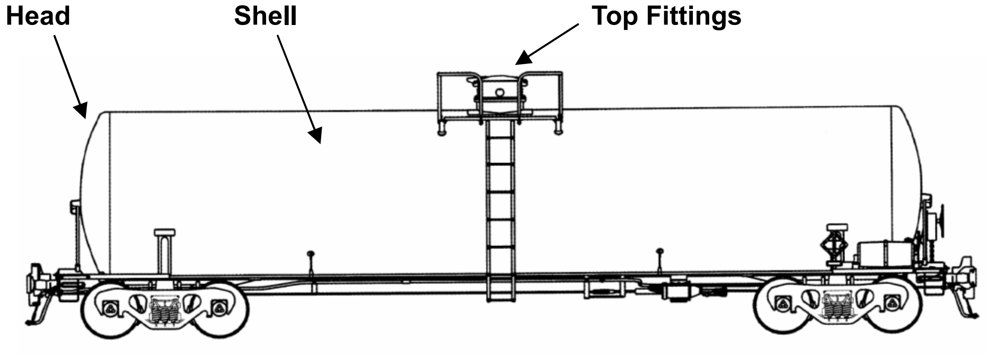

Fig. 3.2. An example of a DOT pressure-specification tank car in TIH service

Table 3.2
TIH material baseline tank car designs and performance levels.

Commodity Name	U.S. DOT Specification	Head Shields Type	Head Thickness (in.)	Shell Thickness (in.)	Nominal Capacity (gal.)	$P_{R\|A}$	Standard Error
Acetone Cyanohydrin	105S300W	Full-Height	0.5625	0.5625	24,027	0.08360	0.00481
Allyl Alcohol	105S300W	Full-Height	0.5625	0.5625	25,847	0.08360	0.00481
Ammonia, Anhydrous	112A340W	Full-Height	0.6080	0.6080	32,035	0.07712	0.00473
Bromine	105A300W	None	0.5625	0.5625	7,957	0.09962	0.00460
Chlorine	105A500W	None	0.8125	0.7751	16,043	0.07045	0.00487
Chlorosulfonic Acid	105S300W	Full-Height	0.5625	0.5625	13,943	0.08360	0.00481
Dimethyl Sulfate	105S300W	Full-Height	0.5625	0.5625	17,643	0.08360	0.00481
Ethyl Chloroformate	105S300W	Full-Height	0.5625	0.5625	20,304	0.08360	0.00481
Ethylene Oxide	105J300W	Full-Height	0.5625	0.5625	25,550	0.08360	0.00481
Hexachlorocyclopentadiene	105S300W	None	0.5625	0.5625	14,243	0.09962	0.00460
Hydrogen Chloride	105J600W	Full-Height	0.9810	0.9810	24,816	0.02824	0.00271
Hydrogen Cyanide	105A500W	None	0.8950	0.8950	28,257	0.06219	0.00479
Hydrogen Fluoride	112A340W	None	0.7040	0.7040	24,238	0.07904	0.00481
Methyl Bromide	105J300W	Full-Height	0.5625	0.5625	14,586	0.08360	0.00481
Methyl Mercaptan	105J300W	Full-Height	0.5625	0.5625	25,648	0.08360	0.00481
Phosphorus Trichloride	105S300W	Full-Height	0.5625	0.5625	15,316	0.08360	0.00481
Sulfur Dioxide	105J300W	Full-Height	0.5625	0.5625	17,433	0.08360	0.00481
Sulfur Trioxide	105S300W	Full-Height	0.5625	0.5625	13,035	0.08360	0.00481
Sulfuric Acid, Fuming	105S300W	Full-Height	0.5980	0.5980	12,343	0.07846	0.00475
Titanium Tetrachloride	105S300W	Full-Height	0.5625	0.5625	14,032	0.08360	0.00481

Enhanced top-fittings protection was also included as one of the risk reduction options (RROs). However, the particular top-fittings design could not be analyzed using the statistics from Treichel et al. (2006) because it was a new design and there was no empirical experience with its performance in accidents. Instead I used information developed by Trinity Rail, the developer of the design (authorized under U.S. DOT Special Permit 14167), who conducted research that involved simulation modeling of pressure tank cars in rollover accidents. This type of accident often damages the housing that protects top fittings on these cars and can lead to a release if the fittings themselves are damaged. They found that the rollover velocity that caused top-fittings failure was 2.6 times higher for the enhanced-design fittings compared to the baseline, chlorine-car-design top-fittings protection (Jiang and Shah 2006). For the purpose of my analysis, I made a conservative assumption that the new design reduces the probability of release from top fittings by 50% compared to the baseline performance of the current chlorine car's top fittings protection.

The conditional probability of release, given that a tank car is derailed in an accident, $P_{R|A}$, and the tank car weight, were enumerated for each possible configuration of alternate design tank car. I analyzed an 18x18 matrix in which the thickness of the head and shell were each increased from the baseline in increments of 1/16 of an inch. The conditional probability of release and the light weight of each alternative car design were used as the proxy for safety and cost, respectively. Mathematical representation of the two objective functions and the weight constraint are as follows:

$$F_{a,b} \; \alpha \; RRO_c \tag{3.2}$$

where:

$F_{a,b}$ = vector of objective functions a and b
a = percent increase in light weight
b = percent reduction in the conditional probability of release
RRO_c = different risk reduction option or safety design combinations
$Cap + LW \leq GRL$
Cap = tank car capacity
LW = tank car light weight
GRL = gross rail load
$LW \; \alpha \; RRO_c$

The vector space representing the set of Pareto-optimal solutions, was developed using the method in Chapter 2. The Pareto efficient frontier represents the set of solutions that provides the greatest reduction in the conditional probability of release with the least increase in light weight (Barkan 2008). An example, Pareto optimal set for one of the TIHs, allyl alcohol, is shown in Fig. 3.3. Similar curves were developed for all the TIHs.

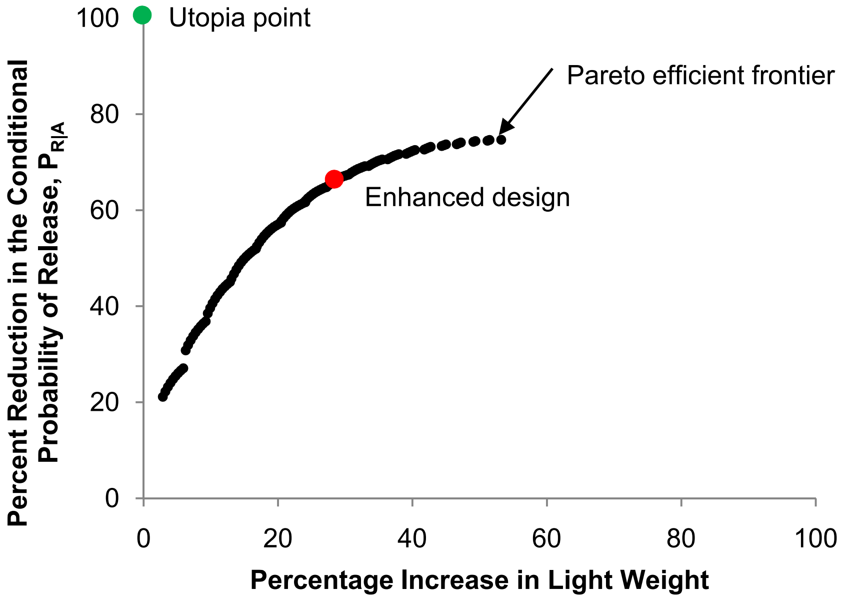

Fig. 3.3. Tank car safety design optimization vector space for allyl alcohol with 263,000-lb maximum GRL

Ideally, the probability of release would be reduced 100 percent, with no loss in capacity as indicated by the utopia point in Fig. 3.3; however, this solution is infeasible. A compromise solution can be determined by identifying the solution along the efficient frontier that is closest to the utopia point (Salukvadze 1971). The utopia point method is often used in game theory and vector optimization to identify an optimal solution using the compromise solution concept (Vincent and Grantham 1981; Vincent 1983). If the per-unit change in the two conflicting objective functions is valued equivalently by the decision-maker then the utopia point approach simply identifies the solution on the Pareto-efficient frontier that minimizes the Euclidean distance, N(x) between the frontier and the utopia point, as shown in Equation 3.3 (Marler and Arora 2004). If some differential weighting of the relative value of the two conflicting objectives is appropriate, the formula can be modified to reflect this. The overall optimization objective can be summarized mathematically as follows:

$$\text{Min } N(x) = |F(x) - F^{o}| = \left\{ \sum_{a,b} [F_{a,b}(x) - F^{o}_{a,b}]^2 \right\}^{1/2} \qquad (3.3)$$

where:

$N(x)$ = Euclidean distance from a point in a decision space to the utopia point
$F_{a,b}$ = vector of objective functions for a pair of vectors a and b
$F^{o}_{a,b}$ = [0, 100] = vector representing the utopia point
a = percent increase in light weight $\forall$ **RRO**
b = percent reduction in the conditional probability of release $\forall$ **RRO**
where:
RRO = combination of risk reduction options

In its consideration of suitable enhanced designs for TIH tank cars, the AAR decided to use the utopia point method with the objective scales equally weighted as an initial approach, and preliminary enhanced designs were selected for each TIH material (Table 3.3). Note that for hydrogen chloride, the baseline tank car already had a robust safety design (Table 3.2). As such, improvement to its design would not yield as much reduction in $P_{R|A}$ compared to the other TIH materials.

Table 3.3
TIH material enhanced tank car designs determined using the utopia point method.

Commodity Name	Head Thickness (in.)	Shell Thickness (in.)	Nominal Capacity (gal.)	$P_{R\|A}$	Standard Error	Percent Reduction in $P_{R\|A}$
Acetone Cyanohydrin	1.2500	1.0000	21,025	0.02845	0.00262	66.0
Allyl Alcohol	1.3125	1.0000	22,415	0.02819	0.00259	66.3
Ammonia, Anhydrous	1.6705	1.1080	27,934	0.02480	0.00228	67.8
Bromine	1.6250	0.8750	7,316	0.03176	0.00284	68.1
Chlorine	1.6250	1.2126	14,571	0.02336	0.00213	66.8
Chlorosulfonic Acid	1.1875	1.0000	12,578	0.02873	0.00264	65.6
Dimethyl Sulfate	1.2500	1.0000	15,744	0.02845	0.00262	66.0
Ethyl Chloroformate	1.3125	1.0000	17,880	0.02819	0.00259	66.3
Ethylene Oxide	1.3125	1.0000	22,183	0.02819	0.00259	66.3
Hexachlorocyclopentadiene	1.0625	0.9375	12,919	0.03137	0.00286	68.5
Hydrogen Chloride	2.0435	1.6060	20,112	0.02048	0.00186	27.5
Hydrogen Cyanide	1.8950	1.2075	24,577	0.02299	0.00209	63.0
Hydrogen Fluoride	1.3915	1.0165	21,277	0.02747	0.00253	65.2
Methyl Bromide	1.2500	1.0000	13,163	0.02845	0.00262	66.0
Methyl Mercaptan	1.3125	1.0000	22,260	0.02819	0.00259	66.3
Phosphorus Trichloride	1.2500	1.0000	13,809	0.02845	0.00262	66.0
Sulfur Dioxide	1.2500	1.0000	15,582	0.02845	0.00262	66.0
Sulfur Trioxide	1.2500	1.0000	11,864	0.02845	0.00262	66.0
Sulfuric Acid, Fuming	1.2855	1.0355	11,169	0.02739	0.00252	65.1
Titanium Tetrachloride	1.2500	1.0000	12,696	0.02845	0.00262	66.0

The preliminary tank car designs identified using this method provided a theoretical starting point to develop practical designs for consideration. However; the exact tank head and shell thicknesses identified using this technique had to be modified to take into account practical considerations related to material properties and availability, as well as fabrication constraints. Furthermore, there is greater uncertainty in the tank car damage resistance estimates for thicknesses beyond the bounds of the data in the regression analysis of tank cars involved in accidents that were used to develop the probability figures (Treichel et al. 2006). Consequently the AAR used the preliminary theoretical designs as the basis for a set of practical, performance-based standards for enhanced tank car designs for TIH service that accounted for these factors (AAR 2008a). They also developed a set of design standards that conformed to the performance standard (Table 3.4) (AAR 2008a). The risk analysis described in the following sections of this Chapter used these examples as the alternate tank car designs.

3.4. RISK ANALYSIS

This section describes the methodology used to estimate the probability and consequence elements in the risk analysis definition. The estimated risk reductions due to the use of enhanced tank car designs (Table 3.4) were calculated for each TIH material. The analysis in this Chapter focuses on Federal Railroad Administration (FRA) reportable incidents on U.S. railroad mainlines. The FRA database and reporting threshold[4] provides a standard baseline accident rate upon which to base consistent risk estimates. Railroads are required to report all accidents that exceed the FRA monetary threshold for damages to track, equipment and structures (FRA 2003). Non-FRA-reportable accidents are, by definition small and rarely involve a release, and thus pose relatively low risk. In addition, this Chapter does not consider yard accidents because they too are a relatively minor source of risk for the types of tank cars being considered. However, the benefits of a safer tank car can be expected to accrue for both non-FRA-reportable mainline and yard accidents. Therefore, the risk and risk reduction estimates presented here are probably slight underestimates. Throughout this Chapter, all derailment and accident terms refer to FRA-reportable accidents.

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[4] The threshold is equal to $8,900 in 2009

Fig. 3.4 shows a generic decision tree summarizing the risk analysis framework used in this study. For simplicity, only one branch is expanded at each node. Each of the probability and consequence elements are described in more detail in the following sub-sections.

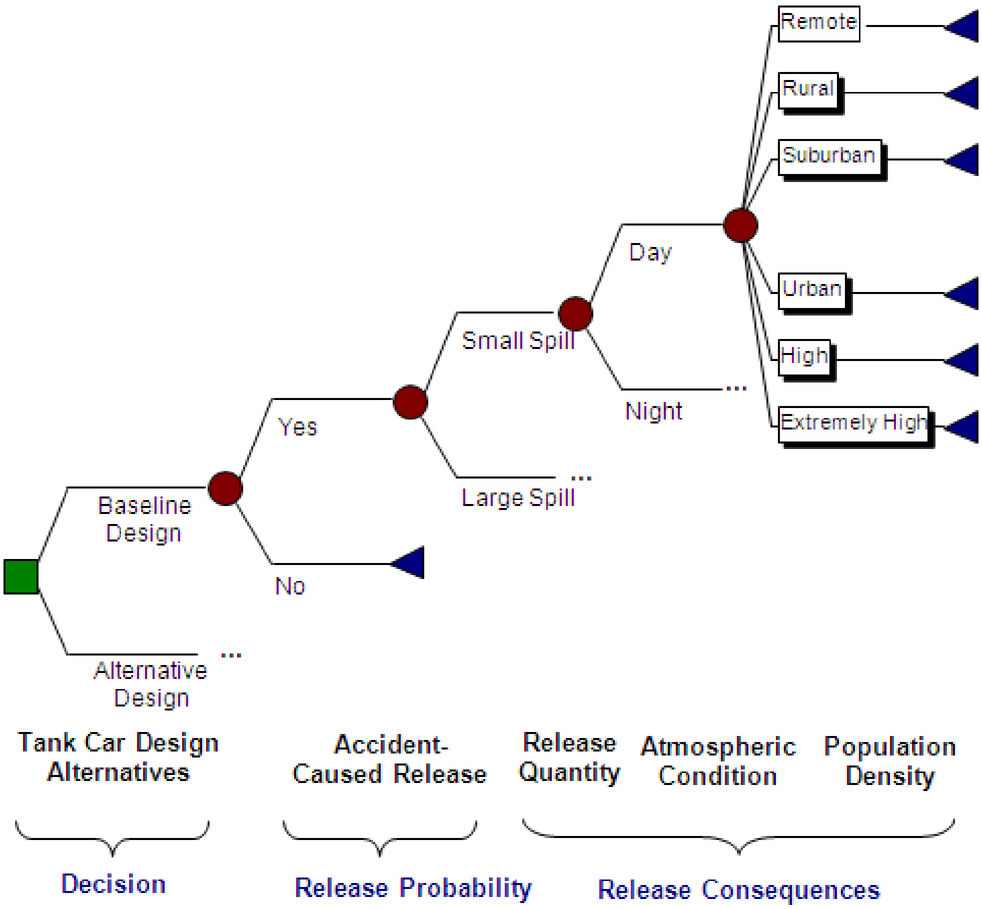


Fig. 3.4. Generic decision tree summarizing risk analysis framework

Table 3.4
Example alternate tank car designs that meet the AAR performance standard

Commodity Name	U.S. DOT Specification	Head Shields Type	Head Thickness (in.)	Shell Thickness (in.)	PR|A	Nominal Capacity (gal.)	$P_{R\|A}$	Standard Error	Percent Reduction in $P_{R\|A}$
Acetone Cyanohydrin	105J500W	Full-Height	0.8951	0.8951	0.0238121	23,823	0.02365	0.00275	71.7
Allyl Alcohol	105J500W	Full-Height	0.8951	0.8951	0.0238121	25,511	0.02365	0.00275	71.7
Ammonia, Anhydrous	105J500W	Full-Height	1.0300	0.8900	0.0231	33,581	0.02283	0.00262	70.4
Bromine	105J500W	Full-Height	0.8125	0.8125	0.0287932	8,111	0.02857	0.00309	71.3
Chlorine	105J600W	Full-Height	1.1360	0.9810	0.019	17,160	0.01886	0.00226	73.2
Chlorosulfonic Acid	105J500W	Full-Height	0.8125	0.8125	0.0287932	14,182	0.02857	0.00309	65.8
Dimethyl Sulfate	105J500W	Full-Height	0.8179	0.8179	0.0284205	17,965	0.02820	0.00307	66.3
Ethyl Chloroformate	105J500W	Full-Height	0.8179	0.8179	0.0284205	20,565	0.02820	0.00307	66.3
Ethylene Oxide	105J500W	Full-Height	0.8951	0.8951	0.0238121	25,237	0.02365	0.00275	71.7
Hexachlorocyclopentadiene	105J500W	Full-Height	0.8125	0.8125	0.0287932	14,443	0.02857	0.00309	71.3
Hydrogen Chloride	105J600W	Full-Height	0.9810	0.9810	0.0199769	27,665	0.01998	0.00225	29.3
Hydrogen Cyanide	105J600W	Full-Height	1.2429	1.2429	0.0134729	27,356	0.01343	0.00157	78.4
Hydrogen Fluoride	105J500W	Full-Height	0.8951	0.8951	0.0238121	24,316	0.02365	0.00275	70.1
Methyl Bromide	105J500W	Full-Height	0.8125	0.8125	0.0287932	14,934	0.02857	0.00309	65.8
Methyl Mercaptan	105J500W	Full-Height	0.8951	0.8951	0.0238121	25,327	0.02365	0.00275	71.7
Phosphorus Trichloride	105J500W	Full-Height	0.8179	0.8179	0.0284205	15,668	0.02820	0.00307	66.3
Sulfur Dioxide	105J500W	Full-Height	0.8179	0.8179	0.0284205	17,772	0.02820	0.00307	66.3
Sulfur Trioxide	105J500W	Full-Height	0.8125	0.8125	0.0287932	13,415	0.02857	0.00309	65.8
Sulfuric Acid, Fuming	105J500W	Full-Height	0.8125	0.8125	0.0287932	12,646	0.02857	0.00309	63.6
Titanium Tetrachloride	105J500W	Full-Height	0.8125	0.8125	0.0287932	14,382	0.02857	0.00309	65.8

3.4.1. Accident-Caused Release Rate

The accident-caused release rate metric from Chapter 2 was used to estimate the annual rate of a release event (the probability term in the risk definition) using the equation as follows:

$$P_R = P_{R|A} \times P_A \times M \times \mathrm{Cap}/\mathrm{Cap}' \qquad (3.4)$$

where:

P_R = tank car accident-caused release rate
$P_{R|A}$ = conditional probability of a tank car release given the car is derailed in an FRA-reportable accident
P_A = tank car derailment rate per car-mile
M = number of car miles
Cap = nominal volumetric capacity of a baseline tank car
Cap’ = nominal volumetric capacity of an alternate-design tank car

The conditional probability of release, $P_{R|A}$, and nominal volumetric capacity from Tables 3.2 and 3.4 were used for the associated variables in Equation 3.3. Anderson and Barkan (2004) developed estimates of Class 1 railroad mainline freight train and freight car accident rates based on the FRA safety statistics. In the analyses described here I used their estimate of average railcar derailment rate per car-mile for P_A:

$$P_A = 1.28 \times 10^{-7} \text{ (s.e. } = 6.6327 \times 10^{-8}).$$

The annual number of U.S. shipments was multiplied by the average car-miles per shipment calculated from the 2006 Surface Transportation Board (STB) waybill sample (STB Waybill 2006) to get the total number of car miles, M. Table 3.5 and Fig. 3.5 summarize the calculated accident-caused release rate, P_R, for all of the TIH materials of interest with the baseline and enhanced tank car designs. This rate accounts for different tank car safety design, annual number of shipments and changes in tank car capacity for each of the chemicals under consideration and thus provides an overall annual expected rate of release for each product. It is evident that a large portion of the potential releases are due to just a few products. This is primarily due to their very high shipment volume compared to the other products.

Table 3.5
Annual accident-caused release rate, P_R for baseline and enhanced design tank cars.

Commodity Name	Cap/Cap'	P_R Baseline	P_R Enhanced	Std. Error Baseline	Std. Error Enhanced	Percent Reduction in P_R
Acetone Cyanohydrin	0.99	0.00805	0.00226	3.19E-10	1.82E-10	71.9
Allyl Alcohol	0.99	0.00054	0.00015	3.19E-10	1.82E-10	72.1
Ammonia, Anhydrous	1.05	0.18732	0.05812	3.14E-10	1.74E-10	69.0
Bromine	1.02	0.00118	0.00035	3.05E-10	2.05E-10	70.8
Chlorine	1.07	0.18465	0.05289	3.23E-10	1.50E-10	71.4
Chlorosulfonic Acid	1.02	0.00161	0.00056	3.19E-10	2.05E-10	65.2
Dimethyl Sulfate	1.02	0.00145	0.00050	3.19E-10	2.04E-10	65.7
Ethyl Chloroformate	1.01	0.00035	0.00012	3.19E-10	2.04E-10	65.8
Ethylene Oxide	0.99	0.06750	0.01886	3.19E-10	1.82E-10	72.1
Hexachlorocyclopentadiene	1.01	0.00036	0.00010	3.05E-10	2.05E-10	70.9
Hydrogen Chloride	1.11	0.00297	0.00221	1.80E-10	1.49E-10	25.6
Hydrogen Cyanide	0.97	0.00048	0.00010	3.18E-10	1.04E-10	79.1
Hydrogen Fluoride	1.00	0.02480	0.00745	3.19E-10	1.82E-10	70.0
Methyl Bromide	1.02	0.00109	0.00038	3.19E-10	2.05E-10	65.0
Methyl Mercaptan	0.99	0.00634	0.00177	3.19E-10	1.82E-10	72.1
Phosphorus Trichloride	1.02	0.00209	0.00072	3.19E-10	2.04E-10	65.5
Sulfur Dioxide	1.02	0.00397	0.00136	3.19E-10	2.04E-10	65.6
Sulfur Trioxide	1.03	0.00358	0.00126	3.19E-10	2.05E-10	64.8
Sulfuric Acid, Fuming	1.02	0.00409	0.00153	3.15E-10	2.05E-10	62.7
Titanium Tetrachloride	1.02	0.01135	0.00398	3.19E-10	2.05E-10	65.0

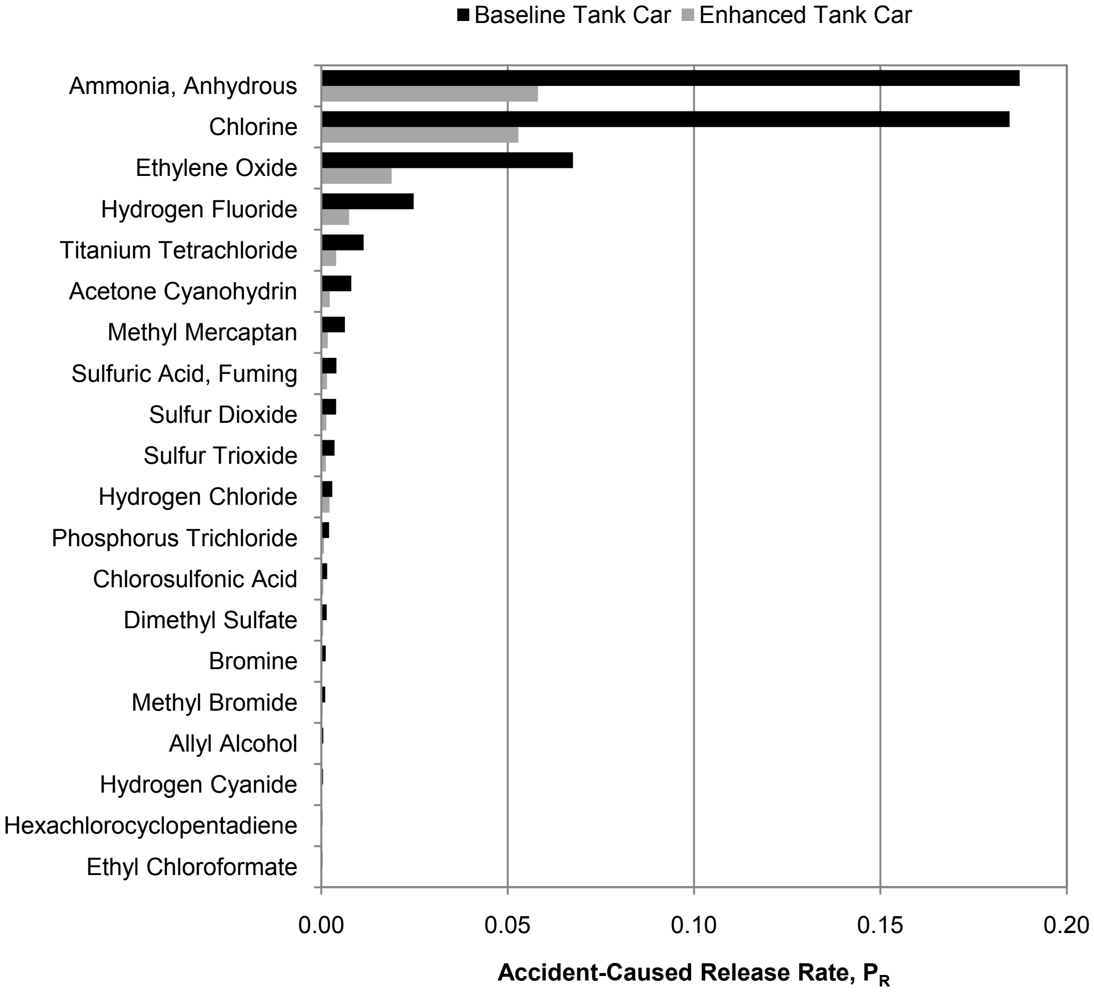


Fig. 3.5. Annual accident-caused release rate, P_R with baseline (dark bars) vs. enhanced (light bars) tank car designs

3.4.2. Hazard Exposure Model

The U.S. Department of Transportation Emergency Response Guidebook (ERG) (U.S. DOT 2008) hazard exposure model was used to estimate the consequence of a release of TIH materials. The affected areas presented in the ERG for each material were determined from a statistical model that used sophisticated emission rate and dispersion models, historical release incidents, meteorological observations in North America and current toxicological exposure guidelines (Brown et al. 2000; Brown and Dunn 2007; U.S. DOT 2008). The area is estimated by adding the protective action area and half of the initial isolation zone defined in the ERG for a specific chemical (Fig. 3.6). In principle this defines the area for which the population could be expected to be evacuated and/or sheltered in-place. Thus the risk metric used in this analysis is the number of people likely to be affected if emergency response personnel conform to the recommendations published in the U.S. DOT ERG. Although circumstances will vary in individual accidents, these are federal guidelines that are widely accepted by the U.S. emergency response community. Consequently, I assumed that on average they will correlate reasonably well with actual experience. Therefore they provide a suitable consequence metric for assessing the relative risk of rail transport of these products.

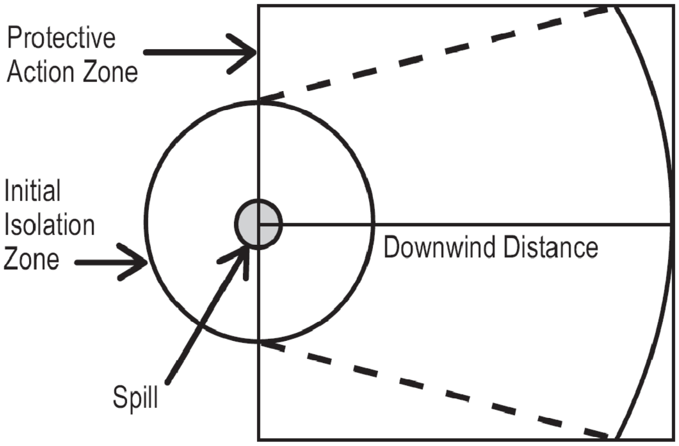


Fig. 3.6. The initial isolation and protective action zones used in the ERG (U.S. DOT 2008)

The affected area was calculated for four different scenarios as specified by the ERG (Table 3.6). It was assumed that overall, incidents involving these chemicals are equally likely to occur during the day or night throughout the year and thus, a 0.5 probability was assigned to these two atmospheric conditions. The proportion of “large” vs. “small” releases was determined using the quantity lost distribution for pressure tank cars derailed in mainline accidents (Treichel et al. 2006). Releases of 5% or less of a car’s capacity were classified as small spills and comprised 22.1% of pressure tank car spills; releases greater than 5% were classed as large spills and accounted for 77.9%.

Table 3.6
Possible affected area (miles^2) due to a spill of TIH material based on DOT ERG recommendations.

	Affected Zone Area (miles^2)				Maximum Downwind Distance (miles)
	Small Spills (0-5% Tank Capacity)		Large Spills (>5% Tank Capacity)		
Commodity Name	**Day**	**Night**	**Day**	**Night**	
Acetone Cyanohydrin	0.0106	0.0406	0.2861	3.6461	1.9
Allyl Alcohol	0.0106	0.0106	0.0423	0.1623	0.4
Ammonia, Anhydrous	0.0106	0.0106	0.1623	1.9623	1.4
Bromine	0.0923	1.2123	4.4782	21.2282	4.6
Chlorine	0.0406	0.6406	2.2861	21.1961	4.6
Chlorosulfonic Acid	0.0106	0.0106	0.0406	0.0906	0.3
Dimethyl Sulfate	0.0106	0.0106	0.0923	0.2523	0.5
Ethyl Chloroformate	0.0106	0.0406	0.3651	1.2151	1.1
Ethylene Oxide	0.0106	0.0106	0.2551	2.2551	1.5
Hexachlorocyclopentadiene	0.0106	0.0106	0.0923	0.0923	0.3
Hydrogen Chloride	0.0106	0.0906	4.9211	42.3311	6.5
Hydrogen Cyanide	0.0106	0.0906	0.6541	5.3041	2.3
Hydrogen Fluoride	0.0106	0.0906	1.4676	7.3176	2.7
Methyl Bromide	0.0106	0.0106	0.2551	1.9651	1.4
Methyl Mercaptan	0.0106	0.0406	0.6541	7.8541	2.8
Phosphorus Trichloride	0.0106	0.0906	1.0141	4.8541	2.2
Sulfur Dioxide	0.0406	0.6406	1.7176	15.2376	3.9
Sulfur Trioxide	0.0423	0.3623	2.3063	16.0563	4.0
Sulfuric Acid, Fuming	0.0423	0.3623	2.3063	16.0563	4.0
Titanium Tetrachloride	0.0106	0.0106	0.0923	0.2523	0.5

3.4.3. Population Exposure

Waybill shipment data from the AAR's railcar movement database, TRAIN II, for the year 2007 (TRAIN II 2008) were used to determine the routes involving specific TIH materials. Each waybill record represents origination and destination (O-D) information as well as all intermediate junctions, interchange points, and railroads involved in each shipment. PC*MILER-Rail, a routing, mileage and mapping software for the North American rail network developed by ALK-Technologies was used to analyze the waybill data to determine the practical route for each O-D pair. Point locations for each specific shipment route were then exported to ArcGIS, a geographic information system (GIS) software from ESRI used for spatial analysis to create the route over the rail network map from the U.S. DOT (NTAD 2007). A spatial buffer was created over the route to represent the worst-case release scenario. The size of the buffer was based on the maximum downwind distance from the DOT ERG (Table 3.6). The exposure buffer along each TIH material-specific route was overlaid on the U.S. census tract map from ESRI Data and Maps (ESRI 2008) to estimate the proportion of different population density levels (U.S. Department of Commerce 1988) along all TIH material routes (Table 3.7 and Fig. 3.7).

Table 3.7
Distribution of population densities along TIH-material-specific routes.

	Percentages of Population Class					
Population Class	***Remote***	***Rural***	***Suburban***	***Urban***	***High***	***Extremely High***
Population Density (people/mile^2)	**≤20**	**>20 to ≤100**	**>100 to ≤1000**	**>1,000 to ≤3,000**	**>3,000 to ≤10,000**	**> 10,000**
Average Population Density* (people/mile^2)	**10**	**60**	**550**	**2,000**	**6,500**	**10,000**
Acetone Cyanohydrin	20.14%	44.92%	26.09%	6.04%	2.74%	0.07%
Allyl Alcohol	18.57%	44.70%	28.24%	5.77%	2.59%	0.14%
Ammonia, Anhydrous	44.45%	30.83%	17.50%	4.47%	2.55%	0.20%
Bromine	24.97%	53.75%	17.11%	3.29%	0.83%	0.05%
Chlorine	37.66%	37.04%	18.89%	3.94%	2.25%	0.23%
Chlorosulfonic Acid	25.95%	41.43%	22.07%	6.28%	3.94%	0.35%
Dimethyl Sulfate	19.86%	48.00%	21.04%	6.55%	4.14%	0.42%
Ethyl Chloroformate	16.18%	50.79%	23.93%	5.67%	3.27%	0.16%
Ethylene Oxide	20.65%	44.16%	24.88%	6.43%	3.48%	0.40%
Hexachlorocyclopentadiene	2.19%	34.50%	42.30%	13.49%	7.23%	0.29%
Hydrogen Chloride	22.12%	48.31%	22.33%	4.74%	2.33%	0.18%
Hydrogen Cyanide	17.44%	47.70%	25.78%	6.34%	2.70%	0.04%
Hydrogen Fluoride	30.05%	39.61%	21.10%	5.51%	3.41%	0.32%
Methyl Bromide	34.61%	35.26%	19.23%	6.11%	4.46%	0.33%
Methyl Mercaptan	23.39%	43.87%	24.44%	5.30%	2.91%	0.10%
Phosphorus Trichloride	6.33%	40.41%	37.71%	10.66%	4.64%	0.25%
Sulfur Dioxide	34.49%	35.49%	21.30%	5.24%	3.20%	0.27%
Sulfur Trioxide	15.49%	53.69%	22.64%	5.45%	2.61%	0.13%
Sulfuric Acid, Fuming	7.94%	49.03%	32.65%	6.99%	3.30%	0.09%
Titanium Tetrachloride	47.50%	26.11%	16.81%	5.99%	3.42%	0.16%
Total	23.50%	42.48%	24.30%	6.21%	3.30%	0.21%

*Average is assumed to equal the median value for the U.S. Dept. of Commerce population class ranges

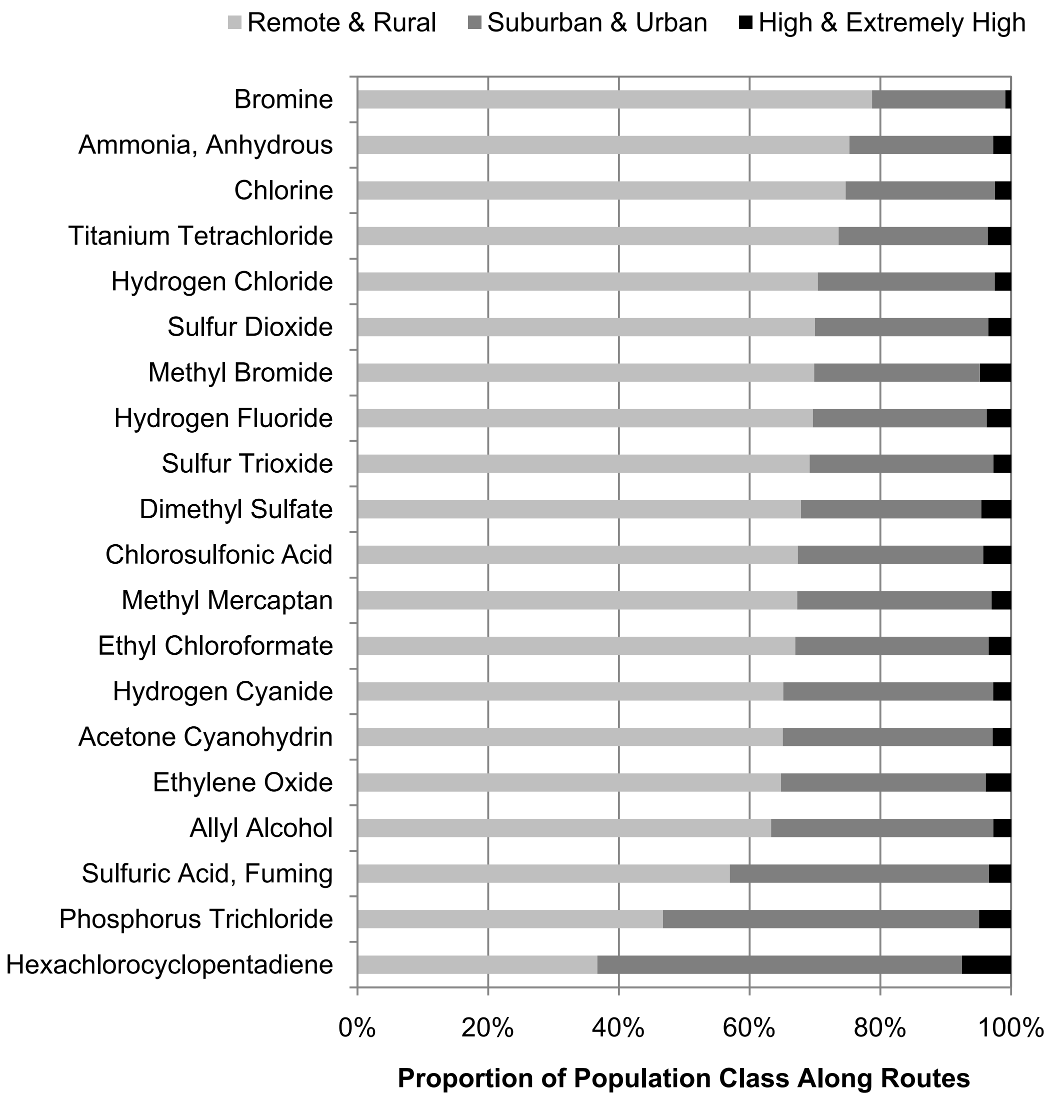


Fig. 3.7. Distribution of population densities along TIH-material-specific routes.

3.4.4. Risk Estimates

Using Equation 3.1 and the risk analysis framework summarized in Fig. 3.4, the risk of transporting each of the TIH materials can be estimated as follows:

$$R_{i,j}=P_{i,j}\times\sum_{k=1}^{2}\sum_{l=1}^{2}\sum_{m=1}^{6}\text{Spill}_k\times\text{Atmos}_l\times\text{Area}_{k,l}\times\text{Pop}_m\times\text{AvePop}_m \qquad (3.5)$$

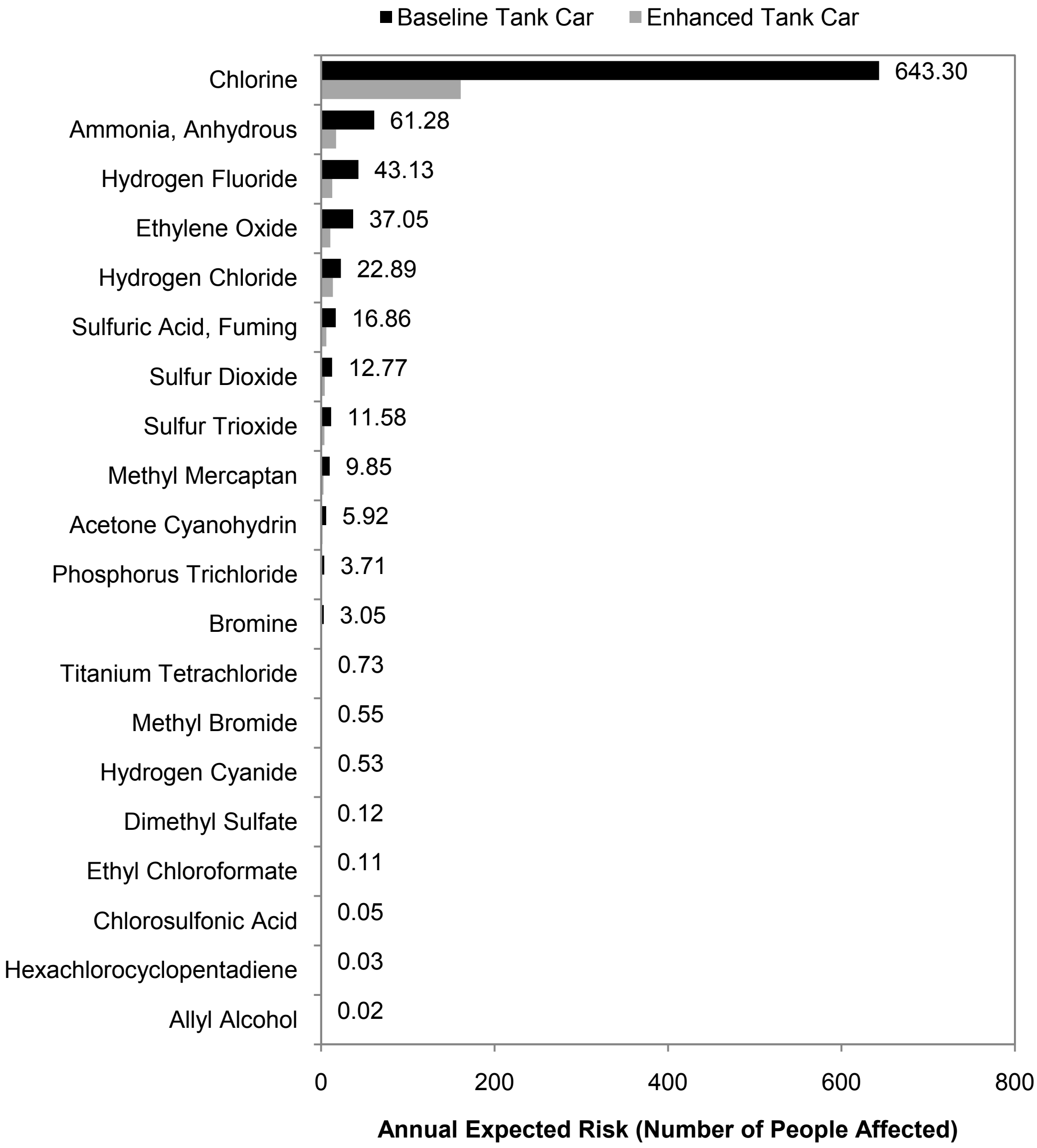
where:

$R_{i,j}$ = risk of transporting chemical *i* in tank car design *j*
$P_{i,j}$ = accident-caused release rate when chemical *i* is transported in tank car design *j* (Table 3.5)
Spill_k = probability of spill size *k* where *k* = small (0.221) or large (0.779)
Atmos_l = probability of atmospheric condition *l* where *l* = day (0.5) or night (0.5)
$\text{Area}_{k,l}$ = evacuated area with spill size *k* and atmospheric condition *l* (Table 3.6)
Pop_m = probability of a release affecting population class *m* (Table 3.7)
AvePop_m = average population density class *m* (Table 3.7)

The annual expected risk, risk per car-mile and risk per ton-mile for chemicals of interest were summarized in Table 3.8 and Fig. 3.8.

Table 3.8
Summary of risk estimates for rail transport of TIH materials.

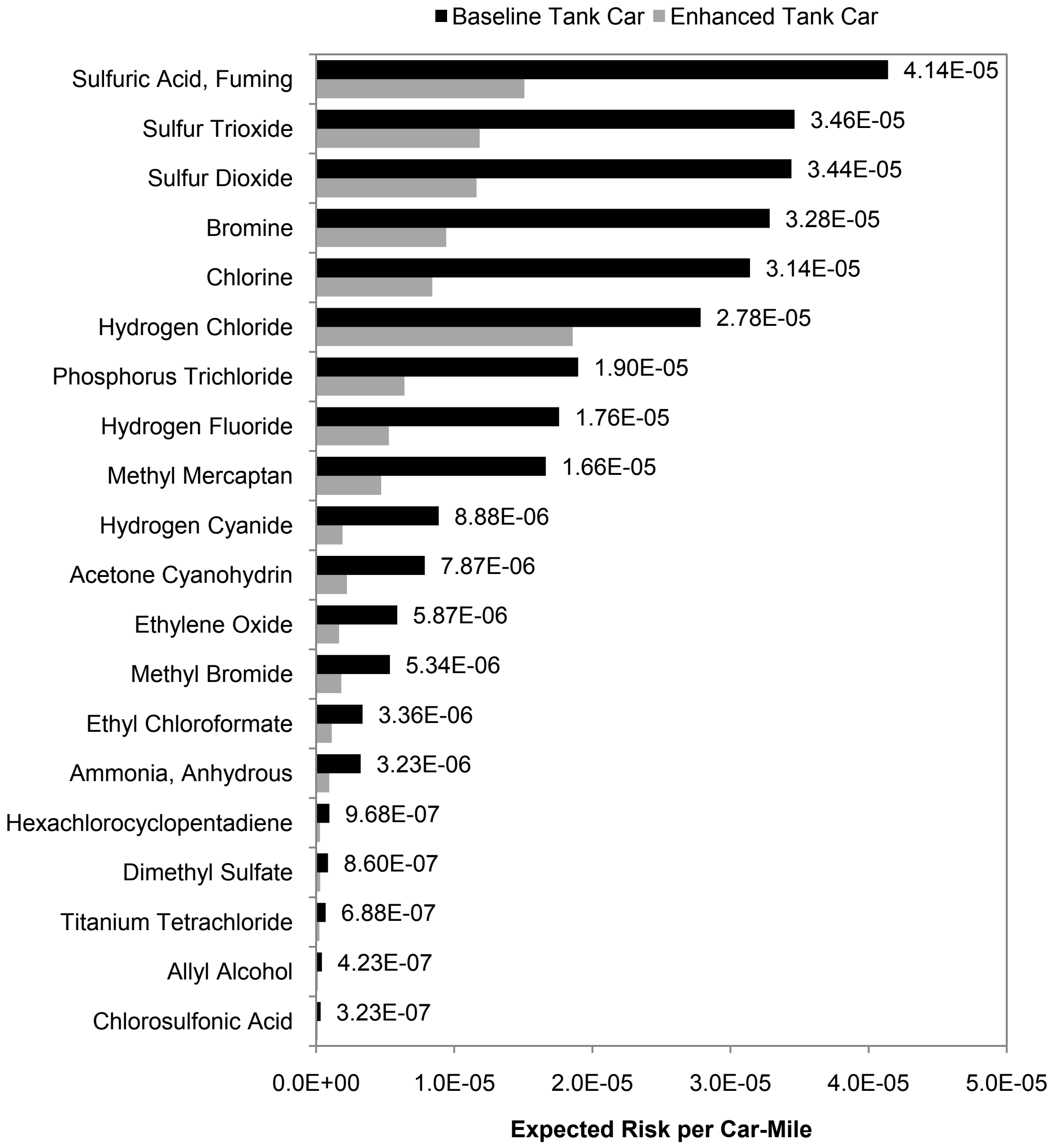
Commodity Name	Annual Expected Risk (number of people affected)			Expected Risk per Car-Mile			Expected Risk per Ton-Mile		
	Baseline Tank Car	Enhanced Tank Car	Percent Risk Reduction	Baseline Tank Car	Enhanced Tank Car	Percent Risk Reduction	Baseline Tank Car	Enhanced Tank Car	Percent Risk Reduction
Acetone Cyanohydrin	6	2	71.5%	7.87E-06	2.23E-06	71.7%	8.61E-08	2.46E-08	71.5%
Allyl Alcohol	0.02	0.01	71.3%	4.23E-07	1.20E-07	71.7%	4.71E-09	1.35E-09	71.3%
Ammonia, Anhydrous	61	17	71.8%	3.23E-06	9.56E-07	70.4%	4.18E-08	1.18E-08	71.8%
Bromine	3.05	0.86	71.9%	3.28E-05	9.42E-06	71.3%	3.24E-07	9.12E-08	71.9%
Chlorine	643	161	75.0%	3.14E-05	8.41E-06	73.2%	3.49E-07	8.74E-08	75.0%
Chlorosulfonic Acid	0.05	0.02	66.4%	3.23E-07	1.10E-07	65.8%	3.23E-09	1.08E-09	66.4%
Dimethyl Sulfate	0.12	0.04	66.9%	8.60E-07	2.90E-07	66.3%	8.96E-09	2.97E-09	66.9%
Ethyl Chloroformate	0.11	0.04	66.7%	3.36E-06	1.13E-06	66.3%	3.60E-08	1.20E-08	66.7%
Ethylene Oxide	37	11	71.4%	5.87E-06	1.66E-06	71.7%	6.52E-08	1.87E-08	71.4%
Hexachlorocyclopentadiene	0.03	0.01	71.7%	9.68E-07	2.77E-07	71.3%	9.67E-09	2.73E-09	71.7%
Hydrogen Chloride	23	14	40.1%	2.78E-05	1.86E-05	33.3%	3.89E-07	2.33E-07	40.1%
Hydrogen Cyanide	0.53	0.12	77.7%	8.88E-06	1.92E-06	78.4%	1.15E-07	2.56E-08	77.7%
Hydrogen Fluoride	43	13	70.2%	1.76E-05	5.26E-06	70.1%	1.96E-07	5.85E-08	70.2%
Methyl Bromide	0.55	0.18	66.6%	5.34E-06	1.82E-06	65.8%	5.42E-08	1.81E-08	66.6%
Methyl Mercaptan	10	3	71.3%	1.66E-05	4.70E-06	71.7%	1.85E-07	5.30E-08	71.3%
Phosphorus Trichloride	4	1	67.0%	1.90E-05	6.40E-06	66.3%	1.93E-07	6.37E-08	67.0%
Sulfur Dioxide	13	4	66.9%	3.44E-05	1.16E-05	66.3%	3.58E-07	1.19E-07	66.9%
Sulfur Trioxide	12	4	66.8%	3.46E-05	1.18E-05	65.8%	3.48E-07	1.16E-07	66.8%
Sulfuric Acid, Fuming	17	6	64.5%	4.14E-05	1.51E-05	63.6%	4.12E-07	1.47E-07	64.5%
Titanium Tetrachloride	0.73	0.24	66.7%	6.88E-07	2.35E-07	65.8%	6.94E-09	2.32E-09	66.7%



a)

Fig. 3.8. a) Annual expected risk, b) expected risk per car-mile, and c) expected risk per ton-mile for rail transport of TIH materials with baseline (dark bars) vs. enhanced (light bars) tank car designs

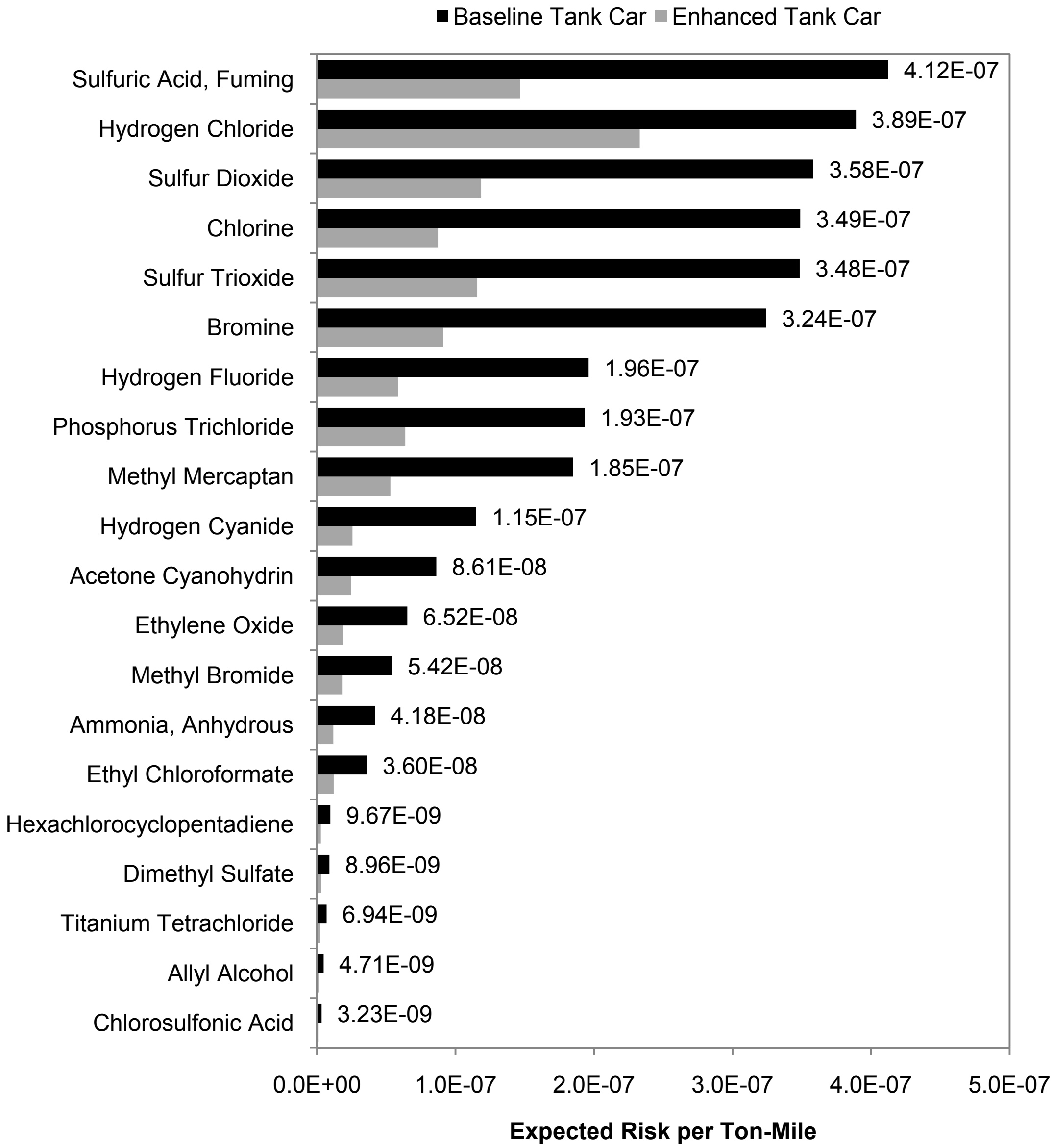
Fig. 3.8, continued.



b)

Fig. 3.8. a) Annual expected risk, b) expected risk per car-mile, and c) expected risk per ton-mile for rail transport of TIH materials with baseline (dark bars) vs. enhanced (light bars) tank car designs

Fig. 3.8, continued.



c)

Fig. 3.8. a) Annual expected risk, b) expected risk per car-mile, and c) expected risk per ton-mile for rail transport of TIH materials with baseline (dark bars) vs. enhanced (light bars) tank car designs

3.5. DISCUSSION

3.5.1. Implications for Risk Estimates

Risk is affected by the likelihood and the severity of an event. Annual expected risk incorporates the type of tank car design, chemical hazard level, average population along the routes and number of car miles. The annual baseline risk reflects current transportation practices and traffic levels estimated based on recent information. Tank car design affects the accident-caused release rate; more robust tank car designs lead to a lower likelihood of release in the event of an accident or a derailment, thereby reducing risk. Accident-caused release rate is also affected by the potential exposure to accidents, the metric for which is car miles. Ceteris paribus, higher car miles due to a larger number of shipments and/or average miles per trip result in greater potential exposure to the possibility of an accident and consequent population impacted.

The severity of a TIH material release is affected by the chemical hazard level. The emergency response guidebook's exposure model incorporated this effect in specifying the protective action area for each chemical. In addition, the larger the size of the population at the place where a release incident takes place, the higher the consequence level. The GIS analysis shows that for most of the TIH materials I analyzed, remote and rural areas are subject to higher exposure (higher annual TIH mileage) than any other population classes (Fig. 3.7).

The risk metric I used represents the estimated number of people to be evacuated or protected in the event of a TIH-material release. The ERG model provides a simple and consistent means of estimating an exposure area for a nation-wide risk analysis without requiring the use of chemical-specific atmospheric dispersion models combined with route and location specific wind rose probability distributions. This level of detail may be necessary for certain route and product-specific analyses, especially if one is interested in the risk at a specific locale. However, to conduct a nationwide, relative risk assessment, use of the methodology developed for the ERG is appropriate, and indeed was part of the underlying rationale for the development of the model (Brown et al. 2000; Hwang et al. 2001; Brown and Dunn 2007). Beyond the simplicity of its use, there are other practical benefits. It is likely to be somewhat correlated with cost thereby enabling its use as input for benefit-cost analyses. It also has value for risk communication because of the relative neutrality of the term “persons affected”. It has no specific implications regarding how many injuries or fatalities may occur. Such estimates are subject to a great deal of uncertainty and can be difficult to communicate effectively. Furthermore, the potentially controversial nature of such specific discussion can inhibit both public and private discourse on the subject of risk, thereby interfering with rational, constructive dialogue on the most effective risk management options to improve public safety.

3.5.2. Implications for Current Packaging Practices

The methodology and analysis described in this Chapter provided insights for development of enhanced tank car specifications for transportation of TIH materials. It was used to support the AAR’s proposed interchange standards for tank cars for these materials (Table 3.4) (AAR 2008a). Subsequently, the U.S. Department of Transportation, Pipeline and Hazardous Materials Safety Administration (PHMSA) proposed a performance-based regulation in which all TIH tank cars were to be designed and manufactured with a shell puncture resistance system capable of withstanding impact at 25 mph and with a tank-head puncture-resistance system capable of withstanding impact at 30 mph (73 FR 17817).

However, both the Railway Supply Institute (RSI), the trade organization representing tank car builders, and the AAR raised questions regarding the feasibility of these requirements in the Notice of Proposed Rulemaking (NPRM). They argued that the new performance standards were unattainable in the proposed time frame with existing tank car safety designs, and that the materials and manufacturing techniques needed to achieve them were, as yet, unproven (see the following sub-section).

Although cars with the safety characteristics proposed by DOT are desirable, attaining the intended level of performance will require extensive research and development (R&D). Cars designed to the new standard would have to survive rigorous, full-scale testing and adequate service trials (RSI 2008; AAR 2008b). There was concern that while awaiting the successful outcome of the necessary R&D there would be no replacement of the current fleet with safer cars built using the feasible design concepts evaluated by Saat and Barkan (2006) and subsequently used by AAR (2008a) in their proposal due to the uncertainty about the final design requirements. Consequently, at the request of the FRA, the RSI and AAR, together with the American Chemistry Council (ACC), the American Short Line and Regional Railroad Association (ASLRR) and the Chlorine Institute (CI) filed a joint petition requesting interim TIH tank car design standards based on these design concepts (ACC et al. 2008). The petition proposed use of specified minimum tank thickness requirements and conditional probability of release (CPR) performance standards similar to those proposed in Casualty Prevention Circular (CPC) -1187 (AAR 2008a), as described earlier in this Chapter. In summary, the petition proposed the following interim standards:

a) TIHs currently being transported in DOT 105*300W or 112*340W shall be transported in DOT 105J500W with a minimum 13/16” tank thickness and 1/2" full-height head shields

b) TIHs currently being transported in DOT 105*500W or 105*600W shall be transported in DOT 105J600W with a minimum 15/16” tank thickness and 1/2" full-height head shields

c) Top fittings protection shall withstand a 9-mph linear velocity rollover

PHMSA subsequently published an interim final rule (HM-246) (74 FR 1769) containing standards similar to items a) to c) above, but without specifying minimum tank thicknesses greater than allowed under the existing regulations for the particular DOT car types, and without specifying the conditional probability of release performance standard. The HM-246 interim standards specify the minimum tank thickness to be 5/8” for A516-70 steel, or 9/16” for TC128-B steel, or using an existing formula in § 179.100-6(a) in the Code of Federal Regulations Title 49 as follows (CFR 2009):

$$t = Pd / 2SE \qquad (3.6)$$

where:

t = minimum thickness of plate in inches after forming
P = minimum required bursting pressure in p.s.i.
d = inside diameter (ID) in inches
S = minimum tensile strength of plate material in p.s.i
E = 1.0 welded joint efficiency, except for heads with seams = 0.9

I identified example tank car designs that meet HM-246 interim standards based on my assumptions regarding inside diameter and the type of steel to be used (Table 3.10), derived from information previously provided by a major tank car builder (Table 3.9). I then compared the minimum tank car designs currently allowed for specific TIH materials

(Table 3.2) with the proposed new minimum designs specified in CPC-1187 (Table 3.4) and in HM-246 (Table 3.10). A summary of the comparisons is shown in Table 3.11 and Fig. 3.9. For the example HM-246 tank car designs, the minimum tank thicknesses calculated using Equation 3.6 for 13 of the 20 TIH materials are similar or identical to CPC-1187 in terms of their CPR. However, using the same method and assumptions in Table 3.9, seven materials could be permitted for transport in tank cars that meet the HM-246 requirements, but have a tank thickness less than specified in CPC-1187 (Table 3.10, highlighted in grey). For these seven materials, the minimum tank thickness calculated using Equation 3.6 with the specified inside diameter is lower than the minimum tank thickness specified in CPC-1187. Tank cars transporting bromine could have a 60% reduction in CPR relative to the baseline car, compared to a 71% reduction if transported in cars built in accordance with CPC-1187. Another example is fuming sulfuric acid, in which cars could be constructed in accordance with HM-246 and have a reduction in CPR relative to their baseline car of 56% compared to a 64% reduction for the CPC-1187 car.

Table 3.9
TIH alternate tank car designs inside diameter and steel type assumptions

Commodity Name	Head Steel Type	Shell Steel Type	Tank Inside Diameter (in)
Acetone Cyanohydrin	128	128	116
Allyl Alcohol	128	128	116
Ammonia, Anhydrous	516-70	128	115.35
Bromine	128	128	88
Chlorine	516-70	128	106
Chlorosulfonic Acid	128	128	102
Dimethyl Sulfate	128	128	106
Ethyl Chloroformate	128	128	106
Ethylene Oxide	128	128	116
Hexachlorocyclopentadiene	128	128	102
Hydrogen Chloride	516-70	128	106
Hydrogen Cyanide	516-70	516-70	116
Hydrogen Fluoride	128	128	116
Methyl Bromide	128	128	102
Methyl Mercaptan	128	128	116
Phosphorus Trichloride	128	128	106
Sulfur Dioxide	128	128	106
Sulfur Trioxide	128	128	99
Sulfuric Acid, Fuming	128	128	96
Titanium Tetrachloride	128	128	102

Table 3.10
Example alternate tank car designs that meet the HM-246 interim standards

Commodity Name	U.S. DOT Specification	Head Shields Type	Head Thickness (in.)	Shell Thickness (in.)	$P_{R\|A}$	Standard Error	Percent Reduction in $P_{R\|A}$ vs. Baseline (%)
Acetone Cyanohydrin	105J500W	Full-Height	0.8951	0.8951	0.02365	0.00275	72
Allyl Alcohol	105J500W	Full-Height	0.8951	0.8951	0.02365	0.00275	72
Ammonia, Anhydrous	105J500W	Full-Height	1.0300	0.8900	0.02283	0.00262	70
Bromine	105J500W	Full-Height	0.6790	0.6790	0.04029	0.00358	60
Chlorine	105J600W	Full-Height	1.1360	0.9810	0.01886	0.00226	73
Chlorosulfonic Acid	105J500W	Full-Height	0.7870	0.7870	0.03040	0.00320	64
Dimethyl Sulfate	105J500W	Full-Height	0.8179	0.8179	0.02820	0.00307	66
Ethyl Chloroformate	105J500W	Full-Height	0.8179	0.8179	0.02820	0.00307	66
Ethylene Oxide	105J500W	Full-Height	0.8951	0.8951	0.02365	0.00275	72
Hexachlorocyclopentadiene	105J500W	Full-Height	0.7870	0.7870	0.03040	0.00320	69
Hydrogen Chloride	105J600W	Full-Height	0.9810	0.9810	0.01998	0.00225	29
Hydrogen Cyanide	105J600W	Full-Height	1.2429	1.2429	0.01343	0.00157	78
Hydrogen Fluoride	105J500W	Full-Height	0.8951	0.8951	0.02365	0.00275	70
Methyl Bromide	105J500W	Full-Height	0.7870	0.7870	0.03040	0.00320	64
Methyl Mercaptan	105J500W	Full-Height	0.8951	0.8951	0.02365	0.00275	72
Phosphorus Trichloride	105J500W	Full-Height	0.8179	0.8179	0.02820	0.00307	66
Sulfur Dioxide	105J500W	Full-Height	0.8179	0.8179	0.02820	0.00307	66
Sulfur Trioxide	105J500W	Full-Height	0.7639	0.7639	0.03221	0.00329	61
Sulfuric Acid, Fuming	105J500W	Full-Height	0.7407	0.7407	0.03419	0.00337	56
Titanium Tetrachloride	105J500W	Full-Height	0.7870	0.7870	0.03040	0.00320	64

Table 3.11. Conditional Probability of Release for Baseline vs. CPC-1187 vs. HM-246 TIH Tank Cars

	Baseline	CPC-1187		HM-246	
Commodity Name	**$P_{R\|A}$**	**$P_{R\|A}$**	**Percent Reduction in $P_{R\|A}$ vs. Baseline (%)**	**$P_{R\|A}$**	**Percent Reduction in $P_{R\|A}$ vs. Baseline (%)**
Acetone Cyanohydrin	0.08360	0.02365	72	0.02365	72
Allyl Alcohol	0.08360	0.02365	72	0.02365	72
Ammonia, Anhydrous	0.07712	0.02283	70	0.02283	70
Bromine	0.09962	0.02857	71	0.04029	60
Chlorine	0.07045	0.01886	73	0.01886	73
Chlorosulfonic Acid	0.08360	0.02857	66	0.03040	64
Dimethyl Sulfate	0.08360	0.02820	66	0.02820	66
Ethyl Chloroformate	0.08360	0.02820	66	0.02820	66
Ethylene Oxide	0.08360	0.02365	72	0.02365	72
Hexachlorocyclopentadiene	0.09962	0.02857	71	0.03040	69
Hydrogen Chloride	0.02824	0.01998	29	0.01998	29
Hydrogen Cyanide	0.06219	0.01343	78	0.01343	78
Hydrogen Fluoride	0.07904	0.02365	70	0.02365	70
Methyl Bromide	0.08360	0.02857	66	0.03040	64
Methyl Mercaptan	0.08360	0.02365	72	0.02365	72
Phosphorus Trichloride	0.08360	0.02820	66	0.02820	66
Sulfur Dioxide	0.08360	0.02820	66	0.02820	66
Sulfur Trioxide	0.08360	0.02857	66	0.03221	61
Sulfuric Acid, Fuming	0.07846	0.02857	64	0.03419	56
Titanium Tetrachloride	0.08360	0.02857	66	0.03040	64

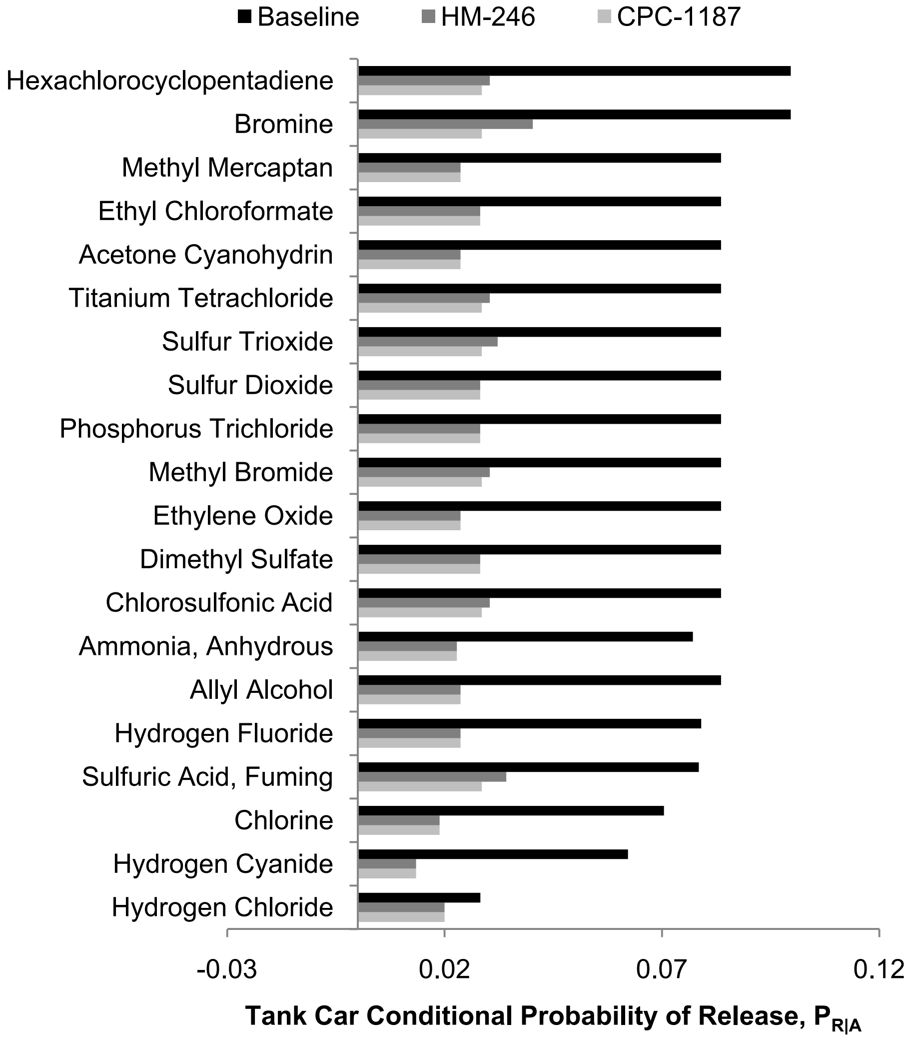


Fig. 3.9. Conditional Probability of Release for Baseline vs. CPC-1187 vs. HM-246 TIH Tank Cars

I found that without a minimum tank thickness requirement, HM-246 interim standards can be attained with the existing tank thicknesses for DOT 105*500W or 105*600W by reducing the inside diameter according to the CFR formula shown in Equation 3.6. Without a higher minimum tank thickness requirement and the lack of the CPR performance standard, the HM-246 interim rule could allow cars to be built with a higher CPR than would be allowable under CPC-1187 for certain products; however, according to AAR, under its authority delegated by the DOT, the AAR's Tank Car

Committee is able to take this into consideration when reviewing applications for construction of new, interim tank car designs for TIH materials and ensure that such cars are not constructed.

3.5.3. Implications for New Tank Car Design Concepts

Recent tank car research has been investigating the feasibility and effectiveness of new materials and designs. These include the use of new, stronger grades of steel for the tank and composite or corrugated metal structures that are intended to absorb the energy of an object impacting a tank car before it penetrates the tank itself (Ward et al. 2007; Tyrell et al. 2007a, b; Kirkpatrick 2009; Jeong et al. 2009). New valve designs are also being evaluated that will substantially reduce the likelihood of release in an accident (Midland Manufacturing 2009).

However, one of the challenges associated with this work is that in the absence of statistical estimates of the performance of these designs in the wide variety of accident scenarios that can occur, it is difficult to quantify their safety performance as accurately as is possible for more conventional designs for which there is an abundance of operating experience and statistical data. Nevertheless, if accident performance estimates and weight data can be developed for these new design concepts, the analytical framework presented in this Chapter can be used to evaluate their effectiveness in reducing risk.

3.5.4. Implications for Other Strategies to Reduce Risk

In the larger context of hazardous materials transportation, there are inter-related factors that can also be considered to reduce the risk (Fig. 3.1). Besides improving tank car safety design, other strategies include infrastructure improvement such as improving track conditions to reduce accident probability; operational changes such as lower operating speed that may reduce release probability or severity; and rerouting to reduce exposure of people or the environment to spills. Implementing any of these strategies may reduce risk, but will also tend to increase cost. These different strategies will also provide widely varying levels of risk reduction for any specific level of investment. The application of the generalized tank car optimization model from Chapter 2 presented here provides a means of developing a set of optimized solutions for a particular group of hazardous materials. This is an essential first step, but the challenge is how to incorporate this into a larger framework, in which all possible approaches to reduce hazardous materials transportation risk are simultaneously evaluated in order to determine the most efficient approach possible.

3.5.5. Uncertainties

The accident-caused release rate metric used in my analysis was statistically derived. In Chapter 2 the metric and associated uncertainties involving tank car conditional probability of release and accident exposures were discussed in more detail, and a method provided to develop confidence intervals around estimates based on the metric. In this Chapter, I reported the standard error of the release rate metric for all tank car designs of interest. The final risk estimates are also subject to uncertainty in the underlying data, such as the emission and atmospheric models used to estimate the potential exposure areas in the emergency response guidebook as discussed by Brown et al. (2000).

3.6. CONCLUSIONS

This Chapter describes an application of a tank car safety design optimization model to evaluate the potential reduction in risk due to rail transport of TIH materials. I used the generalized tank car safety design optimization model developed in Chapter 2 that considers conditional probability of release and tank car weight as proxies for safety and transportation efficiency, respectively. I then employed the utopia-point method to provide insight regarding the best enhanced tank car designs. This model was successfully used by the railroad industry to efficiently develop new tank car design specifications for TIH materials. My analysis showed that the use of these enhanced design standards can potentially reduce the risk by 40 to 78 percent depending on the particular TIH. These results are consistent when one compares the accident-caused release rate, risk per car-mile and risk per ton-mile for baseline versus enhanced tank car safety designs. In subsequent chapters I extend the optimization model in Chapter 2 to include use of the risk analysis model presented here as a framework for benefit-cost analyses to identify optimized tank car safety designs that account for the individual materials' specific hazards.

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CHAPTER 4

RISK-BASED RAILROAD TANK CAR SAFETY DESIGN OPTIMIZATION

4.1. INTRODUCTION

Most railroad transport of hazardous materials is in tank cars (BOE 2009). All regulated materials are not equally hazardous and in general, tank car safety specifications and packaging requirements are commensurate with the degree of risk posed by the product (CFR 2009). However, no formal optimization method has previously been applied to the process of matching safety design features with product hazard. For nearly a century the nominal burst pressure of the tank has been used as a proxy for tank car damage resistance because of its relationship with tank thickness and thus its resistance to damage in accidents (TRB 1994).

Several examples of this practice date to the early decades of the 20th century for tank cars transporting chlorine and sulfur dioxide (Heller 1970; Barkan 2008). Due to the high hazard they pose if released, these products have long been “over-packaged” during rail transportation. The term “over-packaging” is used to describe cars with tanks that are stronger than required to contain the product based solely on the physical and pressure characteristics of the material they are intended to transport. The intent is to provide extra protection from damage in accidents for particular hazardous materials. Beginning in the 1990s, this practice was extended to include poisonous liquids and certain products that pose risk to the environment (60 FR 49047). However, in all these instances the nominal burst pressure and its consequent effect on the tank thickness continued to be used as the metric of safety performance. This practice was also reflected in the recent DOT Interim Final Rule for toxic inhalation hazard (TIH) tank cars (74 FR 1769).

Although controlling tank thickness using the nominal burst pressure rating in the DOT tank specification is consistent with the general objective of matching hazard to tank car damage resistance, it is inexact because other factors affecting tank thickness are not considered. A rational decision making process to reduce the risk of transporting hazardous materials should incorporate the explicit hazard and safety performance of the products being transported to estimate the benefit of changes in tank car damage resistance. Furthermore this can be used in tandem with a cost model to estimate the associated economic implications of using different-design tank cars to identify the optimal design to transport a specific hazardous material.

Tank car design enhancements such as increasing tank head or shell thicknesses, protecting the fittings, or use of head shields, each have a unique functional relationship between incremental safety benefit and weight that affects transportation efficiency and cost (Chapter 2). This tradeoff must be accounted for when optimizing the safety performance of a tank car. Optimality techniques were first applied to tank car safety design by Barkan et al. (2007) who used minimization of conditional probability of release as the objective function to calculate the optimal thickness of a tank. Barkan (2008) subsequently described a goal programming approach used to develop specifications for higher capacity tank cars for transportation of hazardous materials. In Chapter 2 I extended and generalized the optimization techniques used in Barkan (2008) by developing a new, modular approach to consider all of the current elements of tank car safety design, both independently and in combination with one another.

The model described in Chapter 2 enables identification of a specific, Pareto-optimal set that represents the most efficient combinations of tank car safety design options. It accounts for the conflicting objectives of minimizing release probability and quantity, which improves safety, versus the increased capital required for a more robust car and transportation cost due to the reduction in tank car capacity. However, that model does not provide a means of determining what the optimal level of safety or performance is for any particular product.

Two recent examples of enhanced tank car safety design development employed earlier versions of the conceptual approach described in Chapter 2. Barkan (2008) described the approach used to identify the optimal safety design combinations for higher capacity, non-pressure specification tank cars for the Association of American Railroads (AAR). The gross rail load of tank cars was to be increased from 263,000 lbs. to 286,000 lbs. The industries agreed *a priori* that one third of the incremental 23,000 lbs would go toward enhanced safety and the remaining two thirds to extra capacity. Consequently the optimality problem was to develop the appropriate Pareto-optimal sets for both non-insulated and insulated cars and determine which combinations of safety design options came closest to these goals. Another example was discussed in Chapter 3 in which I used the utopia point method to select among the Pareto-optimal set of combinations to identify candidate designs for enhanced tank cars for toxic inhalation hazard chemicals. In that example, I assumed that safety and transportation efficiency were equally weighted, in part because that was what the AAR specified, but largely because no explicit information on how to differentially assign the preference level or weight on safety performance versus railcar capacity or cost was available. Use of the utopia-point method resulted in a reasonably high level of improvement within the feasibility bounds of current tank car design and fabrication concepts and constraints.

The utopia point method or a goal programming formulation can provide an objective approach to identify the optimal solution. However, the underlying assumption of equal preference in the utopia point method, or a decision maker’s specification to allocate a specific weight increment for safety leaves an element of subjectivity in the process of identifying the final decision for individual car designs. In this Chapter I develop a quantitative model that combines the optimization method from Chapter 2 with a benefit-cost approach to determine what the optimal design tank car should be, based on maximizing the net present value (NPV) as the objective function. This is accomplished by assuming a direct relationship between risk and cost and then using the incremental reduction in risk to calculate the benefit term for each alternative design and comparing that to the incremental increase in cost of the corresponding design. The model enables chemical-specific hazard and risk to be used to objectively determine the optimal tank car safety design for each material. The risk-based tank car safety design optimization concept is illustrated in this Chapter by considering three hypothetical chemicals with different hazard levels. Sensitivity analyses of several other parameters affecting the optimal design were also conducted.

4.2. IDENTIFYING PARETO-OPTIMAL SOLUTIONS

In considering safety design enhancements for a given baseline tank car to transport a specific hazardous material, the first step is to identify a set of Pareto-optimal design alternatives using the model developed in Chapter 2. Safety design variables involved are the risk reduction options (RROs) including tank head and shell thicknesses, type of head shields, use of a tank jacket, and other specific RROs discussed in Chapter 2. The feasibility of each RRO depends on the baseline tank car safety design under consideration for improvement, and also the scope of the options specified by stakeholders interested in a specific risk analysis.

For purposes of illustration, in this Chapter I consider a general purpose, 20,000-gallon capacity, non-jacketed DOT 111A100W tank car with 0.4375” tank thickness and equipped with bottom fittings as the baseline tank car design (Fig. 4.1). To illustrate the model, a simplified approach was used in which the only RRO considered was to increase tank head and shell thickness using 1/16-in increments. The methodology can be adapted to any baseline design and any set of RROs of interest in a particular problem.

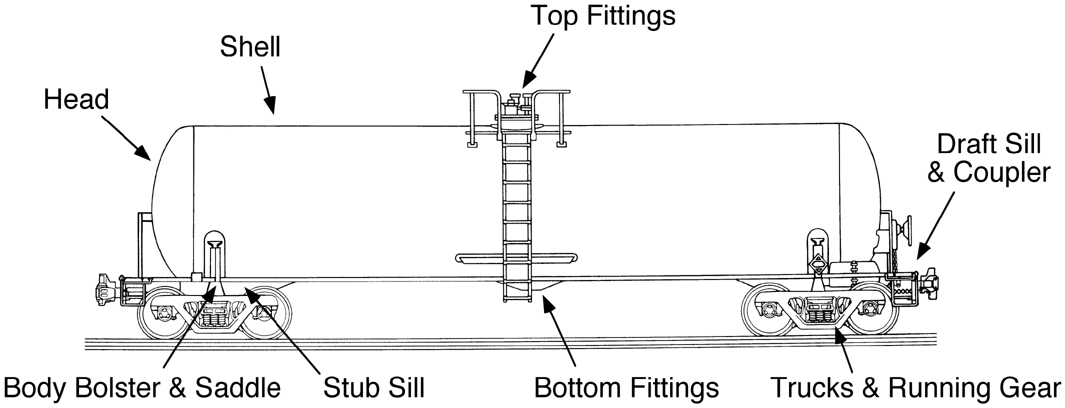

Fig. 4.1. Diagram of a typical non-jacketed North American railroad non-pressure tank car

I applied the generalized tank car safety design optimization model in Chapter 2 to identify the Pareto-optimal set of design solutions that provides the most efficient reduction in the expected quantity lost with the increase in tank car weight (Table 4.1, Fig. 4.2). This set of Pareto-optimal solutions is used in the following sections to illustrate a risk-based tank car safety design optimization model to identify the optimal design to transport three chemicals; L, M and H corresponding to products with the same density, but but with low, medium and high hazard levels, respectively.

Table 4.1
Enumeration of the expected quantity lost in an accident and weight for the Pareto-optimal solutions based on the 20,000-gallon baseline tank car with increasing tank thickness

Head and Shell Thickness (in.)	Light Weight (lb)	Capacity (gallons)	Expected Quantity Lost (gallons)	Percentage Change in Light Weight (%)
0.4375 (Baseline)	59,535	20,000	3,124	0
0.5000	62,370	19,722	2,773	5
0.5625	65,133	19,450	2,468	9
0.6250	67,828	19,185	2,207	14
0.6875	70,455	18,927	1,985	18
0.7500	73,019	18,675	1,798	23
0.8125	75,522	18,429	1,641	27
0.8750	77,964	18,189	1,509	31
0.9375	80,350	17,954	1,398	35
1.0000	82,680	17,725	1,305	39
1.0625	84,956	17,502	1,226	43
1.1250	87,181	17,283	1,159	46
1.1875	89,356	17,069	1,102	50
1.2500	91,483	16,860	1,054	54
1.3125	93,564	16,655	1,011	57
1.3750	95,599	16,455	975	61
1.4375	97,590	16,260	943	64
1.5000	99,540	16,068	914	67

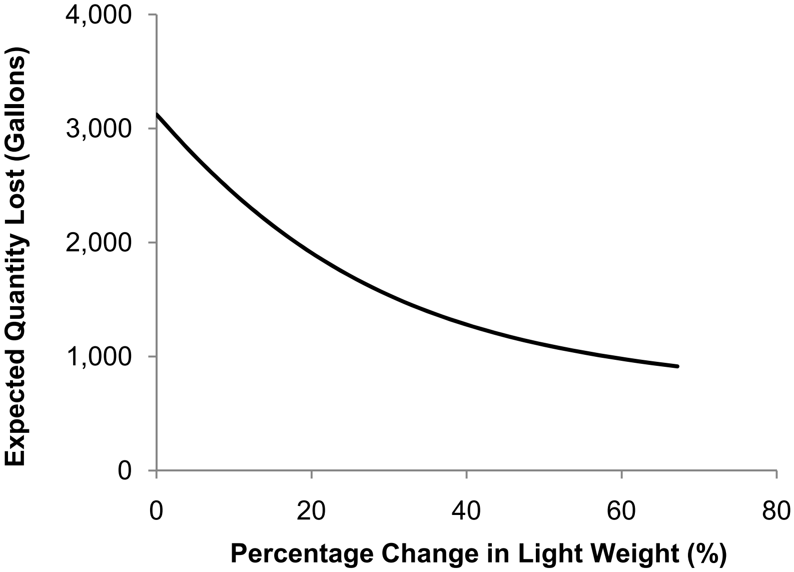

Fig. 4.2. Relationship between the weight and expected quantity lost for the Pareto-optimal solutions based on the 20,000-gallon capacity baseline tank car

4.3. RISK ANALYSIS FRAMEWORK

Risk can be defined as the probability of an event multiplied by the consequence of the event. For a set of Pareto-optimal solutions identified, the accident-caused release risk can be estimated as follows:

$$R_{R_j} = P_{R_j} \times P_{Q_i|R} \times Q_i \times C_j \qquad (4.1)$$

where:

R_{R_j} = accident-caused risk for transporting chemical j

P_{R_j} = accident-caused release rate for a tank car transporting chemical j as defined in Chapter 2

= $P_{R|A} \times P_A \times M_j \times Cap/Cap'$

where:

$P_{R|A}$ = conditional probability of a tank car release given the car is derailed in an FRA-reportable accident

P_A = tank car derailment rate per car-mile

M_j = number of car miles involved to transport chemical j

Cap = nominal volumetric capacity of a baseline tank car

Cap’ = nominal volumetric capacity of an alternate-design tank car

$P_{Q_i|R}$ = probability of release size i given that a tank car released its contents
Q_i = average release quantity
= average percentage tank capacity lost for release size i × tank car capacity
C_j = chemical j release consequence

The term P_R represents the “probability” or the frequency in the risk definition, while the other terms on the right side of the equation represent the consequence. The severity of release consequence, C, is based on the chemical-specific hazard and the quantity released. For the three hypothetical chemicals L, M and H, I assumed $C_L < C_M < C_H$, where $C_M = 5\ C_L$ and $C_H = 10\ C_L$. Fig. 4.3 shows possible hypothetical risk per ton-mile functions associated with chemicals L, M and H.

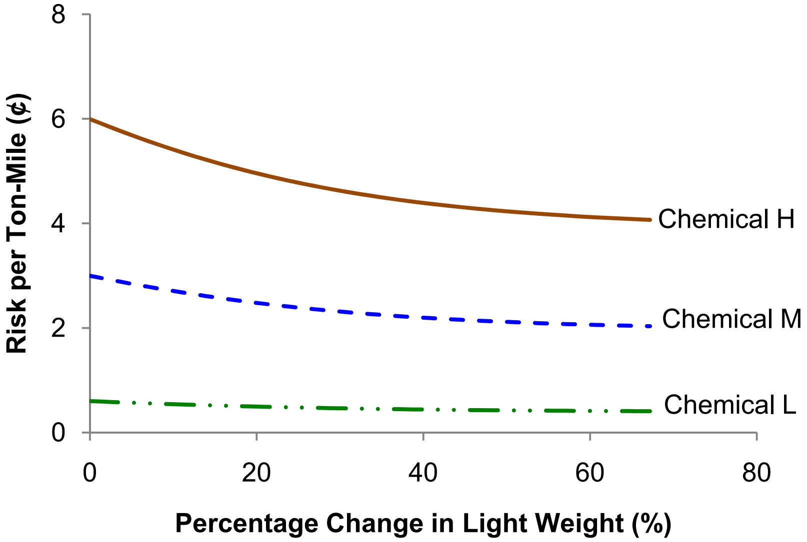

Fig. 4.3. Risk per ton-mile for the Pareto-optimal set of solutions for a car transporting three hypothetical chemicals with the same density but, with low (L), medium (M) and high (H) hazard levels

4.4. NET PRESENT VALUE ANALYSIS

A net present value (NPV) approach is used in this Chapter to determine the cost-effectiveness of replacing tank cars in a specific hazardous material service. Cost and benefit streams generally extend into the future from some decision point. The NPV method accounts for the future benefits and costs, and the time value of money within a specific analysis period, to provide an objective means for decision makers to compare the cost-effectiveness of different feasible alternatives.

4.4.1. Fleet Replacement Schedule

The time-frame over which the current fleet of tank cars is replaced, i.e. total years needed to completely replace a tank car fleet with a new alternative, enhanced-design car, is important for the benefit-cost analysis. Chemicals with extremely high hazard may justify an immediate fleet replacement with enhanced-design tank cars. With this scenario, the full benefit and cost would be accrued immediately. Even if this can be economically cost-justified, in practice, this scenario is only likely to be feasible for a relatively small fleet of cars because of limits in car-building capacity. Alternatively, in an attrition-based schedule, tank cars are replaced with enhanced designs at the end of their normal service life, typically between 30 to 40 years. With this scenario, the full benefit and cost are accrued proportionately over the life-span of a tank car. Another possible scenario is an accelerated replacement schedule over a specified period of n years. With this scenario, $1/n$ of the fleet is replaced annually, and the benefit and cost would be accrued proportionally over the n-year period after which the benefit and cost would be fully realized (Anand 2006).

4.4.2. Benefit Analysis

Given a specific replacement schedule, the benefit at year t within a specific present-value analysis period for replacing baseline tank cars with enhanced-design cars in a fleet can be calculated as follows:

$$\text{Benefit}_t = \left(\widehat{R}_R - R_R\right) \times \rho_t \qquad (4.2)$$

where:

Benefit_t = risk reduction or benefit at year t
$\widehat{R}_R$ = accident-caused risk (Eqn. 1) when baseline tank car design is used
R_R = accident-caused risk (Eqn. 1) when enhanced tank car design is used
ρ_t = proportion of total tank car fleet replaced at year t
    $\rho_t = (t + 1)/\theta$ if $(t + 1) \leq \theta$, else $\rho_t = 1$
θ = phase-in period based on tank car fleet replacement schedule

Subsequently, present-value benefit can be estimated as follows:

$$PV_{\text{Benefit}} = \sum_{t=0}^{Y} \frac{\text{Benefit}_t}{(1+i)^t} \qquad (4.3)$$

where:

PV_{Benefit} = present-value benefit or risk reduction
Y = present-value analysis period
i = interest rate

Fig. 4.4 shows the incremental present-value benefit per ton-mile for chemicals L, M and H as a function of increasing weight as tank thickness increases.

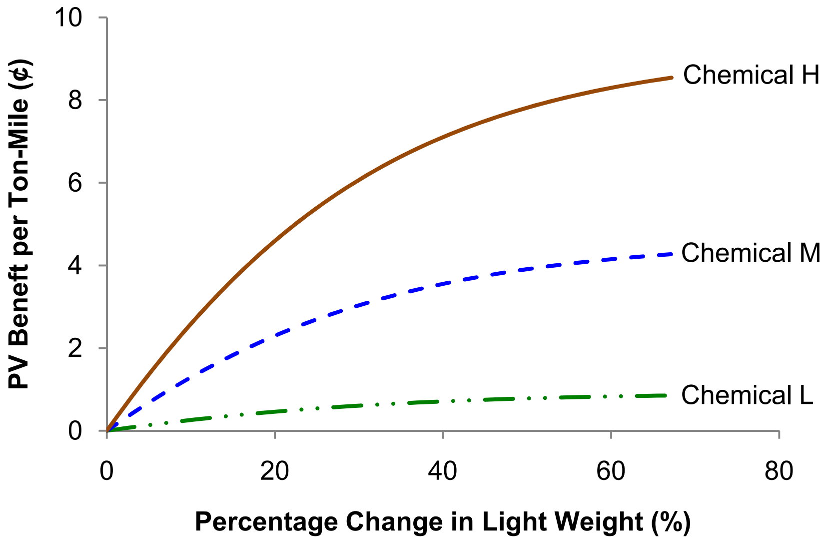

Fig. 4.4. Benefit per ton-mile for the Pareto-optimal solutions relative to the baseline tank car transporting three hypothetical chemicals with the same density but different hazard levels

4.4.3. Cost Analysis

Tank car replacement incurs incremental increases in both capital and operating costs. In the analysis presented here, capital includes total tank car life-cycle cost, i.e. the cost of buying a new car, maintenance costs and other expenses throughout the life-span of a car. It must also account for the total number of tank cars required to replace a fleet, and the replacement schedule. Operating cost accounts for the total number of shipments and the cost per trip. Total cost is the sum of capital and operating costs for any particular design. Note that in my model, tank car maintenance cost was included in the capital cost estimation, but in practice, maintenance cost may be treated as an operating cost. In terms of the NPV calculation the difference in the estimated total costs using either approach is not large enough to affect the outcome of the optimality analysis.

4.4.3.1. Identifying Minimum Tank Car Fleet Size

The weight of a fully loaded railcar in North America is constrained to not exceed what is referred to as the maximum gross rail load (GRL), which for tank cars is affected by both federal regulations and rail industry interchange standards (CFR 2009; AAR 2007). Most conventional tank car safety enhancements increase the weight of the car, thereby reducing its capacity and transport efficiency due to the limit on the maximum GRL. Consequently, more shipments and possibly more cars are needed to transport the same amount of product. Increasing tank car utilization rate, i.e. the number of trips per car per year, has the potential to compensate for the reduction in tank car capacity due to use of heavier, but more damage resistant designs. These two approaches have slightly different effects on the cost function because certain capital costs will increase due to the larger fleet size, whereas these extra costs will not be incurred if utilization is increased. Conversely, certain maintenance-related costs may increase with higher utilization.

For tank car fleet replacement involving a specific enhanced-design car, the minimum total number of cars to be replaced and possible additional cars needed to compensate for the reduction in capacity can be calculated as follows:

$$N = \frac{S \times Cap/Cap'}{T} \qquad (4.4)$$

where:

N = minimum total enhanced-design tank cars in a fleet
S = annual number of shipments with baseline tank cars
Cap = nominal volumetric capacity of a baseline tank car
Cap’ = nominal volumetric capacity of an enhanced-design tank car
T = tank car utilization rate (annual trips per car)

4.4.3.2. Tank Car Fleet Replacement or Capital Cost Estimation

The total cost of replacing a fleet of tank cars within a specific present-value analysis period can be estimated by multiplying the total number of tank cars replaced in year *t* with tank car life-cycle cost as follows:

$$PV_{Fleet} = \sum_{t=0}^{Y} \frac{LC_{TankCar} \times m_t}{(1+i)^t} \qquad (4.5)$$

where:

PV_{Fleet} = present value of total fleet replacement cost
$LC_{TankCar}$ = life-cycle cost of a tank car
m_t = total number of enhanced-design tank cars entering the fleet in year t
Y = present-value analysis period

Determination of a tank car's life-cycle cost requires information regarding its unit cost and detailed maintenance and depreciation schedules. The life-cycle cost can also be inferred from tank car weight. Heavier and larger cars, in general, have higher life-cycle costs due to the larger quantity of steel and certain other materials required for construction. Information on actual tank car costs was used to develop a hypothetical capital cost function to illustrate the model using the Pareto-optimal solutions defined in Section 4.1 (Fig. 4.5).

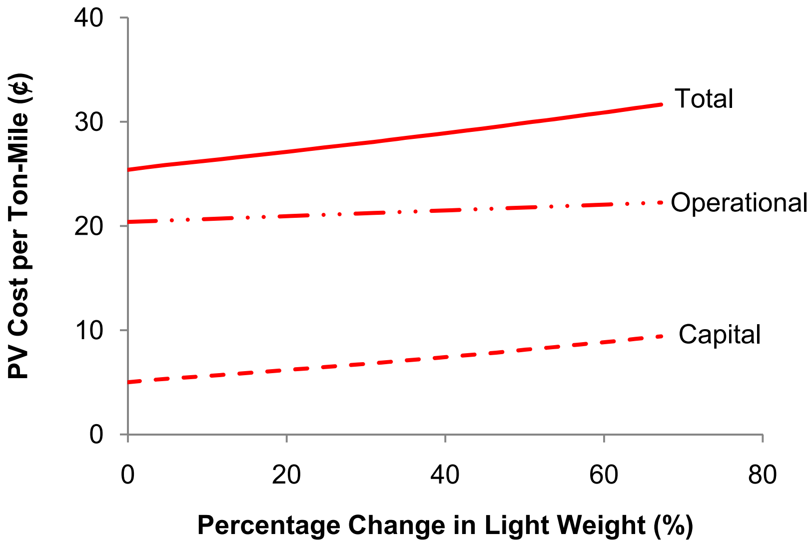

Fig. 4.5. Present-value capital, operational and total costs per ton-mile for the Pareto-optimal solutions based on the 20,000-gallon capacity baseline tank car

4.4.3.3. Operating Cost Estimation

The cumulative present value of the operating cost for a fleet over a particular analysis period can be calculated as follows:

$$PV_{Opr} = \sum_{t=0}^{Y} \frac{M \times C_{Opr}}{(1+i)^{t}} \qquad (4.6)$$

where:

PV_{Opr} = present value of total fleet operational cost
M = number of car miles
C_{Opr} = operating cost per mile

Using the Surface Transportation Board (STB) waybill cost data for Chemicals or Allied Products, operating cost per car mile was estimated to be $1.46 (STB 2006). This value remains constant for any alternative tank car designs as the total number of shipments is held unchanged by Equation 4.4.

4.4.3.4. Incremental Cost Estimation

For the NPV analysis, estimated present-value costs can be compared to the baseline costs to get the incremental present-value costs (Fig. 4.6) as follows:

$$PV_{\text{Incremental Cost}}=\left[PV_{\text{Fleet}}+PV_{\text{Opr}}\right]-\left[\widehat{PV}_{\text{Fleet}}+\widehat{PV}_{\text{Opr}}\right] \qquad (4.7)$$

where:

$PV_{\text{Incremental Cost}}$ = present value of total incremental cost
PV_{Fleet} = present value of fleet replacement cost with enhanced-design tank cars
PV_{Opr} = present value of operational cost with enhanced-design tank cars
$\widehat{PV}_{\text{Fleet}}$ = present value of fleet replacement cost with baseline tank cars
$\widehat{PV}_{\text{Opr}}$ = present value of operational cost with baseline tank cars

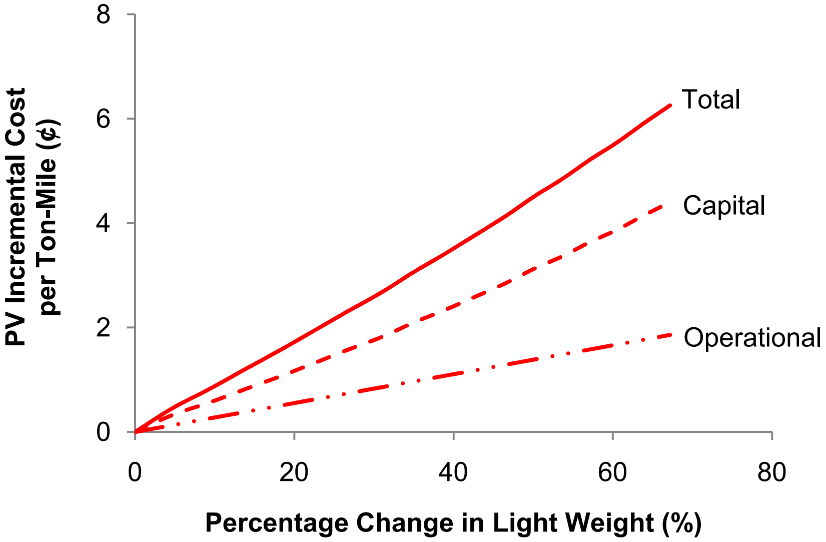

Fig. 4.6. Incremental present-value capital, operational and total costs per ton-mile for the Pareto-optimal solutions based on the 20,000-gallon capacity baseline tank car

4.4.4. Cost Effectiveness Evaluation

Once the benefit and total incremental cost associated with each of the Pareto-optimal design solutions under consideration have been estimated, an objective function must be specified to evaluate the cost-effectiveness of the designs. In the context of a benefit-cost analysis, the objective function is to maximize net present value as follows:

$$\mathbf{Max}\ \mathrm{NPV} = \mathrm{PV}_{\mathrm{Benefit}} - \mathrm{PV}_{\mathrm{Incremental\ Cost}} \qquad (4.8)$$

Optimal tank car designs for the hypothetical chemicals L, M and H, based on hypothetical benefit and total incremental cost functions defined above, are shown graphically in Figs. 4.7 and 4.8. When the chemical's hazard level and the consequent risk are high, as illustrated by the curve for Chemical H (Fig. 4.7), the benefit is greater than the incremental cost over the entire range of tank car designs considered. Solution A gives the maximum NPV for Chemical H. On the other hand, in the case when the chemical's hazard level and the consequent risk are sufficiently low, as illustrated by the curve for Chemical L, the incremental cost is greater than the benefit over the entire range of tank car designs considered. In this case, tank car safety design enhancement is not cost-justified, and the status-quo with the baseline tank car design, solution C, is the optimal solution. For cases falling between these two scenarios, as illustrated by the curve for chemical M, the Pareto-optimal solutions yield a positive NPV up to a point when the cost equals the benefit. For Chemical M, solution B gives the maximum NPV, and solution D provides the maximum safety enhancement without any increase in cost, which I refer to as the cost-neutral or zero-NPV solution.

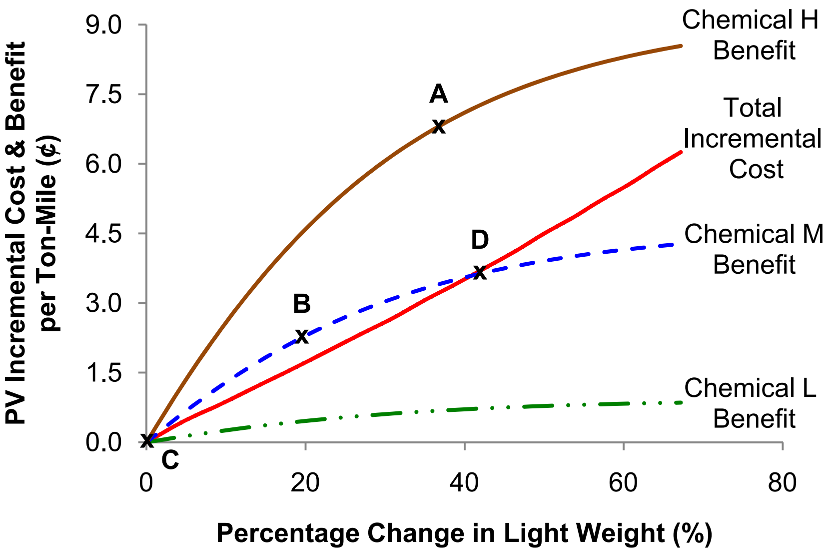

Fig. 4.7. Present-value benefit and incremental total costs per ton-mile for the set of Pareto-optimal solutions based on the 20,000-gallon capacity baseline tank car for chemicals with the same density but different hazard levels

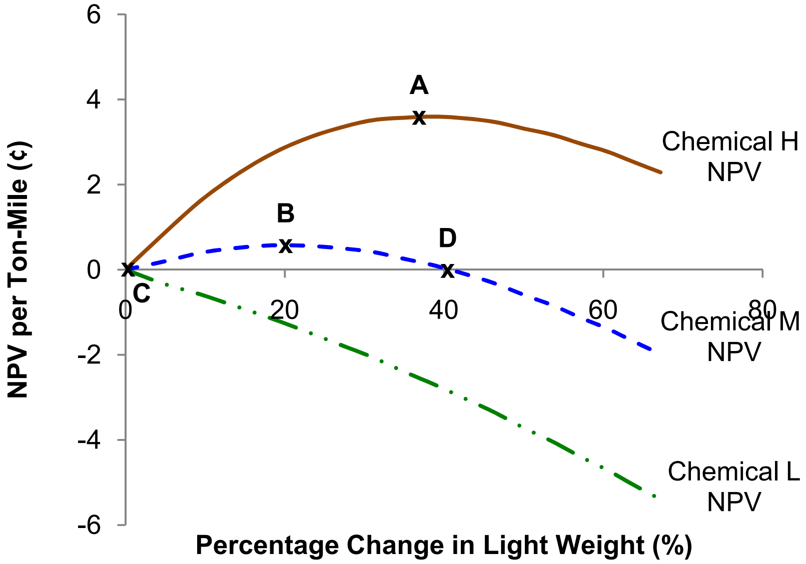

Fig. 4.8. Net present value per ton-mile for the set of Pareto-optimal solutions based on the 20,000-gallon capacity baseline tank car for chemicals with the same density but different hazard levels

4.5. SENSITIVITY ANALYSIS

The risk-based tank car safety design optimization model and its components have been developed and illustrated with a set of hypothetical functions and assumptions. In actual applications in which more different RROs are considered, there will often be one or more non-linearities in the benefit and cost estimations associated with the various parameters that will affect the particular optimal solution. Analyzing the implications of varying certain key parameters offers additional insights in estimating the sensitivity level of the optima to these parameters. Two important parameters to analyze are tank car utilization rate and product density.

4.5.1. Effect of Varying Tank Car Utilization Rate

Varying tank car utilization rate, “T” in Equation 4.4, changes the minimum number of tank cars in a fleet (see earlier discussion in Section 4.3.3.1). Fig. 4.9 shows the hypothetical capital cost functions when T is varied by factors of 0.5 and 3 relative to the base-case assumption used in Section 4.3.4 to analyze the Pareto-optimal set of solutions for Chemical M. Even without considering enhanced tank car designs, the capital cost is expected to change when tank car utilization rate is varied. This is reflected by a higher intercept when the rate is reduced by 50 percent (0.5 T), and a lower intercept when a higher utilization rate is used (3.0 T) (Fig. 4.9). The shift in the capital cost function with the change in tank car utilization rate changes the incremental cost function in the NPV analysis. Consequently, this results in different optima as noted by solutions B (the original optima), B_1 and B_2 (Fig. 4.10). Specifically, higher tank car utilization rate reduces the incremental cost, and thus increases the NPV, and moves the optima to the right for more robust safety designs.

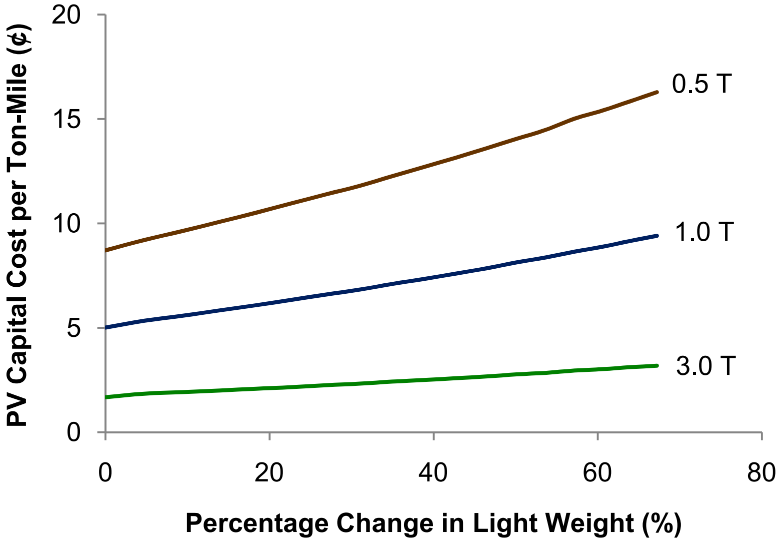

Fig. 4.9. Net Present value capital cost per ton-mile for the set of Pareto-optimal solutions based on the 20,000-gallon capacity baseline tank car for Chemical M

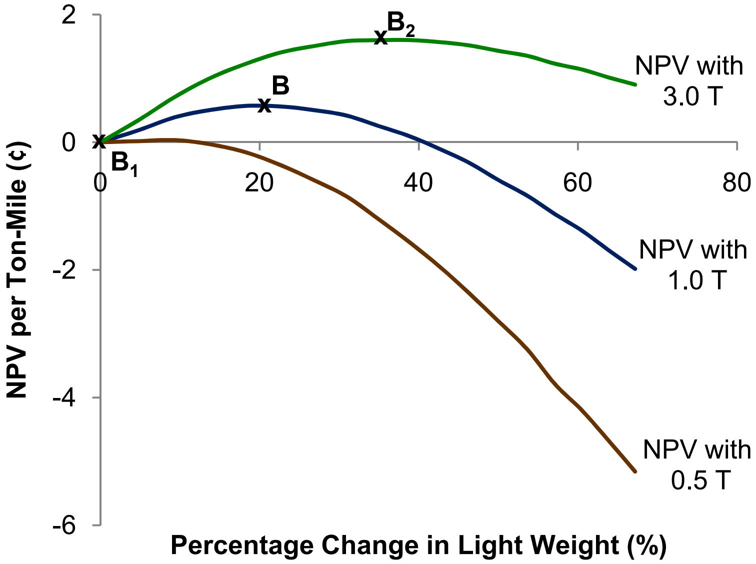

Fig. 4.10. Net present value per ton-mile for the set of Pareto-optimal solutions based on the 20,000-gallon capacity baseline tank car for Chemical M

4.5.2. Effect of Varying Product Density

I varied the capacity of the baseline tank car considered in Section 4.1 from 20,000 to 10,000 and 30,000 gallons by changing the product density from 10.2 to 21.4 and 6.4 lbs/gal., respectively, and followed the same procedures to identify the set of

Pareto-optimal solutions for each baseline tank car (Fig. 4.11). Assuming a hazard level equivalent to Chemical M, I expect the benefit and incremental cost functions to be different due to the difference in the Pareto-optimal set (Fig. 4.12). Different size tank cars, even with the same safety designs, have different expected quantity lost given the cars are involved in accidents (Chapter 2). This affects the risk and the consequent benefit estimation (Equations 4.1 and 4.2). Similarly, as tank car weight and size influence a car's unit cost, the incremental cost function varies for products with different densities (Equation 4.5). The change in the benefit and cost result in different optima as noted by solutions B (the original optima), B_1 and B_2 (Fig. 4.12).

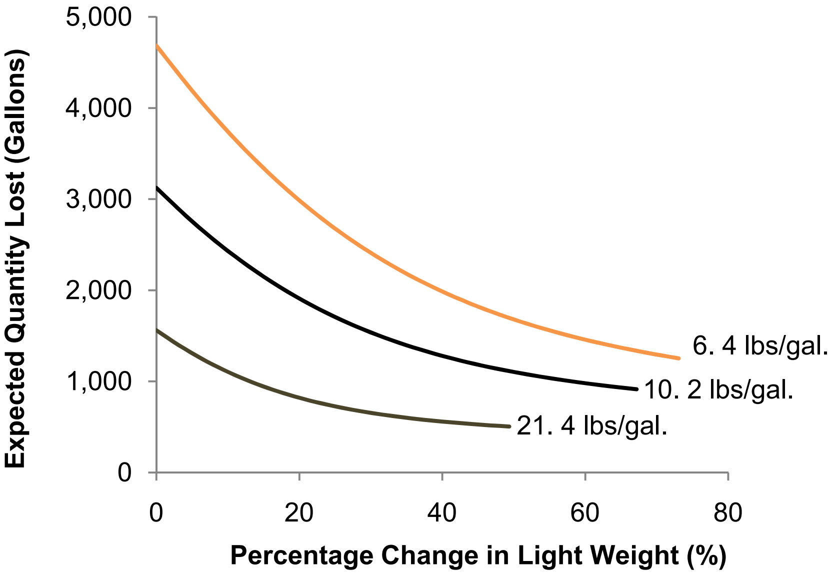

Fig. 4.11. Relationship between the weight and expected quantity lost for the sets of Pareto-optimal solutions based on the baseline tank cars for chemicals with different product densities

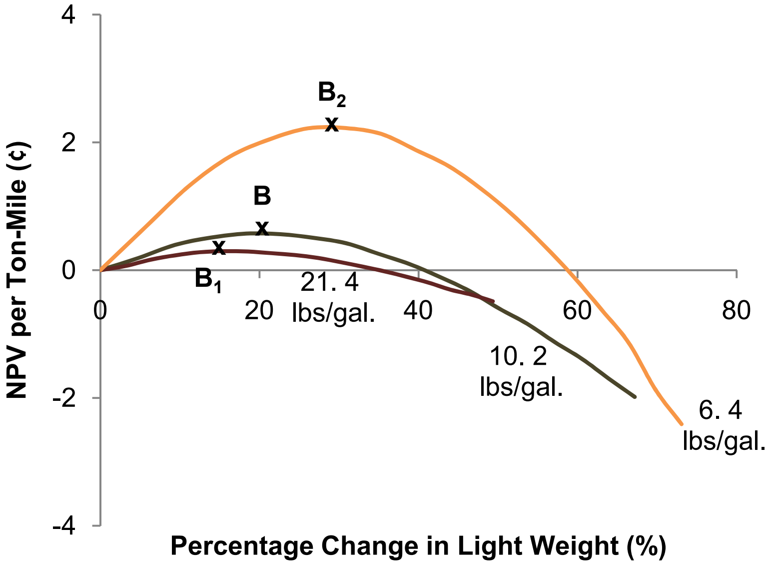

Fig. 4.12. Net present value per ton-mile for the sets of Pareto-optimal solutions based on the baseline tank cars for chemicals with different product densities

4.6. DISCUSSION

4.6.1. Implications for Current Packaging Practices

The model presented provides an approach to incorporate chemical hazard level to explicitly determine the optimal tank car safety design. Not surprisingly, the model predicts that chemicals with higher hazards will have optimal tank car designs that are heavier and more damage-resistant than those of less hazardous chemicals. In an application of this model, the unique, Pareto-optimal set of combinations for tank car safety enhancement designs would be used for each particular chemical and car design problem. On the cost side, a more detailed model would also be used that accounts for tank car unit cost, depreciation, maintenance and inspection costs, and other factors that may uniquely pertain to the particular products and car designs.

4.6.2. Implications of Higher Car Utilization Rate

Car utilization rate has a major impact on cost (Fig. 4.9) which in turn can dramatically affect the optimal solution (Fig. 4.10). Improving tank car productivity by increasing its utilization rate offers the potential to reduce the overall cost of fleet replacement. This approach does not change the benefit, but can result in a smaller fleet to transport the same amount of product, thus reducing the capital cost.

However, there are other factors that may constrain increasing utilization rate to enhance the economics of more damage-resistant tank cars. The average utilization rate for tank cars transporting some products may be as low as four or five trips per year. While this may seem inefficient the explanation is that in addition to their transportation function, tank cars frequently serve in a warehouse function. Cars will be loaded with product and held pending a customer order or request for delivery, or alternatively may provide a storage function to customers as the product is used at the destination. This practice constrains and complicates analysis of the effect of car utilization rate on optimized tank car safety design. Nevertheless, it is worthwhile for railroads, tank car owners and chemical shippers alike to understand the implications of these logistical decisions and the effect they have on tank car safety design economics.

4.6.3. Implications of Different Product Densities

The optimal solution is also affected by product density, due to its effects on both spill volume and tank car size and thus cost. The size of tank cars is generally optimized for the density of the specific product they are intended to transport (Saat and Barkan 2005; Barkan et al. 2007; Barkan 2008). Products vary considerably in their density, and the size of a tank car is inversely related to the density of its intended product due to the maximum

GRL constraint discussed in Section 4.3.3.1. There are a different set of Pareto-optimal solutions for tank cars transporting products of different densities. This affects both the benefit and cost estimations. This factor must also be taken into account along with chemical hazard, when comparing the risk reduction, and consequent cost to identify optimal tank car design.

4.6.4. Implications for New Tank Car Design Concepts

The risk-based tank car safety design optimization model presented in this Chapter was illustrated by considering conventional tank car risk reduction options involving designs, materials and construction processes currently available in the industry. As discussed in Chapter 2, there is ongoing tank car safety research on new tank car design concepts (Ward et al. 2007; Tyrell et al. 2007a, b; Kirkpatrick 2009; Jeong et al. 2009). However in the absence of statistical estimates of the performance of these designs, it is difficult to quantify their performance as accurately as is possible for conventional designs. If the needed performance, weight and cost data can be developed for the new design concepts, the model described in this Chapter can be adapted to evaluate them with the same objective of identifying the optimal combination of design features based on chemical-specific hazard and risk.

4.7. CONCLUSIONS

This model is intended to provide a formal framework to consider the cost-effectiveness of using more robust tank car designs in hazardous material service. For the purpose of illustration, idealized sets of benefit and cost curves derived from empirical data were developed. The NPV approach was used to select the optimal solution among the

Pareto-optimal set of solutions. Chemical hazard level affects the cost-effectiveness of tank car safety design enhancements, and more robust designs are justified for transport of higher-hazard chemicals. In addition, tank car utilization rate and product density affect the optimal solutions.

To my knowledge this is the first formal approach to optimizing tank car safety design, based on product hazard and tank car characteristics. This model can be used in conjunction with other strategies such as rail infrastructure and operations changes, and route alternative analysis as part of a consolidated approach to manage the risk of transporting hazardous materials in the most efficient and effective manner.

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CHAPTER 5

ENVIRONMENTAL RISK ANALYSIS OF RAIL TRANSPORTATION OF HAZARDOUS MATERIALS

5.1. INTRODUCTION

In North America, rail offers the safest and generally the most economical means of transporting hazardous materials. Rail safety has continued to improve due to effective prevention of accidents, and prevention of spills from railcars involved in accidents (Harvey et al. 1987; Barkan et al. 1991; Gallamore 1999; Dennis 2002; Barkan 2008; BOE 2009). In addition to ongoing infrastructure and train control improvement efforts to reduce the likelihood of accidents, the railroad industry and the U.S. Department of Transportation (DOT) has been involved in continuous initiatives to improve the safety design of tank cars transporting hazardous materials (TRB 1994; 60 FR 49047; FRA 1996; Barkan et al. 1991; Barkan 2008; AAR 2008; 74 FR 1769; Chapter 3). These initiatives involved hazardous materials risk assessments and evaluations of tank car safety design enhancements to reduce the risk.

In Chapter 4, a risk-based tank car safety design optimization model that accounts for chemical-specific hazard and consequent benefit and cost was introduced. This is an extension of the bicriteria optimization model in Chapter 2 that addressed the tradeoff between safety and transportation efficiency to identify the set of Pareto-optimal tank car safety design solutions. The risk-based optimization model is intended to be used to analyze the cost-effectiveness of replacing tank cars in any hazardous material service with more robust design alternatives. A comprehensive risk assessment is needed to use the model or to evaluate other possible risk reduction strategies. Chapter 3 presented a risk analysis of transporting toxic inhalation hazard (TIH) materials by rail, and the possible risk reduction if enhanced safety tank car designs are used. The main concern addressed in that Chapter was risk to human safety. In this Chapter, I focus on environmental risk, in particular, the risk of soil and groundwater cleanup expense in the event of a hazardous material spill from a railroad tank car involved in an accident. The risk analysis framework developed in this Chapter will be combined in Chapter 6 with the risk-based tank car safety design optimization model from Chapter 4 to evaluate the cost-effectiveness of different tank car safety design alternatives.

Most previous analyses of hazardous material transportation risk have been primarily concerned with acute risk to human health due to release of toxic or flammable materials (Purdy et al. 1988; Brockhoff et al. 1992; Purdy 1993; Saccomanno and Shortreed 1993; Zhang et al. 2000; Hwang et al. 2001; Chapter 3). The first study addressing environmental risk due to hazardous material rail transportation was presented by Barkan et al. (1991). They conducted a quantitative environmental risk analysis for the Association of American Railroads (AAR) using empirical environmental cleanup cost data from major railroads in the U.S. Their research focused on a group of halogenated organic liquids because railroad experience indicated that these were the most difficult and costly to clean up. Other materials such as light, non-aqueous-phase liquid (LNAPL) chemicals and many other materials were not considered. Their work also did not account for variations in chemical properties among different materials or hydrogeological features along rail lines. Since then, advances in environmental modeling, geographic information system (GIS) and accessible railroad and environmental feature databases have enabled more sophisticated exposure analyses.

The AAR has continued its interest in developing better quantitative understanding of the environmental risk due to spills of hazardous materials, and supporting research in this area. Anand and Barkan (2006) developed geographical probability distributions of soil types and depths to groundwater along rail lines in the U.S. Subsequently, Anand (2006) developed a risk analysis model that accounted for railroad accident probabilities, tank car safety performance, chemical characteristics and the variation of different soil types and depths to groundwater at the location of a spill. The environmental consequence model available to Anand (2006) at that time did not consider mechanistic NAPL movement and chemical dissolution and transport in groundwater. Yoon et al. (2009) developed a more comprehensive, quantitative screening model to assess NAPL infiltration into soils, groundwater transport, and groundwater cleanup time. Hridaya (2008) updated the Hazardous Materials Transportation Environmental Consequence Model (HMTECM) developed by Yoon et al. (2009) to include a free product recovery module to simulate pumping extraction of low-solubility LNAPL from the lens at the groundwater table, and Schaeffer et al. (2008) conducted a series of validation and verification analyses of the HMTECM.

In this Chapter, I used the latest version of HMTECM combined with a set of unit costs for specific remediation technologies from multiple databases to estimate the soil and groundwater cleanup costs. I extended the risk analysis model in Anand (2006) by developing a more comprehensive groundwater geographic dataset and considered chemical-specific rail transportation routes to determine the exposure to different hydrogeological features along rail lines. I then developed generalized regression equations for a set of LNAPL chemicals to estimate expected cleanup cost for soil and groundwater as a function of spill volume. I also considered the consequence costs related to potential exposure to human population and train delay. Accident-caused release rate was estimated based on the most common tank car specifications used to transport the set of LNAPLs under consideration, their total annual shipments, and train derailment accident rate. Resultant risk estimates are presented in terms of annual risk, and risk per car-mile and per ton-mile.

5.2. RISK ANALYSIS METHODOLOGY

Risk in general can be defined as the product of the probability and the consequences of an event. In the context of railroad hazardous materials transportation, a simplified definition of risk is as follows:

$$R=\sum_{i} P_R \times P_i \times C_i \qquad (5.1)$$

where:

R = risk of transporting a hazardous material
P_R = accident-caused release rate as defined in Chapter 2
P_i = probability of a release impact i occurring
C_i = consequence level from a release impact i
i = release impacts to people, property, the environment and other risk receptors

My analysis focused on Federal Railroad Administration (FRA) reportable incidents on U.S. railroad mainlines. The FRA database and reporting threshold[5] provides

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[5] The threshold is equal to \$8,900 in 2009

a standard baseline accident rate upon which to base consistent risk estimates. Railroads are required to report to the FRA all accidents that exceed a specified monetary threshold for damages to track, equipment and structures (FRA 2009). Non-FRA-reportable accidents were not considered because by definition they are small and are less likely to result in a release and thus pose less risk. I also do not consider yard accidents because they too are a less important source of risk. Throughout this Chapter, all derailment and accident terms refer to FRA-reportable mainline accidents.

Fig. 5.1 shows a generic event tree summarizing the risk analysis framework used in this study. For simplicity, only one branch is expanded at each node. Each of the probability and consequence elements are described in more detail in the following sections.

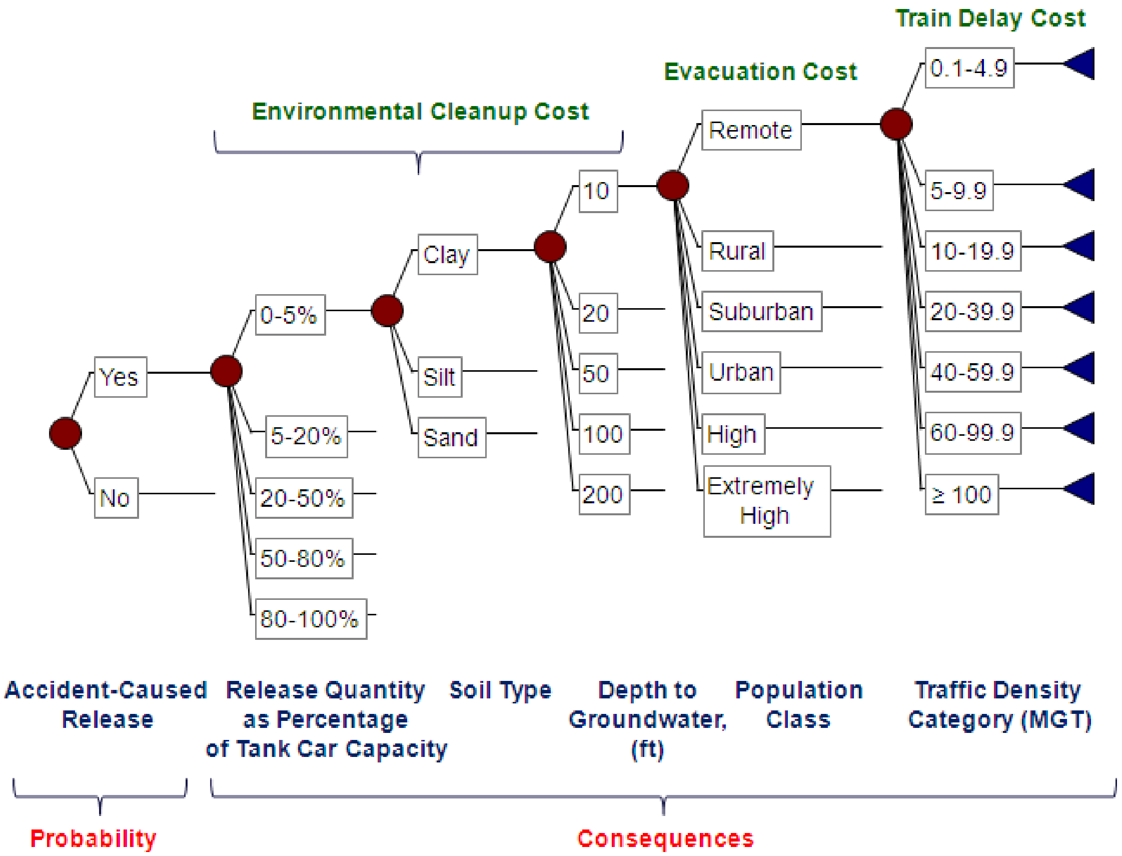

Fig. 5.1. Generic event tree summarizing risk analysis framework

5.2.1. Chemicals for Consideration

Table 5.1 summarizes the group of chemicals considered in this study. The set represents the most commonly shipped pure LNAPL chemicals that can be analyzed using the current version of HMTECM, which is the most up-to-date environmental consequence model currently available.

Table 5.1
Chemicals of interest.

Chemical Name	Hazardous Material Code
Acrylonitrile	UN1093
Benzene	UN1114
Butyl Acrylates	UN2348
Cyclohexane	UN1145
Ethanol	UN1170
Ethyl Acetate	UN1173
Ethyl Acrylate	UN1917
Methanol	UN1230
Methyl Methacrylate	UN1247
Styrene	UN2055
Toluene	UN1294
Vinyl Acetate	UN1301
Xylenes	UN1307

5.3. PROBABILITY ANALYSIS

The accident-caused release rate metric from Chapter 2 was used to estimate the rate of an accident-caused release event using the equation:

$$P_R = P_{R|A} \times P_A \times M \times Cap/Cap' \qquad (5.2)$$

where:

P_R = tank car accident-caused release rate
$P_{R|A}$ = conditional probability of a tank car release given the car is derailed in an FRA-reportable accident
P_A = tank car derailment rate per car-mile
M = number of car miles
Cap = nominal volumetric capacity of a baseline tank car
Cap' = nominal volumetric capacity of an alternate-design tank car

5.3.1. Tank Car Conditional Probability of Release

Shipment requirements for hazardous materials transportation in the U.S. are governed by the U.S. Code of Federal Regulations (CFR), Title 49, Parts 100 to 185. Tank car packaging requirements and special design provisions for the chemicals of interest are specified in Part 172.101 (Table 5.2).

Table 5.2
Summary of tank car packaging regulations.

Commodity Name	Packing Group	Label Codes	Special Provisions for Tank Cars	Packaging 173.***
Acrylonitrile	I	3, 6.1	B9: No Bottom Outlet	243
Benzene	II	3	-	242
Butyl Acrylates	III	3	-	242
Cyclohexane	II	3	-	242
Ethanol	II	3	-	242
Ethyl Acetate	II	3	-	242
Ethyl Acrylate	II	3	-	242
Methanol	II	3, 6.1	-	242
Methyl Methacrylate	II	3	-	242
Styrene	III	3	-	242
Toluene	II	3	-	242
Vinyl Acetate	II	3	-	242
Xylenes	II	3	-	242

Parts 173.242 and 173.243 list the possible tank car types to transport the chemicals of interest:

> *§ 173.242 Bulk packaging for certain medium hazard liquids and solids, including solids with dual hazards.*
>
> *(a) Rail cars: Class DOT 103, 104, 105, 109, 111, 112, 114, 115, or 120 tank car tanks; Class 106 or 110 multi-unit tank car tanks and AAR Class 206W tank car tanks*
>
> *§ 173.243 Bulk packaging for certain high hazard liquids and dual hazard materials which pose a moderate hazard.*

(a) Rail cars: Class DOT 103, 104, 105, 109, 111, 112, 114, 115, or 120 fusion-welded tank car tanks; and Class 106 or 110 multi-unit tank car tanks

The chemicals of interest are typically transported in general-purpose DOT 111A100W1 tank cars with 0.4375" head and shell thicknesses without top fittings protection. I assumed an inside tank diameter of 110.25", and other product specific designs for the base case for each chemical in the analyses in the subsequent sections (Table 5.3). The conditional probability of release given a tank car is derailed in a mainline accident, $P_{R|A}$ was calculated using the statistical model in Treichel et al. (2006).

Table 5.3
Baseline tank car designs.

Commodity Name	Bottom Fittings	Jacketed	$P_{R\|A}$
Acrylonitrile	No	No	0.3096
Benzene	Yes	Yes	0.2072
Butyl Acrylates	Yes	Yes	0.2072
Cyclohexane	Yes	No	0.3527
Ethanol	Yes	No	0.3527
Ethyl Acetate	Yes	No	0.3527
Ethyl Acrylate	Yes	No	0.3527
Methanol	Yes	No	0.3527
Methyl Methacrylate	Yes	No	0.3527
Styrene	Yes	Yes	0.2072
Toluene	Yes	No	0.3527
Vinyl Acetate	Yes	No	0.3527
Xylenes	Yes	No	0.3527

5.3.2. Tank Car Derailment Rate

Anderson and Barkan (2004) developed estimates of Class 1 railroad mainline freight train and car accident rates based on the FRA safety statistics. In the analyses described here I used their estimate of average railcar derailment rate per car-mile for P_A:

$$P_A = 1.28 \times 10^{-7} \text{ (s.e. } = 6.6327 \times 10^{-8}\text{)}.$$

5.3.3. Number of Car Miles

Waybill shipment data from the AAR’s railcar movement database, TeleRail Automated Information Network (TRAIN II), for the year 2007 (TRAIN II 2008) were used to determine sample routes involving specific chemicals of interest, and to estimate the average shipment distance. Each waybill record represents origination and destination (O-D) information as well as all intermediate railroads involved in a shipment. Approximately 10 to 45 percent of the full records for each chemical were analyzed using PC*MILER-Rail, a routing, mileage and mapping software for the North American rail network developed by ALK-Technologies, to determine the practical route for each O-D pair. The remaining waybill records used different O-D codes than the one implemented in the current version of PC*MILER-Rail software I used, thus the route creation algorithm could not process these records. Point locations for a specific shipment route from PC*MILER-Rail were then exported to ArcGIS, a GIS software from ESRI used for spatial analysis to create the route over the rail network map from the U.S. DOT (NTAD 2008). Although there were some limitations, this approach incorporates the best method and information available to produce chemical-specific route samples for my analysis.

The average shipment distance for each chemical based on sample routes was multiplied by the total annual carloads to get the total annual number of car miles, M (Table 5.4).

Table 5.4
Estimated average shipment distance, annual carloads and estimated annual car-miles for chemicals of interest.

Commodity Name	Average Shipment Distance (miles)	Annual Carloads	Annual Car Miles
Acrylonitrile	486	2,892	1,406,133
Benzene	435	3,543	1,541,225
Butyl Acrylates	714	4,077	2,910,782
Cyclohexane	470	4,331	2,036,186
Ethanol	737	4,091	3,013,480
Ethyl Acetate	758	1,163	881,173
Ethyl Acrylate	564	1,151	649,216
Methanol	918	17,814	16,361,224
Methyl Methacrylate	725	5,437	3,944,250
Styrene	696	8,856	6,167,904
Toluene	810	3,216	2,604,849
Vinyl Acetate	810	6,210	5,033,087
Xylenes	928	9,950	9,234,437

5.3.4. Tank Car Capacity

Tank car payload capacity (Table 5.5) associated with the baseline design for a specific chemical was estimated using *IlliTank*, a tank car weight and sizing program (Saat 2003; Chapter 2). For the base-case annual risk estimation in this study, the term Cap/Cap’ is equal to 1.

Table 5.5
Baseline tank car payload capacity.

Commodity Name	Capacity (gal.)
Acrylonitrile	29,010
Benzene	25,817
Butyl Acrylates	25,237
Cyclohexane	29,711
Ethanol	29,323
Ethyl Acetate	26,242
Ethyl Acrylate	26,242
Methanol	29,323
Methyl Methacrylate	25,071
Styrene	25,237
Toluene	27,195
Vinyl Acetate	25,354
Xylenes	27,195

5.3.5. Release Rate Calculation

Accident-caused release rate for each of the chemicals of interest was calculated using Equation 5.2 (Fig. 5.2). This rate represents the "probability" or frequency element in calculating the risk. The terms $P_{R|A}$ and Cap in Equation 5.2 account for specific tank car safety designs (Tables 5.3 and 5.5), while the terms P_A and M account for variation in accident exposure, based on the annual traffic or car-mile estimate (Table 5.4). The variability in the accident-caused release rates among different chemicals is mainly due to the difference in chemical-specific accident exposure. For example methanol and xylenes have the highest total annual car miles, so their annual accident-caused release rates are also among the highest (Fig. 5.2).

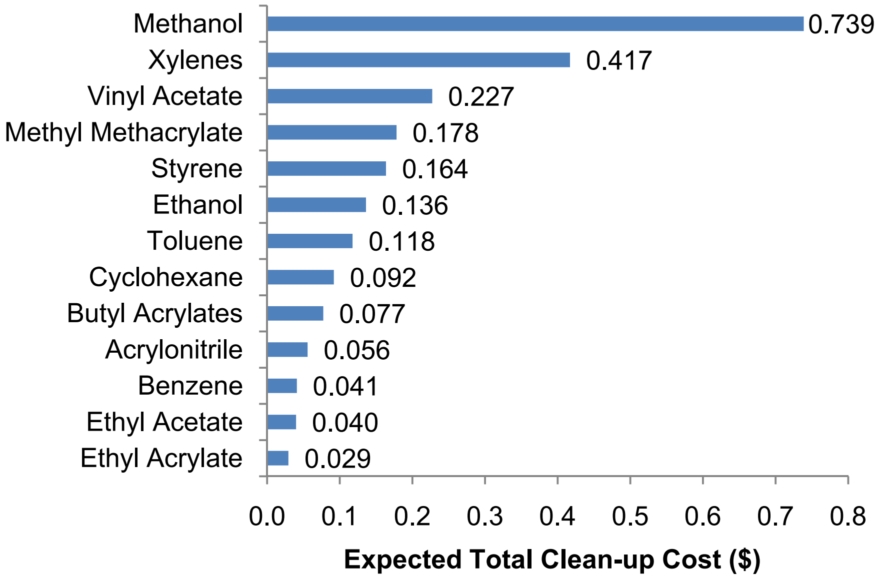

Fig. 5.2. Annual accident-caused release rate

5.4. CONSEQUENCE ANALYSIS

5.4.1. Impacts to Soil and Groundwater

The HMTECM developed by Yoon et al. (2009) with the enhancements described by Hridaya (2008) was used to estimate the total cleanup cost given a spill of the chemicals of interest from a tank car involved in an accident. Spill scenarios considered involve three different soil types, j (sand, silt and clay), and five different depths to groundwater, k (10, 20, 50, 100 and 200-ft).

5.4.1.1. Environmental Consequence Model

The HMTECM combines several different modules and sub-modules representing different elements in the spill and environmental cleanup process (Fig. 5.3). Once a spill has occurred, the Emergency Response Module estimates the cost of immediate response to the incident. The Soil Module simulates the migration of LNAPL contaminants from the surface, downward through the vadose zone, to the groundwater table, and the subsequent formation of an LNAPL lens at the groundwater table (Yoon et al. 2009). The Free Product Recovery Module then simulates the pumping extraction of free, low-solubility LNAPL from the lens at the groundwater table (Hridaya 2008). Finally, the Groundwater Module simulates the dissolution of LNAPL into groundwater, the transport of aqueous phase LNAPL components in groundwater, and the subsequent remediation of groundwater by pumping (Yoon et al. 2009). Fig. 5.4 shows the overall model logic and the associated remediation technologies used in the HMTECM.

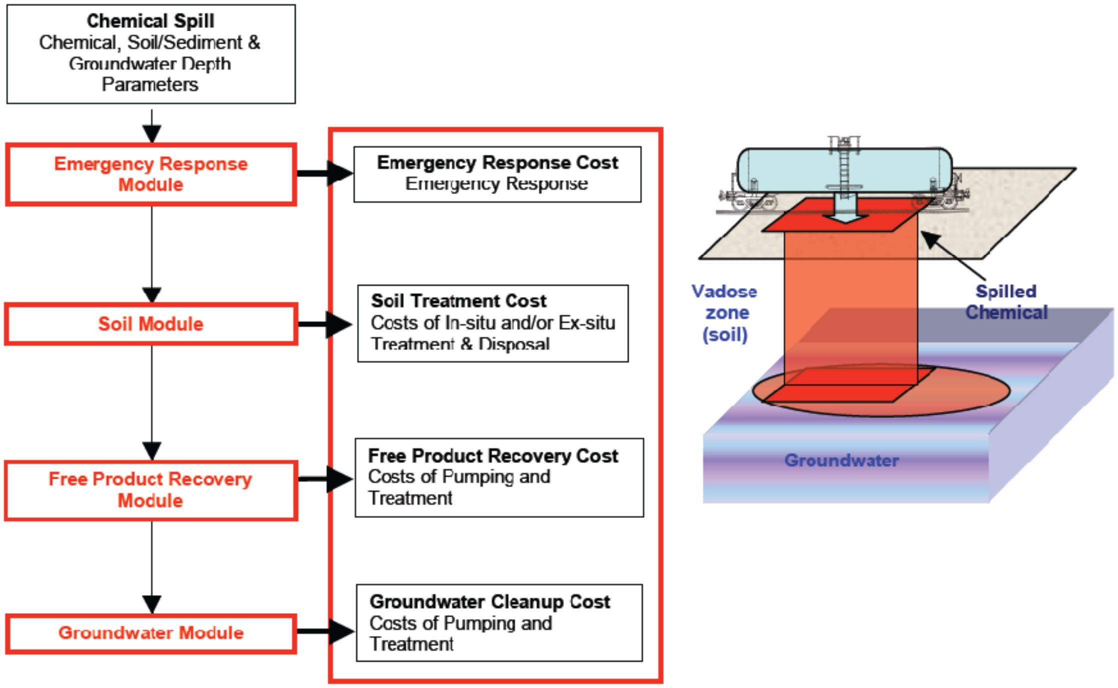

Fig. 5.3. Overview of the Hazardous Materials Transportation Environmental Consequence Model

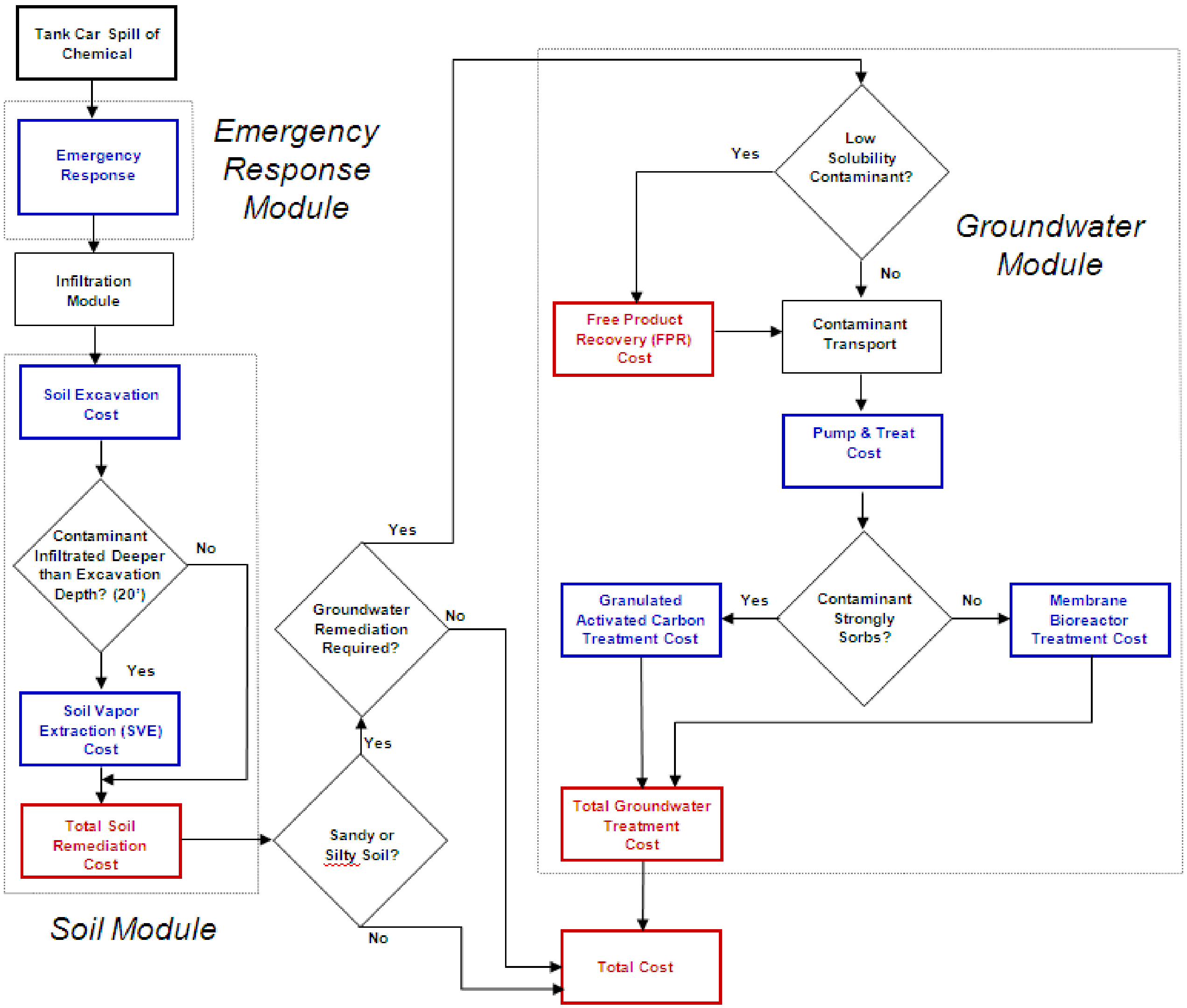

Fig. 5.4. Flowchart of the HMTECM logic

Remediation technologies associated with the chemicals of interest are summarized in Table 5.6. Soil and chemical properties in Tables 5.7 and 5.8, respectively, were used in the HMTECM simulations. Initial outputs from the HMTECM including NAPL volume in groundwater, number of pumps for specific remediation technology and cleanup time were used with the assumptions on unit costs (Tables 5.9 and 5.10) to calculate the total soil and groundwater cleanup cost.

Table 5.6
Remediation technologies for chemicals of interest.

Chemical Name	Incineration	Landfill	Soil Vapor Extraction (SVE)	Free Product Recovery (FPR)	Membrane Bioreactor (MBR)	Granulated Activated Carbon (GAC)
Acrylonitrile	x	-	x	-	x	-
Benzene	x	-	x	x	-	x
Butyl Acrylates	-	x	x	x	x	-
Cyclohexane	x	-	x	x	-	x
Ethanol	-	x	x	-	x	-
Ethyl Acetate	x	-	x	-	x	-
Ethyl Acrylate	x	-	x	-	x	-
Methanol	x	-	x	-	x	-
Methyl Methacrylate	x	-	x	-	x	-
Styrene	-	x	x	x	-	x
Toluene	x	-	x	x	-	x
Vinyl Acetate	-	x	x	-	x	-
Xylenes	x	-	x	x	-	x

Table 5.7
Soil properties used in HMTECM simulations.

Properties	Sand	Silt	Clay
Brooks-Corey lamda	1.13	0.341	0.09
Brooks-Corey air entry head (m)	0.045	0.455	1.244
Residual water saturation	0.105	0.074	0.180
Effective porosity	0.43	0.46	0.38
Hydraulic conductivity (m/day)	7.102	0.610	0.079
Hydraulic gradient	0.006	0.006	0.006
Maximum residual NAPL saturation in vadose zone	0.03	0.03	0.03
Maximum residual NAPL saturation in groundwater	0.1	0.1	0.1
Lens NAPL saturation	0.42	0.42	0.42
Longitudinal dispersivity (m)	1	1	1
Transverse dispersivity (m)	0.01	0.01	0.01
Source zone y-dispersivity (m)	0.05	0.05	0.05
Source zone z-dispersivity (m)	0.025	0.025	0.025

Table 5.8
Physical properties used in HMTECM simulations for chemicals of interest.

Chemical Name	Chemical Density (kg/L)	Viscosity (cp)	NAPL Water Interfacial Tension (dyne/cm)	Water Surface Tension (dyne/cm)	Solubility (g/L)	Vapor Pressure (atm)	Diffusion Coefficient in Gas (cm^2/s)	Air-Oil Surface Tension (dyne/cm)	Freundlich Isotherm K Coefficient	Freundlich Isotherm n Coefficient
Acrylonitrile	0.801	0.350	10.38	50.50	74.5	0.072	0.106	40.12	1.4	0.51
Benzene	0.876	0.600	28.90	60.00	1.8	0.085	0.090	31.10	30.0	0.40
Butyl Acrylates	0.890	0.811	18.00	35.00	1.6	0.004	0.090	20.00	10.0	0.50
Cyclohexane	0.774	0.894	50.00	72.03	0.1	0.080	0.074	24.65	30.0	0.40
Ethanol	0.789	1.200	2.00	25.00	100.0	0.045	0.080	23.00	30.0	0.40
Ethyl Acetate	0.900	0.423	23.39	30.08	79.0	0.100	0.085	6.69	10.0	0.50
Ethyl Acrylate	0.923	0.473	20.00	23.80	15.0	0.040	0.078	3.80	10.0	0.50
Methanol	0.791	0.544	2.20	22.60	100.0	0.097	0.080	20.40	10.0	0.50
Methyl Methacrylate	0.938	0.632	14.30	28.50	15.0	0.038	0.075	14.20	10.0	0.50
Styrene	0.902	0.695	35.48	62.49	0.3	0.006	0.071	32.00	327.0	0.50
Toluene	0.867	0.560	36.10	61.74	0.5	0.037	0.078	27.93	100.0	0.45
Vinyl Acetate	0.926	0.421	30.00	54.00	23.0	0.110	0.085	24.00	100.0	0.50
Xylenes	0.880	0.760	37.50	64.00	0.2	0.012	0.070	29.00	200.0	0.42

Table 5.9
Unit costs used in soil module.

Operation	Cost	Unit	Source	Notes
Emergency Response	$250,000	**Per Spill**	**PHMSA (2008)**	Calculated with Railroad Accident Data only, median value
Excavation Cost	$111	**Cost per cu. meter**	**EPA (2004)**	Calculated using the formula on p. 9 for 20 ft depth, for 500, 750 and 1000 yard^3, and then averaged and converted to m^3
Soil Incineration Cost	$1,017	**Cost per cu. meter**	**FRTR (2002)**	Average from four scenarios
Landfill Cost	$412	**Cost per cu. meter**		Anonymous industry information
Backfilling Cost	$23	**Cost per cu. meter**	**EPA (2004)**	
Soil Vapor Extraction (SVE), Capital Cost	$54,486	**Per Spill**	**EPA (2004)**	Average over all soil types for 20 ft depth (p. 22)
SVE Treatment Cost	$17	**Cost per cu. meter**	**EPA (2004)**	

Table 5.10
Unit costs used in groundwater module.

Operation	Cost	Unit	Source	Additional Note
Capital Cost for Pumping Wells (PW)	\$217 × GW Depth + \$14,588	**Per Well Per foot to Groundwater**	**EPA (2004)**	
OM Cost for Pumping	\$19.71 × GW Depth + \$6,391	**Per Well Per Year**	**EPA (2004)**	p. 31 (50 gal/min PVC extraction well)
Capital Cost for Granular Activated Carbon (GAC) Treatment System	\$111,744	**Per Spill**	**Ren (2003)**	Modular carbon absorbers, dual bed, two in series, less than 100 gallon per minute
GAC OM Cost - Regeneration	IF Influent Conc. > 0 then NAPL Vol × 3.78 × Density (g/L) × 1/Freundlich sorption × \$2.90/0.8, else \$0	**Per Gallon NAPL Volume in Groundwater after Free Product Recovery**	**Environmental Risk Science (1994)**	3.78 = conversion factor of Total NAPL volume in groundwater from gallon to liter Freundlich sorption = 327 × Influent Conc.$^{0.5}$ 0.8 = GAC efficiency factor
GAC OM Cost - Labor, Equipment and Contingency	(10/7 × \$100 × 365 + 0.03 × GAC Cap. Cost + \$9,971) × 1.2 × Day/365	**Per Day**	**Environmental Risk Science (1994)**	
Capital Cost for Membrane Bioreactor	\$250,811	**Per Spill**	**FRTR (2002)**	
OM Cost for Membrane Bioreactor	\$28,982	**Per Year**	**NYSERDA (2004); USBR (1998)**	Scaled down proportionately to size
Capital Cost for Free Product Recovery	\$81,149	**Per Well**	**EPA (2005)**	
OM Cost for Free Product Recovery	\$19,708	**Per Well Per Year**	**EPA (2005)**	

5.4.1.2. Soil and Groundwater Exposure Assessment

The location of a spill along rail lines is an important variable in the environmental risk analysis. The severity of impact and the effectiveness of remediation efforts depend on the characteristics of a spill site. I applied GIS spatial analysis methods similar to those used by Anand and Barkan (2006), but used route specific data for each chemical of interest, as discussed in Section 5.2.3, to develop chemical-specific probability distributions of soil type and depth to groundwater exposures.

The CONUS-SOIL database from Miller and White (1998) was used to assess the potential exposure level of different soil types. It is a multi-layer, soil characteristics dataset for the U.S. continental-scale soil analysis based on the U.S. Department of Agriculture (USDA) State Soil Geographic Database (STATSGO 2008). The CONUS-SOIL database contains the mean permeability rate for eleven standard layers, up to 250 cm (8.2 ft.) from the soil surface for each map unit. The arithmetic mean permeability rate for all of the standard layers was calculated to classify soil type based on the permeability rates in Table 5.7 (Fig. 5.5). The soil database used in my study was derived from the database used by Anand and Barkan (2006), the STATSGO database, but the studies used different soil type classifications based on different minimum permeability rate criteria. This change is due to an improved understanding of the appropriate values to use in the latest version of the HMTECM in Yoon et al. (2009).

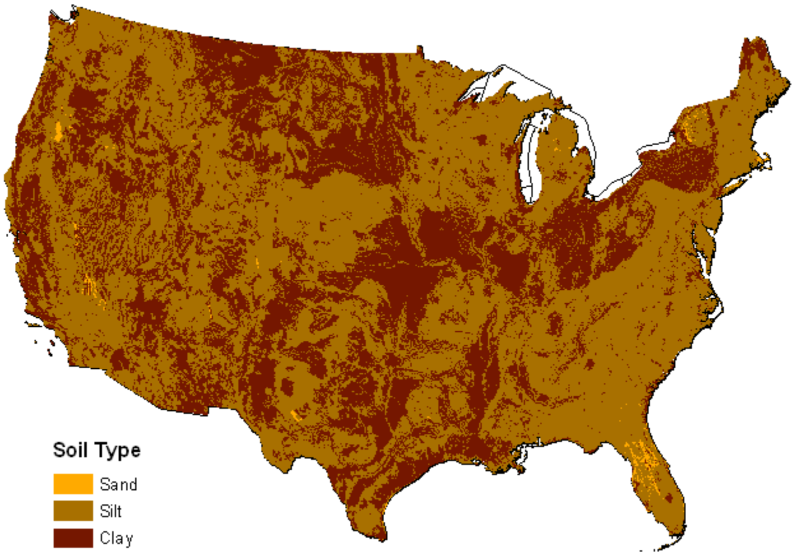

Fig. 5.5. Surface soil types in the U.S.

An overlay analysis using the GIS route of each of the chemicals of interest and the soil database was performed to estimate the probability distribution of different soil types along rail lines (Table 5.11).

Table 5.11
Distribution of soil types along chemical-specific rail routes.

	Percentage of Rail Route on Soil Type *j*			
Soil Type *j*	**Sand**	**Silt**	**Clay**	**Water**
Acrylonitrile	0.0%	49.6%	49.0%	1.4%
Benzene	0.0%	44.1%	55.6%	0.3%
Butyl Acrylates	0.1%	53.9%	44.8%	1.2%
Cyclohexane	0.0%	55.7%	43.5%	0.7%
Ethanol	0.6%	59.3%	39.4%	0.6%
Ethyl Acetate	0.0%	56.7%	42.4%	0.8%
Ethyl Acrylate	0.0%	48.2%	51.3%	0.5%
Methanol	0.2%	60.7%	38.2%	0.9%
Methyl Methacrylate	0.1%	56.3%	42.6%	1.1%
Styrene	0.0%	53.3%	45.6%	1.1%
Toluene	0.1%	56.7%	42.6%	0.6%
Vinyl Acetate	0.1%	53.5%	45.6%	0.8%
Xylenes	0.2%	52.8%	46.3%	0.8%

For groundwater exposure analysis, a spatial database of groundwater sites in the continental U.S. was downloaded from the United States Geological Survey (USGS) National Water Information System (NWIS) (USGS 2008) and several other state-specific groundwater databases (New Mexico Office of the State Engineer 2003, Texas Water Development Board 2008). The average depth to groundwater for each site was calculated using measurements between 1990 and 2008 to get the approximate representation of the current depth to groundwater distribution. The resultant database contains groundwater depth information from approximately 200,000 sites (Fig. 5.6), and is thus much larger than the dataset used by Anand and Barkan (2006), thereby minimizing the geographic bias of well data as they discussed.

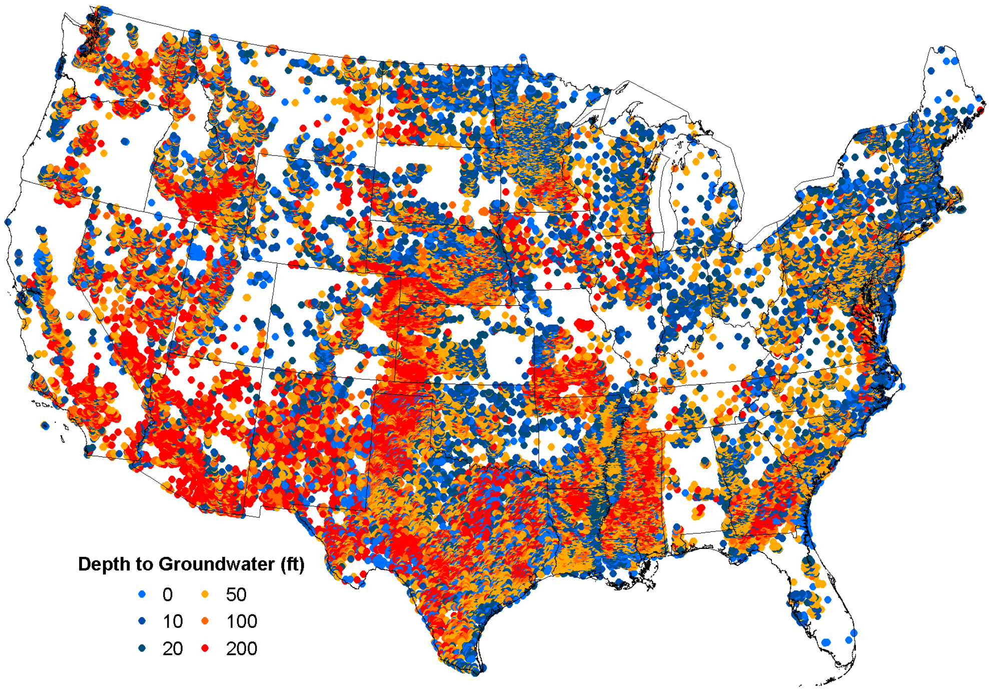

Fig. 5.6. Post-1990 depth to groundwater distribution

I conducted a GIS overlay analysis using the route for each chemical of interest and the groundwater database to estimate the probability distribution of depth to groundwater within 100 ft of the chemical-specific route (Table 5.12).

Table 5.12
Distribution of depth to groundwater along chemical-specific rail routes.

	Percentages of Depth to Groundwater *k* along Rail Route					
Depth to Groundwater Range (ft)	**≤5**	**>5 to ≤15**	**>15 to ≤25**	**>25 to ≤75**	**>75 to ≤125**	**>125**
Average Depth to Groundwater *k* (ft)	**0**	**10**	**20**	**50**	**100**	**200**
Acrylonitrile	15.38%	27.88%	11.54%	28.85%	6.73%	9.62%
Benzene	13.79%	31.90%	6.90%	25.86%	6.03%	15.52%
Butyl Acrylates	7.12%	24.34%	8.61%	27.34%	10.86%	21.72%
Cyclohexane	18.87%	32.08%	7.55%	26.42%	5.66%	9.43%
Ethanol	7.02%	24.16%	13.20%	29.78%	8.99%	16.85%
Ethyl Acetate	5.77%	16.03%	11.54%	33.33%	9.62%	23.72%
Ethyl Acrylate	6.99%	11.89%	10.49%	37.06%	10.49%	23.08%
Methanol	14.31%	27.36%	10.51%	24.46%	7.43%	15.94%
Methyl Methacrylate	7.44%	26.03%	9.92%	24.38%	10.33%	21.90%
Styrene	14.71%	20.32%	10.43%	27.81%	9.36%	17.38%
Toluene	12.73%	22.12%	10.61%	28.18%	9.09%	17.27%
Vinyl Acetate	16.03%	22.76%	7.69%	26.60%	8.33%	18.59%
Xylenes	7.46%	20.52%	11.94%	29.85%	8.96%	21.27%

5.4.1.3. Expected Total Cleanup Cost

The quantity spilled affects the severity and the associated remediation costs of an incident. The volume spilled in a tank car accident can vary from a few gallons to the entire contents of the car. For a specific spill, the expected total cleanup cost, C_{ave}, can be calculated as follows:

$$C_{ave} = \sum_{j,k,l} P_j \times P_k \times P_l \times C_{j,k}(Q_l) \qquad (5.3)$$

where:

C_{ave} = expected total cleanup cost
P_j = probability of a spill occurred on soil type j
P_k = probability of a spill occurred at k ft depth to groundwater
P_l = probability of a release size l per release size category in Treichel et al. (2006) given a tank car released its content
$C_{j,k}(Q_l)$ = cleanup cost estimate from HMTECM with Q_l spill volume for j soil type and k ft depth to groundwater
Q_l = average release quantity with release size l
= average percentage tank capacity lost for release size l × tank car capacity

For each of the soil-depth to groundwater scenarios, spills from 1,000 to 50,000 gallons were simulated in 1,000-gallon increments to get a generalized regression equation for total clean-up cost as a function of spill volume (Figure 5.7). Appendix D summarizes the total clean-up cost regression equations for all the chemicals of interest. The intercepts for these regression equations suggest a very high initial cleanup cost, regardless of the total amount released in an accident. This is due to the high unit cost assumptions per spill used for emergency response and capital costs for granular activated carbon and membrane bioreactor treatment systems. In small spills, the actual cost may not be as high as the estimated cost using the regressions.

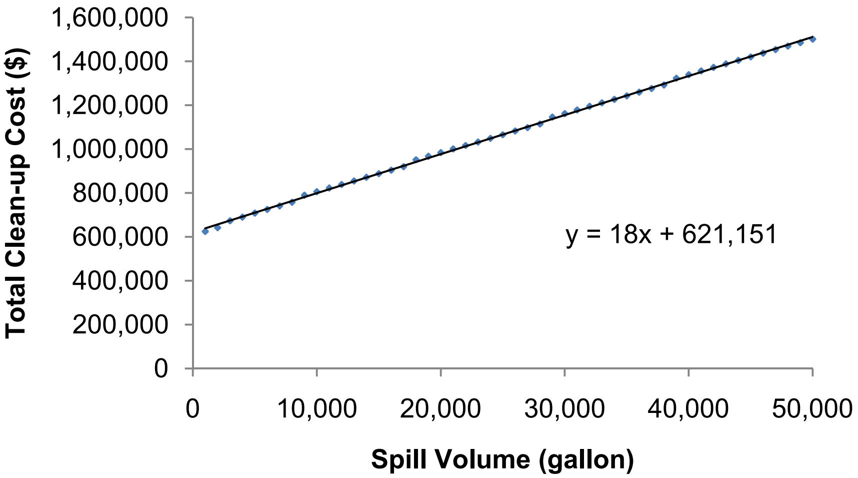

Fig. 5.7. An example total clean-up cost versus spill volume linear regression for acrylonitrile for spills on sand, 10ft from groundwater

For each possible release size category in Treichel et al. (2006) (Table 5.13), the generalized total cleanup regression equations from HMTECM simulations were used to estimate the expected cleanup cost given a spill of each of the chemicals of interest using Equation 5.3 (Table 5.14, Fig. 5.8). This cost estimate accounts for chemical-specific hazard, tank car capacity and estimates of annual route-specific exposure levels to different soil types and depths to groundwater. The highest expected cleanup costs correspond to chemicals with the lowest solubility in water, cyclohexane and xylenes, which require longer groundwater cleanup time.

Table 5.13
Probabilities of different release size given a tank car released its content in an accident from Treichel et al. (2006).

	Probability of Quantity Lost given a Tank Car Release its Content				
Percentage Capacity Lost Range (%)	**0-5**	**5-20**	**20-50**	**50-80**	**80-100**
Average Percentage Capacity Lost (%)	**2.5**	**12.5**	**35.0**	**65.0**	**90.0**
	0.20	0.09	0.14	0.12	0.46

Table 5.14
Expected total cleanup cost given a spill.

Commodity Name	Capacity (gal.)	Expected Total Clean-up Cost ($)
Acrylonitrile	29,010	670,851
Benzene	25,817	618,221
Butyl Acrylates	25,237	528,022
Cyclohexane	29,711	900,171
Ethanol	29,323	419,367
Ethyl Acetate	26,242	708,587
Ethyl Acrylate	26,242	723,279
Methanol	29,323	628,281
Methyl Methacrylate	25,071	678,408
Styrene	25,237	595,307
Toluene	27,195	734,295
Vinyl Acetate	25,354	474,474
Xylenes	27,195	842,198

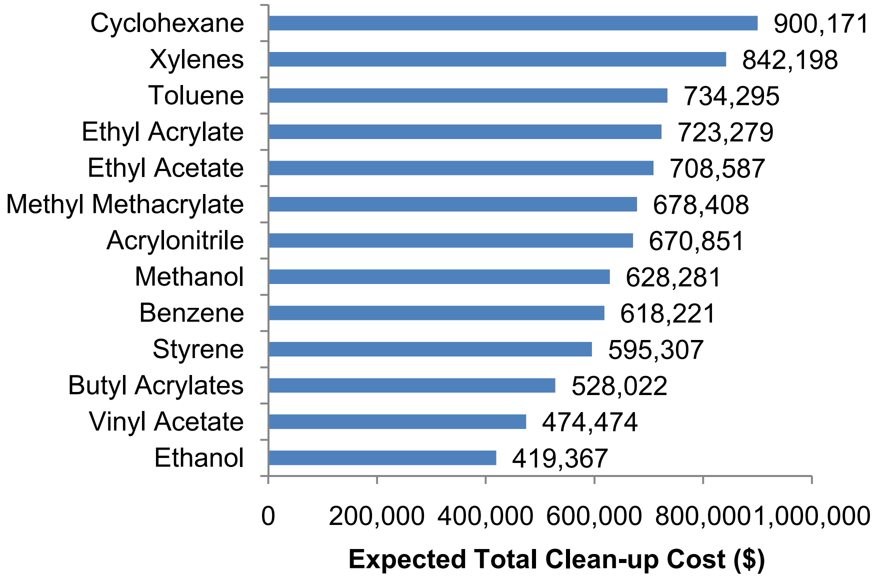

Fig. 5.8. Expected total cleanup cost given a spill

5.4.2. Population Exposure

The total population exposed given a spill of a chemical of interest can be estimated as follows:

$$Pop_c = Area_c \times PopDensity_c \qquad (5.4)$$

where

Pop_c = total population exposure due to a spill of chemical c
Area_c = chemical-specific hazard footprint area
PopDensity_c = average population weighted density by length along a chemical-specific route

5.4.2.1. Hazard Exposure Model

The U.S. DOT Emergency Response Guidebook (ERG) (DOT 2008a) hazard exposure model was used to estimate the consequence of a chemical release to a human population. The affected areas in the guidebook were determined from a statistical model that used sophisticated emission rate and dispersion models, historical release incidents, meteorological observations in North America and current toxicological exposure guidelines (Brown et al. 2000; Brown and Dunn 2007; ERG 2008). All of the chemicals of interest in this study are classified as flammable liquids by the U.S. DOT. The ERG model suggests an initial isolation and protective distance of one half mile in all directions for spills of all the chemicals considered here. This defines the area for which the ERG recommends that the population should be evacuated and/or sheltered in-place. Thus the population exposure metric used in this analysis is the number of people likely to be affected if emergency response personnel conform to the recommendations in the U.S. DOT ERG. The affected area from the ERG model was used as the exposure area to estimate population exposure, and was equal to 0.785 mile^2 for all the chemicals of interest.

5.4.2.2. Population Density

A spatial buffer was created along chemical-specific routes discussed in Section 5.2.3. The size of the buffer was based on the affected area in the DOT ERG (2008a). The buffer for each chemical was then overlaid on the U.S. census tract map from ESRI Data and Maps (2008) (Fig. 5.9) to estimate the proportion of different population density levels (U.S Dept. of Commerce 1988) along the routes for each chemical (Table 5.15).

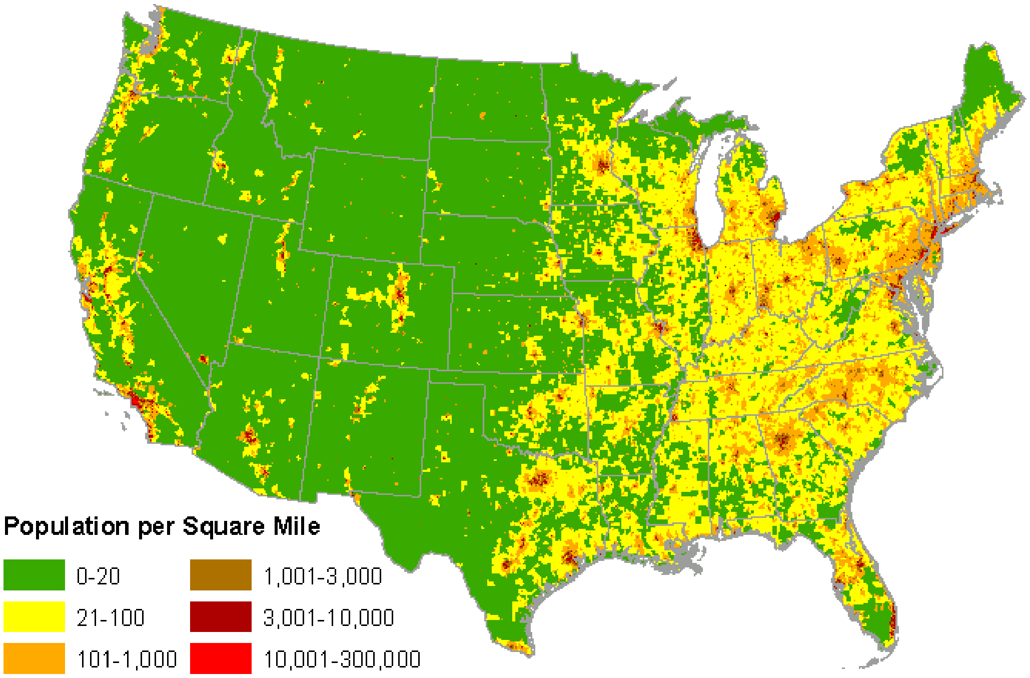

Fig. 5.9. U.S. Population density by census tracts

Table 5.15

Distribution of population densities along chemical-specific rail routes.

	Population Class Percentages Over Total Annual Routes					
Population Class	***Remote***	***Rural***	***Suburban***	***Urban***	***High***	***Extremely High***
Maximum Population Density (people/mile^2)	**20**	**100**	**1,000**	**3,000**	**10,000**	**> 10,000**
Average Population Density (people/mile^2)	**10**	**60**	**550**	**2,000**	**6,500**	**10,000**
Acrylonitrile	11.45%	44.61%	30.39%	9.26%	4.13%	0.16%
Benzene	28.20%	38.24%	23.07%	7.04%	3.35%	0.11%
Butyl Acrylates	29.07%	35.31%	24.02%	7.29%	3.91%	0.40%
Cyclohexane	20.64%	39.51%	28.95%	7.73%	2.95%	0.23%
Ethanol	34.26%	31.14%	22.21%	7.56%	4.31%	0.50%
Ethyl Acetate	28.67%	32.03%	25.45%	8.23%	4.97%	0.65%
Ethyl Acrylate	26.63%	41.85%	22.04%	6.13%	3.10%	0.24%
Methanol	45.54%	27.12%	17.67%	5.83%	3.56%	0.28%
Methyl Methacrylate	24.93%	36.09%	25.95%	8.10%	4.50%	0.44%
Styrene	28.24%	35.11%	23.95%	7.87%	4.40%	0.43%
Toluene	37.44%	31.19%	20.20%	7.06%	3.81%	0.30%
Vinyl Acetate	31.66%	34.52%	22.21%	7.26%	4.00%	0.35%
Xylenes	37.55%	31.80%	20.05%	6.53%	3.84%	0.23%

5.4.2.3. Expected Population Evacuation Cost

The exposure area was multiplied by the average population density along a chemical-specific route to estimate the total population exposed to a potential release incident. The associated evacuation cost was assumed to be $225 per person per day for food and lodging, based on a recent court-approved settlement related to a railroad chemical release incident (DOT 2008b). This figure has also been corroborated by several railroad experts. Analysis of the U.S. DOT Pipeline and Hazardous Materials Safety Administration (PHMSA) incident statistics for railroad release accidents indicated that the average evacuation period involving a release of a flammable liquid is approximately one day (PHMSA 2009), so my analysis assumed this value. The expected evacuation costs in a release incident involving the chemicals of interest were estimated accordingly (Table 5.16).

Table 5.16
Expected evacuation costs given a spill.

Commodity Name	**PopDensity$_c$ (people/mile^2)**	**Pop$_c$ (people)**	**Expected Evacuation Cost**
Acrylonitrile	665	522	$117,499
Benzene	522	410	$92,314
Butyl Acrylates	596	468	$105,453
Cyclohexane	554	435	$97,994
Ethanol	626	492	$110,734
Ethyl Acetate	715	562	$126,448
Ethyl Acrylate	497	391	$87,935
Methanol	494	388	$87,311
Methyl Methacrylate	665	522	$117,611
Styrene	642	504	$113,544
Toluene	553	434	$97,707
Vinyl Acetate	586	460	$103,618
Xylenes	537	422	$94,895

5.4.3. Train Delay

In the event of a derailment, through train traffic at the location of the accident may be disrupted. The length of the delay depends on the severity of a derailment. The density of the rail line affects the possible number of trains delayed due to a release incident. Schafer and Barkan (2008) estimated the single-train delay cost per train-hour, which includes car, locomotive, fuel and crew labor costs. In this Chapter, I used the equation from Schafer and Barkan (2008) to estimate multiple-train delay cost:

$$C_{delay} = Tc + \sum_{n=1}^{m} (T - nt)c \qquad (5.5)$$

where:

C_{delay} = total train delay cost for multiple trains
T = total delay hours due to a release incident
c = cost of delay per train-hour ($233.32)
t = hours per train arrival = 53.33/MGT
MGT = annual traffic (million gross tons)
m = number of following trains delayed = T/t

Based on railroad industry expert opinion, I assumed a release incident involving the chemicals of interest would increase the delay in reopening a rail line following an accident by an average of 24 hours (T = 24). Chemical-specific routes discussed in Section 5.2.3 were used to estimate the distribution of different rail line traffic density (Table 5.17). The weighted average of the expected total train delay costs for all traffic density category are summarized in Table 5.18. The higher the average annual density for a chemical-specific route, the greater the estimated train delay cost.

Table 5.17
Distribution of rail line traffic densities along chemical-specific rail routes.

	Percentage of Traffic						
Traffic Density Category (MGT)	**0.1 - 4.9**	**5 - 9.9**	**10 - 19.9**	**20 - 39.9**	**40 - 59.9**	**60 - 99.9**	**≥ 100**
Average Traffic Density (MGT)	**3**	**7**	**15**	**30**	**50**	**80**	**100**
Acrylonitrile	31%	5%	7%	18%	14%	19%	5%
Benzene	30%	8%	9%	17%	18%	11%	9%
Butyl Acrylates	32%	3%	8%	20%	13%	13%	10%
Cyclohexane	31%	9%	14%	24%	17%	5%	1%
Ethanol	31%	5%	9%	19%	11%	14%	10%
Ethyl Acetate	32%	4%	10%	18%	11%	14%	12%
Ethyl Acrylate	31%	1%	4%	24%	8%	14%	18%
Methanol	35%	5%	9%	16%	11%	14%	9%
Methyl Methacrylate	29%	4%	9%	21%	14%	15%	9%
Styrene	31%	5%	7%	21%	13%	13%	10%
Toluene	28%	3%	10%	19%	13%	17%	10%
Vinyl Acetate	31%	4%	8%	21%	12%	12%	11%
Xylenes	31%	5%	10%	19%	11%	11%	14%

Table 5.18
Expected total train delay costs given a spill.

Chemical	Train Delay Cost ($)
Acrylonitrile	44,506
Benzene	42,061
Butyl Acrylates	44,344
Cyclohexane	30,541
Ethanol	44,593
Ethyl Acetate	45,270
Ethyl Acrylate	51,942
Methanol	42,237
Methyl Methacrylate	45,692
Styrene	44,045
Toluene	48,018
Vinyl Acetate	44,679
Xylenes	45,124

5.4.4. Total Consequence Cost Calculation

Total expected consequence cost, the sum of soil and groundwater cleanup, evacuation and train delay costs, for each of the chemicals of interest were calculated (Fig. 5.10). This cost represents the total expected consequence given a release.

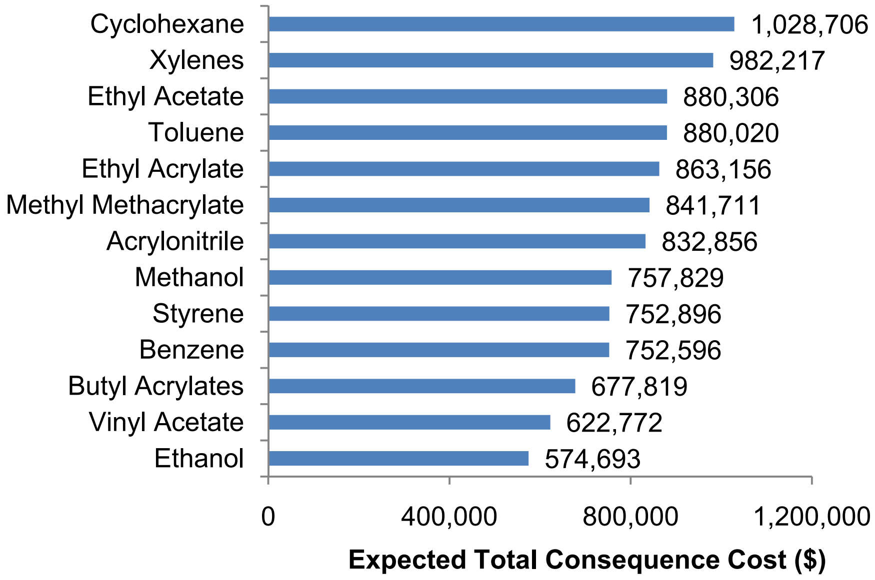

Fig. 5.10. Expected total consequence cost given a spill

5.5. RISK ESTIMATION

The annual risk (Fig. 5.11) was estimated by multiplying the accident-caused release rate in Fig. 5.2 by the total consequence cost in Fig. 5.10. Figs. 5.12 and 13 show the risk per unit exposure by car-mile and ton-mile, respectively.

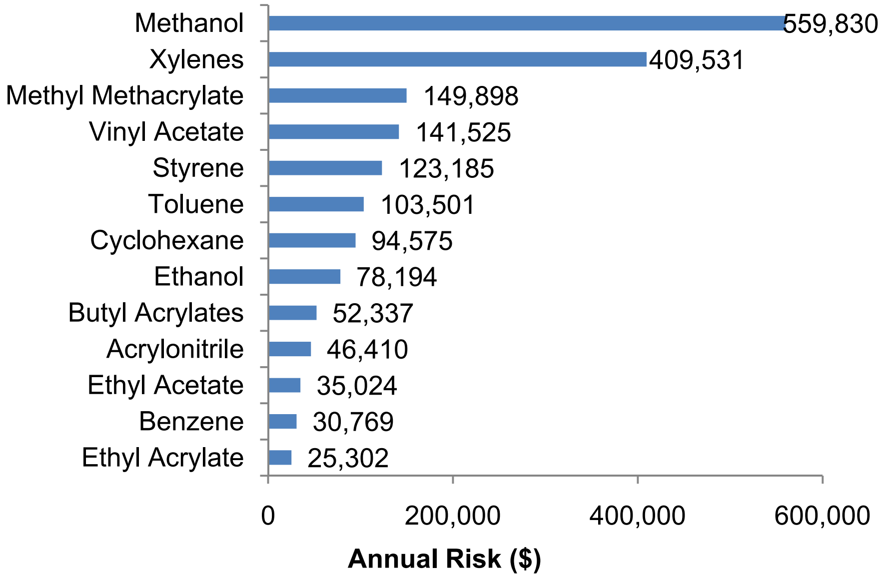

Fig. 5.11. Total annual risk

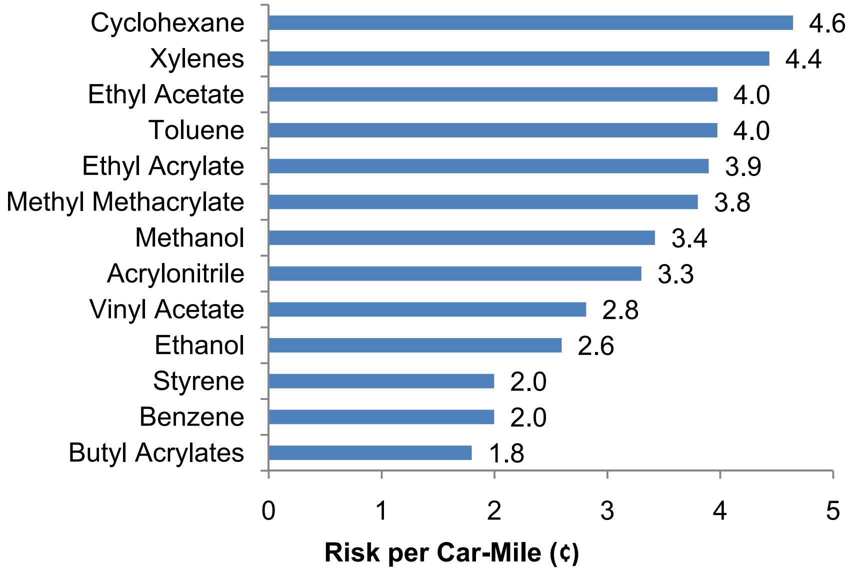

Fig. 5.12. Risk per car-mile

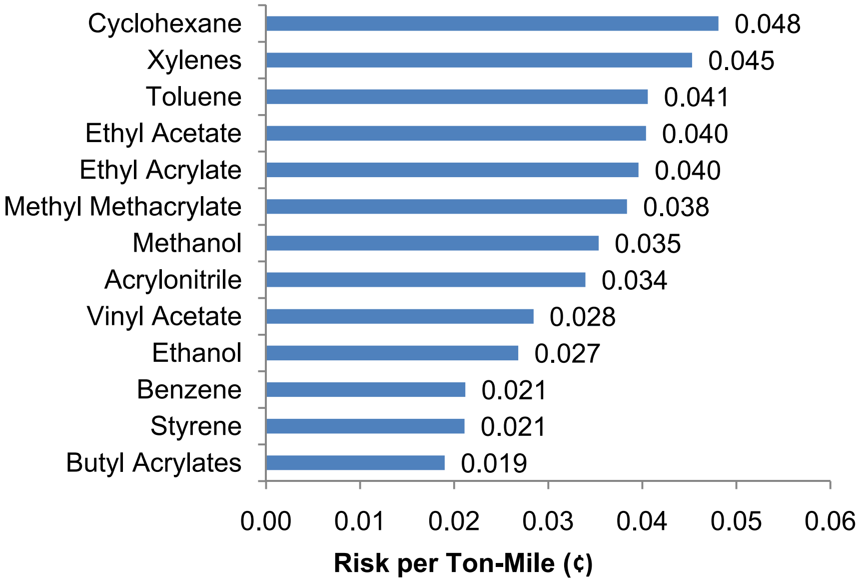

Fig. 5.13. Risk per ton-mile

5.5.1. Risk Profile

The annual risk presented above represents the total expected impact from release incidents at all locations along a chemical-specific route, in which the weighted averages of soil type, depth to groundwater, population class and traffic density are incorporated. In order to get a better perspective on the overall risk problem, the rate of occurrence and impact for all possible release scenarios (Fig. 5.1) can be illustrated using risk profiles, also known as “F-N curves” (Fig. 5.14). It describes the rate that an impact greater than *x* will occur, where *x* ranges from the minimum to the maximum possible value (CCPS 2008). In the context of this study, a risk profile describes the rate of having a release incident resulting in at least a specific level of total consequence cost. Fig. 5.14 shows an example risk profile for methanol. Risk profiles for all the chemicals considered in this study are presented in Appendix E.

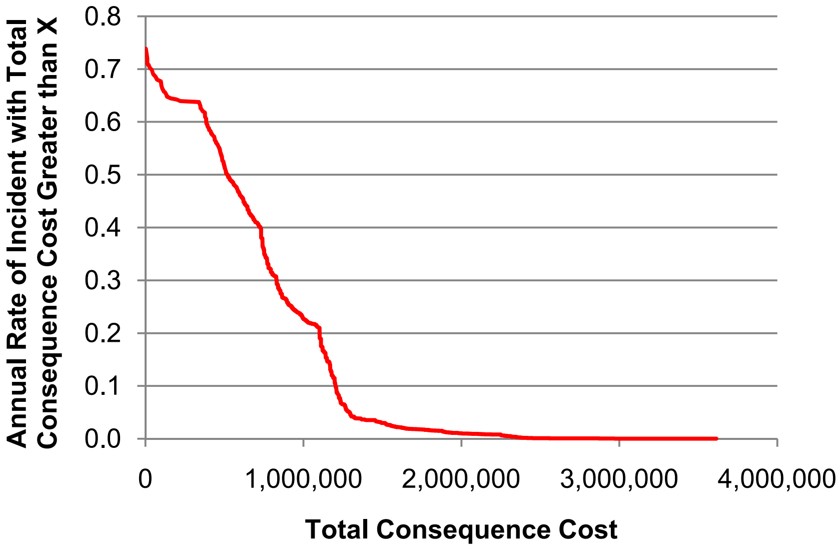

Fig. 5.14. Risk profile for rail transportation of methanol

5.6. DISCUSSION

5.6.1. Current Risk Scenarios

This Chapter provides a quantitative analytical approach to estimate the risk cost of transporting hazardous materials by rail. The estimated annual risk associated with the chemicals under consideration ranged from $25,000 to $560,000 and the risk cost per car-mile ranged from 1.8 to 4.6 cents. The annual risk and the risk per car-mile vary by factors of 22 and 3, respectively. These reflect current practices in transporting the chemicals of interest. The annual risk estimates account for chemical-specific hazard, tank car design, route-specific characteristics and annual accident exposure based on the total number of shipments. The risk per car-mile estimates have the traffic effect normalized to focus on chemical hazard, tank car safety design, and route specific characteristics affecting risk.

The risk estimates provide a single number to represent the expected consequence per year, per car-mile or ton-mile. Consequences for all possible events are weighted by their probabilities of occurrence (Equation 5.1). In addition to expected values for risk it may also be useful to consider the likelihood of the range of possible consequences especially low probability-high consequence events. Risk profiles (Appendix E) provide additional perspective in evaluating the risk by specifying the probability or rate of occurrence of incidents over a range of consequence levels.

5.6.2. Main Factors Affecting Disparities in Risk Estimates

Several factors affect the risk and the magnitude of its severity (Equations 5.1 to 5.5). For the chemicals studied here the variation in safety performance of the baseline tank car designs is minimal (Table 5.3). However, higher variation in total car miles among different chemicals leads to significant differences in their annual accident-caused release rate (Table 5.4 and Fig.5.2). In estimating the consequence cost, chemicals that are less soluble in water, in general, have higher soil and groundwater cleanup cost because of longer remediation time. In terms of evacuation cost, chemicals transported along routes with higher-density population result in higher consequence costs. However, since more than 50 percent of shipments are mainly transported across remote and rural areas (Table 5.15), the variation in evacuation cost is minimal. Meanwhile, train delay cost only accounts for between three to eight percent of total consequence cost as compared to between 76 and 88 percent from soil and groundwater cleanup cost. As such, chemical cleanup cost, together with total number of car miles, dictate the level of the risk.

5.6.3. Other Risk Factors

The environmental consequence model, HMTECM, used in this study focuses on soil and groundwater cleanup. Analysis of damages to natural resources such as surface water bodies would require a different type of model. Inclusion of this would increase the environmental consequence cost, but no satisfactory model presently exists to be used in the context of railroad hazardous material transportation risk. In addition, the HMTECM is currently limited to pure LNAPLs; however, work is currently underway to enhance the model so it can be used to evaluate chemical mixtures. This will enable risk analysis of many other important hazardous materials transported by rail such as gasoline, diesel fuel, denatured alcohol, etc.

Evacuation cost was the only metric considered to assess population exposure in this analysis. For other chemicals that present a more acute hazard to human health and safety, the use of a more detailed hazard consequence model may be appropriate for some types of questions in which estimation of the statistical distribution of potential injuries and fatalities is necessary. The statistical value of life or injury concept could then be used to estimate the associated cost of casualties (Viscusi and Aldy 2003; Kaplow 2005).

Estimated train delay cost in my analysis considered the extra costs related to locomotives, railcars, fuel and crew when multiple trains are delayed after a release accident. In the event of a longer track outage, railroads may need to reroute whole trains, or certain carloads, either over their own network or via other railroads, leading to additional costs.

An important consequence element also not included in this study is litigation cost. Due to the confidential nature of this information, quantitative data on settlement costs is generally not available in the public domain. Based on a survey of major rail accidents involving hazardous materials between 1982 and 1992, Dennis (1996) estimated legal settlement expenses accounted for 56% of the total cost of release incidents, compared to about 40% for environmental costs and other expenses. If this ratio is still relevant then it would be possible to estimate total costs by calculating a factor to multiply the consequence costs estimated in this study.

5.6.4. Risk Model Applications

5.6.4.1. Evaluating Shipment Risk Cost

The risk estimates are useful to evaluate the relative risk of transporting different chemicals. In this Chapter, the risk was analyzed at a national-wide level; however, the same framework can be used to evaluate the risk of transporting a chemical along a particular rail corridor or between an origin and destination. The Surface Transportation Board (STB) is considering incorporating risk cost into their formula for determination of freight transport costs, which in turn has implication for the rates railroads can charge (74 FR 248). The risk model presented in this Chapter can be used to perform such calculations for the risk elements covered here.

5.6.4.2. Evaluating Cost Effectiveness of Alternate Design Tank Cars

The use of a more robust tank car safety design reduces $P_{R|A}$ and thus the risk. In Chapter 4 I presented an approach to evaluate the cost effectiveness of different alternate tank car designs in hazardous material service. It accounted for chemical-specific hazard and consequent risk and cost. The risk model in this Chapter can be used to assess the benefit in terms of reduction in risk due to use of different tank car safety designs. In Chapter 6, I will describe an analysis using the same group of chemicals considered here.

5.6.4.3. Evaluating Alternate Routes

The risk model presented in this Chapter can also be used to evaluate the effect of alternate routes for transporting hazardous materials by rail. Rerouting affects the levels of exposure to both human populations and the environment. In certain cases, rerouting to avoid higher population density or environmentally sensitive areas may reduce risk. However, routing decisions may also affect the total shipment distance, and the quality of track used. Longer shipment distances will increase “M” in Equation 5.2 which in turn may increase accident-caused release rate and risk. Similarly, transporting chemicals using lower quality track may increase P_A and thus increase risk. All these factors can be accounted for using the model presented here to compare both the expected risk and risk profiles for route alternatives.

5.6.4.4. Increase Emergency Response Preparedness

The use of GIS in assessing risk exposure offers detailed route-specific information that can be used to increase emergency response preparedness. This is especially useful when the risk model presented here is used to evaluate micro-level risk by analyzing specific track segments along a route. Track segments with higher risk may justify extra preparation or investment in mitigation capability. In addition, different products and different environmental features may call for different types of preparations in terms of equipment, training or allocation of expertise.

5.6.4.5. Evaluating Infrastructure Improvement

Detailed track-segment specific GIS analysis can also be used to prioritize locations along a rail network for infrastructure improvement and maintenance. It may be justified to allocate resources to focus on track improvement near environmentally sensitive areas, high-density populations or high-density traffic. Each of these affects the environmental cleanup cost, evacuation cost and train delay cost, respectively, in estimating the total possible consequence from a release incident. Infrastructure improvement can also potentially reduce the likelihood of a train accident in the first place by reducing P_A in Equation 5.2.

5.7. CONCLUSIONS

This Chapter provides a quantitative analytical approach to estimate the risk cost of transporting hazardous materials by rail. Focusing on the risk to the environment, an updated environmental consequence model was used to estimate soil and groundwater cleanup costs. GIS analysis was used to account for distributions of different soil types and depths to groundwater along chemical-specific routes. Possible human population exposure to estimate evacuation cost was also considered together with train delay cost. Besides accounting for route-specific characteristics affecting the risk, this model accounts for chemical-specific hazard, tank car design and annual accident exposure based on the total number of shipments.

This model can be used as a framework to incorporate risk cost in freight rate determination, and to evaluate risk reduction options including tank car safety design enhancements, route alternatives and infrastructure improvement. These reflect a variety of changes in practices that may offer opportunities to reduce risk (Kawprasert and Barkan

2008, 2009). A major challenge is to understand the inter-relationships among different factors, that is, how changes in one affect another (Saat and Barkan 2006). Additionally, the cost-effectiveness of addressing these different factors will vary, relative to the others at both a system and scenario-specific level.

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CHAPTER 6

TANK CAR SAFETY DESIGN OPTIMIZATION TO REDUCE THE ENVIRONMENTAL RISK OF TRANSPORTING HAZARDOUS MATERIALS

6.1. INTRODUCTION

Besides prevention of accidents, prevention of spills from tank cars involved in accidents through the use of safety design enhancements has played an important role in improving railroad safety over the past two decades (Barkan et al. 1991; TRB 1994; 60 FR 49047; FRA 1996; Gallamore 1999; Barkan 2008; 74 FR 1769; Chapter 3). Tank car safety design has evolved for more than a century (Heller 1970; Barkan 2008). In general, tank car safety specifications and packaging requirements are commensurate with the degree of risk posed by the product (CFR 2009). Historically, nominal burst pressure of the tank has been used as a proxy for tank car damage resistance because of its relationship with tank thickness and thus its resistance to damage resistance (TRB 1994).

In Chapter 4, a risk-based tank car safety design optimization model that accounts for chemical-specific hazard and consequent benefit and cost was introduced. This offers the first formal approach to optimize tank car safety design, based on product hazard and tank car characteristics. The model is an extension of the bicriteria optimization model in Chapter 2 that addressed the tradeoff between safety and transportation efficiency to identify the set of Pareto-optimal tank car safety design solutions, which is based on previous research by Barkan et al. (2007) and Barkan (2008).

Railroads have had a number of incidents in which environmental cleanup expense has cost tens of millions of dollars, or more. In Chapter 5, an environmental exposure model, the Hazardous Materials Transportation Environmental Model (HMTECM) (Yoon et al. 2008; Hridaya 2008; Schaeffer et al. 2008), was used to estimate the nation-wide risk of rail transportation of a group of light, non-aqueous-phase, liquid (LNAPL) chemicals. The risk analysis accounted for soil and groundwater cleanup costs, route-specific probability distributions of soil type and depth to groundwater, annual traffic volume, railcar accident rate, and tank car safety features. Other release consequences including population exposure and train delay costs were also considered.

In this Chapter, I used the risk analysis results from Chapter 5, and applied the risk-based tank car safety design optimization model from Chapter 4 to identify possible enhanced-design tank cars to reduce the risk of transporting a group of LNAPL chemicals. A generalized tank car life-cycle cost model is presented to enable a comprehensive tank car capital cost analysis to be used in tandem with the tank car fleet financial cost model in Chapter 4. I then present a benefit-cost analysis and consider maximizing the net present value (NPV) to identify possible optimal, enhanced tank car safety designs to transport the chemicals of interest. This work has been used to advise the Association of American Railroads (AAR) with regards to the feasibility of using enhanced tank car designs to transport chemicals that pose risk to the environment.

6.1.1. Chemicals under Consideration

Table 6.1 lists a group of chemicals considered in this study and their risk as estimated in Chapter 5. While the objective in this Chapter is to identify a possible optimal tank car design for all of the chemicals of interest, detailed methodologies are illustrated only for cyclohexane, methanol and butyl acrylates which correspond to the chemicals with the highest, median and lowest hazard levels, respectively, as represented by their annual release risk per ton-mile.

Table 6.1
Chemicals of interest and their associated annual risk as estimated in Chapter 5.

Commodity Name	Annual Risk ($)	Risk per Car-Mile (¢)	Risk per Ton-Mile (¢)
Cyclohexane	94,575	4.64	0.048
Xylenes	409,531	4.43	0.045
Toluene	103,501	3.97	0.041
Ethyl Acetate	35,024	3.97	0.040
Ethyl Acrylate	25,302	3.90	0.040
Methyl Methacrylate	149,898	3.80	0.038
Methanol	559,830	3.42	0.035
Acrylonitrile	46,410	3.30	0.034
Vinyl Acetate	141,525	2.81	0.028
Ethanol	78,194	2.59	0.027
Benzene	30,769	2.00	0.021
Styrene	123,185	2.00	0.021
Butyl Acrylates	52,337	1.80	0.019

6.2. IDENTIFYING PARETO-OPTIMAL SOLUTIONS

In considering safety design enhancements for a given baseline tank car to transport a specific hazardous material, the first step is to identify a set of Pareto-optimal design alternatives using the model developed in Chapter 2. The tank car designs for the chemicals of interest specified in Chapter 5 were used in this Chapter as the baseline for improvement. They correspond to general-purpose DOT 111A100W1 tank cars with

0.4375” head and shell thicknesses, 110.25” inside tank diameter, and without top fittings protection.

Safety design variables involved are the risk reduction options (RROs) summarized in a generic decision tree (Fig. 6.1) (for simplicity, only one branch is expanded at each decision node). For the jacket option, the choices were binary; “yes” or “no”. For top fittings protection, three options were considered; none, typical (similar to the protective housing designs currently in service for pressure tank cars), and enhanced (any relatively new design that conforms to the latest amendment to the Hazardous Materials Regulations (CFR 2009))[6]. For head shields, three options were considered; none, half- or full-height. The next two RROs, increasing tank head and shell thicknesses were considered independently and represented by a two-dimensional matrix in which thickness of each was increased from the baseline thickness of 0.4375” to 1.5”, in 0.0625-inch increments. Collectively, Fig. 6.1 represents a total of 5,832 (2 × 3 × 3 × 18 × 18) unique tank car safety designs.

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[6] The amendment requires top fittings protection to withstand a rollover accident at a speed of 9 miles per hour. An analysis of a new design developed by TrinityRail (authorized under U.S. DOT Special Permit 14167) found that the rollover velocity that caused top-fittings failure was 2.6 times higher for the enhanced-design fittings compared to the baseline, chlorine-car-design for top-fittings protection. I assumed any enhanced design would reduce the probability of release from top fittings by 50%.

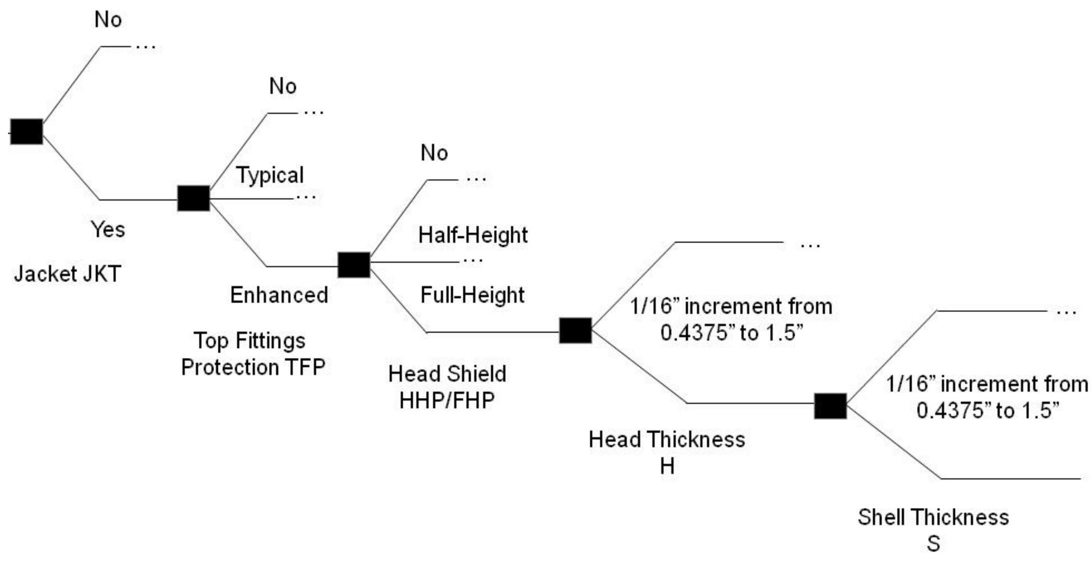


Fig. 6.1. Decision tree framework of possible RRO combinations

Removing bottom fittings was not considered in this analysis. Although it can potentially improve safety and transport efficiency by reducing the expected quantity lost and increasing tank car capacity, respectively, bottom fittings removal requires significant investment to retrofit terminals and tank cars for unloading from top fittings (Barkan et al. 1991; Chapter 2). Cost information on these types of terminal retrofits was not available.

The expected quantity lost and the weight of each of the RRO combinations were enumerated to identify the Pareto-optimal set of design solutions (Chapter 2). The Pareto-optimal solutions for a baseline tank car design fall along a curve called an efficient frontier as shown in Fig. 6.2 for cyclohexane, acrylonitrile and butyl acrylates. Besides the baseline tank car design, the density of the chemical affects the shape and the members of the Pareto-optimal set (Chapter 4). Each RRO has a unique functional relationship between reduction in the expected quantity lost and the increase in weight. The non-linearities in the efficient frontiers reflect the step-wise decision process in evaluating each possible RRO combination (Chapter 2). The benefit-cost analysis in later sections focused on the set of Pareto-optimal solutions for each chemical to identify the optimal, chemical-specific tank car safety design.

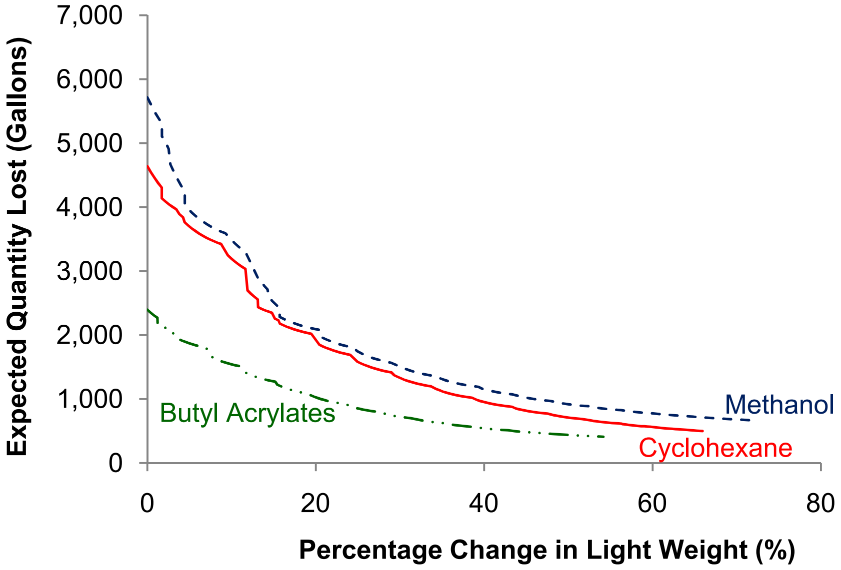


Fig. 6.2. The efficient frontier representing the Pareto-optimal solutions for tank cars transporting cyclohexane, acrylonitrile and butyl acrylates

6.3. BENEFIT ANALYSIS

The NPV approach from Chapter 4 is used in this Chapter to determine the cost-effectiveness of replacing tank cars in a specific hazardous material service. In this section, I evaluated the risk and the benefit for tank car safety design alternatives. I defined 40 years as my present value analysis period, representing a typical tank car life-span. I considered a natural attrition replacement schedule, in which a baseline tank car is replaced at the end of its service life, and the discount rate used in my analysis was 7% (OMB 1992).

The risk analysis framework in Chapter 5 was used to assess the risk associated with the use of each of the Pareto-optimal solutions (Fig. 6.3). Tank car safety design enhancement affects $P_{R|A}$ in Equation 5.2, tank car capacity, total car miles, the expected quantity lost and thus the consequence and risk. Appendix F shows the risk per ton-mile curves for the Pareto-optimal solutions of all chemicals under consideration.

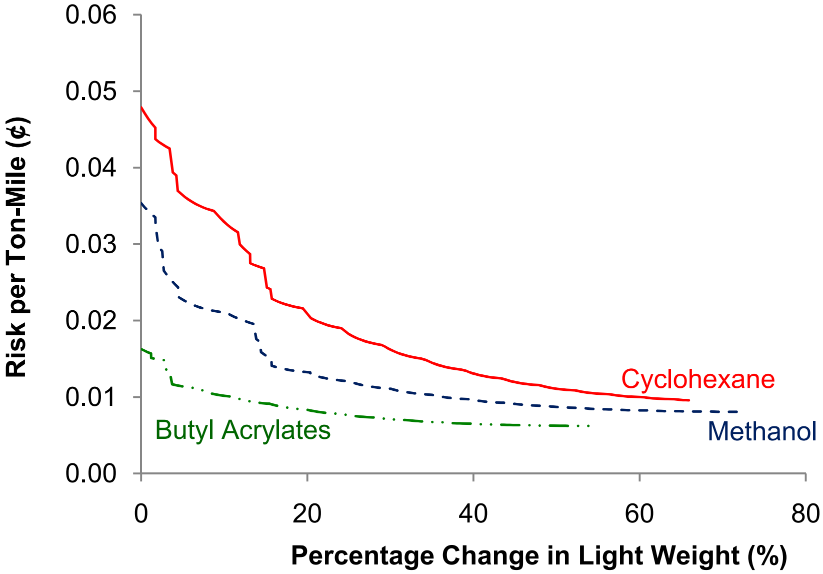


Fig. 6.3. The risk per ton-mile estimated using the risk analysis approach in Chapter 5 for the Pareto-optimal solutions for cyclohexane, acrylonitrile and butyl acrylates

The risk if each of the Pareto-optimal solutions was used was compared to the risk with the baseline tank car to estimate the incremental benefit, using Equation 4.2. The estimated benefit accounts for the incremental number of tank cars replaced annually over the 40-year analysis period. The present-value benefit was then estimated using Equation 4.3, based on the interest rate assumption defined above. Fig. 6.4 illustrates the benefit per ton-mile for the Pareto-optimal solutions of cyclohexane, acrylonitrile and butyl acrylates. Appendix G shows the benefit per ton-mile curves for all the chemicals of interest.

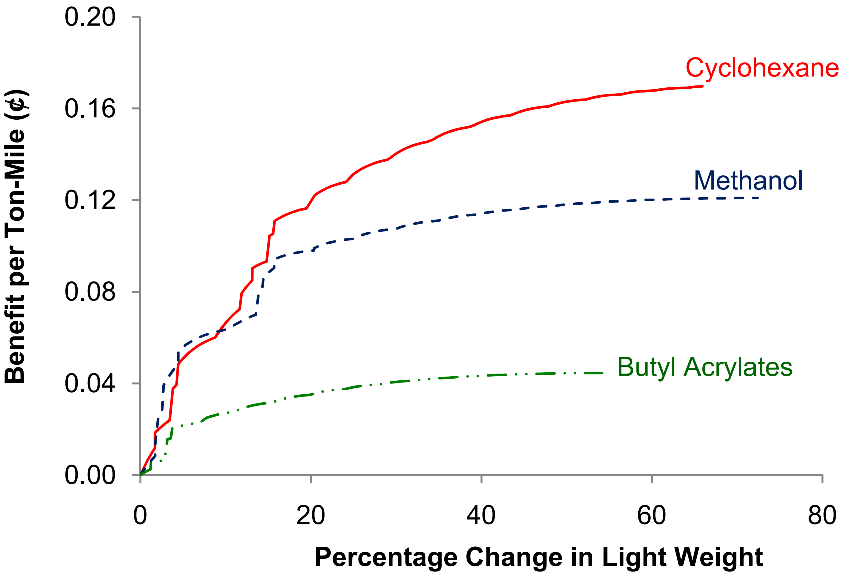


Fig. 6.4. Benefit per ton-mile estimated for the Pareto-optimal solutions for cyclohexane, acrylonitrile and butyl acrylates

6.4. COST ANALYSIS

A detailed tank car life-cycle cost is presented in this section and was used with the cost model from Chapter 4 to estimate the financial impact due to the tank car fleet replacement with enhanced safety design alternatives. The model included estimation of the capital cost that accounts for the life-cycle cost of a tank car, specific fleet size and tank car utilization rate (Table 6.2) and replacement schedules, and the operating cost. It incorporated the change in tank car capacity that affects the number of shipments required to transport a specific amount of product. Total cost, which is the sum of capital and operating costs for the Pareto-optimal solutions for each chemical of interest, and the incremental cost, which is the difference in cost as compared to when the baseline tank car is used, were estimated in this section.

Table 6.2
Total number of tank cars in the fleet transporting the chemicals of interest and their utilization rate (TRAINII 2007).

Commodity Name	Total Tank Cars in the Fleet	Average Tank Car Utilization Rate (Trips/Year)
Acrylonitrile	438	7
Benzene	555	6
Butyl Acrylates	572	7
Cyclohexane	295	15
Ethanol	1,164	4
Ethyl Acetate	304	4
Ethyl Acrylate	186	6
Methanol	3,743	5
Methyl Methacrylate	745	7
Styrene	2,627	3
Toluene	990	3
Vinyl Acetate	1,172	5
Xylenes	1,293	8

6.4.1. Tank Car Life-Cycle Cost

Tank car life-cycle cost estimates the after-tax cost to replace a tank car in a fleet. This includes the unit and maintenance costs, and other expenses over the life-span of a car. It is an input needed to calculate the life-cycle cost to estimate the capital cost required to replace a fleet of tank cars in a specific service (Equation 4.5).

6.4.1.1. Tank Car Pricing Model

Information on how a tank car is priced in the market is not usually available in the public domain. I developed a tank car pricing model to estimate the unit cost of a tank car as a proxy for its market price for a specific tank car size and design. The tank car pricing model's structure and cost assumptions presented here are based on expert knowledge elicited from my discussion with industry personnel. I assumed that tank car unit cost corresponds to the total of direct material costs, material overhead cost, direct labor cost, labor overhead cost and markup.

Direct material costs consist of the following unit cost items:

i. Non-Tank Purchased Components

Table 6.3
Costs of non-tank purchased components.

Component	Cost per car
Truck Castings	$6,000
Wheel Set	$4,000
Steel Surcharge	$4,000
Top Fittings (Pressure)	$2,500
Top Fittings (Non-Pressure)	$1,500
Braking System	$1,500
Bottom Fittings	$1,200
Draft Gear	$800
Couplers	$800
Yokes	$400

ii. Steel-Based Tank Components

Table 6.4
Costs of steel-based tank components.

Component	Cost per lb.
Tank Jacket	latest hot-rolled steel plate price ($0.45*)
Tank Head, Shell and Head shields	20% more than the latest hot-rolled steel plate price reflecting pressure-quality steel ($0.54)

** Price in Nov. 2008 from www.steelonthenet.com*

iii. Fabricated Tank Attachment – Draft Sill and Body Bolster ($2,500 per car)

iv. Thermal Protection ($1.10/lb)

v. Insulation ($0.50/lb)

Material overhead cost accounts for transportation and storage, and I assumed the cost is equal to 140% of direct material costs. Direct labor cost was assumed to be 15% of direct material costs. Labor overhead cost corresponds to fringe benefits, annual costs for running, maintaining and making capital improvements to the manufacturing facility, and I assumed the cost is equal to 140% of direct labor cost. 10% of the total cost was assumed to be the markup level.

The weights of tank components including the head, shell, thermal protection and insulation are needed to estimate the material costs. This weight varies for differently sized tank cars and with different design variations. I used a tank car sizing program called *IlliTank* (Saat 2003; Chapter 2) to estimate the component-specific weights. Table 6.5 shows an example unit cost calculation for a 20,000-gallon capacity, DOT 111A100W specification, non-pressure, non-jacketed tank car with 0.4375” tank thickness.

Table 6.5
Example unit cost calculation for a 20,000-gal. capacity, DOT 111A100W specification, non-pressure, non-jacketed tank car with 0.4375” tank thickness.

MATERIAL WEIGHTS			
	Commodity-Steel Based	0	lbs
	Pressure-Steel Based	22,110	lbs
	Thermal Protection	0	lbs
	Insulation	0	lbs
MATERIAL UNIT COSTS			
	Commodity Steel	0.45	$/lb
	Premium for Pressure Quality Steel	20%	
	Premium for Pressure Quality Steel	0.54	$/lb
	Thermal Protection	1.10	$/lb
	Insulation	0.50	$/lb
DIRECT MATERIAL COSTS			
	Non-Tank Purchased Components	$20,200	
	Commodity-Steel Based	$0	
	Pressure-Steel Based	$12,035	
	Fabricated Tank Attachment	$2,500	
	Thermal Protection	$0	
	Insulation	$0	
	Total	$34,735	
MATERIAL OVERHEAD COST			
	Percent of Material Cost	140%	
	Material Overhead Cost	$48,629	
DIRECT LABOR COST			
	Percent of Material Cost	15%	
	Direct Labor Cost	$5,210	
LABOR OVERHEAD COST			
	Percent of Direct Labor Cost	140%	
	Direct Labor Cost	$7,294	
TOTAL COST			
	Material + Labor and Overhead Costs	$95,868	
MARKUP			
	Percent of Total Cost	10%	
	Markup	$9,587	
MARKET PRICE			
	Costs + Markup	**$105,455**	

6.4.1.2. Tank Car Life-Cycle Cost

Fig. 6.5 shows a cash flow diagram representing the life-cycle cost of a tank car over a typical 40-year life span. Capital cost corresponds to the tank car unit cost calculated using the pricing model in the previous sub-section. The modified accelerated cost recovery system (MACRS) was used to calculate depreciation (IRS 2008). Details of maintenance expenses are shown in Table 6.6. The scrap value was assumed to be 15% of the initial tank car unit cost, based on discussion with an industry expert.

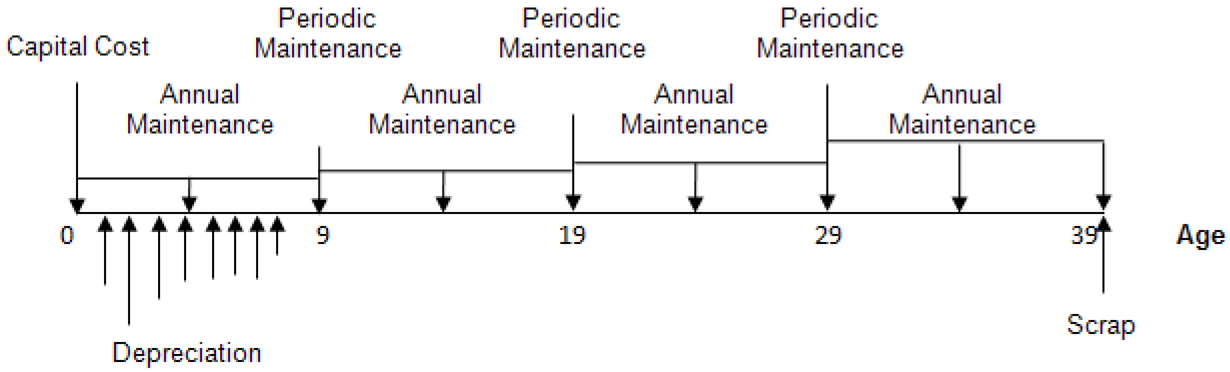


Fig. 6.5. Tank car life-cycle cash flow diagram

Table 6.6
Tank car maintenance cost and schedule

Maintenance Item	Interval between Maintenance Events	Cost	Total Cost Per Maintenance Event
Annual Running Repairs	every year	$750	$750
5-Year Maintenance Items			$4,500
Valve maintenance	5-Year	$1,500	
Cleaning	5-Year	$1,000	
Centerband/Patch paint	5-Year	$2,000	
10-Year Maintenance Items			
Exterior paint	10-Year	$3,500	
Reflectorization	10-Year	$200	
Clean car	10-Year	$1,000	
HM-201 (Detection and Repair of Cracks, Pits, Corrosion, Lining, Flaws, Thermal Protection Flaws, and Other Defects of Tank Car Tanks)	10-Year	$3,500	
General maintenance at year 10	10-Year	$1,200	$9,400
General maintenance at year 20	10-Year	$2,000	$10,200
General maintenance at year 30	10-Year	$3,000	$11,200

I assumed a 14-year asset book life, 36% corporate tax rate and 7% real discount rate (OMB 1992), and after-tax life cycle cost was calculated using a spreadsheet model as illustrated for a 20,000-gallon capacity, DOT 111A100W specification, non-pressure, non-jacketed tank car with 0.4375” tank thickness (Table 6.7). The net after-tax life cycle cost for this tank car is $80,632 ($64,164 + $16,469).

Table 6.7
After-tax capital cost for a 20,000-gal. capacity, DOT 111A100W specification, non-pressure, non-jacketed tank car with 0.4375” tank thickness.

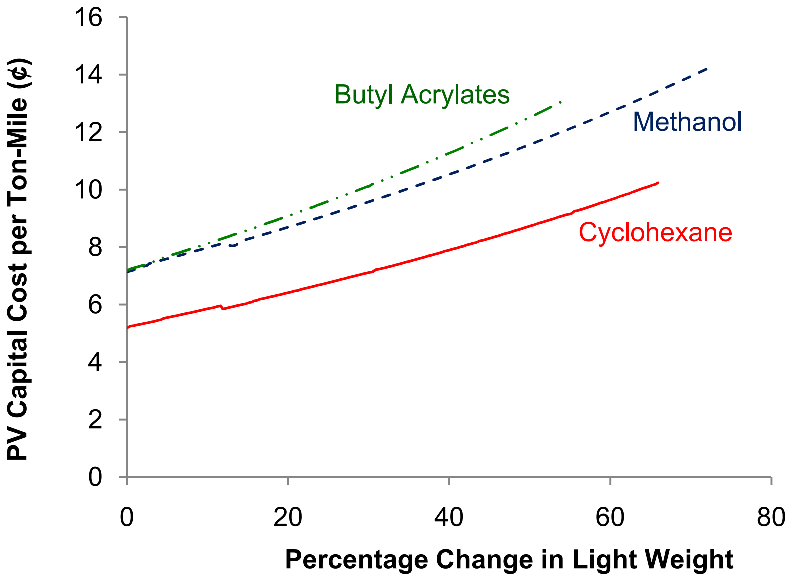
Present Value Summary:				**Debt Analysis Subtotal**	
Before Tax PV:	$65,470	$47,367		$112,837	
Tax Shield PV:		($16,886)	($31,786)	($48,673)	
After-Tax PV:	$65,470	$30,481	($31,786)		**$64,164**

Present Value Summary (Expense Items):				**Expense Analysis Subtotal**	
Before Tax PV:	$10,699	$16,024	($1,130)	$25,592	
Tax Shield PV:	($3,814)	($5,713)	$403	($9,124)	
After-Tax PV:	$6,885	$10,311	($727)		**$16,469**

Year	Capital	Beginning Balance	Principal Payment	Ending Balance	Interest Expense	Depreciation	Pre-tax Cash Flow	Tax Shield	After-tax Cash Flow	Year	Annual Maint	Periodic Maint	Scrap Value	Pre-tax Cash Flow	Tax Shield	After-tax Cash Flow
0	105,455	105,455	4,676	100,779	7,382	15,070	12,058	(8,004)	4,054	0	750	-	-	750	(267)	483
1	-	100,779	5,004	95,775	7,055	25,826	12,058	(11,722)	336	1	750	-	-	750	(267)	483
2	-	95,775	5,354	90,421	6,704	18,444	12,058	(8,965)	3,093	2	750	-	-	750	(267)	483
3	-	90,421	5,729	84,692	6,329	13,171	12,058	(6,952)	5,106	3	750	-	-	750	(267)	483
4	-	84,692	6,130	78,562	5,928	9,417	12,058	(5,471)	6,588	4	750	4,500	-	5,250	(1,872)	3,378
5	-	78,562	6,559	72,003	5,499	9,407	12,058	(5,314)	6,744	5	750	-	-	750	(267)	483
6	-	72,003	7,018	64,985	5,040	9,417	12,058	(5,154)	6,904	6	750	-	-	750	(267)	483
7	-	64,985	7,509	57,476	4,549	4,703	12,058	(3,298)	8,760	7	750	-	-	750	(267)	483
8	-	57,476	8,035	49,441	4,023	-	12,058	(1,434)	10,624	8	750	-	-	750	(267)	483
9	-	49,441	8,597	40,844	3,461	-	12,058	(1,234)	10,824	9	750	9,400	-	10,150	(3,618)	6,532
10	-	40,844	9,199	31,645	2,859	-	12,058	(1,019)	11,039	10	750	-	-	750	(267)	483
11	-	31,645	9,843	21,802	2,215	-	12,058	(790)	11,269	11	750	-	-	750	(267)	483
12	-	21,802	10,532	11,269	1,526	-	12,058	(544)	11,514	12	750	-	-	750	(267)	483
13	-	11,269	11,269	-	789	-	12,058	(281)	11,777	13	750	-	-	750	(267)	483
14	-	-	-	-	-	-	-	-	-	14	750	4,500	-	5,250	(1,872)	3,378
15	-	-	-	-	-	-	-	-	-	15	750	-	-	750	(267)	483
16	-	-	-	-	-	-	-	-	-	16	750	-	-	750	(267)	483
17	-	-	-	-	-	-	-	-	-	17	750	-	-	750	(267)	483
18	-	-	-	-	-	-	-	-	-	18	750	-	-	750	(267)	483
19	-	-	-	-	-	-	-	-	-	19	750	10,200	-	10,950	(3,904)	7,046
20	-	-	-	-	-	-	-	-	-	20	750	-	-	750	(267)	483
21	-	-	-	-	-	-	-	-	-	21	750	-	-	750	(267)	483
22	-	-	-	-	-	-	-	-	-	22	750	-	-	750	(267)	483
23	-	-	-	-	-	-	-	-	-	23	750	-	-	750	(267)	483
24	-	-	-	-	-	-	-	-	-	24	750	4,500	-	5,250	(1,872)	3,378
25	-	-	-	-	-	-	-	-	-	25	750	-	-	750	(267)	483
26	-	-	-	-	-	-	-	-	-	26	750	-	-	750	(267)	483
27	-	-	-	-	-	-	-	-	-	27	750	-	-	750	(267)	483
28	-	-	-	-	-	-	-	-	-	28	750	-	-	750	(267)	483
29	-	-	-	-	-	-	-	-	-	29	750	11,200	-	11,950	(4,260)	7,690
30	-	-	-	-	-	-	-	-	-	30	750	-	-	750	(267)	483
31	-	-	-	-	-	-	-	-	-	31	750	-	-	750	(267)	483
32	-	-	-	-	-	-	-	-	-	32	750	-	-	750	(267)	483
33	-	-	-	-	-	-	-	-	-	33	750	-	-	750	(267)	483
34	-	-	-	-	-	-	-	-	-	34	750	4,500	-	5,250	(1,872)	3,378
35	-	-	-	-	-	-	-	-	-	35	750	-	-	750	(267)	483
36	-	-	-	-	-	-	-	-	-	36	750	-	-	750	(267)	483
37	-	-	-	-	-	-	-	-	-	37	750	-	-	750	(267)	483
38	-	-	-	-	-	-	-	-	-	38	750	-	-	750	(267)	483
39	-	-	-	-	-	-	-	-	-	39	750	-	(15,818)	(15,068)	5,372	(9,696)

6.4.2. Capital, Operating, Total and Incremental Costs

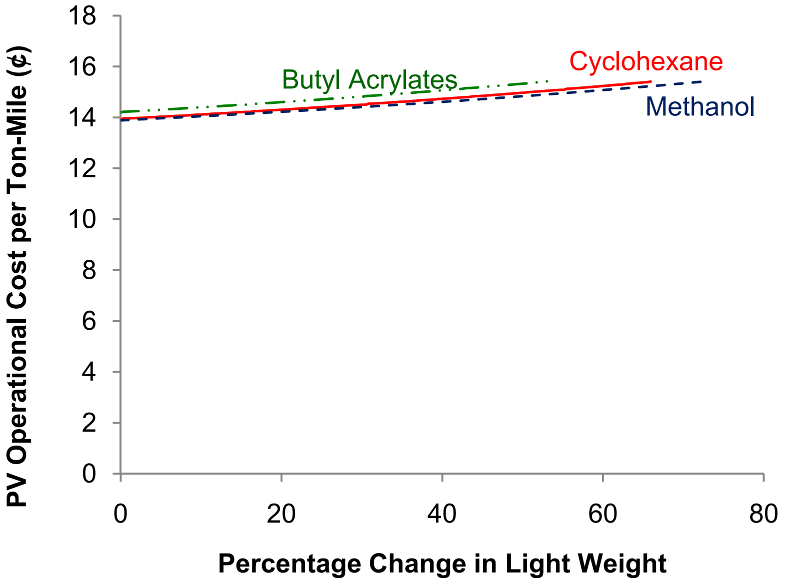
The tank car life-cycle cost model above was used to estimate the capital cost associated with each Pareto-optimal solution using Equation 4.5. Assuming an operating cost of $1.46 per car-mile, as estimated using the STB waybill cost data for Chemicals or Allied Products (STB 2006), the operating cost was calculated using Equation 4.6. Fig. 6.6 shows the capital, operating and total costs per ton-mile for the Pareto-optimal solutions of cyclohexane, acrylonitrile and butyl acrylates. Appendix H shows the costs per ton-mile curves for all chemicals of interest.



a)

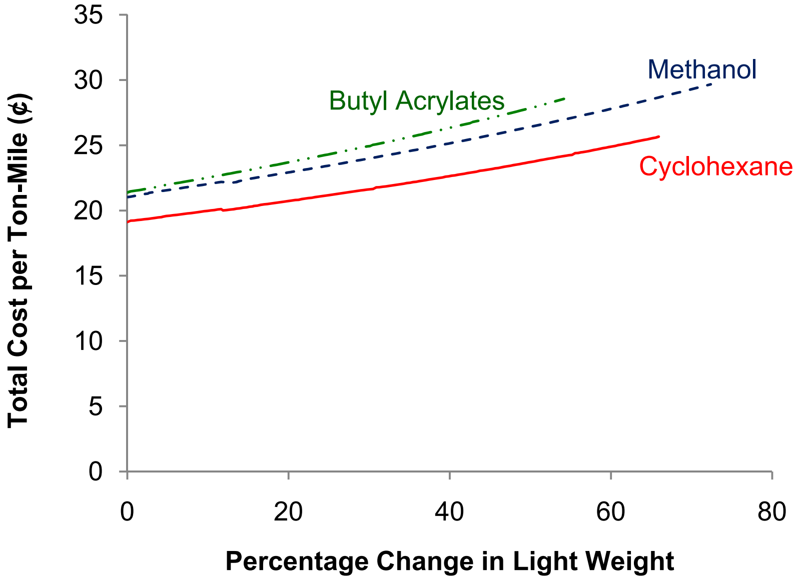
Fig. 6.6. a) Capital, b) operating and c) total costs per ton-mile estimated for the Pareto-optimal solutions for cyclohexane, acrylonitrile and butyl acrylates

Fig. 6.6, continued.



b)

Fig. 6.6. a) Capital, b) operating and c) total costs per ton-mile estimated for the Pareto-optimal solutions for cyclohexane, acrylonitrile and butyl acrylates



c)

Fig. 6.6. a) Capital, b) operating and c) total costs per ton-mile estimated for the Pareto-optimal solutions for cyclohexane, acrylonitrile and butyl acrylates

The total cost if a Pareto-optimal solution was used was compared to the total cost with the baseline tank car to estimate the incremental cost, using Equation 4.7. Fig. 6.7 illustrates the incremental cost per ton-mile for the Pareto-optimal solutions of cyclohexane, acrylonitrile and butyl acrylates. Appendix I shows the incremental cost per ton-mile curves for all of the chemicals of interest.

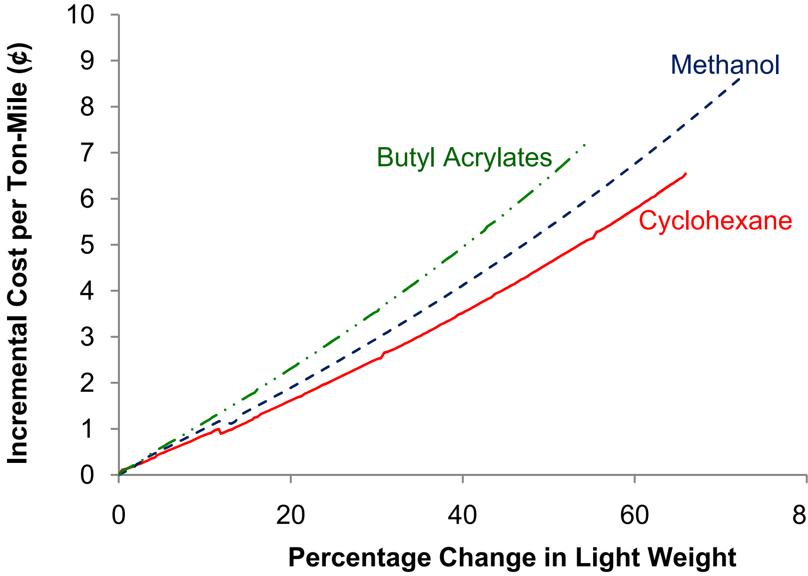


Fig. 6.7. Incremental cost per ton-mile estimated for the Pareto-optimal solutions for cyclohexane, acrylonitrile and butyl acrylates

6.5. NET PRESENT VALUE ANALYSIS APPROACH

I used maximization of NPV as the objective function to identify the optimal tank car safety design for each chemical. The NPV of an enhanced tank car was calculated by subtracting the benefit from the incremental cost. Fig. 6.8 shows the NPV associated with the Pareto-optimal tank car designs for cyclohexane, acrylonitrile and butyl acrylates. Appendix J shows the NPV per ton-mile curves for all of the chemicals of interest. My analysis found that on the basis of the NPV, it is not cost justified to replace the fleets of any of the chemicals of interest with enhanced-design tank cars.

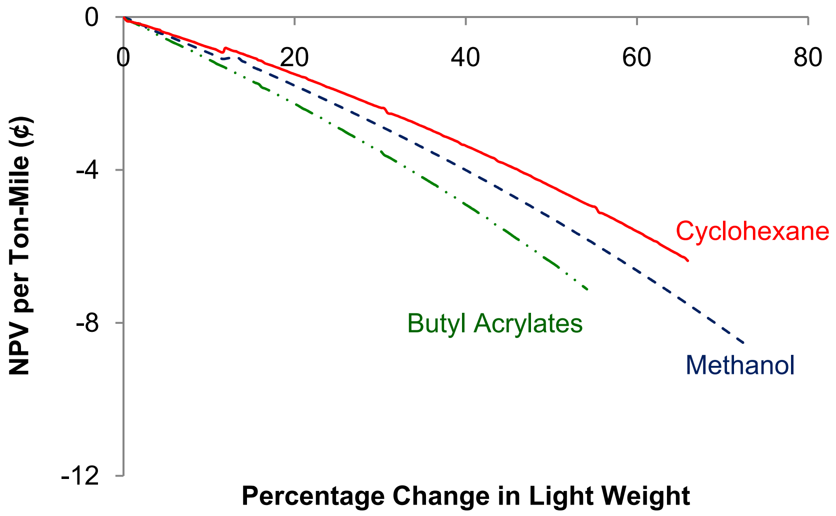


Fig. 6.8. The NPV per ton-Mile for the Pareto-optimal solutions for cyclohexane, acrylonitrile and butyl acrylates

6.6. SENSITIVITY ANALYSIS

The NPV analysis presented was based on a specific set of assumptions and risk elements considered to estimate the benefit in Chapter 5, and the cost model illustrated in this Chapter and Chapter 4. It was of further interest to analyze the levels of sensitivity of the benefit and cost estimates to change the cost-effectiveness of tank car safety design enhancements.

I performed a sensitivity analysis to analyze how high the risk or how low the cost associated with each of the chemicals of interest must be before any of the Pareto-optimal solutions would yield a positive NPV. I identified the minimum risk and cost multipliers, μ and $1/ \mu$, respectively, that would result in a positive NPV (Fig. 6.9). The associated design solution for each of the chemicals corresponds to adding enhanced top fittings protection. Relative to the baseline tank car design, this RRO offers the lowest marginal cost per unit of benefit (Fig. 6.10).

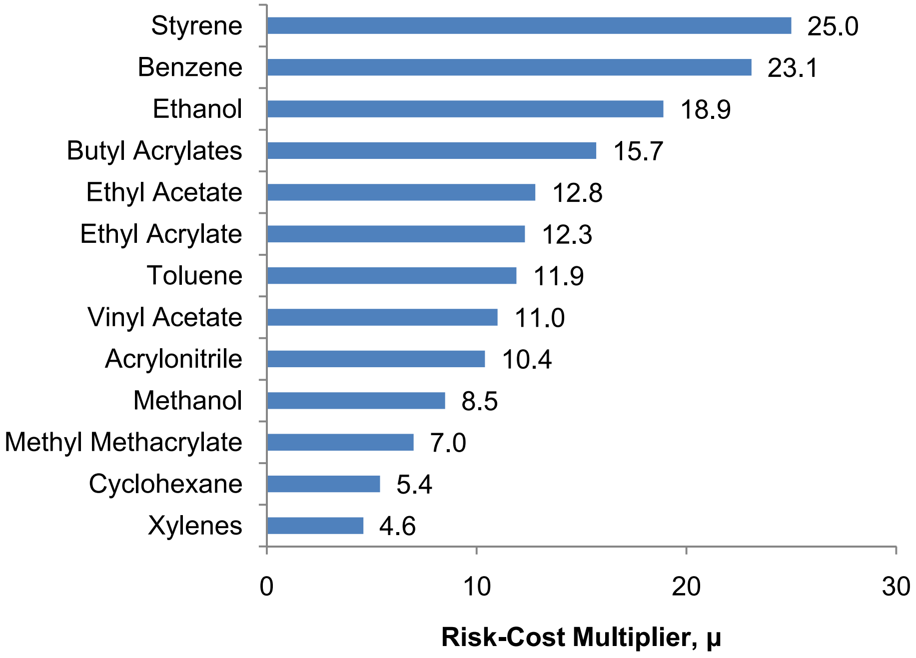


Fig. 6.9. Minimum Risk-Cost Multiplier to Attain Positive NPV Solutions

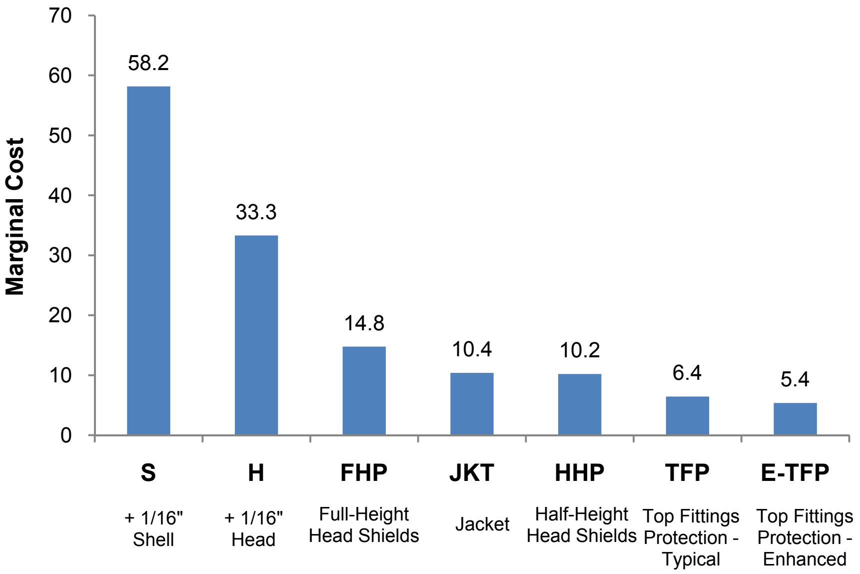


Fig. 6.10. The Marginal Cost Per Unit of Benefit for each RRO from the Baseline Design for Cyclohexane

6.7. DISCUSSION

6.7.1. Cost Effectiveness of Tank Car Safety Design Enhancements

The shape of the efficient frontiers for various chemicals differs due to differences in chemical density and consequent differences in the baseline tank cars' size (Fig. 6.2). For a specific level of tank car design enhancement, represented by a specific increase in light weight, chemicals with higher hazard and consequent risk yield higher benefits (Figs. 6.3 and 6.4). Capital cost functions among various chemicals differ due to differences in the efficient frontiers, tank car sizes and thus life-cycle costs, and most prevalently in tank car utilization rate as discussed in Chapter 4.

The operating cost per ton-mile functions for all chemicals are almost identical because the same cost per car-mile assumption was used (Fig. 6.6b). The increasing slope is due to the conversion from per car-mile to per ton-mile as the capacity or tonnage decreases with increasing tank car light weight. Overall, the incremental cost is greater than the benefit for any of the Pareto optimal solutions for all chemicals under consideration. On the basis of the NPV maximization objective function, tank car safety design enhancement is not a cost-effective means of improving the safety of transporting these chemicals based on the benefits accrued due to reduction in the risks considered in this analysis.

6.7.2. Implications of the Sensitivity Analysis

For cyclohexane and xylenes, the chemicals of interest with the highest risk per ton-mile, tank car safety design enhancements would be cost-effective if the risk was approximately five times greater, or if the costs were reduced by the same factor. Inclusion of human casualties and litigation costs or other factors not included in the risk model as discussed in Chapter 5 may have the potential to increase the risk estimate and thus the benefit term in the benefit-cost analysis. Similarly, reducing the unit cost or capital tax incentives, or increasing the tank car utilization rate, would all have the effect of reducing life-cycle cost. Overall, the magnitudes of these results suggest boundaries on uncertainty that would have to be exceeded before that uncertainty could affect decision to use enhanced tank car designs to transport these materials.

For all chemicals of interest, when the risk is increased or cost is reduced incrementally, the first safety design solution that would yield a positive NPV corresponds to the same RRO combinations of adding enhanced top fittings protection. Fig. 6.10 shows the typical marginal costs to increase a unit of benefit for each individual RRO relative to the baseline design. These marginal costs change at each stepwise decision for each tank car safety design included in the Pareto optimal set. A more detailed analysis may be warranted to understand the optimality of each design alternative with changes in the benefit and/or cost estimates using marginal concepts from economics.

6.7.3. Implications of Different Preference over Benefit and Cost

Using the NPV approach, none of the alternative tank car designs for any of the chemicals is cost-justified. This method assumes an equal preference over benefit and cost. In the context of hazardous materials transportation risk, it is possible that one may have a higher preference for safety benefit than cost. In order to incorporate such preference levels, the benefit-cost analysis can be modeled as a multi-attribute decision problem (Howard 1968; Matheson and Howard 1968; Keeney and Raiffa 1976; Howard 2007). A utility or value function that accounts for a specific preference over safety and cost can be used to assign the consequence for all possible risk scenarios or outcomes. The alternative with the highest expected value is then selected as the optimal solution (Modarres 2006).

6.8. CONCLUSIONS

This Chapter applied a risk-based tank car safety design optimization model to consider the cost effectiveness of using enhanced tank car safety designs to transport a group of LNAPL chemicals. On the basis of cost alone, the analysis showed that tank car safety design improvement is not justified for any of the chemicals. The risk consequences considered include soil and groundwater cleanup, evacuation and train delay costs. Further analyses that include other risk consequences not able to be measured might alter the benefit-cost results enough to change the decision. However, as shown by the sensitivity analysis, changes in risk or cost would need to be substantial, at least five times the estimated risk and cost for the chemical with the highest risk (more for others) in order to justify tank car safety design changes based on the objective function that maximizes NPV.

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CHAPTER 7

FUTURE RESEARCH

7.1. INTRODUCTION

In this Chapter I discuss some of the constraints on addressing certain questions related to the risk analysis and tank car safety design research discussed in this dissertation. I also briefly consider some ideas for new research questions and directions in these areas.

7.2. ADDRESSING CONSTRAINTS IN EXISTING WORK

7.2.1. Considering Multiple-Car Derailments and Multiple-Car Releases

Throughout my dissertation, the scope of the risk assessment focused on possible impacts due to a release from a single tank car involved in an accident. This assumption has been used to illustrate the risk analysis and optimization models concisely and effectively. Nevertheless, railroad mainline accidents may involve multiple-car derailments and releases (Verma and Verter 2007). The cost and risk impacts associated with multiple-car derailments and releases can be accounted for in the future by using the binomial probability distribution, based on viewing the occurrence of multiple tank car releases as a Bernoulli process as presented by Glickman et al. (2007).

7.2.2. Improving Chemical-Specific GIS Route Creation Process

Not all of the chemical-specific shipment waybill data were able to be used successfully in Chapter 5 to create the GIS routes for the chemicals of interest. Use of the most-updated version of PC*Miler Rail software may be able to improve the GIS route creation process. This can potentially improve the representation of chemical-specific routes to get better distributions of route-specific characteristics in risk analysis.

7.2.3. Considering Other Decision Making Techniques

The NPV approach was used to determine the cost-effectiveness of tank car safety design enhancements. This method assumes an equal preference over benefit and cost. In the context of hazardous materials transportation risk, it is possible that decision makers may have a higher preference for safety benefit than cost. In order to consider such preference levels, the benefit-cost analysis can be modeled as a multi-attribute decision problem (Howard 1968; Matheson and Howard 1968; Keeney and Raiffa 1976; Howard 2007). A utility or value function that accounts for a specific preference over safety and cost can be used to assign the consequence for all possible risk scenarios or outcomes. The alternative with the highest expected value would then be selected as the optimal solution (Modarres 2006).

7.2.4. Developing a More Detailed Uncertainty Analysis

The accident-caused release rate metric used in my dissertation was statistically derived. In Chapter 2 the metric and associated uncertainties involving tank car conditional probability of release and accident exposures were discussed in more detail, and a method provided to develop confidence intervals around estimates based on the metric. The final risk estimates are also subject to uncertainty in the underlying data and exposure models used. The use of risk profiles enables better appreciation of the variability in risk and certain subjective uncertainties related to a risk assessment problem. A more detailed uncertainty analysis that quantitatively propagates all possible errors and uncertainties could be developed. Formal treatment of both aleatory and epistemic uncertainties in the models can improve the confidence in the risk results estimated using the models presented in my dissertation.

7.3. NEW RESEARCH DIRECTIONS

7.3.1. Evaluating Unconventional Tank Car Designs' Performance

The tank car safety design optimization model presented in this dissertation was illustrated by considering conventional tank car risk reduction options involving designs, materials and construction processes currently used by tank car manufacturers. As discussed in Chapter 2, there is ongoing tank car safety research on new tank car design concepts (Ward et al. 2007; Tyrell et al. 2007a, b, Kirkpatrick 2009; Jeong et al. 2009). However in the absence of statistical estimates of the performance of these designs, it is difficult to quantify their performance as accurately as is possible for conventional designs. If the needed performance and weight data can be developed for the new design concepts, the model described in this Chapter can be adapted to evaluate them with the same objective of identifying the optimal combination of design features based on chemical-specific hazard and risk.

Statistical analyses have been extensively used to evaluate the safety performance of conventional tank car designs. These are feasible due to the availability of a large tank car accident database that was used to develop a robust statistical model by Treichel et al. (2006). However, we lack similar empirical experience with new tank car design concepts. Consequently, we must rely on structural modeling analyses that have been validated with physical testing (Tyrell et al. 2007a, b; Kirkpatrick 2009; Jeong et al. 2009). In order to use the tank car safety design optimization and risk analysis models presented in my dissertation, safety performance metrics associated with structural responses or failure methods such as maximum tensile strength and puncture velocity need to be translated into estimates of conditional probability of release given a tank car is involved in an accident. The first logical step is to relate these non-probabilistic metrics to the existing statistical model in Treichel et al. (2006). The use of Monte Carlo techniques may offer initial advances needed in this area (Hughes et al. 1989).

7.3.2. Considering Multiple Hazards and Risk Impacts

The physicochemical properties of a chemical affect its inherent hazard and the potential adverse consequences in a release incident and hence its risk. The types of hazard to be considered may include flammability, explosivity, toxicity, corrosivity, reactivity, environmental damage and radioactivity (CCPS 2008). It is not unusual for chemicals to have multiple types of hazards, and each has different potential levels of impact and severity that include human casualties, evacuation, environmental impacts, property damage, business interruption, adverse public relations and increased insurance premiums. Ideally, a comprehensive risk analysis would account for all these different hazards and impacts. An integrated risk metric should be developed to enable objective assessment and comparison of all chemicals that takes into account all the different "dimensions" of the hazard that each material may pose. The most useful unit of measurement for this metric would likely be monetary, thereby enabling benefit-cost analysis to be used in the decision process.

7.3.3. Considering Transportation Security

Consideration of transportation security can affect the overall objective and cost-effectiveness criteria in hazardous materials risk management. Increased awareness of the vulnerabilities of the transportation infrastructure and the potential consequences if a shipment was intentionally compromised has reaffirmed the need to consider transportation security together with safety (CCPS 2008). Some risk reduction strategies may have the potential to improve transportation security, and vice-versa. This effect should be accounted for in benefit-cost analyses of tank car safety design, railroad infrastructure improvements, and routing and operating decisions.

7.3.4. Considering Other Strategies to Reduce Hazardous Materials Transportation Risk

In the larger context of hazardous materials transportation safety and risk, tank car design is just one of several important factors. Others that can be evaluated and potentially modified to affect risk are accident likelihood and severity, operational practices and routing. There are a variety of changes in practices that may offer opportunities to reduce risk (Kawprasert and Barkan 2008, 2009). A major challenge to address is understanding the inter-relationships among different factors; that is, how changes in one affect another (Saat and Barkan 2006). Additionally, the cost-effectiveness of addressing these different factors will vary, relative to the others at both a system and scenario-specific level. As such, the existing benefit-cost analysis model presented in this dissertation ultimately needs to simultaneously account for the effect of implementing various different risk reduction strategies and their potential interactions.

7.3.5. Considering Multiple Decision Makers to Determine Optimal Strategies to Reduce Hazardous Materials Transportation Risk

In this dissertation, the optimal tank car safety design is identified by assuming the decision is made by a single decision maker. In addition, it is assumed that the associated costs and benefits are incurred and gained, respectively, by the same decision maker. In practice, railroad hazardous materials transportation involves a number of different entities including railroads, shippers, consignees and car owners. Different parties are subject to different liabilities, although, railroads generally assume principal liability in accidents, unless it can be shown that the accident or release was the fault of one of these other parties. Meanwhile, the additional costs for use of enhanced tank car safety designs are generally incurred by tank car owners and/or shippers, whereas the benefit of the reduction in risk is generally accrued by the railroad. The tank car safety design optimization model in this dissertation provides a globally optimal solution if all entities behave rationally and have the same goal to minimize risk. However, with one set of parties paying for the enhancements and another set receiving the benefit, the potential exists for conflicting objectives and constraints. These should be taken into account when considering the optimal tank car design relative to other infrastructure or operational strategies to reduce risk. A possible approach is use of game theory to mathematically evaluate the optimal strategy of both individual and multiple decision makers to understand the conditions that favor selfish versus cooperative strategies (von Neumann and Morgenstern 1944). The objective would be to gain insight regarding approaches that encourage players to behave in such a way as to minimize risk and do so in the most efficient manner possible.

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APPENDIX A

GAMS CODE FOR ILLITANK

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SCALAR
*Group 1
steelDensity steel density in lbs per cubic inch /0.283564815/
insulate1Density ceramic fiber density in lbs per cubic inch /0.002604167/
insulate2Density fiberglass density in lbs per cubic inch /0.000434028/

*Group 2
GRL gross rail load in lbs /263000/
productDensity product density in lbs per gallon /7.6/
outage tank outage in % /2/
insideDia inside diameter in inch /110.25/
headThick tank head thickness in inch /0.4375/
shellThick tank shell thickness in inch /0.4375/
insulate1Thick ceramic fiber thickness in inch /0/
insulate2Thick fiberglass thickness in inch /0/
jacket jacket constant (0=none 1=jacketed) /0/
headShield head protection constant (0=none 1=half 2=full) /0/
bottomFit bottom fittings constant (0=none 1=equipped) /1/
topFitProtect top fittings protection constant (0=none 1=equipped) /0/
addWeight additional weight increase or reduction /0/
TFPEnhanced TFP Enhanced constant (0=none 1=equipped) /0/

*Group 3
topFitProtectWeight top fittings protection weight /0/
bottomFitWeight bottom fittings weight/0/
nonTankComponentsWeight non-tank weight in lbs /0/
jacketThick tank jacket thickness in inch /0/
HSThick head shields thickness in inch /0/
tankHeadWeight tank head weight in lbs /0/
headShieldsPreWeight head shields weight in lbs /0/
headShieldsWeight height-specified head shields weight in lbs /0/
insulate1EllipWeight ceramic fiber ellipsoidal weight in lbs /0/
insulate2EllipWeight fiberglass ellipsoidal weight in lbs /0/
jacketEllipWeight tank head weight in lbs /0/;

*Redefine functional variables
topFitProtectWeight = 1700*topFitProtect + 500*TFPEnhanced;
bottomFitWeight = 500*bottomFit;
jacketThick = 0.1196*jacket;
HSThick $(headShield ne 0) = 0.5-jacketThick;
nonTankComponentsWeight = 31300$(GRL = 263000) + 31800$(GRL = 286000);

tankHeadWeight = (4/3*22/7*((insideDia+2*headThick)/2)
```

```
           *((insideDia+2*headThick)/2)*(0.5*(insideDia+2*headThick)/2)-
           4/3*22/7*(insideDia/2)*(insideDia/2)*(0.5*insideDia/2))*steelDensity;

headShieldsPreWeight = (4/3*22/7*((insideDia+2*headThick+2*HSThick)/2)
    *((insideDia+2*headThick+2*HSThick)/2)*(0.5*(insideDia+2*headThick
    +2*HSThick)/2)- 4/3*22/7*((insideDia+2*headThick)/2)
    *((insideDia+2*headThick)/2)*(0.5*(insideDia+2*headThick)/2))*steelDensity;

headShieldsWeight = headShieldsPreWeight$(headShield = 2)
                  + 0.5*headShieldsPreWeight$(headShield = 1);

insulate1EllipWeight = (4/3*22/7*((insideDia+2*headThick+2*HSThick
           +2*insulate1Thick)/2)*((insideDia+2*headThick+2*HSThick
           +2*insulate1Thick)/2)*(0.5*(insideDia+2*headThick+2*HSThick
           +2*insulate1Thick)/2)-4/3*22/7*((insideDia+2*headThick+2*HSThick)/2)
           *((insideDia+2*headThick+2*HSThick)/2)
           *(0.5*(insideDia+2*headThick+2*HSThick)/2))*insulate1Density;

insulate2EllipWeight =
         (4/3*22/7*((insideDia+2*headThick+2*HSThick+2*insulate1Thick
         +2*insulate2Thick)/2)*((insideDia+2*headThick+2*HSThick+2
         *insulate1Thick+2*insulate2Thick)/2)*(0.5*(insideDia+2*headThick+2
         *HSThick+2*insulate1Thick+2*insulate2Thick)/2)- 4/3*22/7*((insideDia
         +2*headThick+2*HSThick+2*insulate1Thick)/2)*((insideDia+2*headThick
         +2*HSThick+2*insulate1Thick)/2)*(0.5*(insideDia+2*headThick
         +2*HSThick+2*insulate1Thick)/2))*insulate2Density;

jacketEllipWeight =(4/3*22/7*((insideDia+2*headThick+2*HSThick+2*insulate1Thick
         +2*insulate2Thick+2*jacketThick)/2)*((insideDia+2*headThick+2*HSThick
         +2*insulate1Thick+2*insulate2Thick+2*jacketThick)/2)*(0.5*(insideDia
         +2*headThick+2*HSThick+2*insulate1Thick+2*insulate2Thick
         +2*jacketThick)/2)-4/3*22/7*((insideDia+2*headThick+2*HSThick
         +2*insulate1Thick+2*insulate2Thick)/2)*((insideDia+2*headThick
         +2*HSThick+2*insulate1Thick+2*insulate2Thick)/2)*(0.5*(insideDia
         +2*headThick+2*HSThick+2*insulate1Thick+2*insulate2Thick)/2))
         *steelDensity;


VARIABLE GRLconstraint GRL maximum limit;

POSITIVE VARIABLES
TankLength tank length in inch
galCap tank capacity in gallons
tankWeight tank weights in lbs
insulate1Weight ceramic fiber weight in lbs
insulate2Weight fiberglassweight in lbs
jacketWeight jacket weights in lbs
lightWeight total light weight in lbs;

EQUATIONS
TankCapacity calculating tank gallon capacity
TankWeightEqn calculating tank head and shell weights
Insulate1WeightEqn calculating total ceramic fiber insulation weight
Insulate2WeightEqn calculating total fiberglass insulation weight
JacketWeightEqn calculating total jacket weight
LightWeightEqn calculating total light weight
```

```
Objective objective function;


TankCapacity.. galCap=e=(4/3*22/7*(insideDia/2)*(insideDia/2)*(0.5*insideDia/2)
                        + 22/7*(insideDia/2)**2*TankLength)
                        *((100-outage)/100)*0.004329004;


TankWeightEqn.. tankWeight =e= tankHeadWeight+2*22/7*insideDia/2
                               *shellThick*TankLength*steelDensity;

Insulate1WeightEqn.. insulate1Weight =e= insulate1EllipWeight
                                    +2*22/7*(insideDia+2*shellThick+2*HSThick)/2
                                    *insulate1Thick*TankLength*insulate1Density;

Insulate2WeightEqn.. insulate2Weight =e= insulate2EllipWeight
                   +2*22/7*(insideDia+2*shellThick+2*HSThick+2*insulate1Thick)/2
                   *insulate2Thick*TankLength*insulate2Density;

JacketWeightEqn.. jacketWeight =e= jacketEllipWeight
           +2*22/7*(insideDia+2*shellThick+2*HSThick+2*insulate1Thick
           +2*insulate2Thick)/2*jacketThick*TankLength*steelDensity;

LightWeightEqn.. lightWeight =e= tankWeight+headShieldsWeight+insulate1Weight
                         +insulate2Weight+jacketWeight+bottomFitWeight
                         +topFitProtectWeight+nonTankComponentsWeight+addWeight;

Objective.. GRLconstraint =e= GRL-lightWeight-galCap*productDensity;

GRLconstraint.lo=0;

MODEL IlliTank /All/
SOLVE IlliTank minimizing GRLconstraint Using NLP;

Options decimals =5;
Display galCap.l,lightWeight.l,TankLength.l;Display galCap.l,lightWeight.l,TankLength.l;
```

APPENDIX B

CONFIDENCE INTERVALS FOR CONDITIONAL PROBABILITY OF RELEASE, $P_{R|A}$

The basic form of the logistic regression for release source *i* is as follows:

$$L(i) = b_0 + b_1x_1 + b_2x_2 + \ldots + + b_nx_n$$

The estimated variance of the logistic regression linear combination *L* for release source *i* is calculated by using this equation:

$$\sigma^2_{L(i)} = \varphi^2 \sum_{j=0}^{n} x_j^2 \sigma_b^2 + \sum_{j \neq k} \sum x_j x_k \, \sigma_{b_j}^2 \sigma_{b_k}^2 \rho_{jk}$$

where:

$\sigma^2_{L(i)}$ = estimated variance of source *i* logistic regression
φ = mainline or yard multiplier from Treichel et al. (2006)
x = the value of the independent variable that corresponds to an attribute of a release-source logistic regression where $x_0 = 1$
σ^2_b = estimated variance of the regression coefficient *b*
ρ_{jk} = correlation coefficient between the regression coefficients b_j and b_k as shown in Tables A.1 to A.4

Given $L = \ln\left(\frac{P_{R|A}}{1-P_{R|A}}\right)$, where $P_{R|A}$ is calculated using Equation 2.2 in the text, the estimated variance of *L* is calculated as follows:

$$\sigma_L^2 = \varphi^2 \frac{1}{P_{R|A}^2} \sum_i P_{R|A}^2 \, \sigma^2_{L(i)}$$

The upper and lower (1-α)100% bounds of L are respectively given by:

$L^{hi} = L + \Phi^{-1}(1-\alpha)\, \sigma_L$
$L^{lo} = L - \Phi^{-1}(1-\alpha)\, \sigma_L$

where $\Phi^{-1}(1-\alpha)$ is the inverse standard normal distribution value for (1-α)100%.

Finally, the (1-α)100% confidence interval for the $P_{R|A}$ estimate is: hi

$$\left(\frac{e^{lo}}{1+e^{lo}}, \frac{e^{hi}}{1+e^{hi}}\right)$$

Table A.1
Coefficients of Correlation for Head-Release-Source Regression

	Const.	YARD	HMT	HST	JKT	SHELF
Const.	1.00000	-0.10282	-0.97195	0.28412	-0.29754	-0.22713
YARD	-0.10282	1.00000	0.03671	-0.00443	-0.05992	-0.02923
HMT	-0.97195	0.03671	1.00000	-0.28176	0.20445	0.14233
HST	0.28412	-0.00443	-0.28176	1.00000	-0.15754	-0.23600
JKT	-0.29754	-0.05992	0.20445	-0.15754	1.00000	-0.09978
SHELF	-0.22713	-0.02923	0.14233	-0.23600	-0.09978	1.00000

Table A.2
Coefficients of Correlation for Shell-Release-Source Regression

	Const.	YARD	STS	JKT
Const.	1.00000	-0.08632	-0.97047	-0.25807
YARD	-0.08632	1.00000	0.03814	-0.04391
STS	-0.97047	0.03814	1.00000	0.10833
JKT	-0.25807	-0.04391	0.10833	1.00000

Table A.3
Coefficients of Correlation for Top-Fittings-Release-Source Regression

	Const.	YARD	PRESS	JKT	SHELF
Const.	1.00000	-0.27201	-0.30541	-0.40454	-0.42656
YARD	-0.27201	1.00000	0.03798	-0.07536	0.07760
PRESS	-0.30541	0.03798	1.00000	0.00750	-0.00121
JKT	-0.40454	-0.07536	0.00750	1.00000	-0.20167
SHELF	-0.42656	-0.04782	-0.00121	-0.20167	1.00000

Table A.4
Coefficients of Correlation for Bottom-Fittings-Release-Source Regression

	Const.	YARD	JKT	SHELF
Const.	1.00000	-0.18484	-0.60362	-0.33320
YARD	-0.18484	1.00000	-0.04037	-0.02270
JKT	-0.60362	-0.04037	1.00000	-0.12154
SHELF	-0.33320	-0.02270	-0.12154	1.00000

APPENDIX C

CONFIDENCE INTERVALS FOR ACCIDENT-CAUSED RELEASE RATE, P_R

From Equation 2.4 in the text, the accident-caused release rate is the multiplication of the conditional probability of release given a tank car derailed $P_{R|A}$, the accident rate P_A, number of car shipments and the change in tank capacity multiplier Cap/Cap'. The first two variables, $P_{R|A}$ and P_A, are the main source of uncertainties. Assuming these variables are independent, which is reasonable given that the likelihood of a tank car derailed is subject to different accident-related conditions than the ones that affect the likelihood of a tank car release its product once derailed, the variance of the P_R estimate is approximated as follows:

$$\sigma_{P_R}^2 = \left(\frac{\left| \frac{e^{L^{lo}}}{1+e^{L^{lo}}} - \frac{e^{L^{hi}}}{1+e^{L^{hi}}} \right|}{2} / \Phi^{-1}(1-\alpha) \right)^2 \sigma_{P_A}^2$$

The (1-α)100% confidence interval for the P_R estimate is:

$$\left(P_R - \Phi^{-1}(1-\alpha)\sigma_{P_R}^2 , P_R + \Phi^{-1}(1-\alpha)\sigma_{P_R}^2 \right)$$

APPENDIX D

HMTECM COST REGRESSIONS FOR CHEMICALS OF INTEREST IN CHAPTER 5

a) Acrylonitrile

Soil Type, *k*	Depth to Groundwater, *j* (ft)	Total Cost Regression ($), $C_{j,k}$ = Spill_Volume Q × b_1 + b_2 b_1	 b_2	 Std. Error	 R^2
Sand	10	17.80	621,151	5,769	0.9995
	20	35.71	716,144	8,352	0.9997
	50	41.47	722,025	68,813	0.9875
	100	40.77	523,930	14,293	0.9994
	200	40.53	520,190	14,912	0.9994
Silt	10	23.69	531,223	51,673	0.9785
	20	31.71	346,522	12,559	0.9993
	50	31.71	346,522	12,559	0.9993
	100	31.71	346,522	12,559	0.9993
	200	31.71	346,522	12,559	0.9993
Clay	10	24.98	326,973	8,181	0.9995
	20	24.98	326,973	8,181	0.9995
	50	24.98	326,973	8,181	0.9995
	100	24.98	326,973	8,181	0.9995
	200	24.98	326,973	8,181	0.9995

b) Benzene

Soil Type, *k*	Depth to Groundwater, *j* (ft)	Total Cost Regression ($), $C_{j,k}$ = Spill_Volume × b_1 + b_2			
		b_1	b_2	Std. Error	R^2
Sand	10	23.77	578,936	22,577	0.9959
	20	41.37	655,855	22,376	0.9987
	50	45.93	561,410	54,054	0.9937
	100	38.41	470,361	24,194	0.9982
	200	38.13	469,903	23,702	0.9982
Silt	10	31.66	453,413	52,970	0.9873
	20	28.20	356,140	9,729	0.9995
	50	28.20	356,140	9,729	0.9995
	100	28.20	356,140	9,729	0.9995
	200	28.20	356,140	9,729	0.9995
Clay	10	21.45	334,531	2,815	0.9999
	20	21.45	334,531	2,815	0.9999
	50	21.45	334,531	2,815	0.9999
	100	21.45	334,531	2,815	0.9999
	200	21.45	334,531	2,815	0.9999

c) Butyl Acrylates

Soil Type, *k*	Depth to Groundwater, *j* (ft)	Total Cost Regression ($), $C_{j,k}$ = Spill_Volume × b_1 + b_2			
		b_1	b_2	Std. Error	R^2
Sand	10	16.67	704,036	23,094	0.9912
	20	27.21	755,150	24,335	0.9963
	50	33.69	573,327	88,592	0.9691
	100	24.85	429,210	7,907	0.9995
	200	24.99	419,055	10,641	0.9992
Silt	10	25.85	502,812	101,102	0.9341
	20	16.55	328,046	5,906	0.9994
	50	16.55	328,046	5,906	0.9994
	100	16.55	328,046	5,906	0.9994
	200	16.55	328,046	5,906	0.9994
Clay	10	12.52	319,904	1,160	1.0000
	20	12.52	319,904	1,160	1.0000
	50	12.52	319,904	1,160	1.0000
	100	12.52	319,904	1,160	1.0000
	200	12.52	319,904	1,160	1.0000

d) Cyclohexane

Soil Type, *k*	Depth to Groundwater, *j* (ft)	Total Cost Regression ($), $C_{j,k}$ = Spill_Volume × b_1 + b_2			
		b_1	b_2	Std. Error	R^2
Sand	10	108.24	2,982,444	326,575	0.9597
	20	116.14	2,511,027	413,007	0.9449
	50	73.48	377,859	154,695	0.9800
	100	37.37	465,018	8,171	0.9998
	200	37.10	469,215	8,854	0.9997
Silt	10	144.61	112,237	366,677	0.9712
	20	24.96	353,929	9,172	0.9994
	50	24.96	353,929	9,172	0.9994
	100	24.96	353,929	9,172	0.9994
	200	24.96	353,929	9,172	0.9994
Clay	10	21.52	332,114	3,859	0.9999
	20	21.52	332,114	3,859	0.9999
	50	21.52	332,114	3,859	0.9999
	100	21.52	332,114	3,859	0.9999
	200	21.52	332,114	3,859	0.9999

e) Ethanol

Soil Type, *k*	Depth to Groundwater, *j* (ft)	Total Cost Regression ($), $C_{j,k}$ = Spill_Volume × b_1 + b_2			
		b_1	b_2	Std. Error	R^2
Sand	10	10.85	574,537	6,087	0.9986
	20	22.27	622,321	35,307	0.9885
	50	30.98	361,100	51,948	0.9872
	100	24.14	424,080	7,102	0.9996
	200	24.14	424,080	7,102	0.9996
Silt	10	9.81	329,529	1,730	0.9999
	20	9.81	329,529	1,730	0.9999
	50	9.81	329,529	1,730	0.9999
	100	9.81	329,529	1,730	0.9999
	200	9.81	329,529	1,730	0.9999
Clay	10	5.36	307,288	1	1.0000
	20	5.36	307,288	1	1.0000
	50	5.36	307,288	1	1.0000
	100	5.36	307,288	1	1.0000
	200	5.36	307,288	1	1.0000

f) Ethyl Acetate

Soil Type, *k*	Depth to Groundwater, *j* (ft)	Total Cost Regression ($), $C_{j,k}$ = Spill_Volume × b_1 + b_2			
		b_1	b_2	Std. Error	R^2
Sand	10	17.66	599,254	8,440	0.9989
	20	35.37	686,130	8,321	0.9997
	50	40.37	651,793	60,947	0.9896
	100	38.49	506,892	63,024	0.9878
	200	38.78	493,977	62,797	0.9881
Silt	10	25.65	498,388	60,553	0.9750
	20	29.99	352,092	10,343	0.9995
	50	29.99	352,092	10,343	0.9995
	100	29.99	352,092	10,343	0.9995
	200	29.99	352,092	10,343	0.9995
Clay	10	24.66	336,470	5,222	0.9998
	20	24.66	336,470	5,222	0.9998
	50	24.66	336,470	5,222	0.9998
	100	24.66	336,470	5,222	0.9998
	200	24.66	336,470	5,222	0.9998

g) Ethyl Acrylate

Soil Type, *k*	Depth to Groundwater, *j* (ft)	Total Cost Regression ($), $C_{j,k}$ = Spill_Volume × b_1 + b_2			
		b_1	b_2	Std. Error	R^2
Sand	10	18.68	642,350	10,430	0.9986
	20	36.26	721,582	10,647	0.9996
	50	41.23	690,246	67,666	0.9877
	100	39.10	487,938	10,437	0.9997
	200	39.36	477,186	10,299	0.9997
Silt	10	28.79	554,507	73,719	0.9707
	20	31.64	342,869	11,943	0.9993
	50	31.64	342,869	11,943	0.9993
	100	31.64	342,869	11,943	0.9993
	200	31.64	342,869	11,943	0.9993
Clay	10	28.04	328,940	8,849	0.9995
	20	28.04	328,940	8,849	0.9995
	50	28.04	328,940	8,849	0.9995
	100	28.04	328,940	8,849	0.9995
	200	28.04	328,940	8,849	0.9995

h) Methanol

Soil Type, *k*	Depth to Groundwater, *j* (ft)	Total Cost Regression ($), $C_{j,k}$ = Spill_Volume × b_1 + b_2			
		b_1	b_2	Std. Error	R^2
Sand	10	17.83	599,035	6,469	0.9994
	20	35.24	688,487	8,244	0.9997
	50	41.45	628,011	61,629	0.9899
	100	38.77	481,675	9,643	0.9997
	200	38.28	483,812	10,741	0.9996
Silt	10	26.04	479,170	60,624	0.9756
	20	28.29	352,709	9,396	0.9995
	50	28.29	352,709	9,396	0.9995
	100	28.29	352,709	9,396	0.9995
	200	28.29	352,709	9,396	0.9995
Clay	10	15.29	325,565	2	1.0000
	20	15.29	325,565	2	1.0000
	50	15.29	325,565	2	1.0000
	100	15.29	325,565	2	1.0000
	200	15.29	325,565	2	1.0000

i) Methyl Methacrylate

Soil Type, *k*	Depth to Groundwater, *j* (ft)	Total Cost Regression ($), $C_{j,k}$ = Spill_Volume × b_1 + b_2			
		b_1	b_2	Std. Error	R^2
Sand	10	18.61	635,528	10,521	0.9985
	20	36.02	714,168	12,551	0.9994
	50	41.18	658,343	71,417	0.9863
	100	38.62	476,111	8,678	0.9998
	200	38.04	478,876	10,126	0.9997
Silt	10	28.10	512,814	69,723	0.9724
	20	30.00	341,421	12,393	0.9992
	50	30.00	341,421	12,393	0.9992
	100	30.00	341,421	12,393	0.9992
	200	30.00	341,421	12,393	0.9992
Clay	10	25.28	309,216	13,796	0.9986
	20	25.28	309,216	13,796	0.9986
	50	25.28	309,216	13,796	0.9986
	100	25.28	309,216	13,796	0.9986
	200	25.28	309,216	13,796	0.9986

j) Styrene

Soil Type, *k*	Depth to Groundwater, *j* (ft)	Total Cost Regression ($), $C_{j,k}$ = Spill_Volume × b_1 + b_2			
		b_1	b_2	Std. Error	R^2
Sand	10	35.34	1,148,530	68,049	0.9832
	20	46.27	1,139,495	85,758	0.9844
	50	42.17	608,118	100,319	0.9746
	100	25.13	432,827	8,536	0.9995
	200	24.87	431,443	9,567	0.9993
Silt	10	54.10	1,043,589	247,167	0.9122
	20	17.48	324,444	7,923	0.9991
	50	17.48	324,444	7,923	0.9991
	100	17.48	324,444	7,923	0.9991
	200	17.48	324,444	7,923	0.9991
Clay	10	14.50	316,324	4,245	0.9996
	20	14.50	316,324	4,245	0.9996
	50	14.50	316,324	4,245	0.9996
	100	14.50	316,324	4,245	0.9996
	200	14.50	316,324	4,245	0.9996

k) Toluene

Soil Type, *k*	Depth to Groundwater, *j* (ft)	Total Cost Regression ($), $C_{j,k}$ = Spill_Volume × b_1 + b_2			
		b_1	b_2	Std. Error	R^2
Sand	10	40.86	695,130	88,136	0.9790
	20	49.44	834,931	41,051	0.9968
	50	49.38	606,879	64,275	0.9923
	100	38.65	476,638	8,524	0.9998
	200	37.93	480,608	10,114	0.9997
Silt	10	46.34	669,820	128,554	0.9657
	20	29.94	351,533	10,160	0.9995
	50	29.94	351,533	10,160	0.9995
	100	29.94	351,533	10,160	0.9995
	200	29.94	351,533	10,160	0.9995
Clay	10	24.58	337,806	3,859	0.9999
	20	24.58	337,806	3,859	0.9999
	50	24.58	337,806	3,859	0.9999
	100	24.58	337,806	3,859	0.9999
	200	24.58	337,806	3,859	0.9999

l) Vinyl Acetate

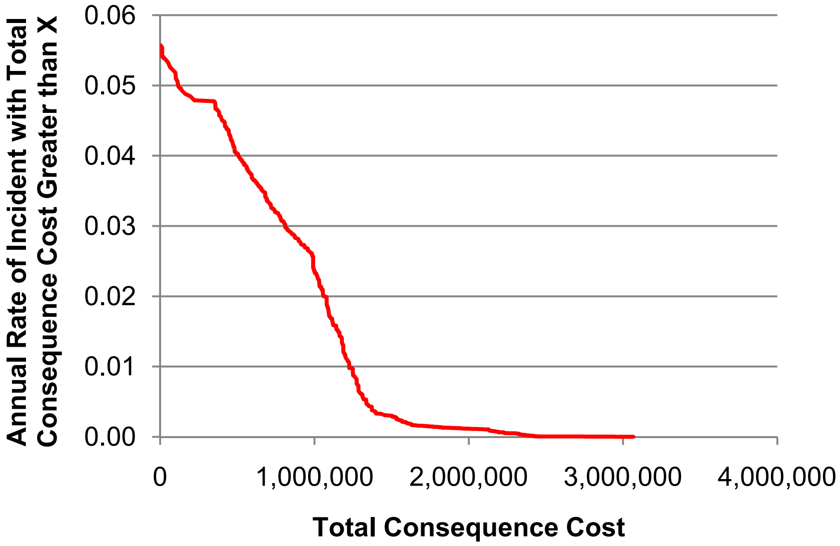
Soil Type, *k*	Depth to Groundwater, *j* (ft)	Total Cost Regression ($), $C_{j,k}$ = Spill_Volume × b_1 + b_2			
		b_1	b_2	Std. Error	R^2
Sand	10	11.40	596,365	9,847	0.9966
	20	22.36	659,358	10,553	0.9990
	50	27.57	642,298	65,149	0.9749
	100	26.37	450,360	11,321	0.9992
	200	26.57	439,934	11,104	0.9992
Silt	10	17.02	482,746	91,560	0.8822
	20	17.66	321,009	47,352	0.9679
	50	17.66	321,009	47,352	0.9679
	100	17.66	321,009	47,352	0.9679
	200	17.66	321,009	47,352	0.9679
Clay	10	14.52	315,295	18,378	0.9927
	20	14.52	315,295	18,378	0.9927
	50	14.52	315,295	18,378	0.9927
	100	14.52	315,295	18,378	0.9927
	200	14.52	315,295	18,378	0.9927

m) Xylenes

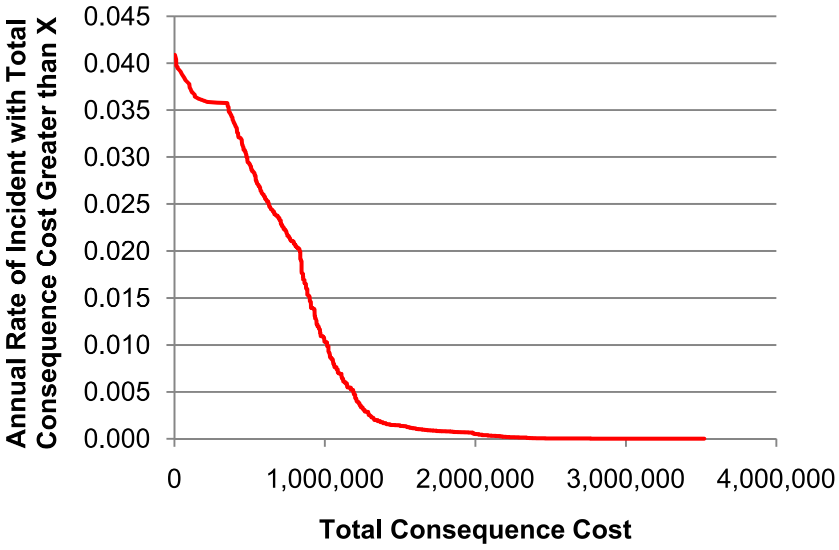
Soil Type, *k*	Depth to Groundwater, *j* (ft)	Total Cost Regression ($), $C_{j,k}$ = Spill_Volume × b_1 + b_2			
		b_1	b_2	Std. Error	R^2
Sand	10	55.10	1,515,537	124,051	0.9772
	20	70.14	1,439,193	137,797	0.9825
	50	61.35	641,452	115,493	0.9839
	100	38.02	474,615	8,782	0.9998
	200	38.23	465,171	9,286	0.9997
Silt	10	85.18	1,114,891	334,099	0.9338
	20	28.24	353,661	9,556	0.9995
	50	28.24	353,661	9,556	0.9995
	100	28.24	353,661	9,556	0.9995
	200	28.24	353,661	9,556	0.9995
Clay	10	21.40	336,146	1,213	1.0000
	20	21.40	336,146	1,213	1.0000
	50	21.40	336,146	1,213	1.0000
	100	21.40	336,146	1,213	1.0000
	200	21.40	336,146	1,213	1.0000

APPENDIX E

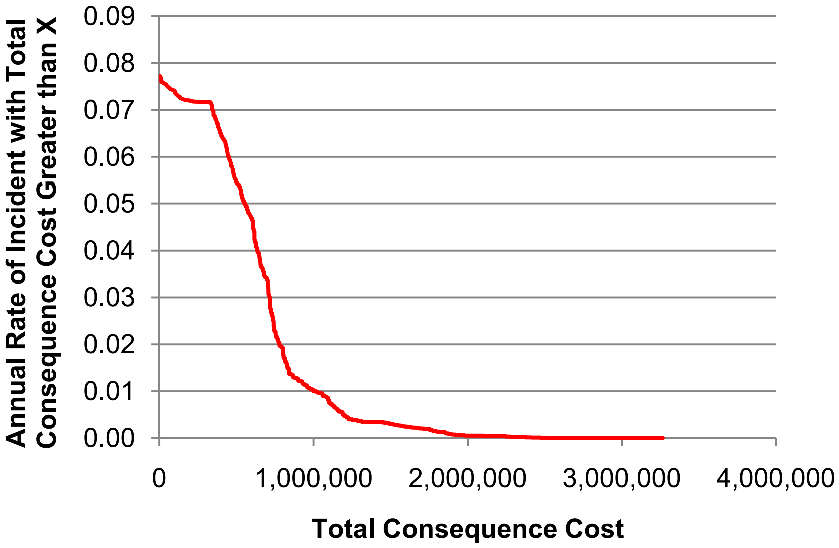
RISK PROFILES FOR CHEMICALS OF INTEREST IN CHAPTER 5



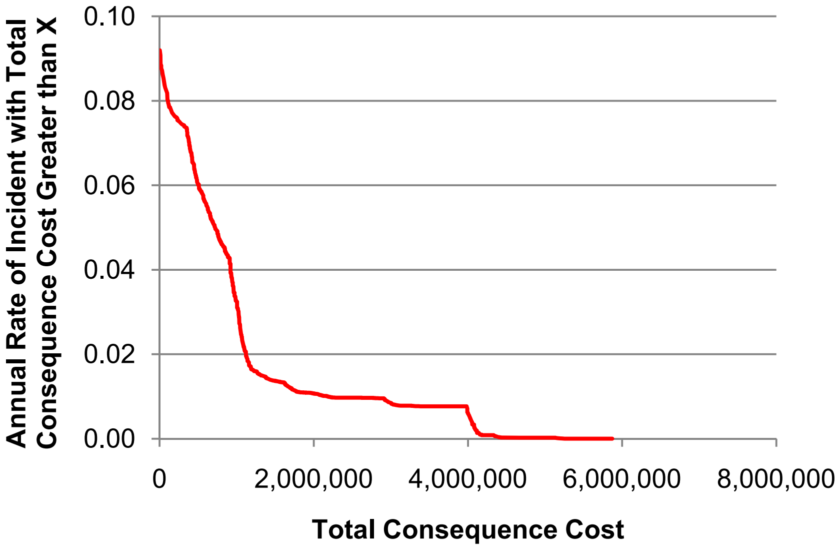
a) Acrylonitrile



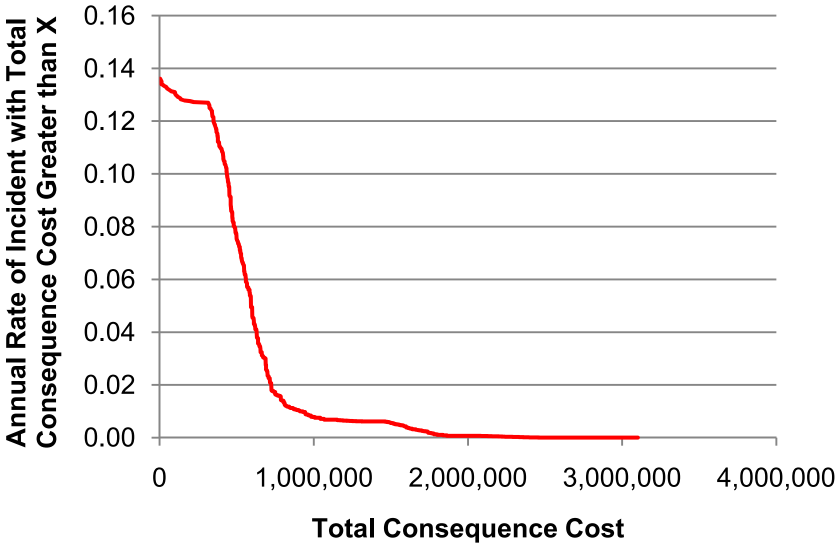
b) Benzene



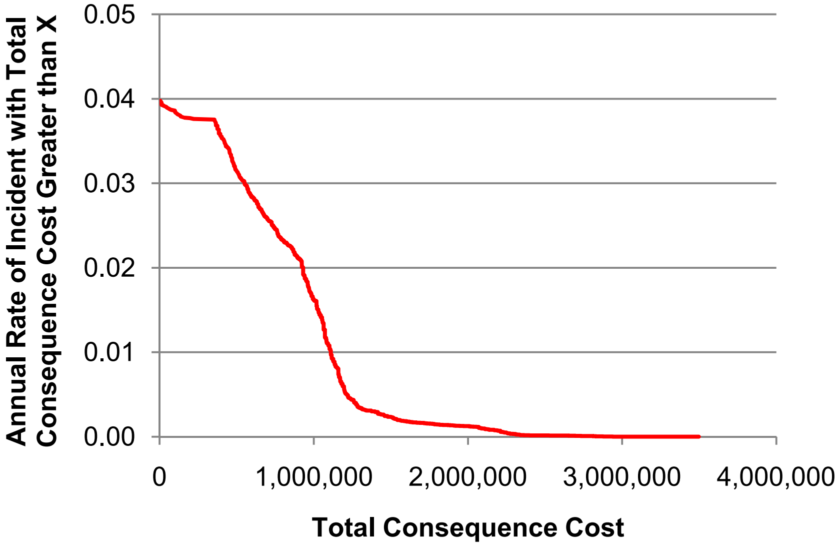
c) Butyl Acrylates



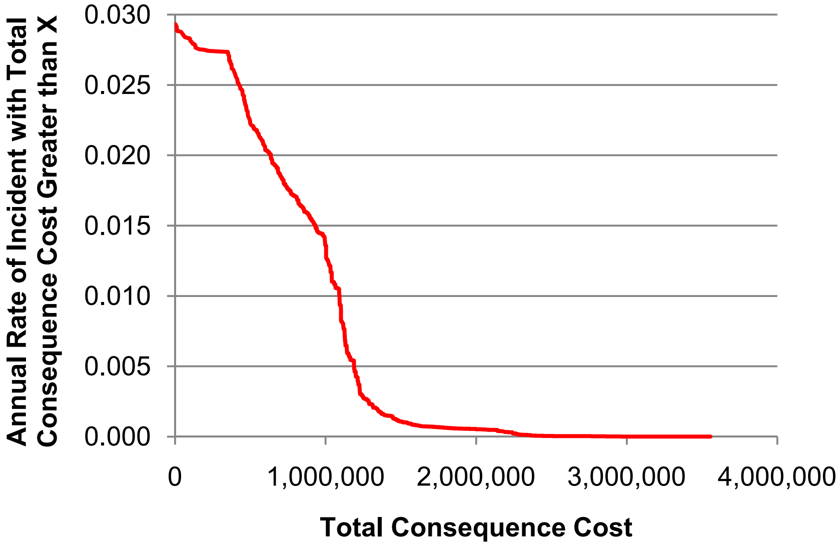
d) Cyclohexane



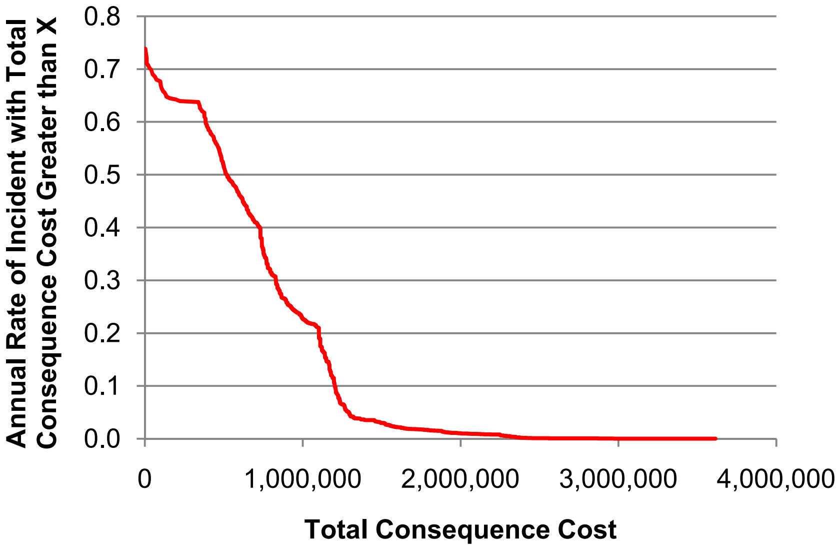
e) Ethanol



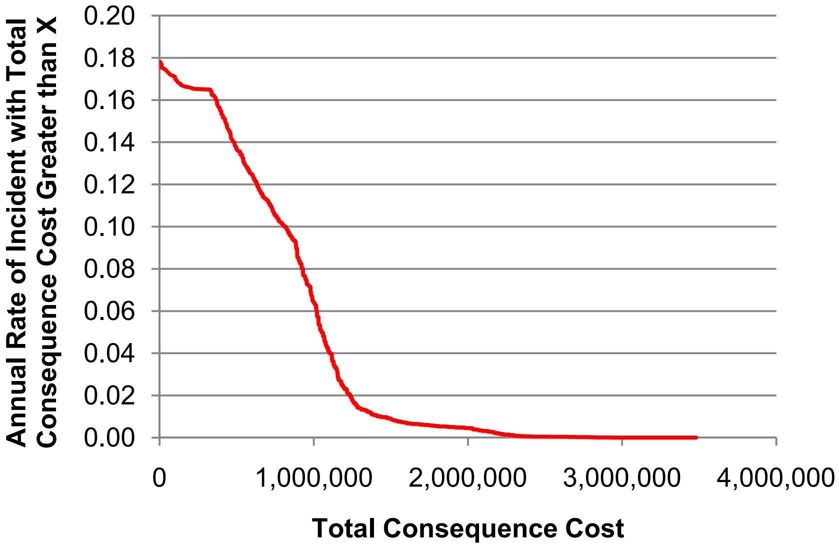
f) Ethyl Acetate



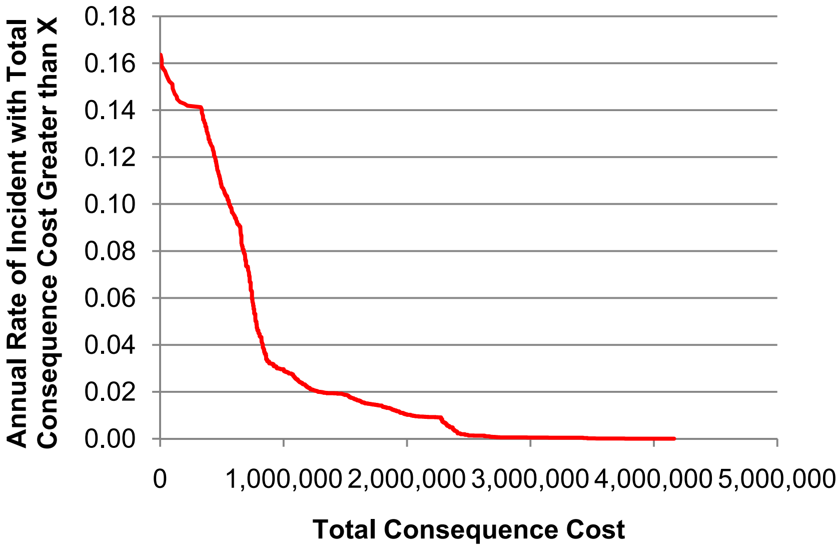
g) Ethyl Acrylate



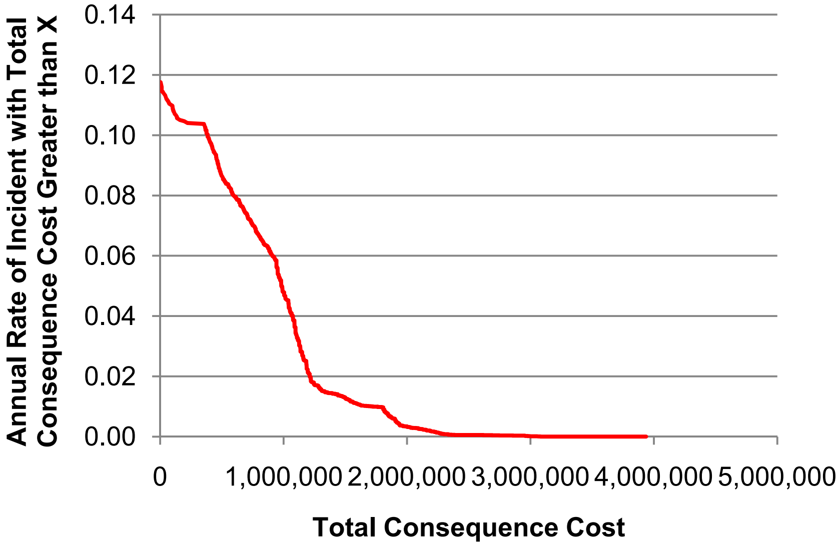
h) Methanol



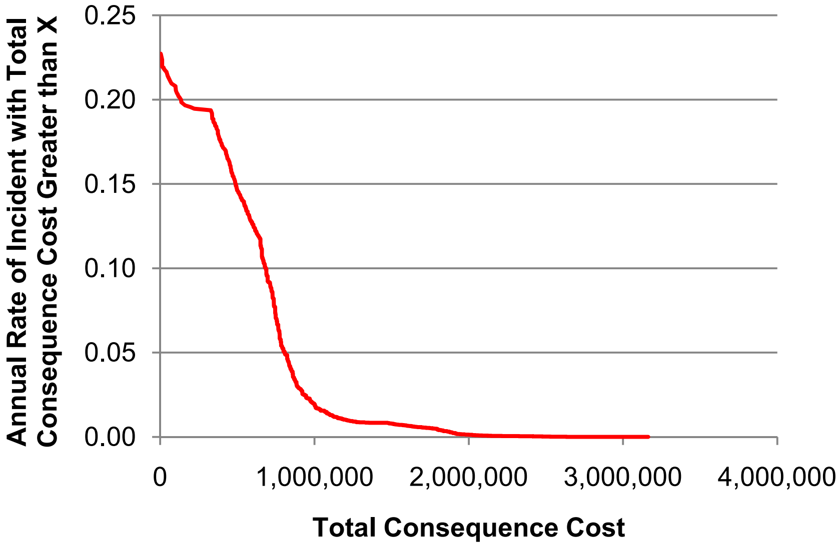
i) Methyl Methacrylate



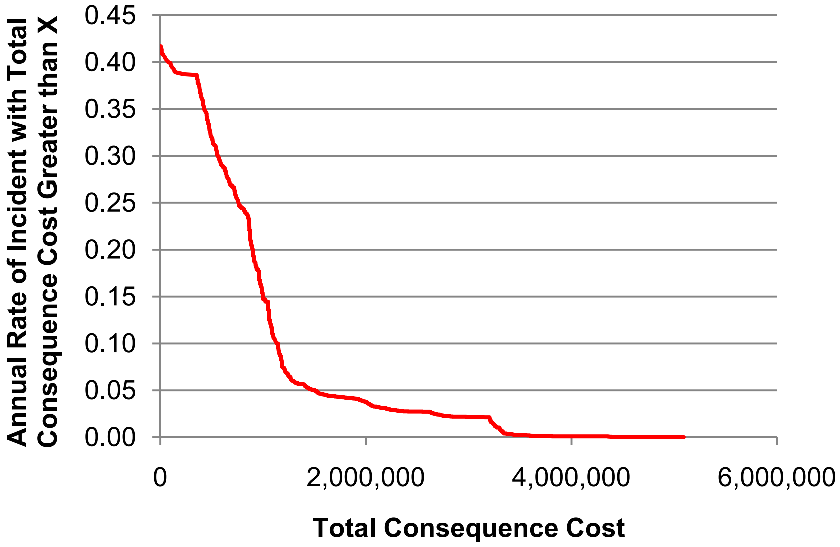
j) Styrene



k) Toluene



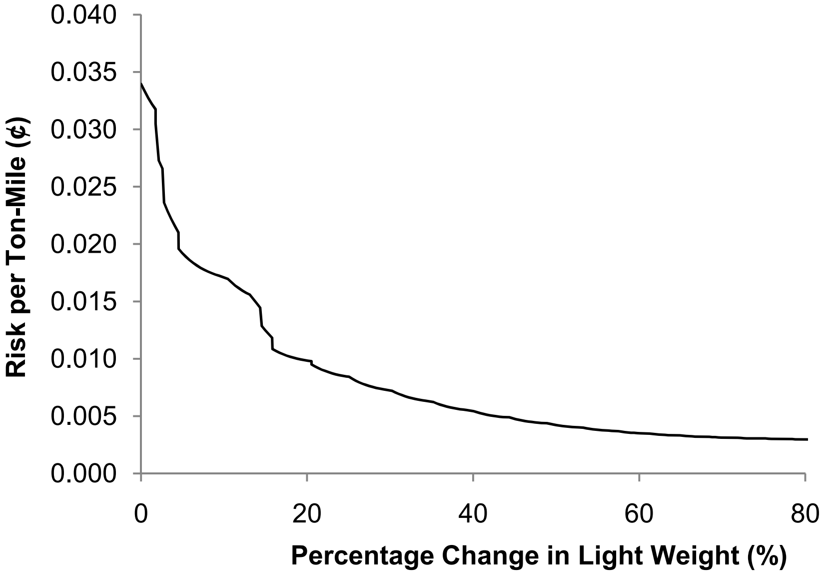
l) Vinyl Acetate



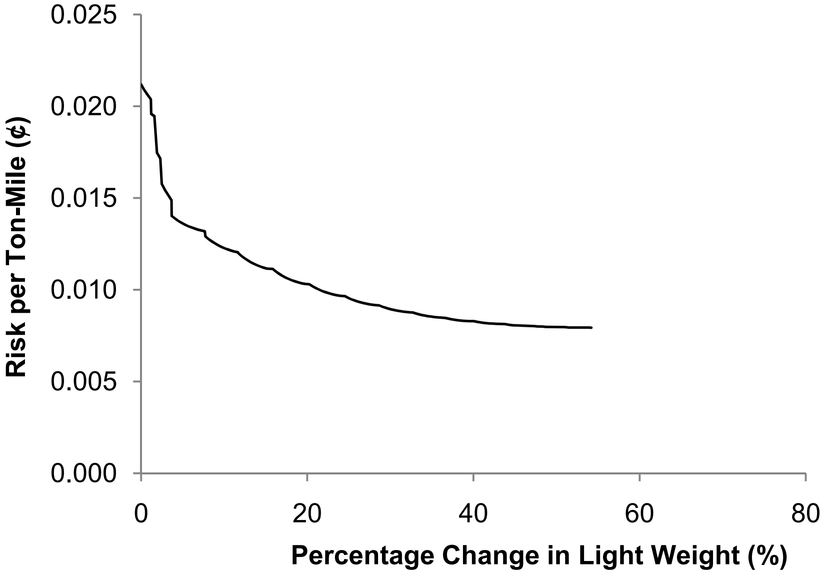
m) Xylenes

APPENDIX F

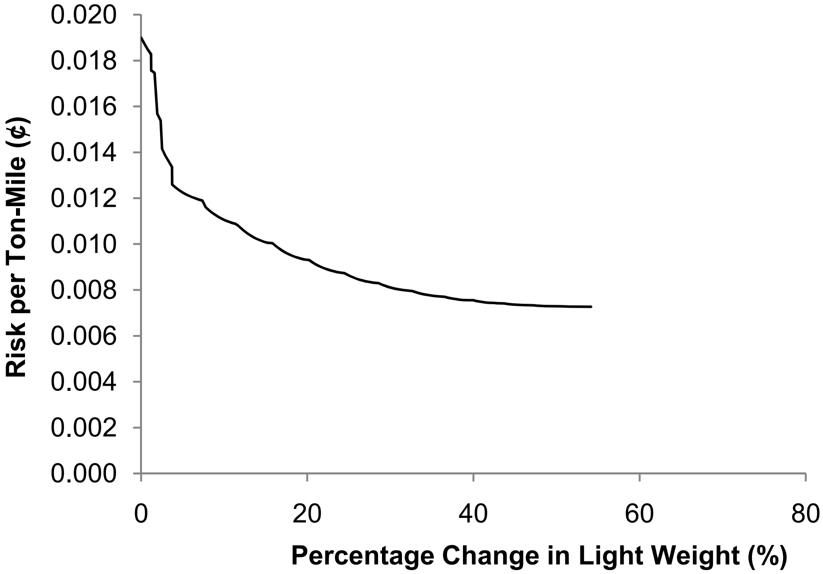
RISK PER TON-MILE FOR THE PARETO-OPTIMAL SOLUTIONS OF CHEMICALS OF INTEREST IN CHAPTER 6



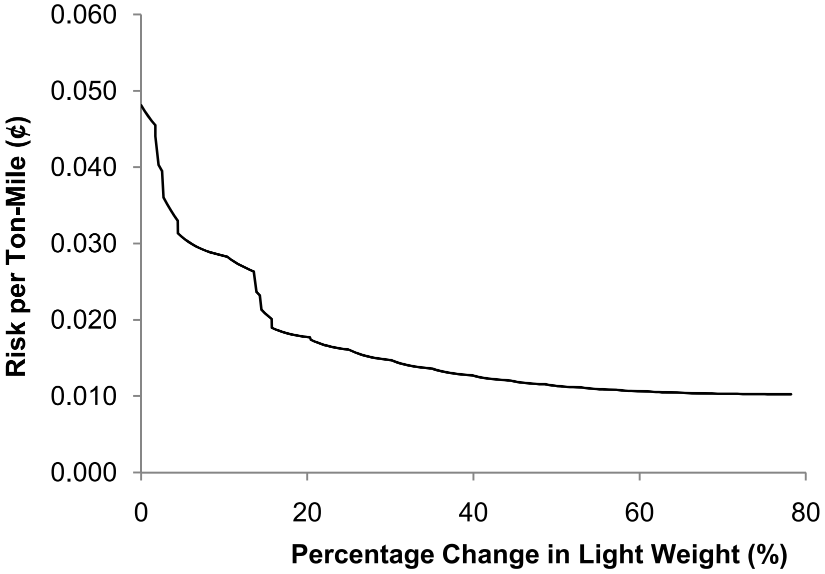
a) Acrylonitrile



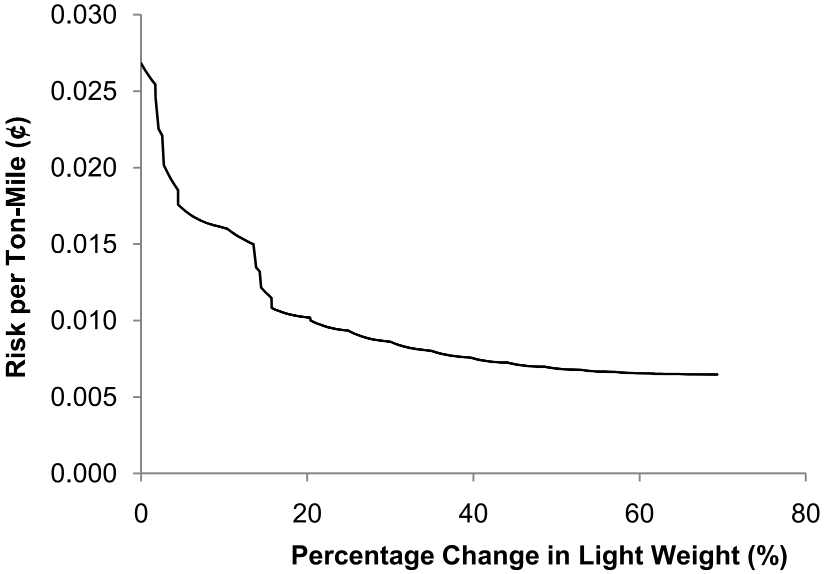
b) Benzene



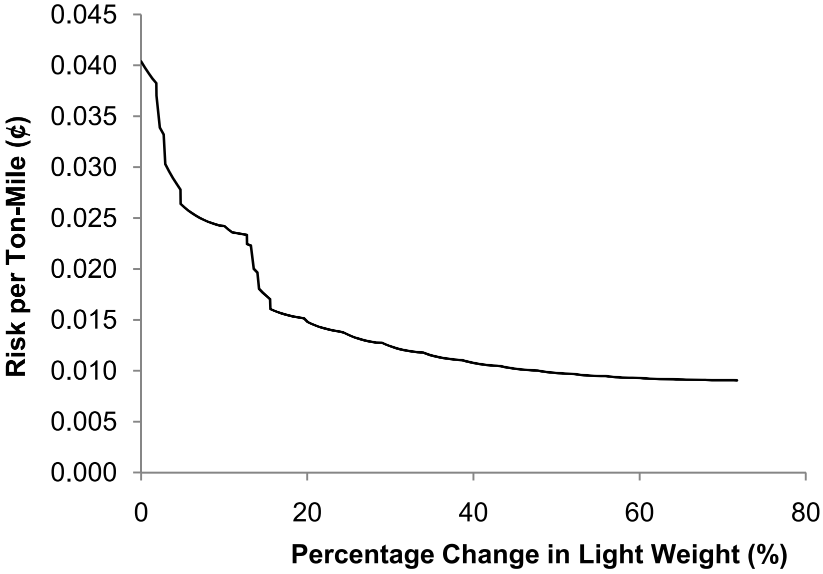
c) Butyl Acrylates



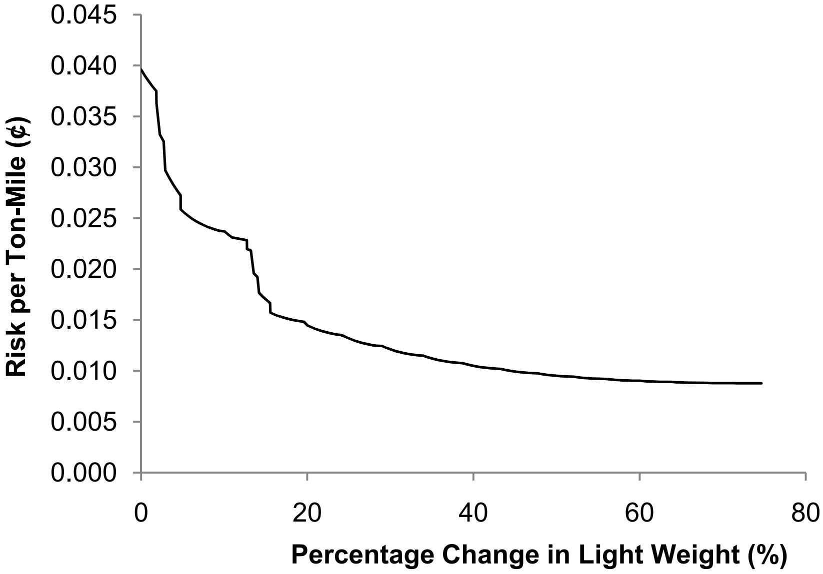
d) Cyclohexane



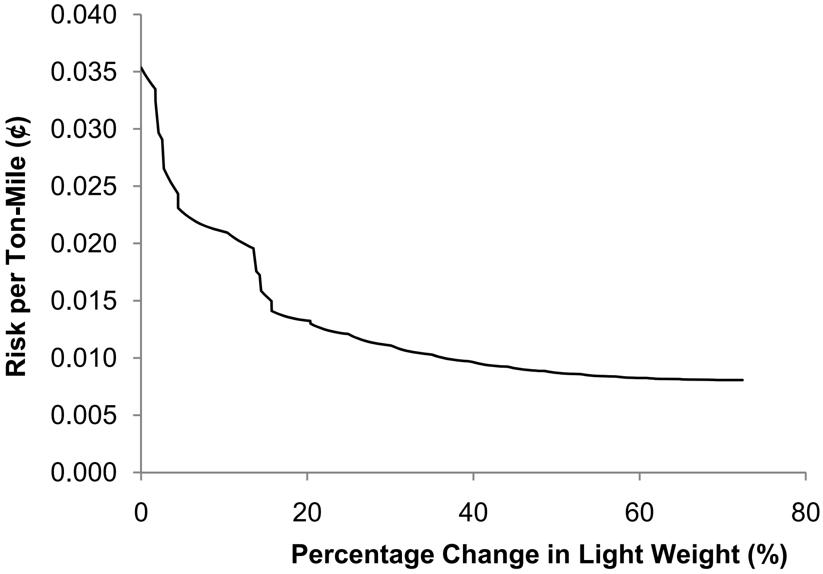
e) Ethanol



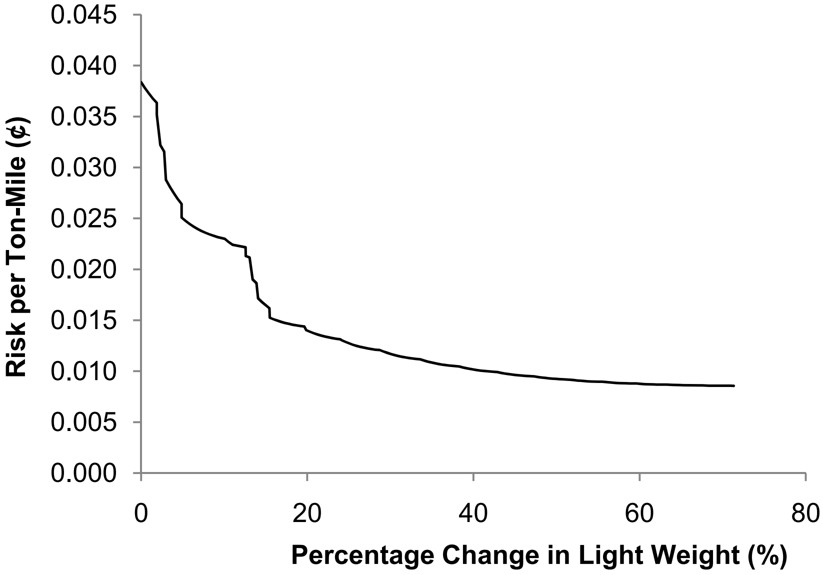
f) Ethyl Acetate



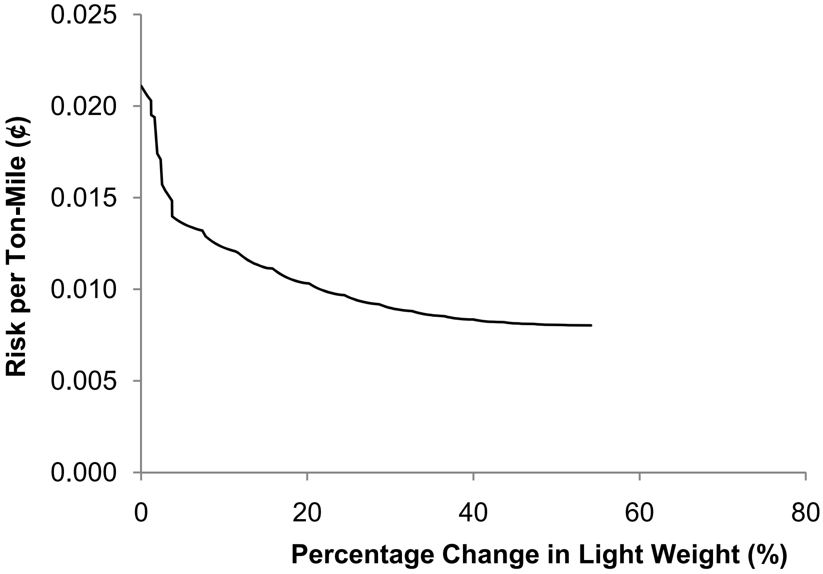
g) Ethyl Acrylate



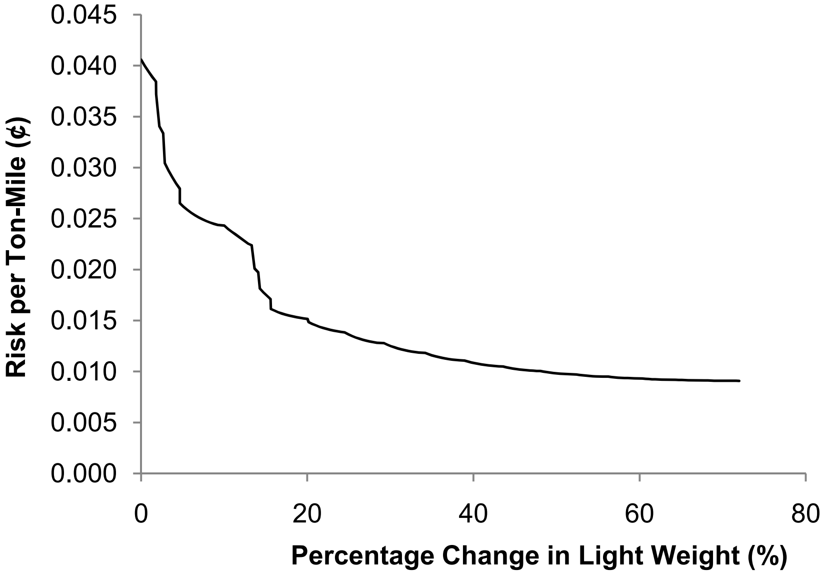
h) Methanol



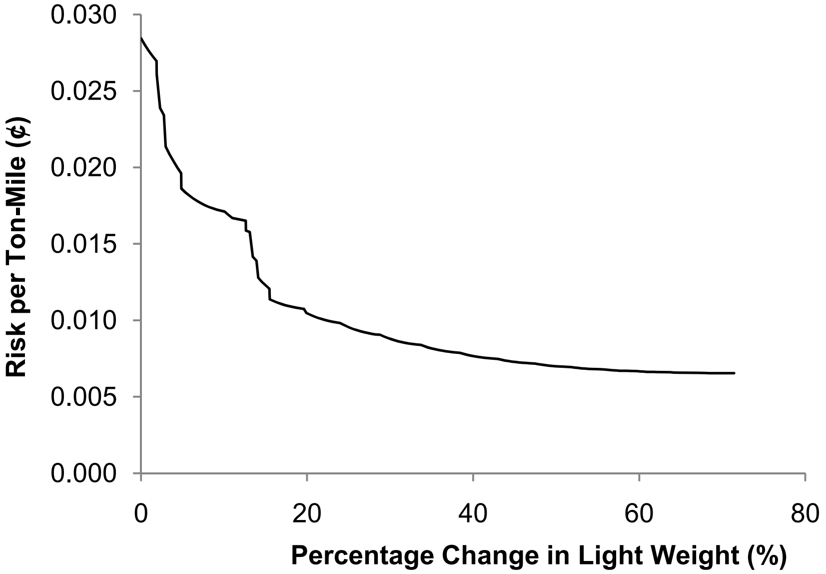
i) Methyl Methacrylate



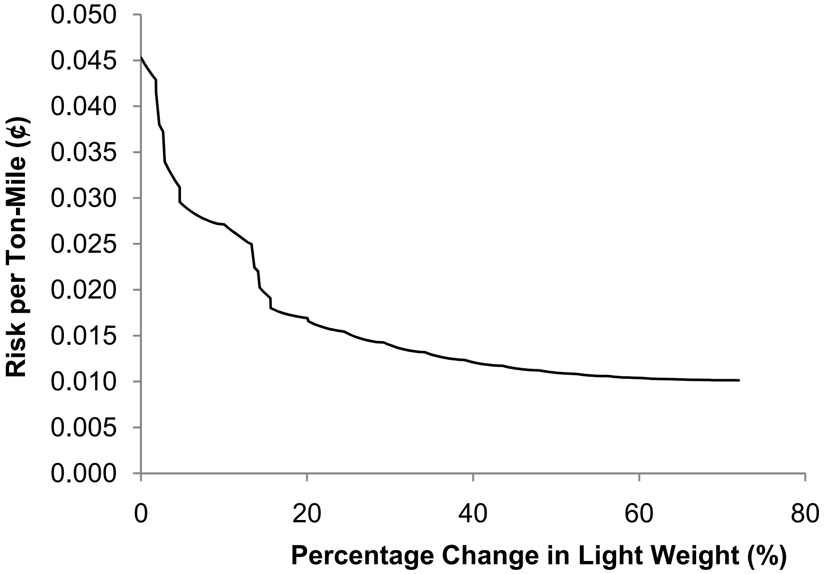
j) Styrene



k) Toluene



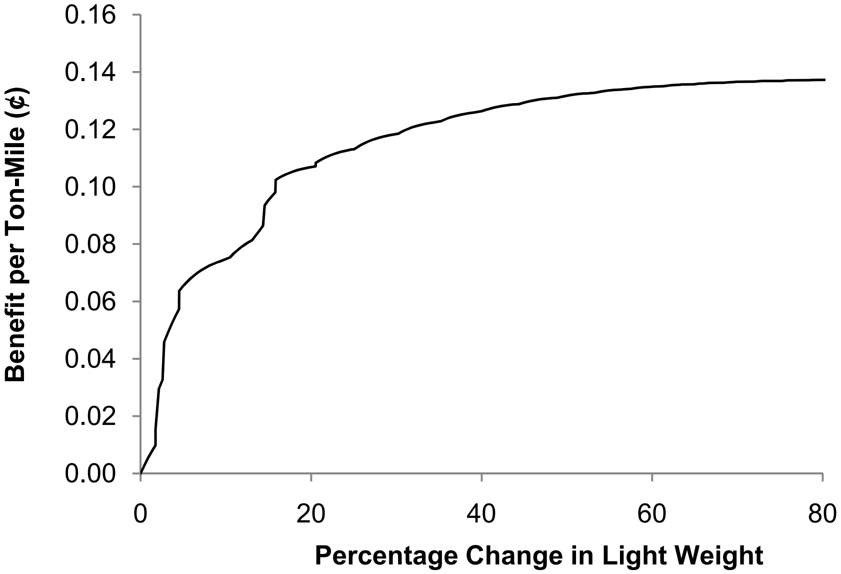
l) Vinyl Acetate



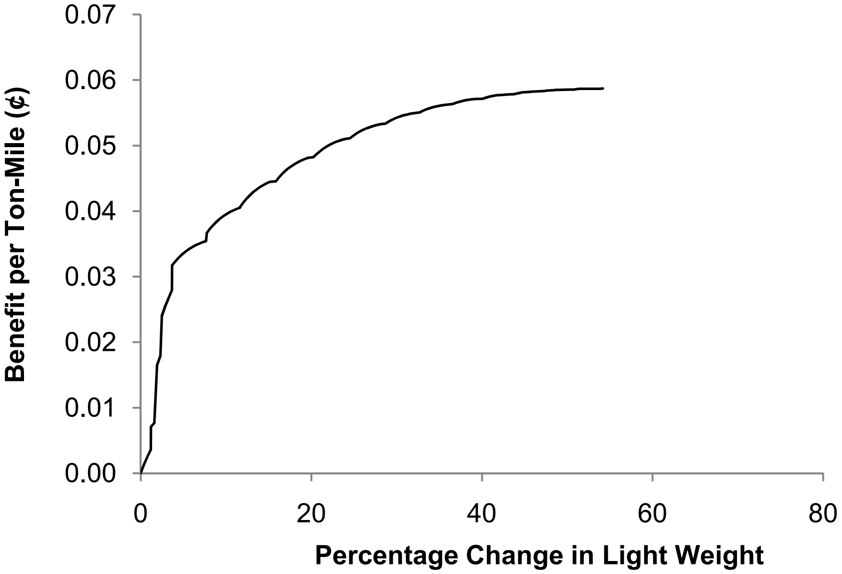
m) Xylenes

APPENDIX G

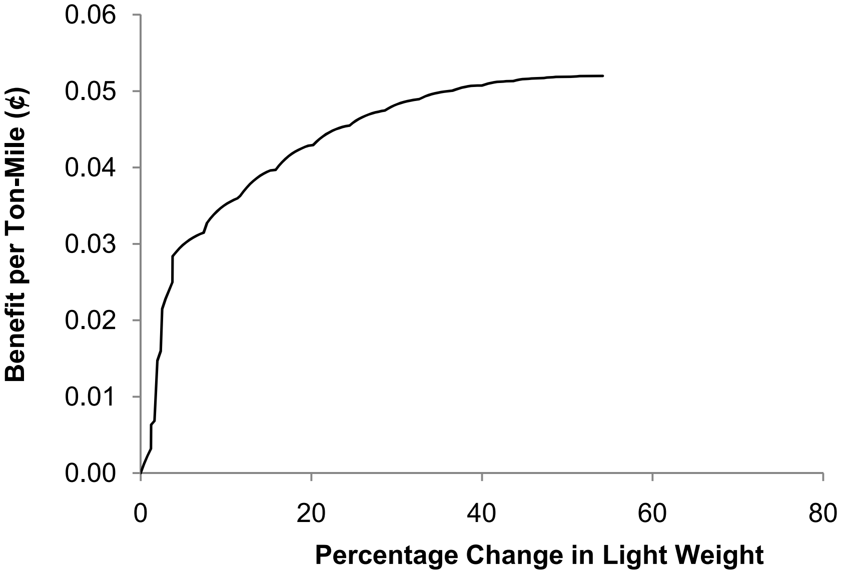
BENEFIT PER TON-MILE FOR THE PARETO-OPTIMAL SOLUTIONS OF CHEMICALS OF INTEREST IN CHAPTER 6



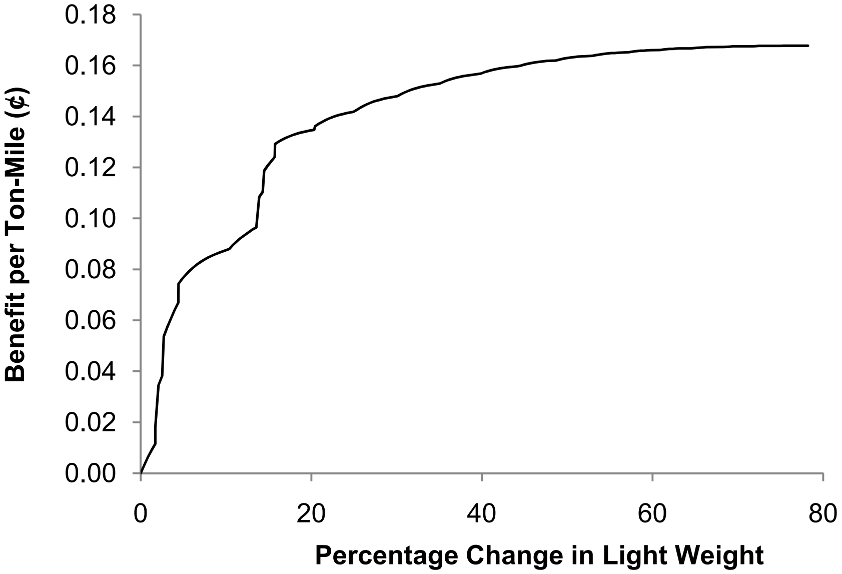
a) Acrylonitrile



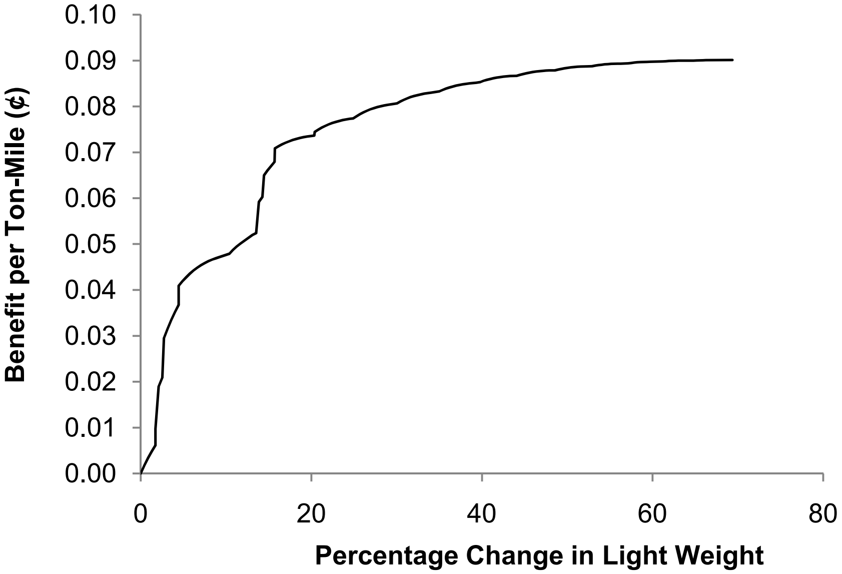
b) Benzene



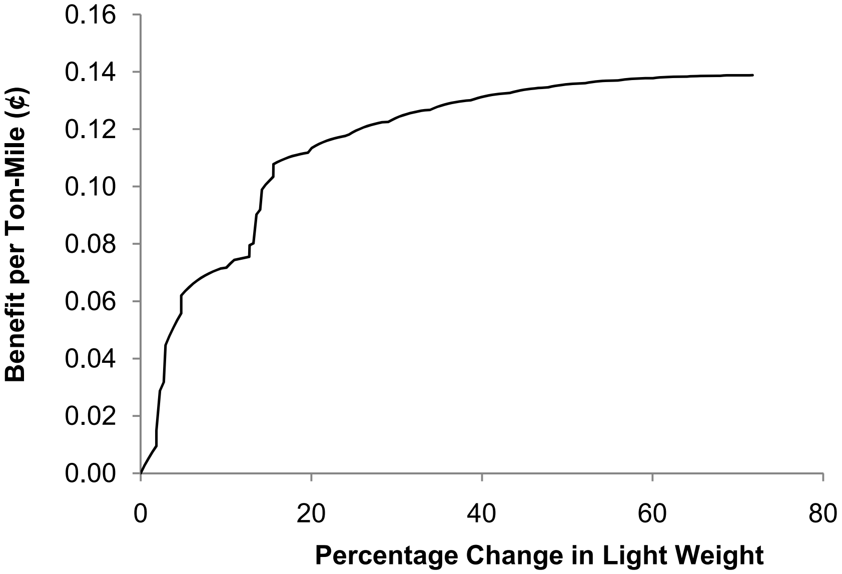
c) Butyl Acrylates



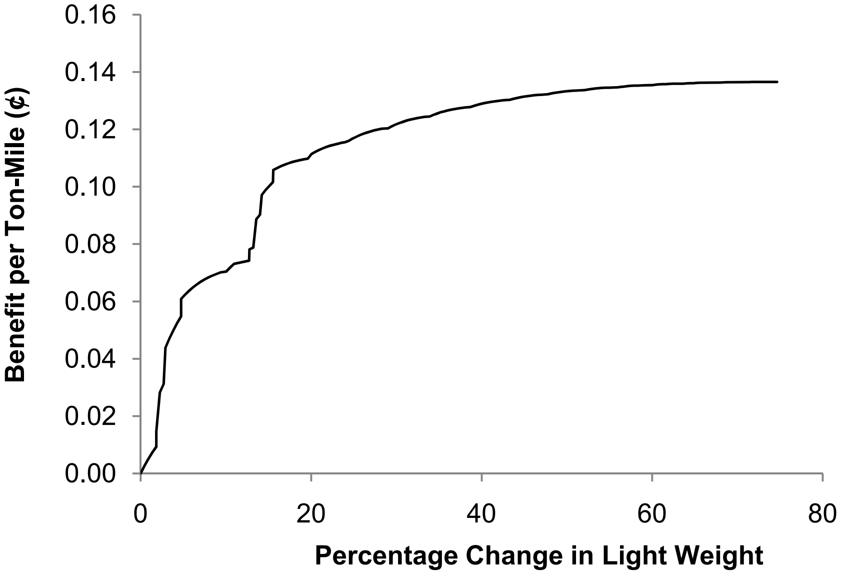
d) Cyclohexane



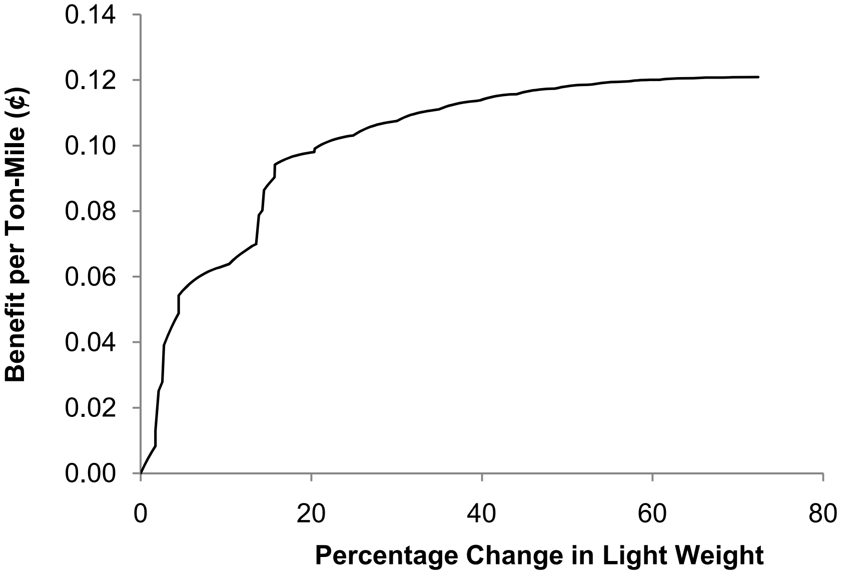
e) Ethanol



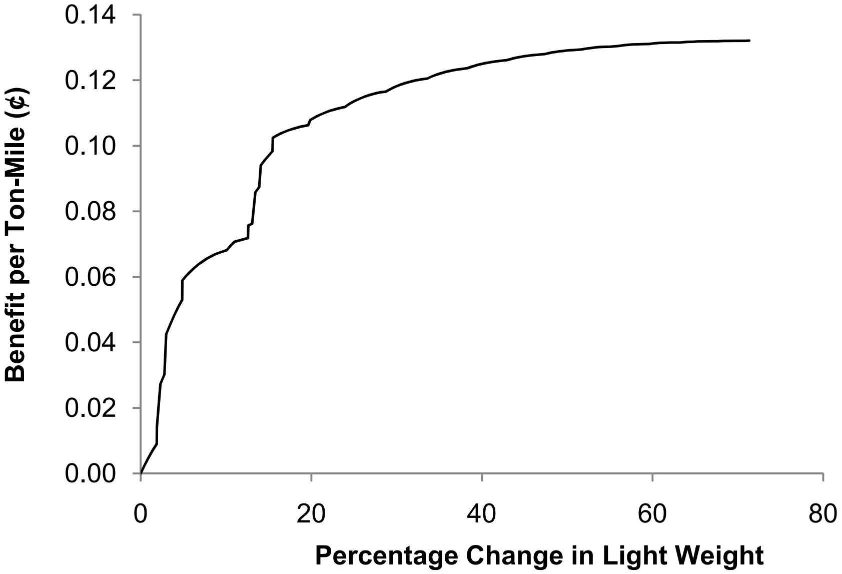
f) Ethyl Acetate



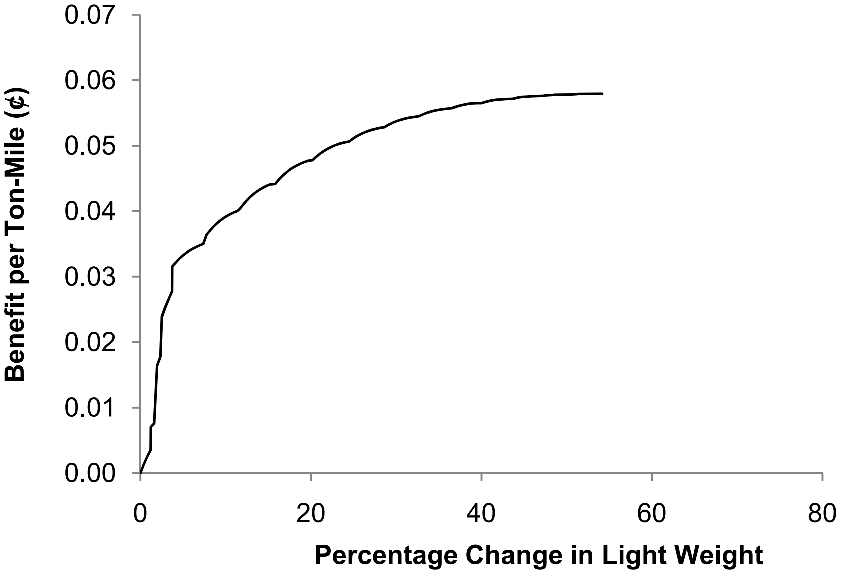
g) Ethyl Acrylate



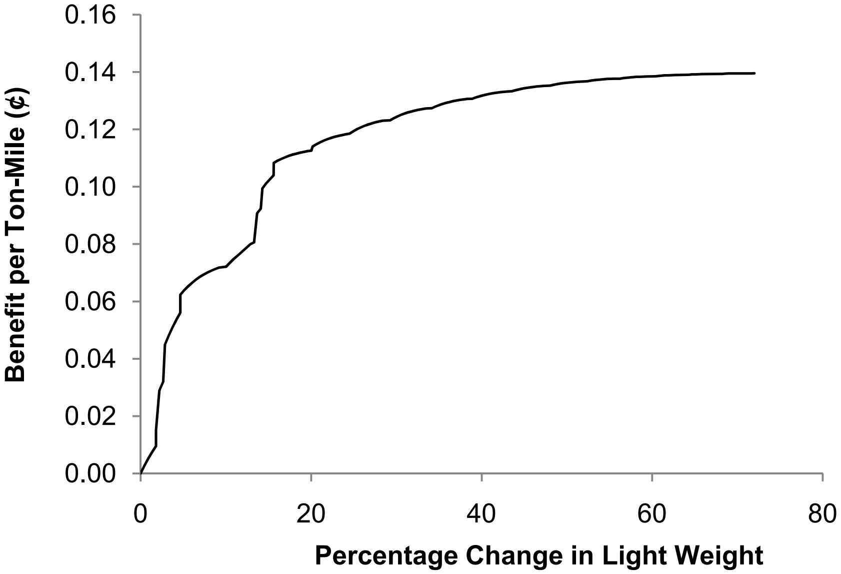
h) Methanol



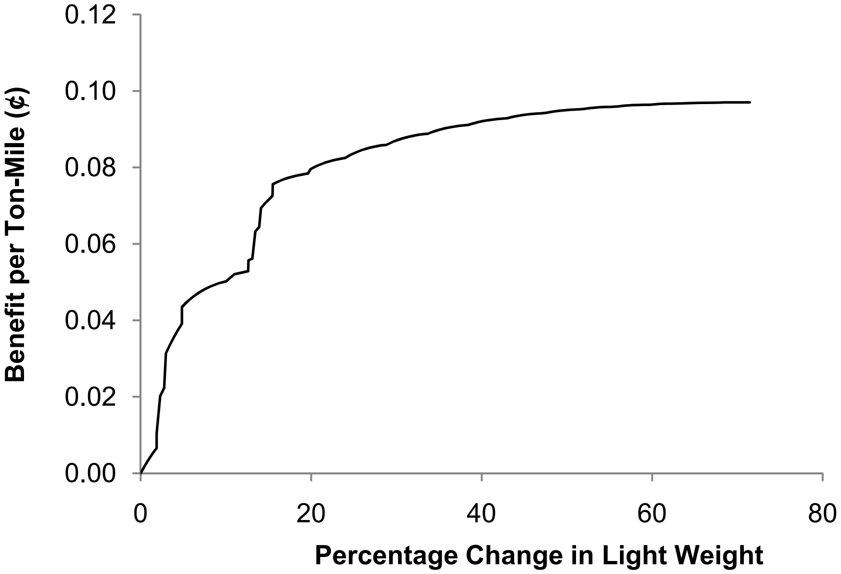
i) Methyl Methacrylate



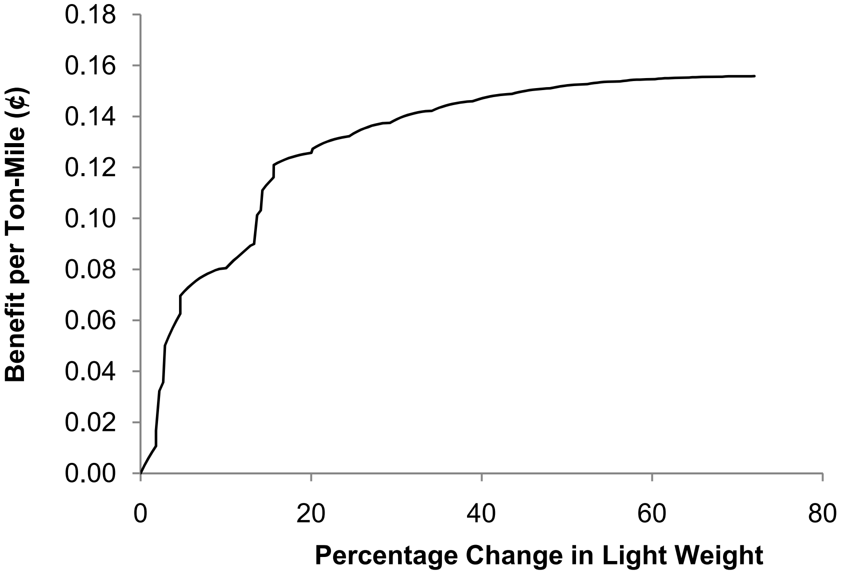
j) Styrene



k) Toluene



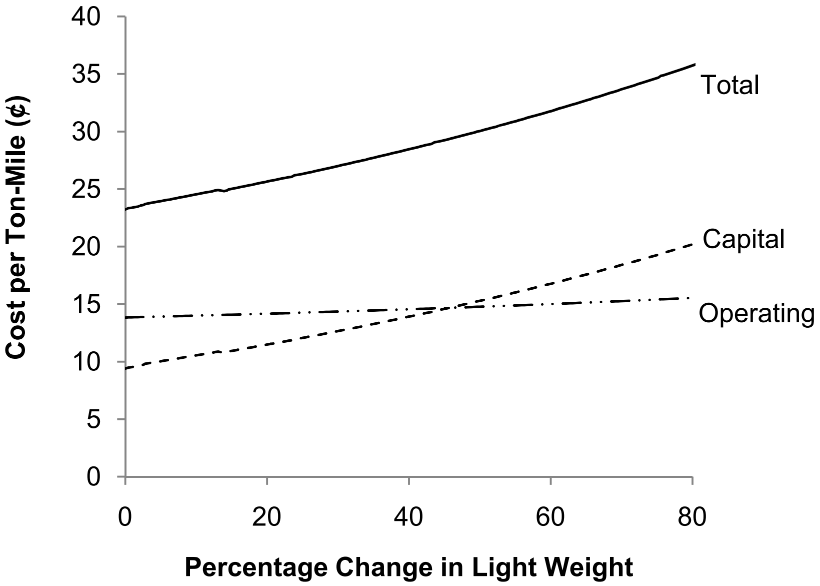
l) Vinyl Acetate



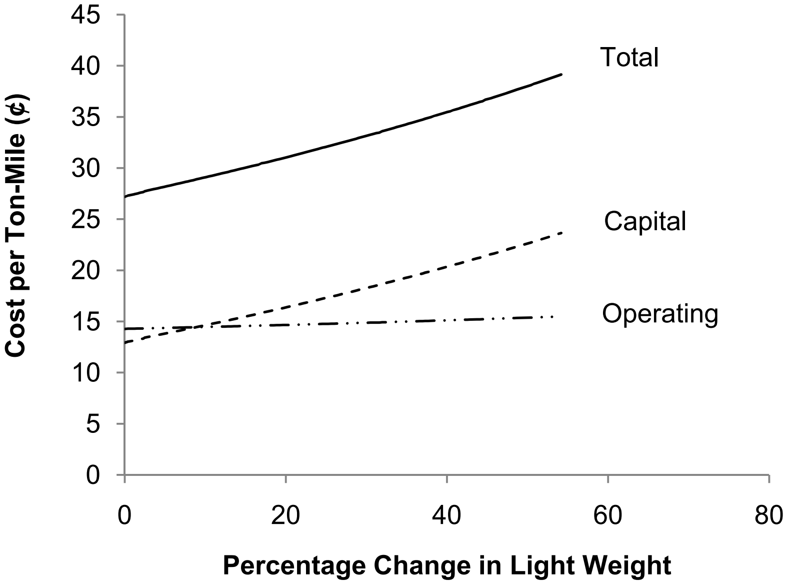
m) Xylenes

APPENDIX H

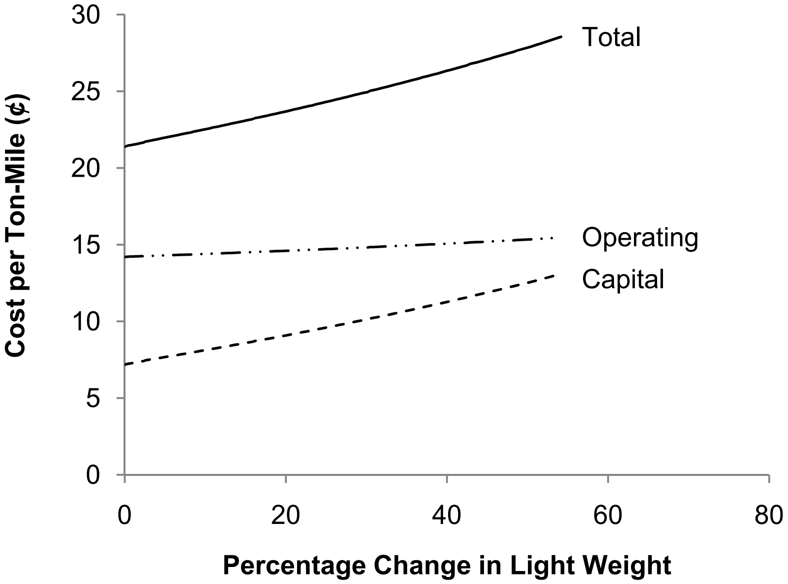
CAPITAL, OPERATING AND TOTAL COSTS PER TON-MILE FOR THE PARETO-OPTIMAL SOLUTIONS OF CHEMICALS OF INTEREST IN CHAPTER 6



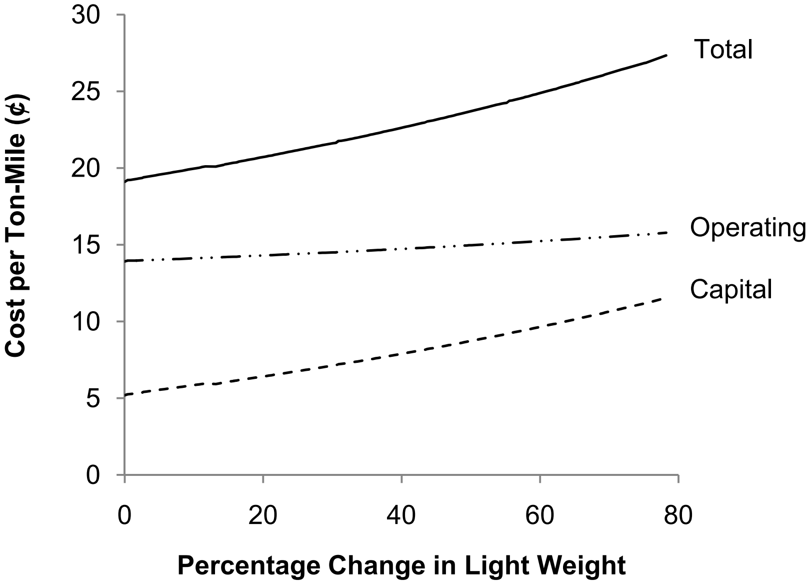
a) Acrylonitrile



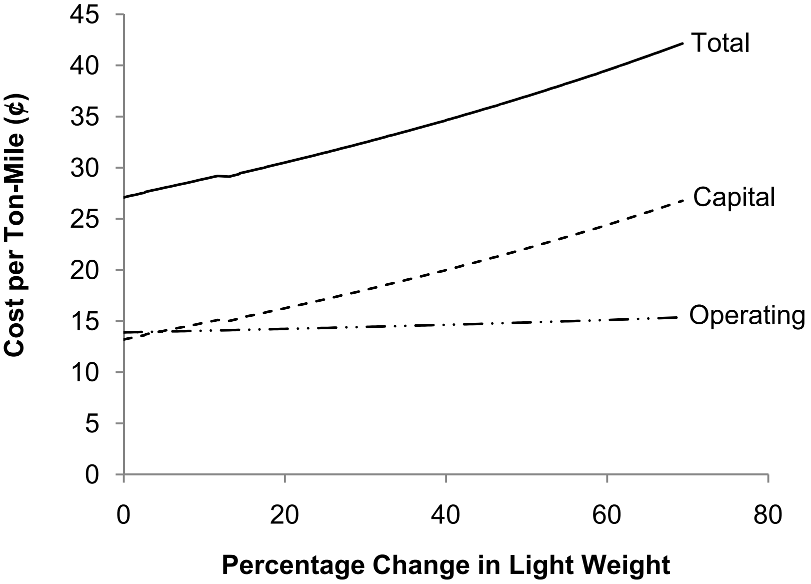
b) Benzene



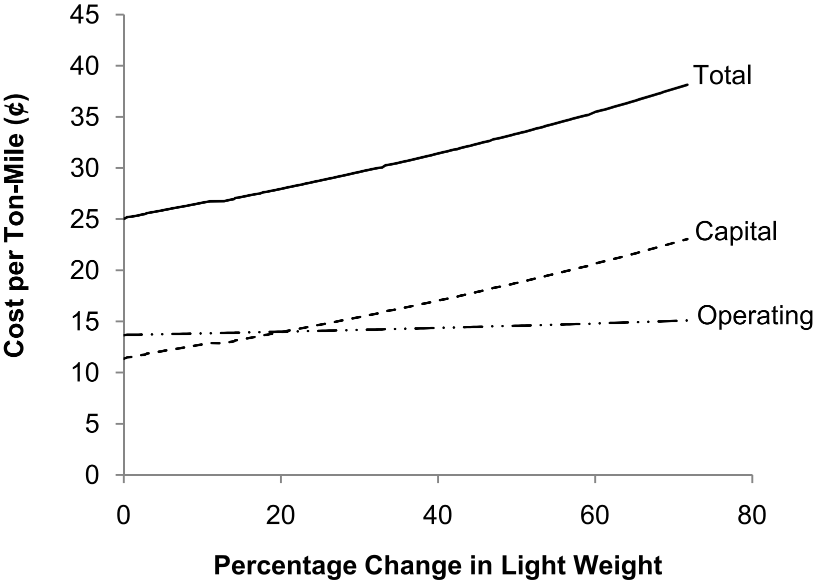
c) Butyl Acrylates



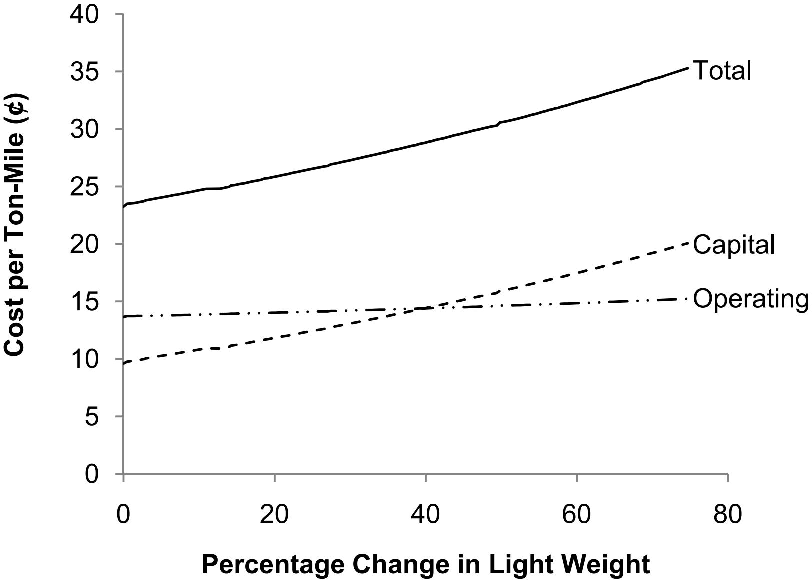
d) Cyclohexane



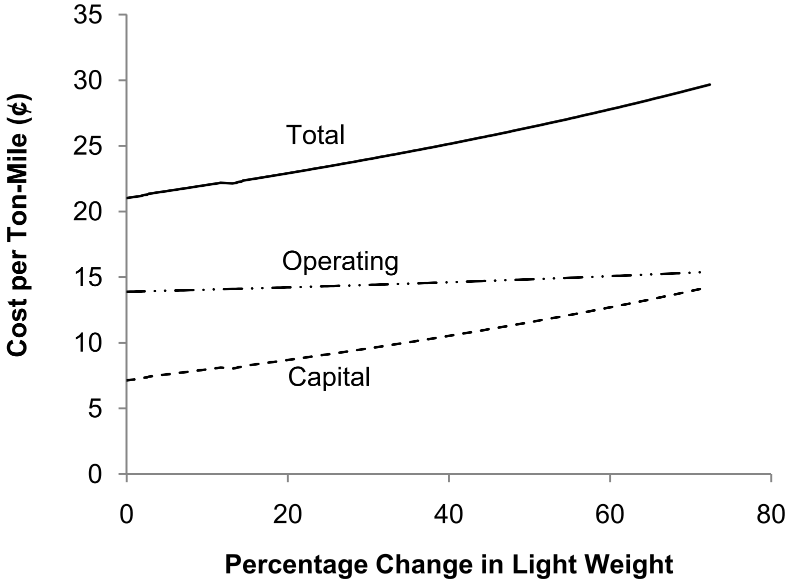
e) Ethanol



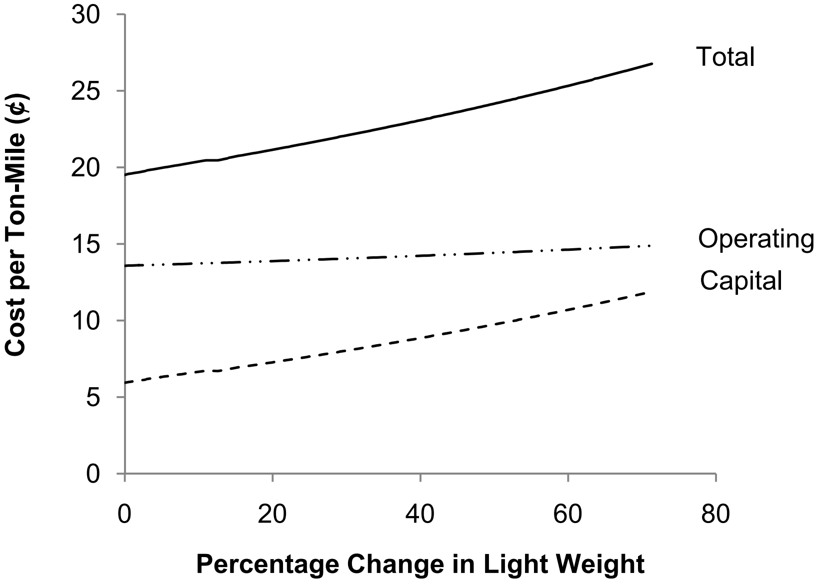
f) Ethyl Acetate



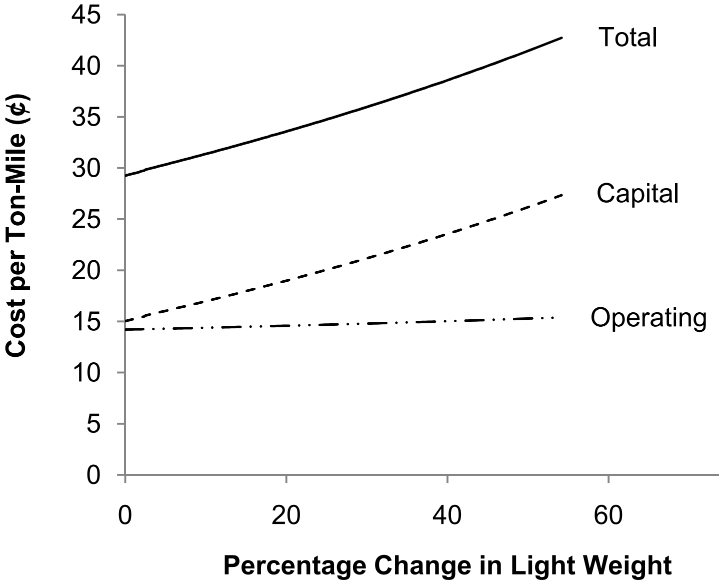
g) Ethyl Acrylate



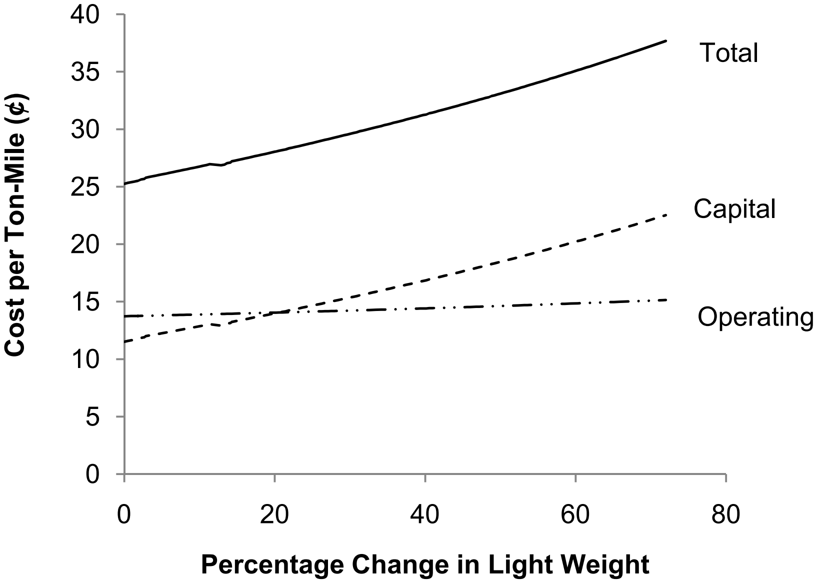
h) Methanol



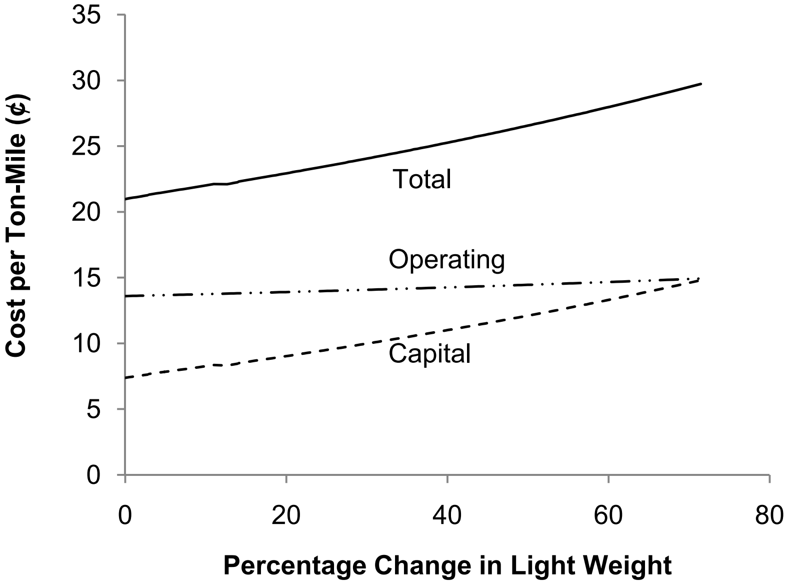
i) Methyl Methacrylate



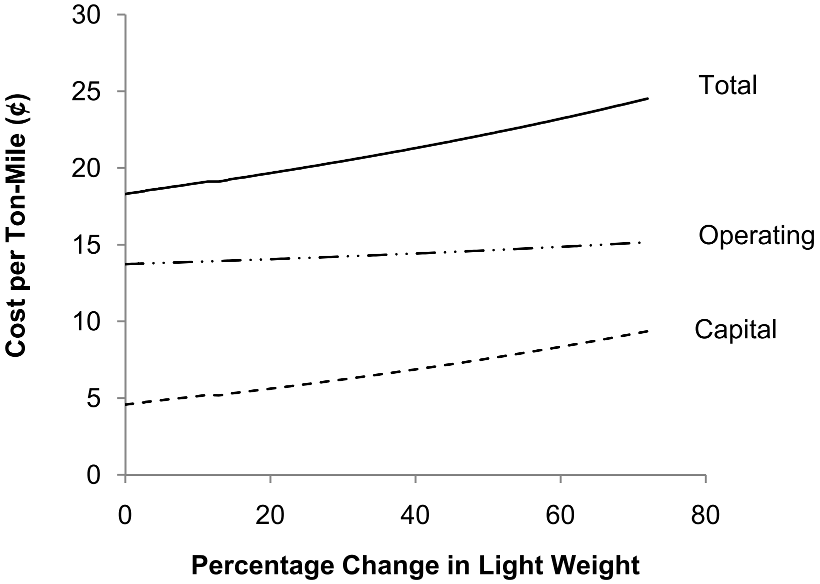
j) Styrene



k) Toluene



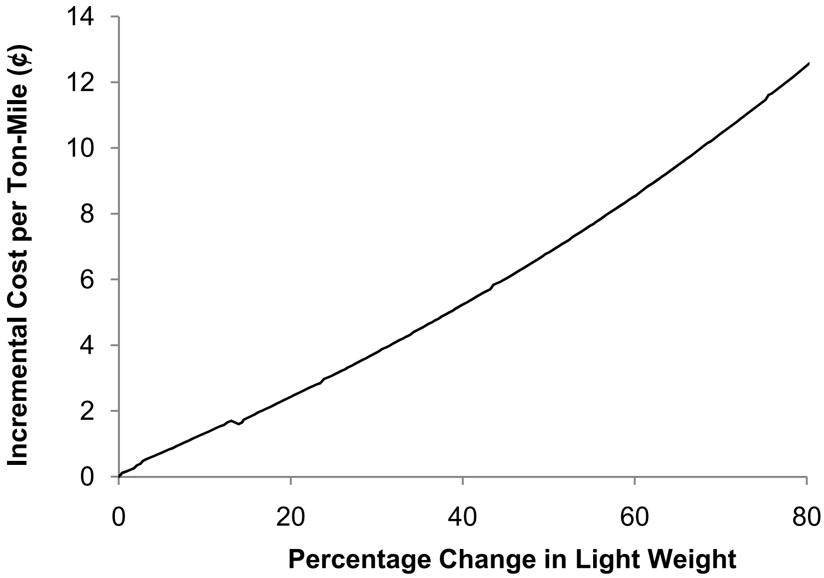
l) Vinyl Acetate



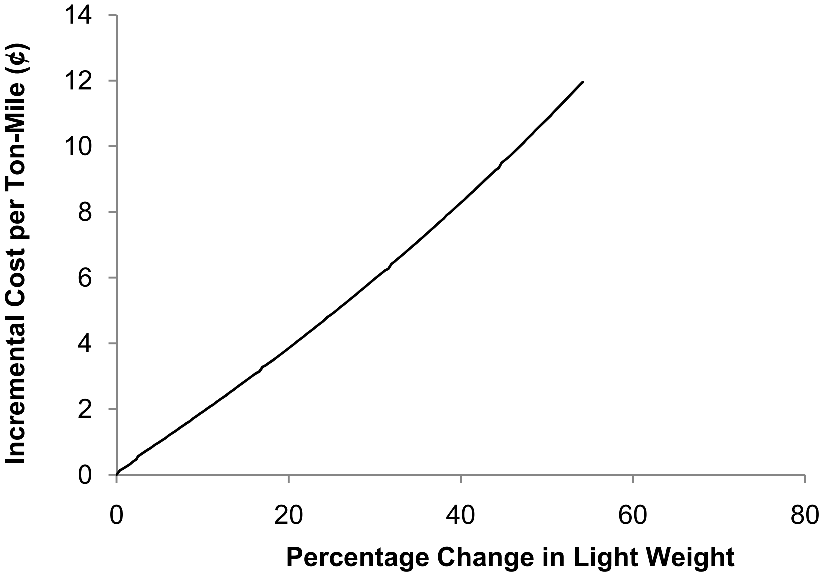
m) Xylenes

APPENDIX I

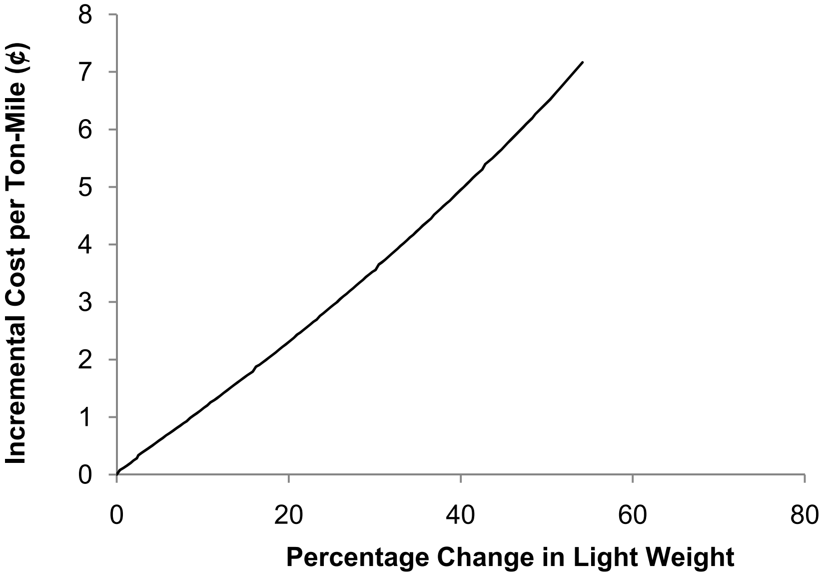
INCREMENTAL COST PER TON-MILE FOR THE PARETO-OPTIMAL SOLUTIONS OF CHEMICALS OF INTEREST IN CHAPTER 6



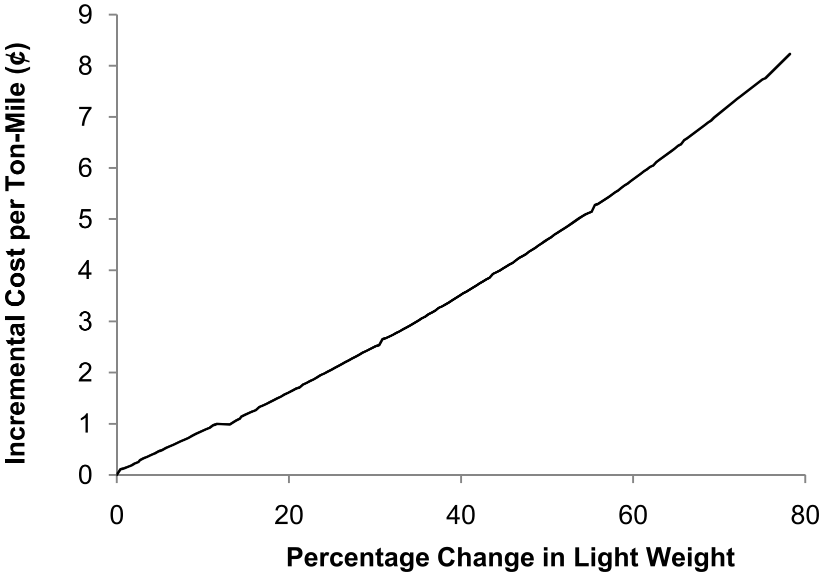
a) Acrylonitrile



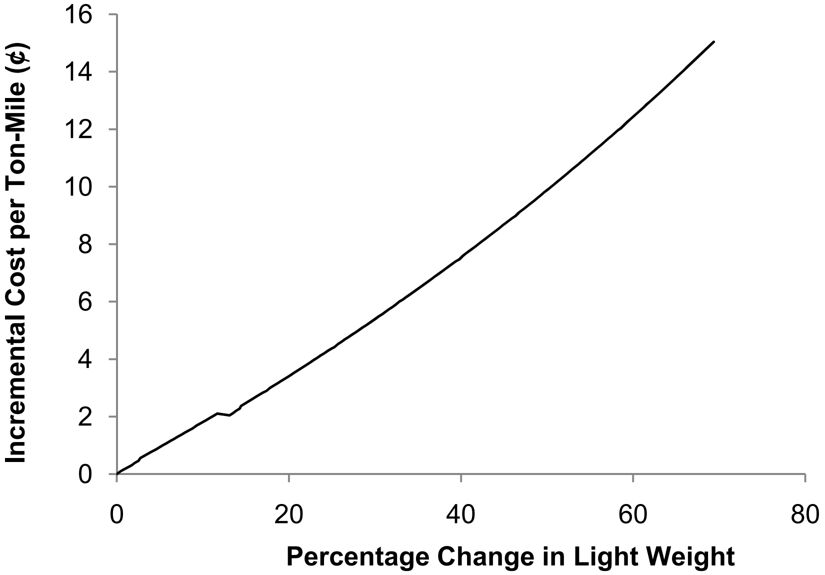
b) Benzene



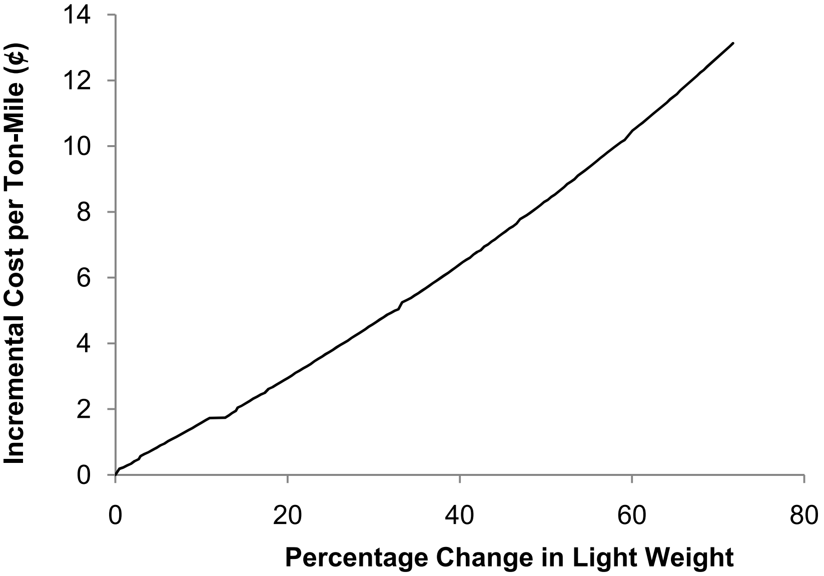
c) Butyl Acrylates



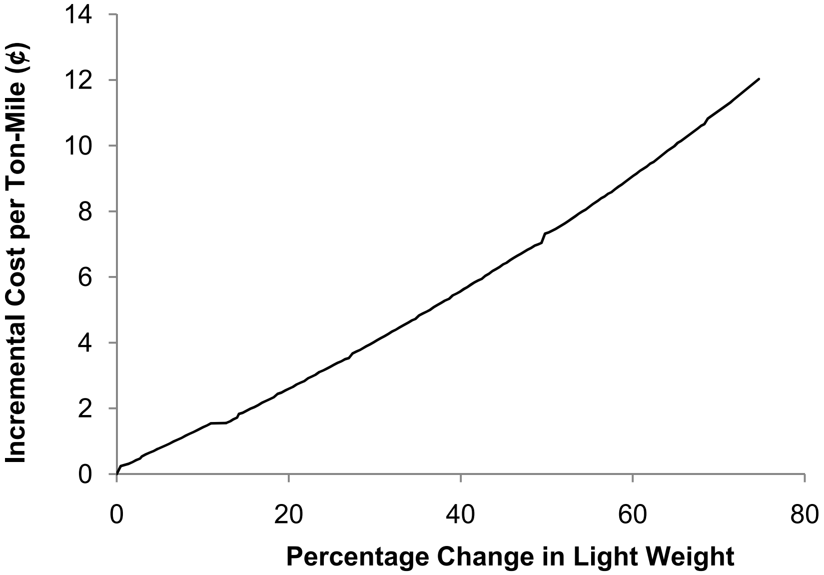
d) Cyclohexane



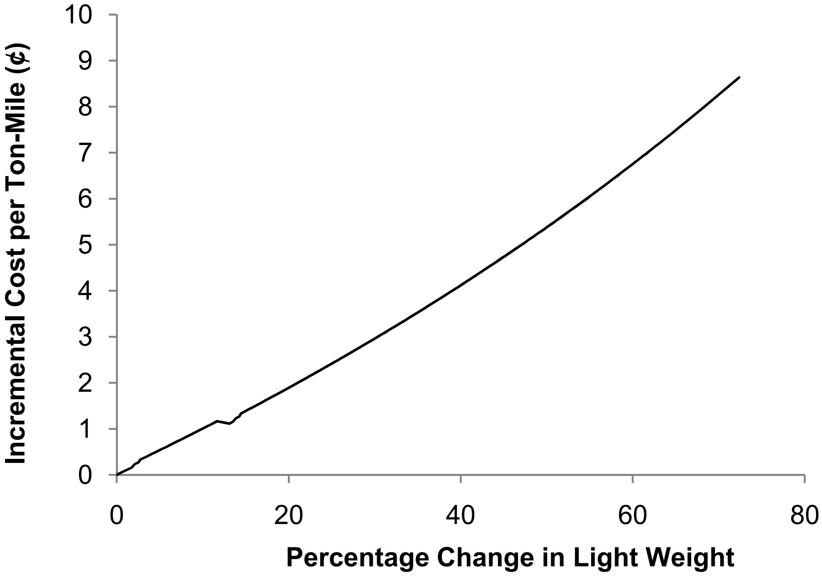
e) Ethanol



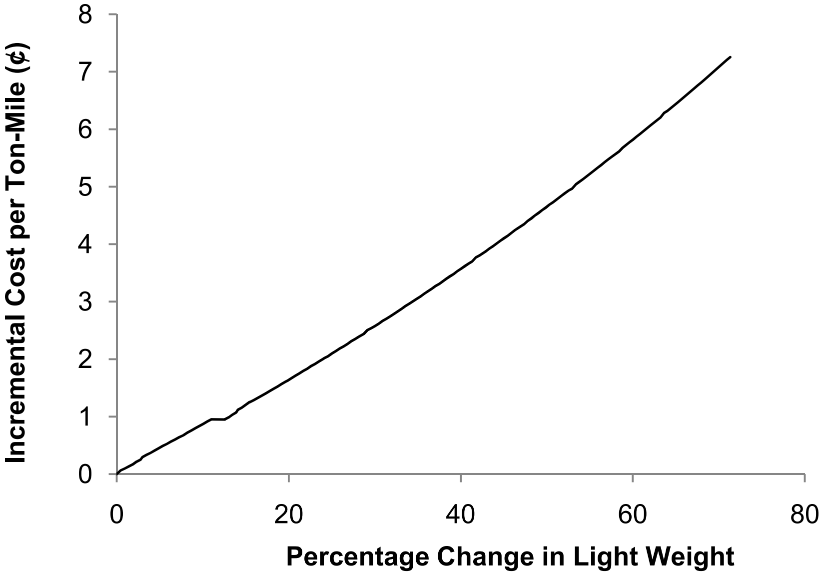
f) Ethyl Acetate



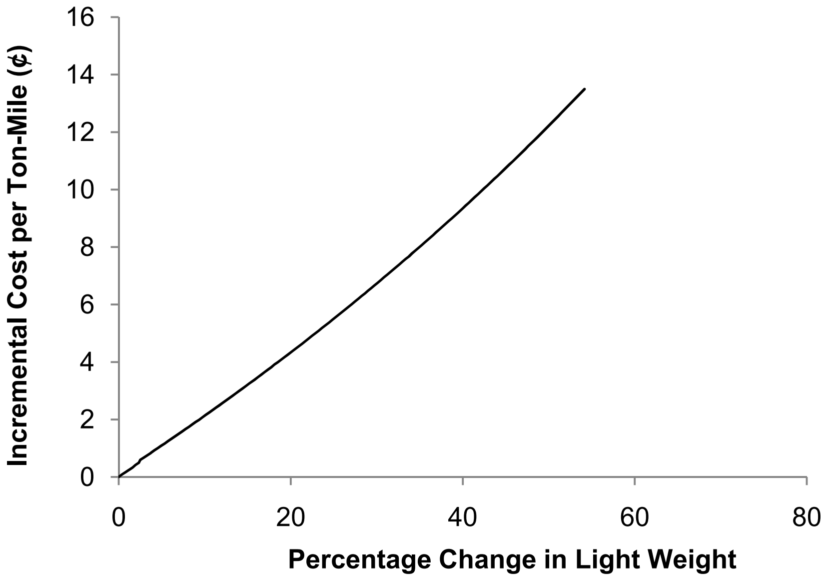
g) Ethyl Acrylate



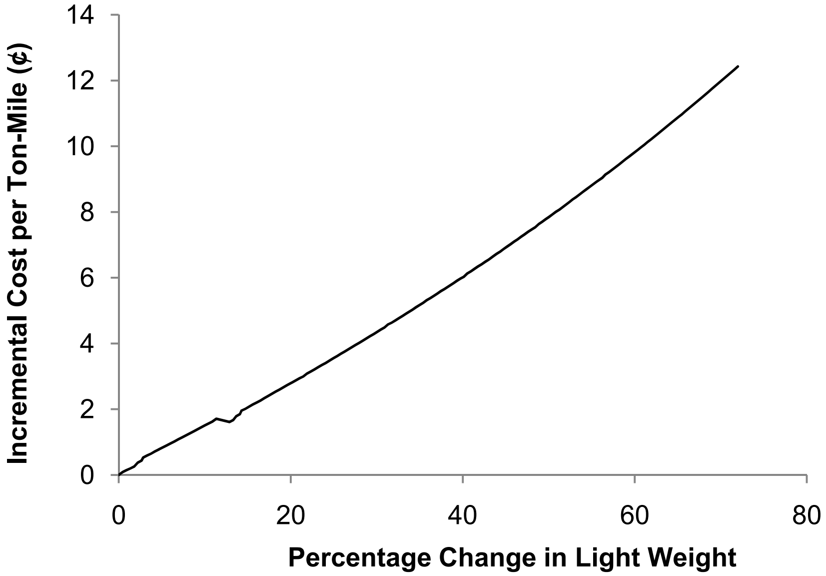
h) Methanol



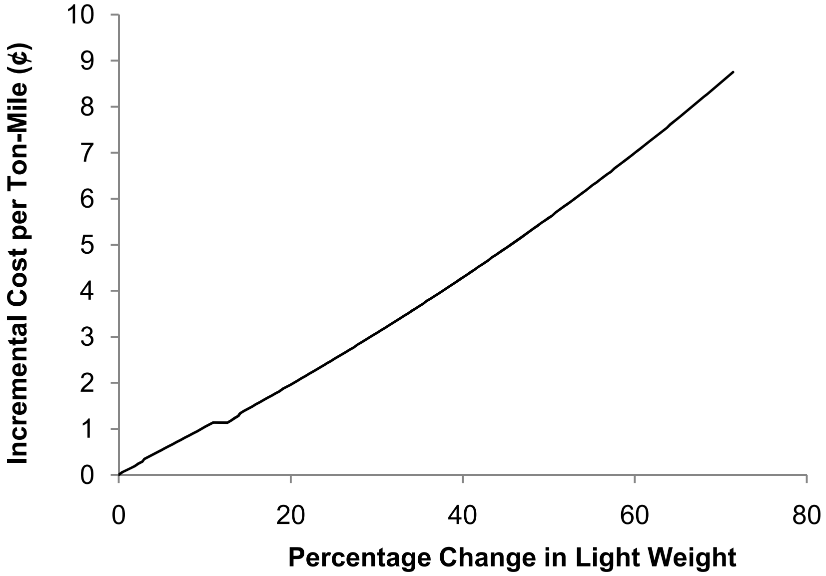
i) Methyl Methacrylate



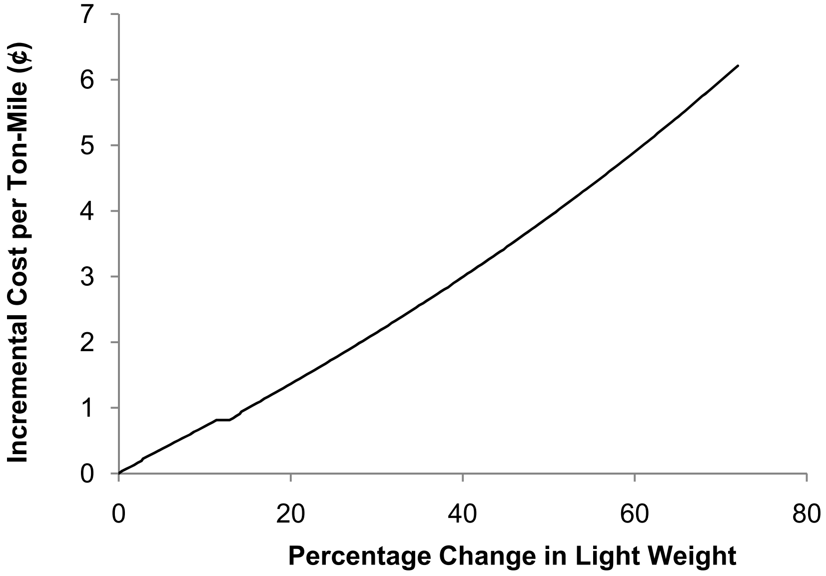
j) Styrene



k) Toluene



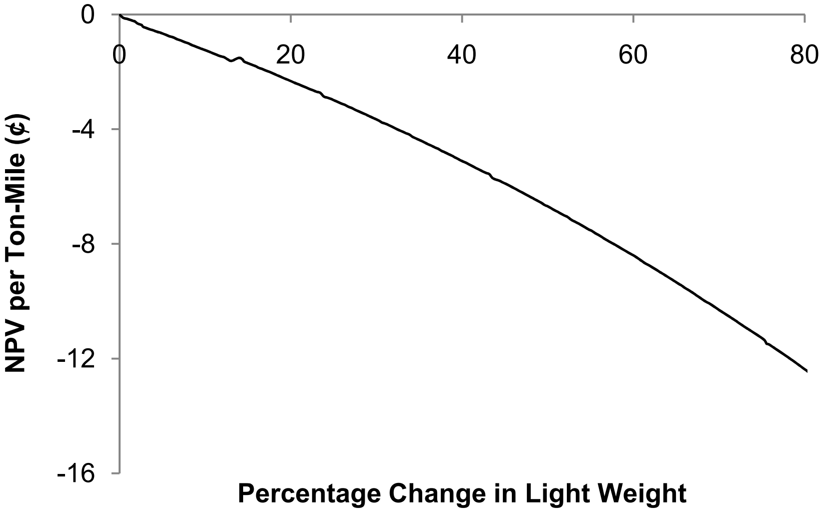
l) Vinyl Acetate



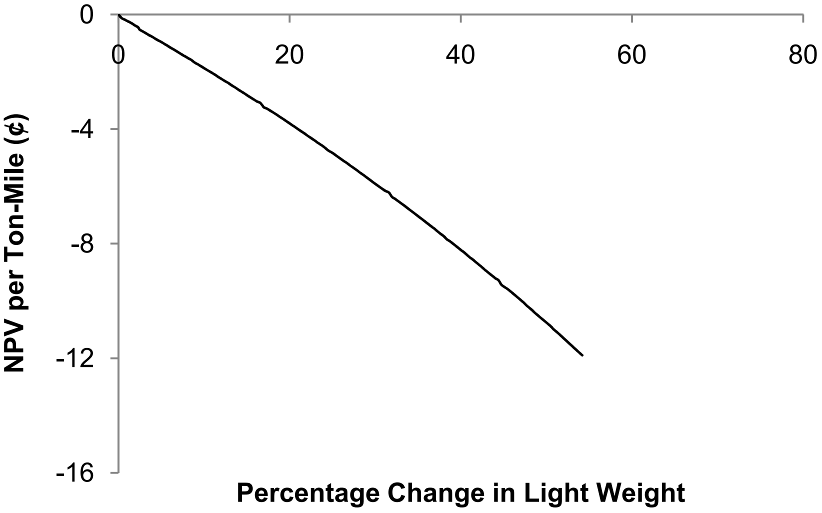
m) Xylenes

APPENDIX J

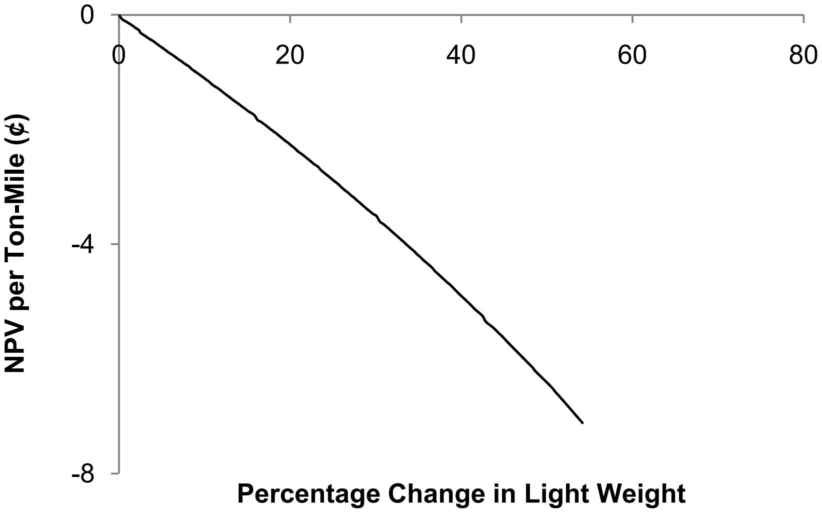
NET PRESENT VALUE PER TON-MILE FOR THE PARETO-OPTIMAL SOLUTIONS OF CHEMICALS OF INTEREST IN CHAPTER 6



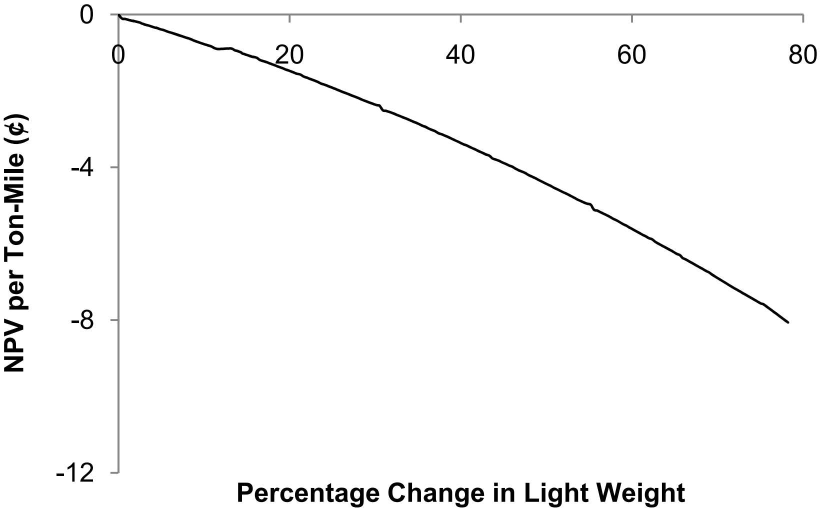
a) Acrylonitrile



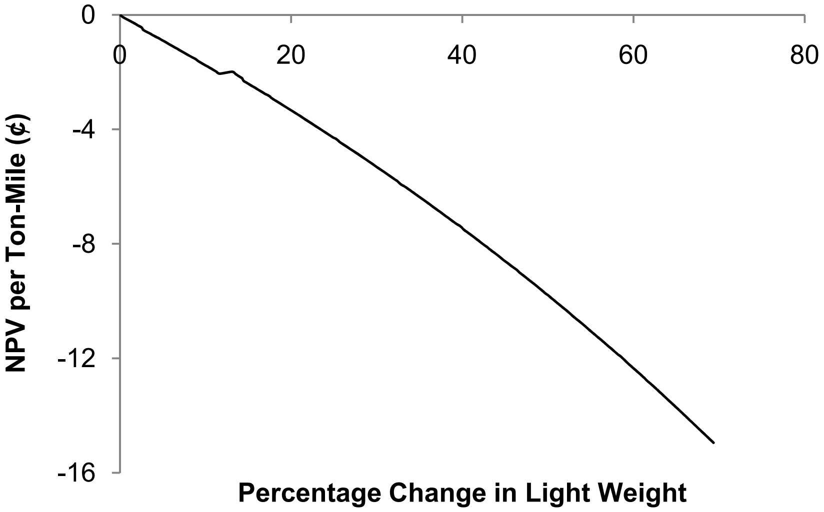
b) Benzene



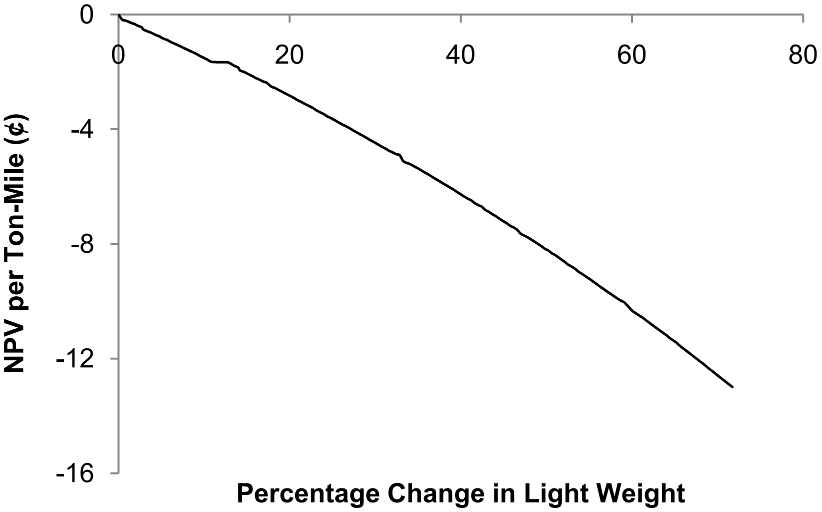
c) Butyl Acrylates



d) Cyclohexane



e) Ethanol



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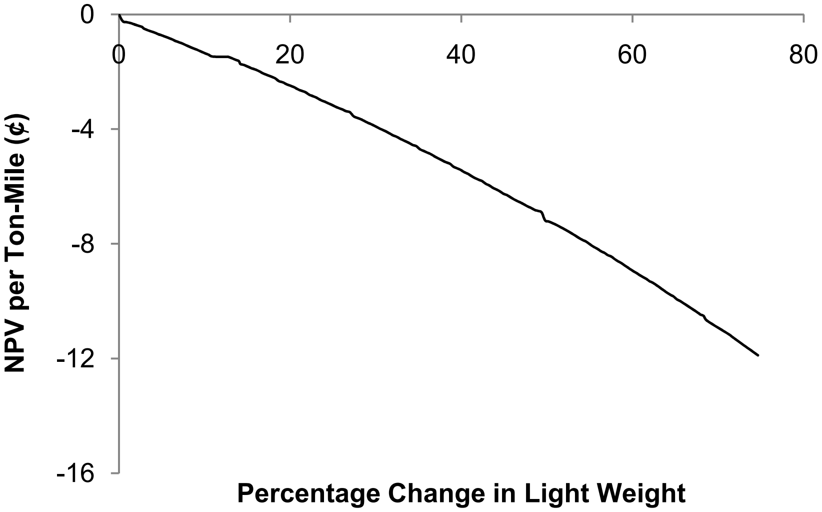
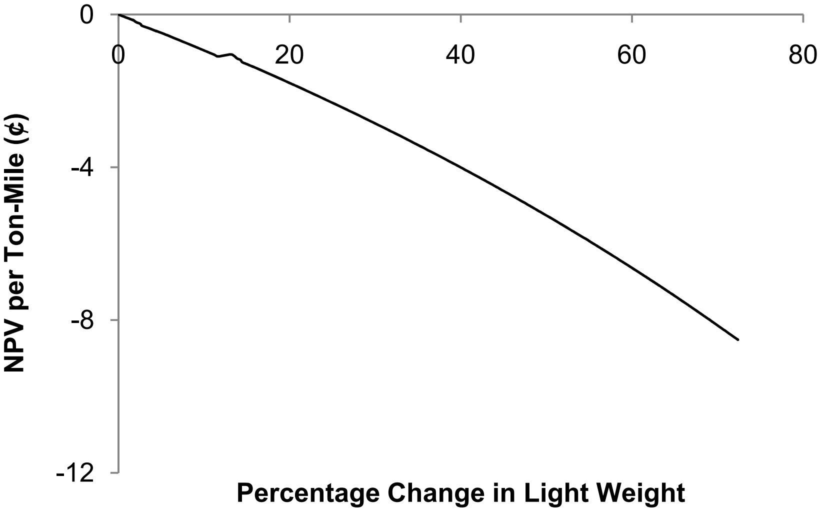
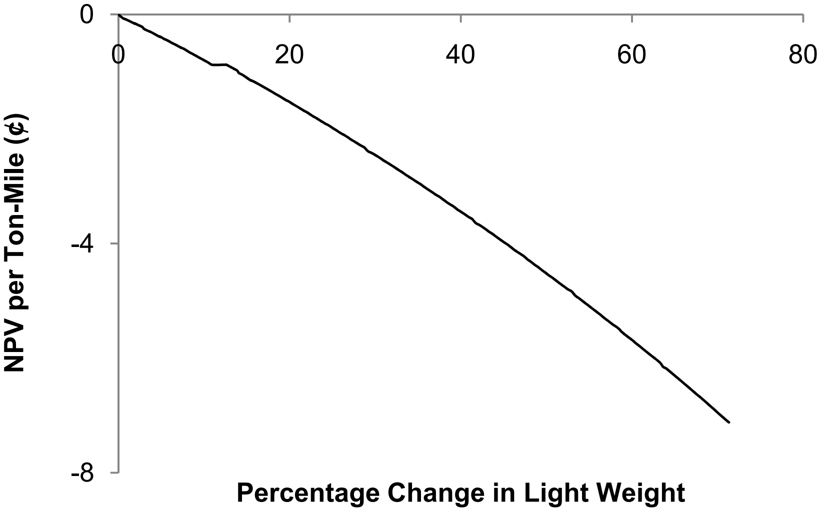


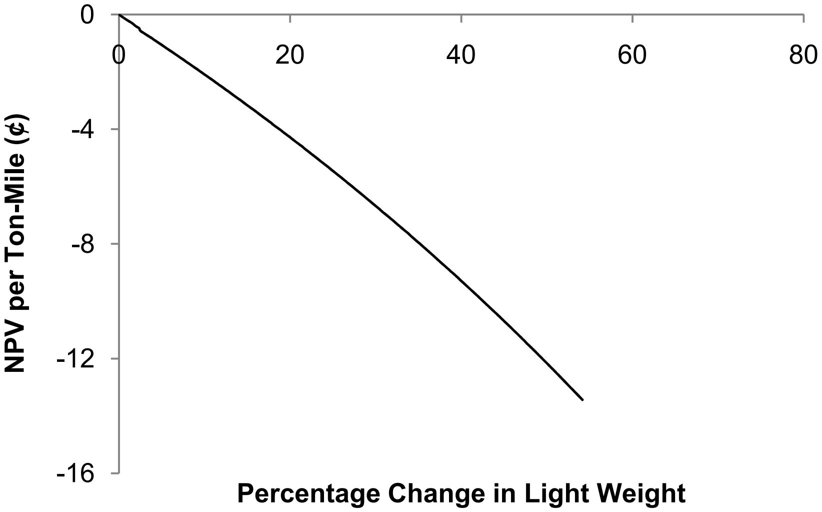
g) Ethyl Acrylate



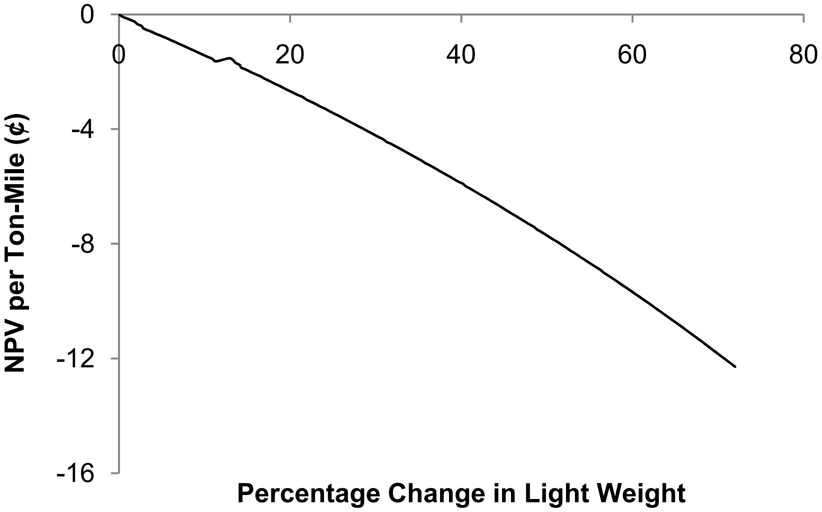
h) Methanol



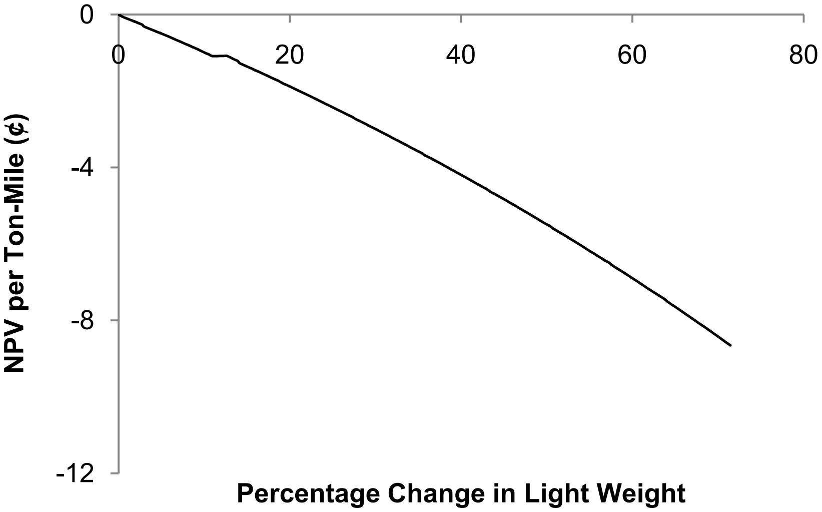
i) Methyl Methacrylate



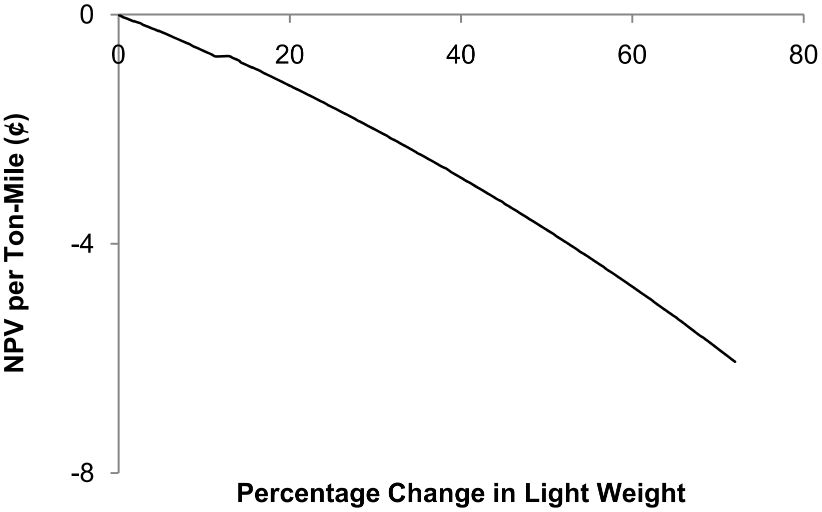
j) Styrene



k) Toluene



l) Vinyl Acetate



m) Xylenes

AUTHOR'S BIOGRAPHY

Mohd Rapik Saat was born in Kuala Lumpur, Malaysia, on August 12th, 1980. He received his B.S. and M.S. degrees in Civil and Environmental Engineering from the University of Illinois at Urbana-Champaign (UIUC) in 2003 and 2005, respectively. His principal research interests are railroad tank car safety and hazardous materials transportation risk analysis and use of operations research and decision analysis techniques particularly as they relate to these topics. During his graduate work he has been supported by grants from the Association of American Railroads (AAR), the RSI-AAR Railroad Tank Car Safety Research and Test Project and the Dow Chemical Company. In 2008 he was awarded a CN Research Fellowship in Railway Engineering in recognition of his intellectual strength, academic accomplishments, and potential for significant contributions and achievement in the field of rail transportation engineering. In 2002, while still an undergraduate, he received a scholarship in support of his studies from the American Railway Engineering and Maintenance-of-Way Association (AREMA), and in 2008 AREMA awarded him the Michael W. & Jean D. Franke Family Foundation Scholarship. In 2007 he received the Frank J. Richter Scholarship from the American Association of Railroad Superintendents. Beyond his work on projects sponsored by AAR and RSI-AAR, he has also worked on hazardous materials transportation risk analysis projects supported by Monsanto, ICL Performance Products and ABS Consulting. He has presented his research at numerous conferences including the Transportation Research Board, the World Congress on Railway Research, the International Heavy Haul Association and the Institute for Operations Research and Management Science. He has published one peer-reviewed journal article and several conference proceedings papers and industry reports. In addition to his studies and research he has had principal daily oversight responsibility for UIUC students working on the RSI-AAR Tank Car Safety Project since 2004.