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QUANTITATIVE ANALYSIS OF OPTIONS TO REDUCE RISK OF HAZARDOUS
MATERIALS TRANSPORTATION BY RAILROAD

BY

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DISSERTATION

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ABSTRACT

The risk associated with railroad transportation of hazardous materials is an ongoing subject of interest to the transportation industries, the government, and the public. A variety of approaches have been considered or adopted to manage and reduce risk. These include improving operating practices and personnel training, improving transportation packaging, maintaining and upgrading infrastructure, and rerouting hazardous materials traffic. Certain risk reduction options have received particular attention in recent years. Realizing the interest and the need for research in this area, this study focuses on consideration of routing, track infrastructure improvement and speed management as approaches to reducing the risk from railroad hazardous materials transportation.

For each approach, potential benefits in terms of risk reduction are analyzed using operations research (OR) and quantitative risk assessment (QRA) methods. The goal is to facilitate the consideration of each approach and evaluate its potential application for a particular objective of interest. Furthermore, this study considers improvement of several parameters in the risk model to enhance the quality of risk estimates and to better understand their sensitivity to various assumptions. When resources are limited so that a complete analysis of the entire routes is not possible, statistical methods for route risk comparison are introduced to help decision makers choose the most appropriate route, thereby providing further confidence in an evaluation of routing alternatives or risk reduction options.

Route risk analysis is often complex and generates results that can be difficult to interpret. The results from quantitative risk assessment are not very helpful if critical information is not properly interpreted and effectively conveyed to the concerned parties. This is one of the most important issues in risk analysis but has received relatively less attention. This study illustrates several new techniques to present, interpret, and communicate risk results more effectively.

Overall, this study aims to develop information on the potential and effectiveness of different risk reduction approaches to facilitate the consideration of the most appropriate option according to the objective of interest of different parties in the railroad hazardous materials transportation supply chain. Part of the findings will help clarify the mutual roles of these parties, including carriers, shippers, and municipalities, and help them develop and implement the most appropriate and effective risk management, reduction, and mitigation options accordingly. Furthermore, the information provided may be useful for regulators and researchers who might be interested in the subjects presented in this dissertation.

*To My Parents, My Grandparents
And To My Mentor, Chris Barkan*

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CHAPTER 1

INTRODUCTION

1.1 Introduction

Hazardous materials traffic originates and terminates at thousands of locations in North America. Rail shipments of these products are vital to the national economy and provide a substantial source of revenue to the railroads. Rail shipments of hazardous materials steadily increased from 2001, when there were approximately 1.7 million shipments in the U.S. and Canada until 2008, when there were nearly two million (BOE, 2009). About 22% of all U.S. hazardous materials ton-miles are rail shipments – the second highest after truck (U.S. DOT, 2005). Nevertheless, the number of rail hazardous materials incidents is only 6% of highway incidents, indicating the greater safety of rail. However, the consequences in terms of the number of injuries is 72% of highway (PHMSA, 2009), indicating that rail incidents have greater average consequences and illustrating the low frequency-high consequence nature of railroad transportation risk (Barkan, 2006).

Railroads have long placed a high priority on safe transportation of hazardous materials (Aldrich, 2002; Barkan, 2008). Traditionally, this activity focused on product hazard identification, placarding, emergency information and response capability (Moses and Lindstrom, 1993; PHMSA, 2008) and development of special operating practices intended to reduce the likelihood or severity of accidents involving trains transporting hazardous materials (AAR, 1990; Borener et al., 2006). Recent interest in the rail industry has focused on transportation packaging (AAR, 2007; BOE, 2007) in particular enhancing packaging and tank car safety design to reduce transportation risk (Barkan et al., 1991; Freeman and Kleffner, 1997; Saat and Barkan, 2005; Barkan et al., 2007; Jeong and Tyrell, 2008; Ward et al., 2008; Barkan, 2008; Paltrinieri et al., 2009; Saat, 2009). Recent advances in geolocation monitoring and information technologies have introduced sophisticated vehicle tracking systems (Luczak, 2004; Ward, 2008). Expanded deployment of various new wayside defect detection technologies (Resor and Zarembski, 2004; Hawthorne et al., 2005; Tournay and Cummings, 2005; Ouyang et al., 2009) appears to be reducing accident rate (Robert et al., 2009). Track infrastructure upgrade (Saat and Barkan, 2006b; Kawprasert and Barkan (2009a; 2010a-b) is another alternative that could help reduce accident likelihood and consequently risk. In addition, there has been research

on routing as an option for managing hazardous materials risk (Glickman, 1983; Abkowitz, 1989; Saat and Barkan; 2006; Carotenuto et al., 2007; Erkut et al., 2007; Glickman et al., 2007; Kawprasert and Barkan, 2008) and reducing the speed of trains transporting hazardous materials passing through critical areas (The Toronto Area Rail Transportation of Dangerous Goods Task Force, 1988). These approaches have gained increasing attention from municipalities eager to reduce the risk to local residents and analytical attention among researchers studying route planning and management of hazardous materials transportation.

Due to security concerns and several fatal railroad hazardous materials accidents, railroads' interest in all possible means of reducing hazardous materials transportation risk has intensified in recent years, especially for Toxic Inhalation Hazard (TIH) materials such as chlorine, ammonia and approximately two dozen other chemical products classified as TIHs and shipped by rail (BOE, 2007; PHMSA, 2008). The issuance of PHMSA-RSPA-2004-18730 (HM-232E) – Final Rule, effective December 26, 2008 (U.S. DOT, 2008), requiring U.S. rail carriers to gather information on products, routes, and risk factors related to shipments of TIH materials and to determine the security risks to high-consequence locations, further highlighted route-specific aspects of risk. This has led to a host of questions about how railroads and government should calculate and interpret the route risk results in accordance with various policy and planning objectives, and evaluate the benefits of differing risk reduction strategies.

This dissertation attempts to address certain aspects of these questions. In particular, the quantitative methods for hazardous materials route risk analyses, the assessment of the potential benefits of different hazardous materials transportation risk reduction options, and the effective communication of route risk results are three major areas covered in this dissertation. This study serves several purposes. The first is to quantitatively consider several different options for railroad hazardous materials transportation risk reduction. To achieve this objective, I use operations research (OR) methods and quantitative risk assessment (QRA) to evaluate particular approaches for risk reduction, including rationalization of the rail transportation route structure, track improvement, and management of train operating speeds. In particular, I combine optimization techniques with a risk analysis model and develop a mathematical framework to formally consider and evaluate the potential of these three different approaches. In addition, I also develop an approach to quantify effects of speed on the conditional probability of release and risk estimate.

The second part of this dissertation is focused on improving risk analysis methodology by considering a probabilistic risk model in which the probability of accident is used instead of accident frequency. To facilitate more effective risk management and decision-making, I present several options for route risk comparison and risk communication techniques.

In summary, this dissertation introduces several mathematical frameworks to inform both private and public sector stakeholders regarding cost-effective approaches for reducing hazardous materials transportation risk. It provides tools that can be used to develop necessary information to better inform risk-based decision making. Furthermore, it offers a background for researchers interested in operations research analysis of hazardous materials transportation risk reduction options.

1.2 Organization of Dissertation and Objectives of Study

This dissertation consists of ten chapters. The specific objectives of each chapter in this dissertation are as follows:

1. Introduction (Chapter 1)
 - a) Introduce the objectives and problems statements to establishing the basis for this research.
 - b) Briefly discuss the essential elements of each chapter in this dissertation and provide a list of potential contributions to the advancement in the field of hazardous materials transportation risk analysis.
2. Review of Railroad Hazardous Materials Risk Analyses (Chapter 2)
 - a) Present a review of selected literature and previous studies related to railroad hazardous materials transportation risk assessment, route analysis, decision support tools for risk analysis, and risk communication. Obtain sufficient background and understanding of these subjects, and their importance to industry, government and the public, and establish the basis for this research.

3. Risk Reduction by Rationalization of Hazardous Materials Transportation Rail Route Structure (Chapter 3)
 - a) Introduce the concepts of route rationalization for railroad hazardous materials transportation risk reduction. Discuss the salient features of route rationalization and distinguish it from the conventional rerouting approach
 - b) Consider the major factors affecting hazardous materials transportation route risks and develop a simple mathematical programming model in accordance with the route rationalization concepts defined.
 - c) Illustrate the capability of the model using a case study of a selected product transported on the U.S. railroad network. Solve the problem and identify alternate shipment flows.
 - d) Perform a multiple-scenario analysis using different objective functions to illustrate the applicability of the framework in handling multi-objective decision-making for hazardous materials shipment management and planning.
4. Effects of Train Speed on Hazardous Materials Transportation Route Risk Analysis (Chapter 4)
 - a) Develop a technique to account for the effect of train speed on tank car conditional probability of release (CPR) and route risk.
 - b) Based on representative shipment route data, calculate route risks using the speed-dependent CPR and compare the risk results with the baseline case in which the average speed CPR is used. Compare and discuss the difference in risk estimates obtained using the two approaches.
 - c) Illustrate an application of speed-dependent CPR using a case study on the route infrastructure upgrade problem. In particular, consider the effects of track upgrade on risk, assuming a change in operating speeds after upgrade. For different upgrade strategies, determine the changes in risk as accident rate decreases due to track improvement and CPR increases as a result of higher operating speed, then suggest the strategy that offers the greatest magnitude of risk reduction.

5. Options for Route Infrastructure Improvement for Risk Reduction (Chapter 5)
 - a) Develop a mathematical programming model for determining the locations for track infrastructure upgrade to minimize risk given a resource constraint.
 - b) Consider different strategies applied to infrastructure improvement and suggest the strategy that will result in the greatest safety benefit in risk reduction.
 - c) Perform a preliminary cost-effectiveness analysis to understand a typical pattern of benefit this option may offer under different levels of investment.
 - d) Analyze the effect of segment length on the optimization results.
6. Managing Train Speed to Reduce Risk and Optimizing Hazardous Material Transportation Risk Reduction Options (Chapter 6)
 - a) Develop a mathematical model to incorporate speed-dependent CPR and determine the locations where train operating speeds should be adjusted to minimize risk and transportation (delay) cost.
 - b) Consider different strategies applied to speed management and compare the degree of risk reduction from each strategy.
 - c) Develop an integrated framework that takes into account multiple risk-reduction options: reducing speed and upgrading track in a single, multi-objective optimization model.
 - d) Apply the above model to consider the most cost-effective risk reduction strategy given a limited annual budget.
7. Probabilistic Risk Model for Route Risk Estimation (Chapter 7)
 - a) Discuss an alternative approach for estimating the risk using a probabilistic model based on a Poisson process to describe accident occurrences.

- b) Compare the risk estimate obtained with that of the simplified risk model and discuss the differences. Determine whether the probabilistic and the simplified approaches may be used interchangeably.

8. Route Risk Comparison Techniques (Chapter 8)

- a) Discuss different approaches for route risk comparison and explore the potential of statistical techniques that may be applicable when the budget is insufficient to perform risk analysis of the entire network.
- b) Illustrate an application of the comparison techniques using a case study. Discuss how the statistical techniques would help complement the conventional representation of risk using a point estimate and risk-profiles.

9. Communication and Interpretation of Results of Route Risk Analyses (Chapter 9)

- a) Develop the options for more effective interpretation and communication of route risk analysis results so that the critical information is delivered to the concerned parties who most need it. In particular, consider different levels of analyses: route-specific vs. system level (combined routes), and illustrate the use of normalized metrics in the representation of risk results.
- b) Determine which information is most useful to different parties including: railroad carriers, chemical shippers, regulators, local authorities and researchers. Develop the appropriate methods including a geographical comparison and segment level comparison of risk to deliver critical information to these parties accordingly.
- c) Develop the techniques to help risk managers visualize the contribution of risk factors along the route and identify the locations on the shipment network with the highest concentration of risk.
- d) Discuss a framework to help clarify the mutual roles of carriers, shippers and local municipalities regarding cooperative risk management and mitigation.

10. Future Research (Chapter 10)

- a) Provide a brief description of topics for future research.

1.3 Contribution Summary

The potential contributions of my dissertation work to industry, risk analysts, and academics are as follows:

1. Contributions to rail carriers and chemical shippers
 - a) Provide a methodology for assessment of hazardous materials transportation route risks at the segment-specific level.
 - b) Provide a basic framework to determine the alternatives for distribution of materials in accordance with the objective of interest.
 - c) Suggest a more cost-effective strategy for track infrastructure improvement that offers the greatest benefit of risk reduction.
 - d) Provide a mathematical model to determine the locations for route infrastructure upgrade to minimize hazardous materials transportation risk under different upgrade policies and a resource constraint.
 - e) Provide a mathematical model to facilitate the consideration of train speed management as alternative measure for risk reduction.
 - f) Provide an integrated framework to suggest an optimal strategy for hazardous materials transportation risk reduction that minimizes risk and cost, given a limited budget.
 - g) Present statistical techniques for risk comparison to facilitate risk-based decision-making.
 - h) Develop graphical illustrations to convey critical information from route risk analysis results to risk managers.
2. Contributions to government, policy makers, transportation regulators, municipalities and local authorities

- a) Evaluate the potential of risk reduction by rationalization of hazardous materials transportation route structure to facilitate the consideration of this approach as a means of risk reduction.
- b) Assess the effectiveness of track infrastructure improvement to deliver information and insight regarding its potential to facilitate strategic risk planning, management, and mitigation.
- c) Evaluate the safety benefits and potential impacts of speed reduction of trains carrying hazardous materials.
- d) Introduce options for a more effective interpretation and communication of route risk results that are most suitable for different parties in the rail transportation supply chain.

3. Contributions to academics and researchers

- a) Introduce the risk-based routing framework for multi-objective analyses of hazardous materials transportation.
- b) Develop the relationship between train speed and CPR applicable to the specific safety design features of the tank car. Introduce an application of speed-dependent CPR in risk analysis and modeling and illustrate the advantages of using it over the conventional risk analysis approach in which a single value of average-speed CPR is used.
- c) Introduce the mathematical model for track infrastructure improvement to minimize risk and cost given a resource constraint.
- d) Introduce the mathematical model that incorporates the speed-dependent CPR and suggest the most cost-effective option for reducing risk by managing train speed under various scenarios.
- e) Introduce the mathematical model that incorporates multiple risk-reduction options and determines the optimal strategy that minimizes risk and cost given a resource constraint.

- f) Discuss a probabilistic model to estimate risk and multiple derailments in accidents.
- g) Develop a basis for comparison of route risks using statistical techniques.
- h) Develop various techniques to interpret and communicate the results of route risk analyses.
- i) Discuss the need for route segmentation to reduce uncertainty errors in track-segment-specific risk analysis and to obtain better results in track infrastructure improvement decisions.

1.4 Conclusions

My dissertation research aims to evaluate the effectiveness of several different approaches to reduce the risk of railroad transportation of hazardous materials: rationalizing the shipment route structure, improving track infrastructure, and managing operating speeds of trains carrying hazardous materials. Under the routing approach, the route rationalization model framework determines various possible route structures for any particular hazardous materials in accordance with different objectives of interest comprising the minimization of: mileage (car-miles), accident rate, release rate, and risk. Enhancement of route risk estimation is made by considering the effect of train speed on hazardous materials transportation risk analysis. Speed-dependent CPR is developed for incorporation into risk optimization models. The route infrastructure improvement selection model combines the effects of speed and infrastructure upgrade on route risks to suggest a more cost-effective route infrastructure improvement strategy that minimizes risk and cost given a resource constraint. The train speed management model suggests the locations on the network where operating speeds can be managed to improve hazardous materials transportation safety. The combined framework determines the optimal strategy given a set of risk reduction measures and resource. These mathematical model frameworks serve as a tool for enhancing the quality of risk-based decision-making of both public and private sectors.

This research also contributes to advancement in the areas of risk estimation, risk comparison, and risk communication. An alternative, probabilistic approach for risk estimation is discussed. In addition to the conventional route-specific risk information: the point estimates of

risk and the risk profiles, a statistical approach for risk comparison is proposed to provide confidence in risk-based decision making when a complete route risk analysis is not possible. A graphical approach for risk communication is introduced to deliver the most relevant and useful information from route risk analysis results to different parties and help clarify their mutual roles regarding risk reduction options.

The above would help fulfill the needs for the framework, analysis methods and techniques that address the questions regarding different approaches for hazardous materials transportation risk reduction. These developments may be considered for further uses or refinements as appropriate by researchers who are interested in railroad hazardous materials risk analysis and operations research.

CHAPTER 2

REVIEW OF RAILROAD HAZARDOUS MATERIALS RISK ANALYSES

2.1 Introduction

In this chapter, I provide a review of the literature related to the subject of this dissertation. The organization of this chapter includes four main sections. In section 2.1, I review Quantitative Risk Analysis (QRA) studies of hazardous materials transportation to develop a general understanding of this subject. In section 2.2, I focus on the papers related to hazardous materials transportation routing and risk analyses, with special emphasis on rail transportation. Section 2.3 is a review of quantitative estimates of risk parameters. In section 2.5, I focus on Decision Support Systems (DSS) for hazardous materials transportation risk analyses, followed by risk communication in Section 2.6. The materials reviewed in this section provide the critical ideas and the rationale for my research work described in the subsequent chapters.

2.2 Quantitative Risk Analysis and Risk Assessment

The field of Quantitative Risk Analysis (QRA) of hazardous material transportation dates back to the 1970s (NTSB, 1971). Advancements in methodology continue, and research and studies on this subject are ongoing. However, QRA has matured to the point that it is considered an effective tool that is used to inform business and government decisions in a variety of contexts (Kawprasert and Barkan, 2009). In recent years, hazardous materials transportation risk management and mitigation have received considerable interest from the rail industry. This interest is part of the motivation for my study of route risk analyses. In this section, I review literature of completed or ongoing work in this area as it relates to my research. Certain references to particular topics are also cited elsewhere in this dissertation.

2.2.1 QRA Guidelines and Definition of Terms

There are several books that provide useful background of hazardous materials transportation risk analysis and management. Philipson and Napadensky (1982) provide discussion of hazardous materials transportation risk assessment. Covelto and Merkhofer (1993) discuss fundamentals for risk assessment and evaluate risk assessment methods used in various

disciplines. The Center for Chemical Process Safety (CCPS) of the American Institute of Chemical Engineers has published a series of books on risk management and analysis (CCPS, 1989; 1995; 2007; 2008). These books are used by rail and chemical industry practitioners, government and academic researchers as a general guide for hazardous materials transportation management. In particular, Guidelines for Chemical Transportation Risk Analysis (CCPS, 1995) describes the methods and techniques used for evaluating the risk of hazardous materials transportation for various modes (Bendixen et al., 1997). It provides a basic framework for risk analysis, along with illustrative examples that are useful for practitioners concerned with various questions on this topic. The second “edition” of this book (CCPS, 2008) is more aptly described as a new book because it provides a more general framework and the common practices for a broad range of transportation practitioners. It focuses more on how the stakeholders in the transportation supply chain, including shippers and carriers, manage their chemical transportation networks by using their existing systems and introduces more qualitative and practical techniques compared to the first edition.

CCPS provides definitions of important terms related to risk analysis, some of which are used extensively in this research. These are:

Quantitative Risk Analysis (QRA): “the development of a quantitative estimate of a risk based on engineering evaluation and mathematical techniques for combining estimates of incident consequence and frequencies”

Risk: “a measure of human injury, environmental damage, or economic loss in terms of both the incident likelihood and the magnitude of the loss or injury”

Risk Assessment: “the process by which the results of a risk analysis are used to make decisions, either through relative ranking of risk reduction strategies or through comparison with risk targets”

Risk Analysis: “the development of a quantitative estimate of risk based on engineering evaluation and mathematical techniques for combining estimates of incident consequence and frequencies”

Risk Reduction: “development, comparison, and selection of options to reduce risk to a target level, if needed, or as needed”

Another term often found in the literature is Transportation Risk Analysis (TRA), which is defined by CCPS (1995) as “the process of hazard identification followed by numerical evaluation of incident consequences and frequencies, and their combination into an overall measure of risk when applied to transportation of hazardous materials.” In my research, however, the term QRA is commonly used.

2.2.2 QRA Studies of Hazardous Materials Transportation

Hazardous materials transportation risk assessment and analyses are an ongoing subject of interest and have received increasing attention from academia in the past decade. A number of studies on hazardous materials transportation management already existed (Warner et al., 2008). Basic QRA methodologies and their application to hazardous materials transportation are well established (Rhyne, 1994) and therefore represent an effective tool to assess the risk associated with transportation of hazardous materials (Fabiano et al., 2002). Considerable development of operations research (OR) modeling has been placed on QRA of hazardous materials transportation. List et al. (1991) surveyed research on hazardous materials transportation risk analysis, routing / scheduling, and facility location, with a focus on a methodological study on truck and rail. Borysiewicz (2006) summarized a QRA approach for both road and rail hazardous materials transportation. Several books also reviewed the literature on this subject; e.g. Moses and Lindstrom (1993), Saccomanno and Cassidy (1993), Verter and Erkut (1995), and Centrone et al. (2008).

Relatively more attention has been given to QRA of road hazardous materials transportation problems compared to rail problems. In this sub-section, I provide a brief review of selected literature concerning QRA of hazardous materials transportation for both road and rail transportation, with an emphasis on the latter.

Glickman and Rosenfield (1984) formulated models to estimate the risks of hazardous material releases in train derailments. In their study, risks were expressed in terms of the probabilities of fatalities in an accident and the frequency and severity of accidents resulting in fatalities. Different spill sizes and release scenarios were considered.

Glickman and Golding (1991) assessed the risk of transporting spent fuel and nuclear waste using dedicated trains. They found that the costs of dedicated service are marginally greater than those of regular freight service, and that these extra costs may be worthwhile to reduce public opposition and increase levels of trust.

Nicolet-Monnier and Gheorge (1996) outlined a quantitative approach to develop numerical estimates of risk for road and rail transportation. They also provided case studies and discussed a computer-based decision support system for hazardous materials transportation.

Madala (2000) developed a simulation model to analyze routing and risk assessment problems for road hazardous materials transportation. His model accommodates the use of multi-criteria decision-making and applies to hazardous materials transportation in selected Canadian cities.

Brown et al. (2001) described risk assessment methodology and assessed the risks of the selected TIH materials transported by road and rail. Their study provided incident rates and consequence levels of the hazardous materials considered.

Nardini et al. (2003) outlined the methodologies for risk assessment of the transport of methanol by road and rail in a European country.

Glickman and Erkut (2007) performed a risk assessment for hazardous material tank car operation in yard using Association of American Railroads (AAR) data to estimate the probabilities of events.

Verma and Verter (2007) presented rail risk assessment for hazardous materials that are airborne upon an accidental release into the environment. Their analysis framework incorporates the characteristics of vehicles, lading, and transportation volume.

In addition to the QRA, alternative approaches for risk assessment exist. These include the use of the analytical hierarchy process (AHP), fuzzy reasoning in risk analysis (An et al., 2007), route planning (Huang et al., 2004). Another approach is to use subjective evaluation or expert opinion for risk management (Cox, 2007).

2.3 Hazardous Materials Transportation Routing and Risk Analyses

In this section, I provide further reviews of the studies related to hazardous materials routing with focus on rail transportation. The routing problems for road and rail differ to some extent due to different characteristics of these two modes. Rerouting rail hazardous material shipments can be more difficult. Compared to road transport, rail generally has fewer rerouting alternatives (Glickman et al., 2007). That is, rail route alternatives can be more stringent and are subjected to more operating constraints than highway routes. Flexibility of the carrier is needed in determining the best route for operational considerations (Allen and Fronczak, 2007), thereby making rail routing a more challenging option to implement. The trade-off between the level of safety, security risks, and economics is another issue in the recent consideration of rail transportation risk management developments (Abkowitz, 2003; Schoonover; 2006; Abkowitz, 2007). These add to the motivation for conducting research on this subject.

2.3.1 Hazardous Materials Transportation Routing Studies and Policies

The reduction of potential consequences of a railroad release on the general public requires community planning, federal regulation priorities, and commitment to safety (Orr et al., 2001). In this sub-section, I review previous studies and related government policies regarding hazardous materials transportation routing in the North America to obtain background information and understanding.

In 1981, the U.S. Department of Transportation (DOT) carried out a study project on rerouting and speed reduction of hazardous material trains on certain Conrail corridors to determine the effects on operations, costs, and population exposure. The analysis assumed that the shipments through populated areas were prohibited or moved at reduced speed (CONSAD Research Corporation, 1981).

The Toronto Area Rail Transportation of Dangerous Goods Task Force (1988) carried out a comprehensive study of the transportation of dangerous goods by rail. Their study includes a feasibility study on rerouting rail traffic of dangerous goods in the Greater Toronto Area to identify high risk locations and fatality rates. The task force concluded that rerouting was feasible and would reduce risk over the entire system, especially in the high risk segments, but risk reduction alone was not sufficient justification. Both economic and safety benefits should be considered in the context of an integrated and rationalized rail transport system in order to justify this approach.

Glickman (2004) indicated the possibilities of rerouting tank cars carrying hazardous materials to avoid locations with dense population concentrations in six high-threat urban areas in the U.S. using the software PC*HazRoute. His study showed the benefit in terms of a reduction of the number of people potentially exposed to release impacts from -2% to -27%, and the cost in terms of increased mileage from -1% to +19%.

Fronczak (2006) pointed out several issues regarding rerouting of rail hazardous material shipments that may be considered as the drawbacks of this approach. These include possible increased hazardous materials shipment mileage, transfer of risk to the areas where emergency response might not be well prepared, and traffic diversion to the routes with lower infrastructure quality. In addition, railroads may have standards for operating and maintenance practices higher than those stipulated in the regulations, leading to questions about the efficacy of rerouting.

Hazardous materials rerouting may involve increased mileage and the increased likelihood of low consequence events (Barkan, 2006). That is, rerouting hazardous materials traffic from populated areas potentially reduces the risk of high consequence events but may result in more lengthy, circuitous routings (Stehly, 2004), as well as increased transit time, number of yard visits, and number of handling events due to the longer mileage. Risk may be transferred to areas where emergency response might not be as capable. Traffic may be diverted to routes with lower quality infrastructure and, therefore, may be more prone to accident exposure (Barkan, 2006). According to Allen and Fronczak (2007), the best route from a railroad safety perspective may be the one with the least mileage and accident likelihood, rather than the longer route with lower consequence.

After 9/11, security concerns became a much more prevalent transportation consideration. Rerouting or restriction of rail hazardous materials traffic in metropolitan areas has or is being considered in major cities, including Washington, D.C., Baltimore, Boston, Chicago, Cleveland, Las Vegas, and Pittsburg (Fronczak, 2006; NCPC, 2007). Consequently, security is being incorporated into route planning and risk assessment to develop an integrated decision-making framework (Abkowitz, 2003; Murray, 2004; Erkut et al, 2007). This adds new complexity to hazardous materials transportation routing problems, making them even more challenging for government, industry, the public, and researchers.

2.3.2 OR Applications to Hazardous Materials Transportation Route Planning

Hazardous materials transportation route risk analyses often have multiple and conflicting objectives. These may involve finding a way to balance the tradeoff between economics and safety in the most efficient manner to maximize safety benefits, minimize costs, and minimize risk to receptors subjected to certain resources and transportation constraints. Operations research and optimization techniques can help facilitate a more informed and rational simultaneous consideration of these different aspects (Glickman and Khamooshi, 2005).

One of the benefits of using an OR approach to study hazardous materials transportation risk is that the various elements affecting decisions can be incorporated into the objective function or the constraints of the problem. Development of computer technology and optimization software packages makes analysis of complicated routing problems feasible in a timely manner. OR applications played an extensive role in transportation routing problems. In this sub-section, I review the literature related to OR applications to hazardous materials transportation and in particular to rail hazardous materials routing problems.

Research and development on OR applications for rail transportation has been much less than that of highway transportation or aviation. This is somewhat ironic in light of the fact that more hazardous materials transportation is by rail than any other mode. However, in the past decade there has been an increased concern regarding its application in railroad transportation (Cordeau, 1998). OR models on railroad network routing, car assignment, and scheduling have been discussed in the literature, e.g. Assad (1977), Haghani (1987), and Cordeau (1998).

Many OR papers have considered highway hazardous materials transportation route risk analyses. This has provided generalized model formulations of hazardous materials transportation risk management for highway questions. Most of these routing problems are based on multi-objective shortest path algorithm, and these can be adapted to address various rail questions. Articles and studies on truck hazardous materials transportation routing problems and risk analyses include work by Cox (1984), Saccomanno and Chan (1985), Abkowitz and Cheng (1988), Wijeratne et al. (1993), Miller-Hooks and Mahmassani (1998), Erkut and Verter (1998), Huang and Fery (2005), Haghani et al. (2006), Alumur and Kara (2007), Carotenuto et al. (2007), and Dadkar et al. (2008). In addition to these, Erkut (2007) and Erkut et al. (2007)

summarized the literature related to OR applications to hazardous materials transportation, including location and routing analyses. Among these articles and studies, there are a few dedicated to railroad hazardous materials transportation routing problems.

Glickman (1983) quantified the risk associated with railroad hazardous material shipments in terms of expected annual casualties and evaluated aggregate effects of rerouting hazardous materials traffic from populated areas, with and without track infrastructure upgrade. His results showed that some areas would benefit from rerouting, provided that track upgrades were implemented along with rerouting. Based on the network studied, he found that rerouting could reduce population exposure by 25–50%. The financial impacts of operating changes and infrastructure upgrade were not considered in his study.

Saat and Barkan (2006a) presented a comprehensive risk assessment model that enables evaluation of different rail route alternatives for transporting hazardous materials. Their model considers the length of the route, number of shipments, track quality, tank car safety design, chemical-specific exposure, and population density.

Glickman et al. (2007) evaluated the tradeoff between cost and risk of rerouting railroad shipments of hazardous materials. An approximate model was used to quantify railroad hazardous materials transportation risk. In the model, route length and population exposure were used as proxies for cost and risk impacts, respectively. They compared an existing route as a case study to a reduced-risk route and found that there was an opportunity to reduce risk without the need to substantially lengthen the route. This suggested the need for further studies on the cost-effectiveness of railroad hazardous materials rerouting in more detail for specific shipments.

Verma (2009) developed a bi-objective optimization model, incorporating transportation risk and costs in the objective function to address different interests of two stakeholders: regulators and carriers. His model accounts for hazardous materials type, transport costs, train frequency, service, and capacity constraints. Operational details were disregarded. The study provides a set of solutions comprising different combinations of risk and cost based on the particular network studied.

2.4 Development of Numerical Estimates of Risk

QRA involves two processes: estimation of factors affecting risk and calculation of risk using a quantitative model (Erkut and Verter, 1995). In the “traditional” risk model, risk is the product of the probability of incident and the consequence of the incident (Erkut et al., 2007). There are also several alternative models that may be used to describe risk (Erkut and Verter, 1998; Erkut and Ingolfsson, 2005). All models, however, rely on estimation of the same two basic components: the probability and the consequence of the incident. In the context of railroad hazardous materials transportation risk, the first component includes the estimation of the probability of a hazardous material release, which is the product of a series of probabilities (Woodward, 1989), i.e. accident rate, probability of car derailment given a train accident, and probability of a hazardous materials release in an accident. The second component concerns the estimation of effects from the hazardous material release. There are various metrics for this, such as the number of fatalities, the number of persons exposed to a release, environmental impact, damage costs, etc. In this section, I focus on literature and studies on estimation of risk parameters of these two components of the QRA model.

2.4.1 Accident Rates and Release Rates

Nayak et al. (1983) developed the procedures for evaluating the probability and impacts of hazardous material accidents in rail transportation and, for the first time, quantified the correlation between the Federal Railroad Administration (FRA) track classes, accident frequencies, and the effect of train speed on accident severity. The analysis focused on track-caused accidents and quantitative estimates were provided in terms of the amount of hazardous material released per accident and the area affected by the releases.

Phillips and Role (1989) described the types of tank cars and their performance in accidents for selected hazardous materials commodities over the 22-year period (1965-1986). In their report, the lading loss data were presented for pressure and non-pressure cars by year and cause of accident. The effectiveness of shelf couplers and head shields on preventing head punctures was specifically considered as well.

Treichel and Barkan (1993) investigated the relationship between track classes and accident probability and severity in the context of QRA modeling. Following Nayak et al. (1983), they developed both “numerator” and “denominator” data enabling calculations of track-class-specific accident rates for use as a proxy for track quality in risk analysis. They developed accident and derailment rates for U.S. Class-1 railroads and also developed estimates of the average number of cars derailed in mainline freight train accidents by track class and train speed. They mentioned that the conditional probability of release, given a derailment, and the expected quantity spilled, given a release, increase with train speed and track class. Therefore, the risk on a specific track class should not be inferred from accident rates alone but should take into account other factors to allow better estimation of track-class-specific risk.

CCPS (1995) suggested quantitative estimates of various risk parameters, including derailment and accident frequencies for specific track classes, the probability of car derailment given an accident, release probabilities, and the effects of speed on the number of cars derailed and on the release probabilities.

Dennis (1996) provided statistics on accident rate and probability of release given an accident during the 13-year period (1982–1994). The rates, however, were not analyzed by specific track class. He also studied the costs incurred as a result of the presence of hazardous materials and developed risk costs associated with railroad hazardous materials transportation.

Arthur D. Little, Inc. (1996) provided track-class-specific train accident and car derailment rates for railroad hazardous materials transportation risk analysis, based on Treichel and Barkan (1993). This report also quantified the benefits of various risk reduction options.

Dennis (2002) studied the changes in railroad accident rates from 1983 to 1994. The rate declined substantially following the economic deregulation of railroads. He assessed the significance of various factors that affected this and concluded that railroad track investment had a statistically significant effect on the decline, while federal regulation had a statistically insignificant effect on the reduction of track accidents. Furthermore, there was not a statistically significant acceleration or deceleration in the rate of change of the accident rates over the period studied.

Anderson and Barkan (2004) used Treichel and Barkan's (1993) results, combined with updated FRA accident data, to develop updated estimates of track-class-specific accident rates. They also conducted sensitivity analyses in order to understand possible track-class-specific change.

Treichel et al. (2006) described a comprehensive statistical analysis of tank car safety performance in FRA-reportable accidents. This study provides regression formulae that can be used to estimate the accident performance of each car configuration and certain major tank car design elements. The report includes statistics on conditional probability of release (CPR) for both mainline and yard accidents, as well as quantity loss amounts and the effect of accident speed on CPR for non-pressure and pressure tank cars.

2.4.2 Consequence of Release

The consequence of a hazardous material release in an accident can be expressed using several metrics, such as human impact (i.e. the number of injuries or fatalities, the number of persons potentially exposed to a release), monetary unit (i.e. costs) due to property damage, environmental change, and litigation or other forms of financial impact. The following is a brief review of some of the literature related to hazardous materials consequence estimation and modeling.

Birk et al. (1990a, 1990b) developed a computer program to simulate the consequences of a train derailment accident. The program used several models that accounted for train derailment mechanics, flammable liquid spills, fire effects on remote targets, fire impingement on tank cars carrying dangerous commodities, explosion blast over-pressure and thermal radiation, and heavy plume and puff dispersion.

Brown et al. (2000; 2005; 2009) described the development of the values in the table of initial isolation and protective action distances used in the Emergency Response Guidebook (ERG), which is jointly developed by the U.S. Department of Transportation, Transport Canada, and the Secretariat of Communications and Transportation of Mexico (PHMSA, 2004; PHMSA, 2008). The ERG is designed for use by first responders to determine the appropriate level of action during the initial stages of a hazardous materials transportation incident (Brown and Dunn, 2007). It also provides initial isolation and protective action distances for consideration in the event of a hazardous materials release for specific chemicals and scenarios of release. More

recently, it has been used as a measure of the relative impact of different hazardous materials (Saat, 2009).

Kara et al. (2003) pointed out that using a Geographic Information System (GIS) to compute consequence with population density data may overestimate the population exposure if an algorithm or computation process double-counts the population in an overlapped exposure area of two or more intersecting route segments. Consequently, it may result in the selection of a suboptimal path. They proposed an approach to this problem by developing an algorithm to allow better estimation of population exposure in the transportation network.

Hanna et al. (2008) tested different gas dispersion models that have been widely used to calculate downwind chlorine gas concentrations. The test used the scenarios of release that occurred in Festus, MO; Macdona, TX; and Graniteville, SC. They concluded that the models evaluated closely agreed in the estimates of downwind dispersion when given the same source emission terms for the scenarios and assumed conditions.

Other than human population units, risk consequences can also be expressed in monetary units, i.e. risk cost. The following are some information sources on cost estimation that may be useful in hazardous materials risk analyses.

In January 1993, the U.S. DOT adopted a guidance memorandum called "Treatment of Value of Life and Injuries in Preparing Economic Evaluations", with recommended economic values to be used in the departmental regulatory and investment analyses. Viscusi and Aldy (2003) provided a comprehensive review of the value of statistical life (VSL). They also provided a detailed discussion of the policy applications of VSL estimates and other related issues. Alberini (2005) explained that the VSL is the rate at which people are prepared to trade off income for a reduction in their risk of dying, and that it is a key input in computing the mortality benefits of environmental and safety policies that save lives. In short, VSL is the trade-off between money and fatality risks (Viscusi and Aldy, 2003). According to the U.S. DOT (2008), the current estimate of the VSL in the U.S. is \$5.8 million.

2.5 Decision Support Systems for Hazardous Materials Transportation Risk Analyses

A Decision Support System (DSS) may facilitate hazardous materials transportation risk management by integrating vehicle routing and emergency response planning decisions (Zografos and Androutsopoulos, 2005). The DSS for hazardous materials transportation includes network modeling, routing software, and GIS application. These systems can be used in

hazardous materials transportation route planning and risk analyses (Chin et al., 2006). In this section, I highlight some studies and literature about the development and application of DSS in hazardous materials transportation risk analyses.

2.5.1 Transportation Network Model

There are several large-scale transportation network models that can be used for route analyses. The Princeton Transportation Network Model (PTNM) (ALK, 1988) is one such model and it uses the Surface Transportation Board (STB) carload waybill sample data to generate the traffic flow map (Kornhauser and Bodden, 1983; Lorig, 2002). It contains over 23,000 links and 43,000 nodes in the North American rail network. A useful feature is that both traffic volume and flow direction can be conveniently displayed on the map (Kawprasert and Barkan, 2008). Previous UIUC railroad engineering program research that has used PTNM includes Day (2002) study of seismic impact on the Midwestern rail network and Anand (2006) study of environmental risk of hazardous materials transportation. I found PTNM to be a useful tool for understanding hazardous material traffic patterns of Toxic Inhalation Hazard (TIH) materials and Environmentally Sensitive Chemicals (ESC).

There are also other network models for freight transportation analyses, including the CACI multimodal Transportation Network Model (TNM) of the University of Pennsylvania/Argonne Lab, the Freight Network Equilibrium Model (FNEM), and the Generalized Spatial Price Equilibrium Model (GSPEM). Munshi and Sullivan (1989) reviewed and described the basic features and algorithms of these transportation network models.

2.5.2 Rail Routing Software

INTERLINE is a rail routing model developed by the Oak Ridge National Laboratory (ORNL) to investigate potential routes for transporting radioactive materials. INTERLINE Version 5.0 routing algorithms have the ability to predict alternative routes, barge routes, and population statistics for any route. Its transportation network contains the U.S. rail network of over 15,000 rail and barge links and over 13,000 stations, interchange points, ports, and other locations (nodes). All rail lines, with the exception of industrial spurs, are included in the INTERLINE network (Johnson et al., 1993). This software has been later superseded by TRAGIS.

PC*HazRoute is a decision support system developed by ALK Associates (ALK, 1994) that offers objective and scientific analysis of the risk of shipping hazardous materials over the U.S. highway and railroad network. Its database includes population data as well as accident probabilities. For a given origin-destination (OD), the software can find the routes that minimize route length, accident probability, release incident probability, total population exposure, and risk (Erkut and Glickman, 1997; Erkut and Verter, 1998). Examples of recent research in which this software had been used include Kara et al. (2003) and Erkut and Ingolfsson (2005).

PC*MILER | Rail (ALK, 2006) is a point-to-point rail routing and mileage software that contains the North American rail network of over 240,000 miles, 49,856 active freight stations, 699 rail carriers, and over 3,600 unique junction interchanges. It allows the user to determine the routes based on specified OD pairs and rail carriers, with routing options including shortest, practical, intermodal, coal/bulk, and auto rack train routes. The detailed algorithms or route formulae for each routing option are not disclosed. According to software Help documentation, “the practical routings are based on mileage as well as on the mainline/branchline code to simulate most likely movements of general merchandise traffic; the shortest routes minimize the distance between two points; intermodal, coal/bulk, or auto racks may be used to determine the exceptional routings that these types of trains sometimes require.” I made extensive use of this software in my research (Kawprasert and Barkan, 2008; 2009), and it has been used in several other hazardous materials risk analysis projects at UIUC. Its network database is more up-to-date than PTNM. One of the significant features of PC*MILER | Rail is that it can generate a detailed geocode report that contains the list of locations enroute that can be used in the consequence analysis with GIS.

2.5.3 Geographic Information Systems

Geographic Information Systems (GIS) have been widely used in the field of transportation. Transportation applications of GIS are often referred to as GIS-T (Waters, 1999; Goodchild, 2000). Application of GIS is also widely used in risk analysis of transportation of hazardous materials (Lepofsky et al., 1993; Panwhar et al., 2000). It enables improved decision support in managing transportation safety (Abkowitz et al., 1990). In particular, it helps facilitate the process of consequence estimation to identify the potential receptors along hazardous materials

shipment routes. GIS is well suited for design and management of hazardous materials routes because of its ability to integrate multiple data themes and data sources into an operational information system (Frank et al., 2000).

Phanwar et al. (2000) described a probabilistic risk assessment framework, in which GIS is incorporated to perform spatial analyses and to assist in the optimization procedure. In particular, the Network Analyst, which is one of the extensions of ArcView GIS, was used to determine the route for road transportation of hazardous materials. In their study, the risk for each segment was calculated, then the optimized route for transportation of hazardous materials was determined.

Verter and Kara (2001) developed a GIS-based model for truck shipment of hazardous materials on the Canadian highway network and evaluated the risks associated with routing alternatives, i.e. the routes that minimize distance, probability of incident, population exposure, and expected number of people to be evacuated in case of an incident.

A number of studies over the past decade have used GIS for rail hazardous materials transportation route risk analyses. These include Lovett et al. (1997), Zhang et al. (2000), Bubbico et al. (2004), and Glickman and Evans (2008).

2.5.4 Transportation Routing Analysis Geographic Information System (TRAGIS)

The Transportation Routing Analysis Geographic Information System (TRAGIS) (Johnson, 1995) is a GIS-based transportation and analysis model, first developed in 1995 by the Oak Ridge National Laboratory of the U.S. Department of Energy (DOE). It has a comprehensive transportation network, including rail, truck, and waterways and has a user interface to graphically display the calculated routes. The TRAGIS output can be used as source data for other risk analysis models, such as RISKIND (Yuan et al., 1995) and RADTRAN (Neuhauser and Kanipe, 2000). The web-based version of TRAGIS, WebTRAGIS (Johnson and Michelhaugh, 2003), was developed to be accessible over the World Wide Web. The WebTRAGIS home page is located at <https://tragis.ornl.gov/> (last accessed May 30, 2009). TRAGIS replaced its original routing models, HIGHWAY and INTERLINE, that were previously developed by ORNL. Further review of these computerized tools for risk assessment of the U.S. DOE was provided by Chen and Kapoor (2003).

Recent development of TRAGIS includes the Rail Routing and Visualization Application (RRVA) (Johnson, 2006). According to Peterson and Church (2007), RRVA is a rail-specific extension to TRAGIS and uses a 1:100,000 scale railroad network developed by the Federal Railroad Administration (FRA). The network consists of over 24,000 nodes and 28,000 link segments contained within 97 sub-networks. These networks identify the various railroads, railroad operators, owners, and trackage rights that comprise the available rail track mileage for each US railroad. RRVA, however, does not account for the consequences of release of a particular material or the probability of a release (Hartong et al., 2007).

2.6 Hazardous Materials Transportation Risk Communication

According to Minor and Abkowitz (2004), risk communication is an integral part of the risk management process. It helps people understand vulnerabilities and informs them of potential protective actions. There have been a number of research studies on hazardous materials risk analyses and assessment, while risk communication, which is vitally important in distribution risk management, is often overlooked and undervalued (Stehly, 2004). The challenge for risk communication is that those potentially affected by hazardous materials transportation risks include a variety of stakeholders and a diverse audience (Minor and Abkowitz, 2004). One of the fundamental problems in communicating risk information is that the public may not interpret risk in the same way as engineers and risk analysts (Vrouwenvelder et al., 2001). The public will often have different educational backgrounds, perspectives, or objectives of interest regarding risk management.

Traditionally, the results from the QRA are presented in the form of numerical risk estimates and risk profiles or F-N curves (Bedford, 2005). Today, modern computer technology has helped enhance the representation of numerical risk results and, therefore, facilitates risk communication. A decision support system for hazardous materials transportation is usually designed for the involvement of stakeholders at all stages in the corresponding risk analysis process and helps improve the risk assessment process by providing appropriate visualization of the results with different levels of information (Gheorghe et al., 2005). For example, some of this information is spatial in nature and, is, best communicated in the form of maps (Fedra, 1998). This kind of information can be visualized geographically on the transportation network with the help of GIS data and tools.

2.7 Conclusions

A number of risk reduction approaches have been studied for rail hazardous materials transportation. These range from routing, packaging design, infrastructure upgrade, vehicle tracking, and operation changes, to rail asset health monitoring. The majority of the literature cited in this chapter is related to hazardous materials route risk analyses, corresponding to the main theme of this dissertation. While a considerable number of studies, including my work in this dissertation, focus on a single risk reduction option, it is important to note that these will generally be only one of a variety of elements in the broader scope of transportation safety. Furthermore, each option may have its own potential benefits and drawbacks, depending on the objective of interest and particular stakeholders. For example, improving packages will not eliminate traffic movement through populated areas, and rerouting will always involve transfer of risks. To obtain the most benefits from risk reduction, several aspects need to be considered and integrated to improve the overall safety and security of rail transportation. Ultimately, these will require mutual cooperation among stakeholders – operators, regulators, and researchers. The research I will present in the following chapters attempts to begin the process of integrating different railroad hazardous materials transportation risk reduction options and more effectively communicating and interpreting the results so as to facilitate this process.

CHAPTER 3

RISK REDUCTION BY RATIONALIZATION OF HAZARDOUS MATERIALS TRANSPORTATION ROUTE STRUCTURE

Adapted from Kawprasert, A., and C.P.L. Barkan. Effects of Route Rationalization on Hazardous Materials Transportation Risk. In *Transportation Research Record: Journal of the Transportation Research Board*, No. 2043, TRB, National Research Council, Washington, D.C., 2008, pp. 65-72.

3.1 Introduction

Hazardous materials traffic originates and terminates at numerous locations throughout the North American railroad network. Rerouting of this traffic, especially Toxic Inhalation Hazard (TIH) materials, away from populated areas has received considerable attention in recent years as a means of reducing risk. However, rerouting on a route specific basis is neither simple nor necessarily effective at reducing risk because of physical constraints in the configuration of the rail network and the possible need to increase the mileage traveled by hazardous materials to avoid populated areas. A more comprehensive approach is rationalization of the transportation route structure for these materials. This does not simply involve trying to reroute traffic between the current set of origins and destinations to avoid population centers en-route. Instead, route rationalization encompasses analysis of the entire route structure for a particular material. The objective is to identify opportunities to reduce risk by considering critical factors associated with each possible route, while simultaneously taking into account the production and consumption levels at each location in the network.

To formally consider risk reduction by means of rationalization of the hazardous materials transportation rail route structure, I combined a risk analysis model with an optimization technique to develop a route rationalization model. This model is flexible and enables optimization of the route structure based on a variety of objective functions including minimization of: mileage traveled, accident (derailment) frequency, likelihood of release, population exposure, and risk. The route rationalization approach encompasses analysis of the entire route structure for a particular material. The route rationalization model is used to illustrate a potential risk reduction for one particular hazardous material being transported over the U.S. rail network. I evaluate the degree of risk reduction using different objective functions and provide a comparison of various analysis scenarios.

3.2 Basic Concepts

3.2.1 Overview of Route Rationalization

Route rationalization is defined as the evaluation of the entire route structure of a particular hazardous material with the objective of reducing risk by considering how the overall route mileage might be reduced. The route rationalization concept considers changing origin and destination (O-D) pairs to take advantage of shorter distances between particular production and consumption centers, while considering the likelihood of an accident, hazardous material release, and exposure to people simultaneously in one single model. It involves a comprehensive analysis of the entire route structure, rather than simply bypassing particular locations in a network. The key distinction is that simple rerouting may often increase total hazardous material mileage traveled, whereas route rationalization involves changing O-D pairs to reduce overall mileage, while taking into account production and consumption levels at each O-D pair and considering all major factors affecting risk.

Based on route rationalization concept above, I introduce a mathematical model – *the route rationalization mode* – which is an optimization model with the objective of evaluating the route structure of a particular material so as to minimize several objective functions, including car-miles, frequency of derailment, and risk. The problem is similar to a traditional operations research topic known as the transportation problem (Wagner, 1975) but is modified to account for the different objective functions. The model and results represent a simple case that is intended to facilitate the consideration of the approach presented. In practice, there may often be more constraints on the ability of rail carriers or chemical manufacturers to make changes in distribution patterns. This work is not intended to suggest that such changes are easy or feasible in all cases. Instead, the purpose is to provide a structure and illustrative example to enhance evaluation of route rationalization as a possible risk management strategy.

This chapter has several goals in support of the objective described above. One is to develop and present a formal quantitative structure to enable the consideration of route rationalization as an option for managing hazardous materials transportation risk. The basic structure provides a framework to which additional constraints and factors can be added if more specificity or realism is desired. It can also help risk managers better understand the types of

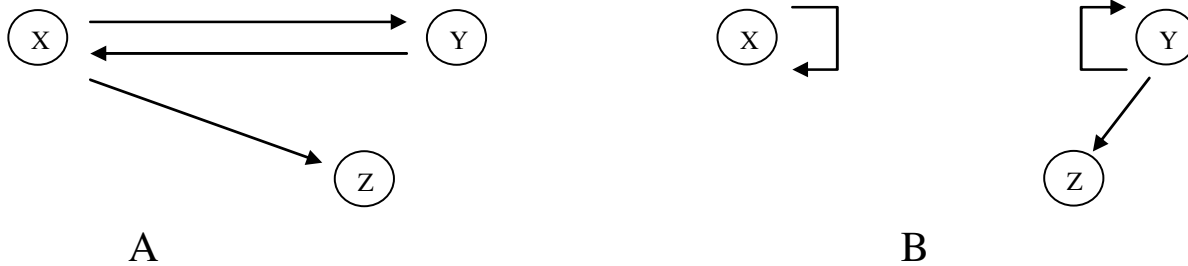
information needed and the factors to be considered if they wish to evaluate this option. Another is to use the model to consider a case study based on rail transport of an actual TIH. In addition to illustrating the model, it provides insight into the potential for risk reduction through use of this approach.

A preliminary consideration of the effect of different risk metrics on the objective functions in the optimization process is introduced through model application. This is of potential use to both researchers and practitioners because different metrics may be more or less difficult to develop in different situations. Understanding the relationship of these metrics to one another may yield insight into their likely effect on risk in cases where complete information is unavailable.

3.2.2 Consideration of a Traffic-routing Problem

Hazardous materials traffic originates and terminates at many different locations in the North American railroad network. Flows of a particular hazardous material, including TIHs, may involve less than a half dozen origin and destination points or many hundreds of different points throughout the network. To illustrate the concept of route rationalization, I considered a simple example of a traffic-routing problem (Figure 3.1a). Material produced at X and Y is shipped from X to Y, X to Z, and Y to X.

Route rationalization involves reducing transportation volume by minimizing the car-mileage required to transport the material to various destination points. This is manifested in two basic ways: either by eliminating or reducing flows to locations that also produce and ship material or by rerouting so that material is shipped to the nearest destination (Figure 3.1b). The computational complexity of the problem is related to the number of O-D pairs, but the basic analytical methodology is the same. In the simple example illustrated in Figure 3.1b, material produced at X is consumed at X rather than being shipped to Y, and, similarly, material produced at Y is consumed at Y. In addition, material produced at X and consumed at Z is instead supplied from Y because it is closer.



**Figure 3.1: Simple Transportation Network for a Hazardous Material
(A) Without Route Rationalization and (B) With Route Rationalization**

3.3 Case Study

I considered a set of traffic flows based on a particular hazardous material transported on the North American railroad network. The portion of the network considered comprised six different locations (Figure 3.2), with the annual carloads and car-miles on each link in the network. The route mileage between these locations was determined using the rail routing software PC*MILER\Rail 13. I used the Princeton Transportation Network Model (PTNM) to develop maps of the traffic volume and directional flow; however, some other railroad network models can also be used for this purpose (Munshi & Sullivan, 1989). After the route mileage is determined, the car-miles are calculated for each O-D flow by multiplying the number of carloads by the mileage. In Figure 3.2 and subsequent flow diagrams, the numbers in *italic* represent carloads and the others represent car-miles.

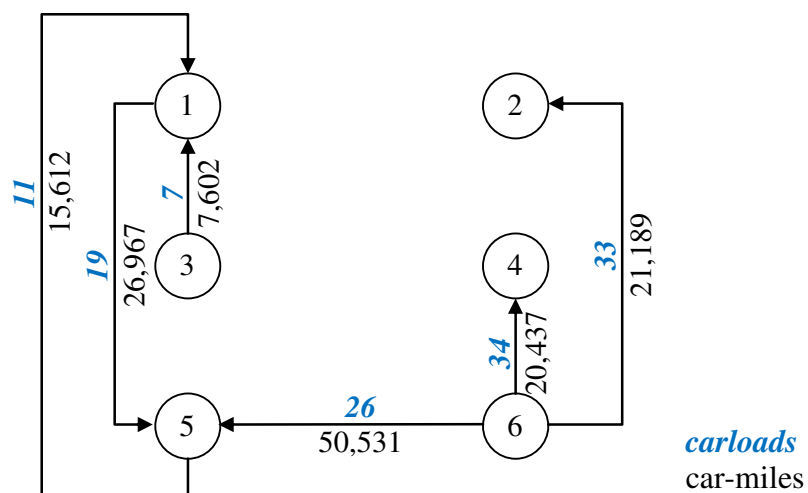


Figure 3.2: Schematic Diagram of Baseline Network Flow for the Case Study

3.4 Model Formulation

To rationalize this traffic flow pattern, I first assume that population exposure, derailment frequency, and other factors potentially affecting risk are homogenous across the entire route structure. Under these simplifying assumptions, risk will be proportional to the length of the route and the number of cars shipped. In this case, the problem reduces to the basic transportation problem in which the objective function is minimization of car-miles. This is synonymous with minimizing risk, while holding shipment volume at each origin and destination constant.

Accordingly, I formulate the model to determine the alternative traffic flow. The objective function is initially set up to minimize total car-miles of hazardous material shipments, with the constraint that incoming and outgoing traffic is held constant for each origin and destination. The constraint can be treated as demand and supply requirements at each location. The problem for minimizing total car-miles is formulated as follows:

$$\text{Minimize total car-miles} = \sum_{od} m_{od} L_{od} \quad (3.1)$$

subject to:

$$\sum_o m_{od} = M_d, \quad \forall d \quad (3.2)$$

$$\sum_d m_{od} = M_o, \quad \forall o \quad (3.3)$$

and

$$m_{od} : \text{non-negative integer}, \quad \forall o, \forall d \quad (3.4)$$

where:

m_{od} = shipments (carloads) between origin o and destination d

L_{od} = mileage from origin o to destination d

M_d = total shipments (carloads) to destination d

M_o = total shipments (carloads) from origin o

The above model is an integer programming (IP) since m is always an integer but the model can be solved using a linear programming (LP). The optimal network flow in which the total car-miles are minimized (Figure 3.3) can be found by solving the above problem. Using the General Algebraic Modeling System (GAMS, 2007), the optimal solution yields 96,121 car-miles, which is 32.5 percent less than the original total of 142,339 car-miles.

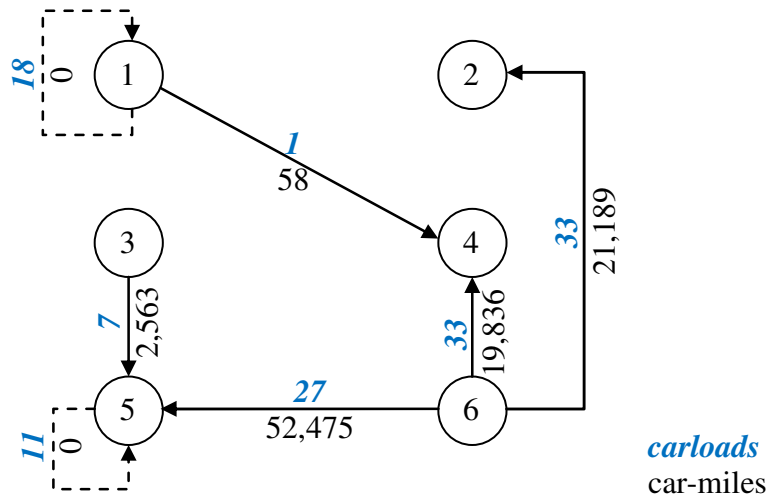


Figure 3.3: Schematic Diagram of the Minimized Car-miles Network Flow

In reality, the assumptions made under this section are too simplistic because there is considerable heterogeneity in various important factors affecting risk along the routes where hazardous materials are shipped, notably accident rates and population exposure. Furthermore, different decisions and policies may require differing consideration of various factors. Accordingly, the model must be capable of accounting for these if it is to provide useful results. Later, I will modify the transportation problem above to incorporate risk analysis parameters into the optimization model.

3.5 Risk Modeling and Quantitative Risk Assessment

3.5.1 Risk Model Formulation

The results presented in the previous section show the effect of route rationalization on reducing car-miles. However, this does not guarantee risk reduction. The alternative network flow in which car-miles are minimized may or may not have lower risk compared to the baseline traffic flow. In other words, the route that minimizes car-miles does not always have risk minimized because the alternate, shorter routes may have a higher population density or accident rate. Therefore, a more sophisticated risk analysis needs to be conducted to determine other possible alternatives to minimize risk.

In this section, I discuss the formulation of a model for estimation of the risk associated with rail shipments of hazardous materials. The risk analysis is performed using a quantitative risk

assessment (QRA) model to develop numerical estimates of the risk (CCPS, 1995). To begin with risk model formulation, I consider the traditional definition of risk. NTSB (1971) describes risk as the function of probability of system failure and the severity of losses from the system failure, i.e.

$$\text{Risk} = f(P_f, C_f) \tag{3.5}$$

where:

- P_f = the probability of system failure
- C_f = the severity of the losses from the system failure

In the context of railroad hazardous materials transportation, risk is the product of the frequency of a release incident and the consequence of that incident (CCPS, 1995).

$$S = F \times C \tag{3.6}$$

where:

- F = the frequency of release incident
- C = the consequence of the release

More specifically, the frequency is the product of the accident rate and a series of incident probabilities, i.e.

$$F = Z \times V \times L \times K \times W \tag{3.7}$$

where:

- Z = accident rate (cars derailed per car-mile)
- V = annual shipments (carloads)
- L = mileage or segment length (mile)
- K = conditional probability of a specific scenario given release in accident
- W = conditional probability of release given accident

The consequence, C , is the impact of release. There are several models available for estimation of the consequence of hazardous material releases. One is to use the U.S. Department of Transportation (DOT) Emergency Response Guidebook (ERG) hazard exposure model (PHMSA, 2008; Brown et al., 2009) to estimate the consequence of a release. The ERG recommended initial isolation and/or protective action (downwind) distances that can be used to estimate the area where people need to be evacuated or sheltered in place in the event of a hazardous material release corresponding to the material and scenario of release considered, thus,

$$C = D \times A \tag{3.8}$$

where:

D = population density (persons per square mile)

A = affected area per the U.S. DOT ERG recommendation (square mile)

The risk metric corresponding to Eq. (3.7) and (3.8) is the number of persons potentially subject to evacuation or sheltering in place as a result of hazardous material release. The risk model can be written as:

$$S = Z \times V \times L \times K \times W \times D \times A \quad (3.9)$$

where:

S = annual risk (persons affected per year)

The risk analysis framework can be summarized as shown in the diagram in Figure 3.4. This diagram provides an overview of the principal input factors and the relationships of factors that influence hazardous materials transportation risk in general.

In Figure 3.4, the shaded ellipses represent the major factors affecting hazardous materials transportation decision: the route to be chosen, the type of cars to be used, the product to be transported, and the amount of product to be shipped. These can be considered as independent variables. Population distribution, property, and environment along the shipment route, mileage, track infrastructure conditions, and operating conditions on the track, such as speed limit, represent characteristics of the routes. Operating conditions are sometimes limited by track infrastructure conditions; for example, lower quality of track may require trains to operate at lower speed. Consequently, speed affects the likelihood of a release if a derailment occurs. Tank car safety design affects both the conditional probability of release (CPR) and the probability distribution of release sizes. Different products have differing degrees of hazard and may require different types of tank cars with different performance in accident. The quantity of release affects the hazard exposure. Multiplication of the frequency of accident and the conditional probability of release gives the frequency of release incident. The possible damage to people, property and environment, and the area exposed to damage is the measure for the consequence of the release. Finally, risk is estimated from the multiplication of the frequency of release incident and the consequence of the incident.

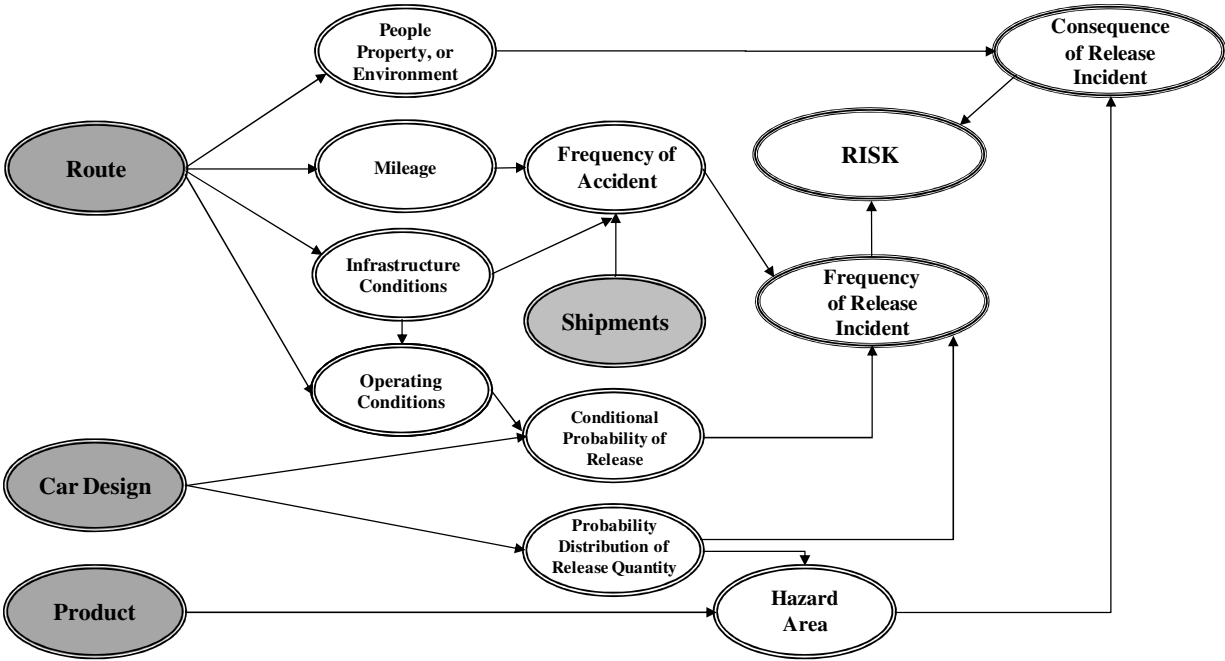


Figure 3.4: Factors and Relationships Influencing Hazardous Materials Transportation Risk

Figure 3.5 shows a diagram of the possible events and the outcomes. This illustrates the basic framework of rail hazardous materials transportation risk analysis.

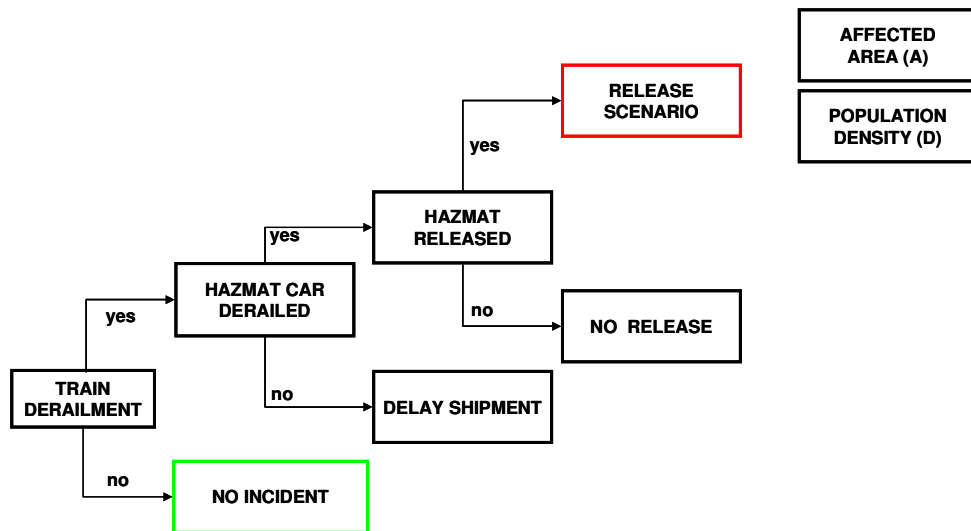


Figure 3.5: Events and Consequences Associated with Railroad Hazardous Materials Transportation Risk

3.5.2 Estimation of Risk Parameters

3.5.2.1 Route Segmentation

In QRA of railroad hazardous materials transportation, different levels of analysis can be performed depending on the degree of precision required for the problem under consideration. For example, accident rate and population density may be accounted for at the route level or track segment level. In this study I consider track-segment-specific parameters in the risk analysis model formulation. Rail routing software and Geographic Information System (GIS) application are used to facilitate segment-specific risk analysis.

First, based on the O-D pairs considered, I use PC*MILER|Rail 13 to determine the intermediate location points along the shipment routes. Then, using ESRI ArcMap 9.2, the route map layer was created for both the baseline and alternate route patterns using the U.S. DOT national railroad network data (BTS, 2007). The route created is divided into segments, indicated by link ID in the network (Figure 3.6). The length of track segments can be directly obtained from the GIS data.

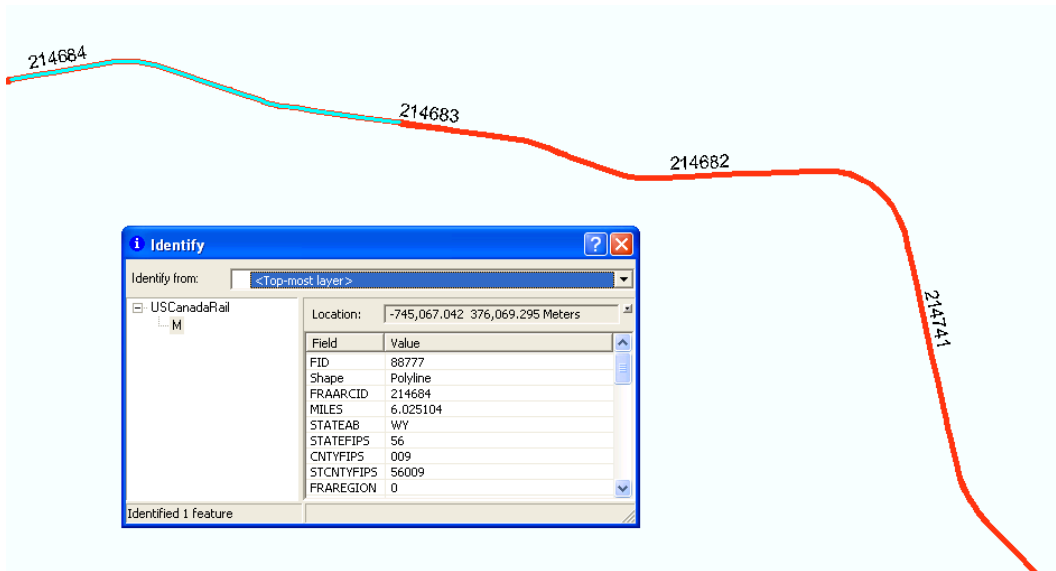


Figure 3.6: Example of Rail Segmentation Using GIS Application

3.5.2.2 Track Class-specific Accident Rates

For the purpose of illustrating the effect of differential accident rates in the model, I developed a proxy variable to estimate FRA track class based on the type of traffic control system listed in the U.S. DOT GIS database. The traffic control system is roughly correlated with allowable train speed and is available in digital a database from the U.S. rail network (BTS, 2007). Train speed reflects FRA track class (Table 3.1), which has been shown to be correlated with railroad accident rates (Nayak et al., 1983). Nevertheless, if data on the actual FRA track classes or other more direct metrics of train accident rates are available for a particular set of routes, these could easily be substituted in the analysis.

Table 3.1. FRA track class and maximum allowable operating speed for freight trains.

Track Class	Maximum Speed (mph)
Excepted track	10
Class 1 track	10
Class 2 track	25
Class 3 track	40
Class 4 track	60
Class 5 track	80

Source: § 213.9 (FRA, 2003)

The accident rates can be determined from previous statistics for individual track segments or other segments determined to have similar characteristics. Here I determine track segment-specific accident rates based on the inferred FRA track classes and the corresponding track class-specific accident rates developed by Anderson and Barkan (2004). These accident rates are provided in several metrics (Table 3.2). In this study, I use the number of cars derailed per billion freight car-miles. I assume that the likelihood of a hazardous material tank car derailling in an accident is independent of the type of material being transported (Anand, 2006).

Table 3.2. Accident rates by FRA track class for class-1 mainline freight train.

FRA Track Class	1	2	3	4	5 & 6
Derailments per million freight train miles	48.54	6.06	2.04	0.53	0.32
Derailments per billion freight car miles	720.1	92.7	31.5	7.8	4.9
Cars derailed per billion freight car miles	3,979	726	300	77	42

Source: Anderson & Barkan (2004)

3.5.2.3 Conditional Probability of Release

According to Treichel et al. (2006), the principal elements affecting tank car safety performance are tank head, tank shell, top fittings, and bottom fittings (Figure 3.7).

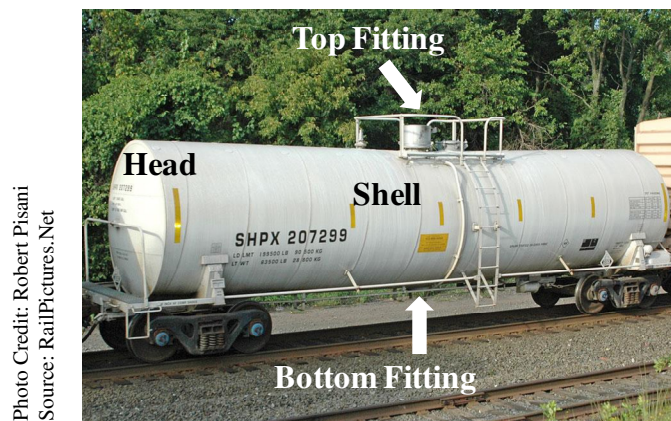


Figure 3.7: Principal Sources of Release from a Tank Car Carrying Hazardous Material

For this particular study, I assumed that only one type of tank car is used to transport the material, a DOT 105J300W pressure car with steel jacket, insulation, full-height head shields, and a tank thickness of 0.6875 inches. However, if several types of cars are used, but the effect of the different design characteristics and the distribution of release sizes are not of interest, the aggregated conditional probability can be computed using the weighted mean of the different car types' conditional probabilities (Kawprasert and Barkan, 2008). I also assumed that there will be no release if there is no derailment.

The conditional probability of release (CPR) of the tank car considered, given that it is derailed in a FRA-reportable mainline accident, can be estimated using the data developed by Treichel et al. (2006), which take into account the design characteristics of the tank car. Accordingly, the tank car CPR is estimated to be 0.0691. At this stage, I assume a single value of CPR applies to all train speeds as has been normal practice in most hazardous materials transportation risk analyses.

3.5.2.4 Probability Distribution of Specific Scenario of Releases

The level of consequence depends on the quantity released to the environment, which may vary with the severity of the accident and the atmospheric conditions. To account for possible degrees of consequence with respect to different scenarios of release, such as spill size (small or large), fire involvement (with or without fire), and time of day (daytime or nighttime), the conditional probability of a specific scenario of release is incorporated in the risk model in Eq. (3.9).

For the material analyzed, I considered four different release scenarios: small and large daytime spills, and small and large nighttime spills. I defined large spills as those in which more than five percent of the tank car's contents are lost (Saat and Barkan, 2006). The proportions of spill sizes were obtained from the distribution of quantity of lading loss for pressure cars in mainline accidents by Treichel et al. (2006). These are 0.2213 and 0.7787 for small and large spills, respectively. In this analysis, I assumed that shipments travel in daytime or nighttime with equal likelihood. Therefore, the proportions of daytime and nighttime release scenarios are 50 percent each for day and night, or 0.1106 each for daytime/nighttime small spills and 0.3894 each for daytime/nighttime large spills.

3.5.2.5 Consequence Estimation

To determine the affected area where people need to be evacuated or sheltered in place for a specific scenario of release, I consulted the 2008 U.S. DOT ERG. The guidelines provided in the ERG are developed and periodically updated by the U.S. DOT. The ERG recommends initial isolation and protective action (downwind) distances for specific chemicals and scenarios of release for emergency response personnel to consider in the event of hazardous material release (Figure 3.8 and Table 3.3). These distances are determined using a statistical model that incorporates sophisticated emission rate and dispersion models, historical release incident data, meteorological observations in North America, and current toxicological exposure guidelines (PHMSA, 2008; Brown et al., 2009).

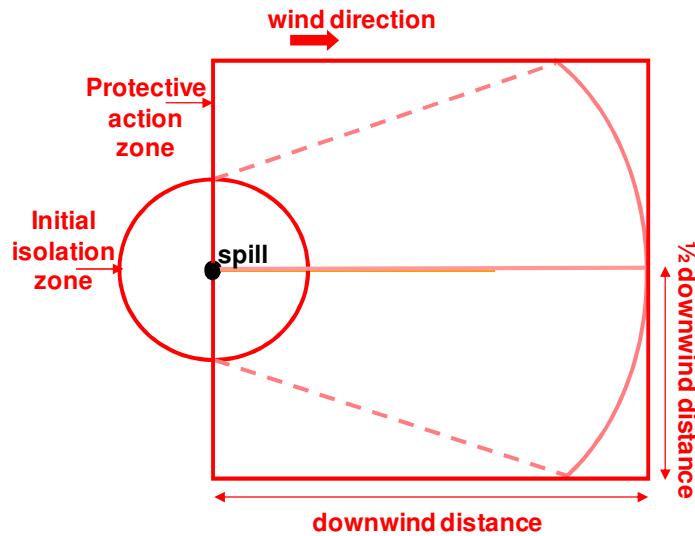


Figure 3.8: The U.S. DOT ERG Hazard Exposure Model

The ERG is widely used by the emergency response community, so it should be reasonably correlated with the events likely to occur in an actual hazardous materials spill. Furthermore, the costs in spill accidents are driven to some degree by the extent of the evacuation, so use of the ERG-affected area as a metric for consequences provides some insight regarding relative expense. The ERG guidelines do not reflect injuries or fatalities due to a release. Instead, they enable a relative comparison in terms of the number of people who might be affected by a release. The ERG guidelines are generally considered conservative and probably lead to overestimation of the number of people who will actually be affected. This is more likely to affect absolute estimates of risk than the relative estimates that are important in the analyses considered, so it represents a satisfactory metric for use in this analysis.

The affected areas for different atmospheric conditions and release sizes for the material analyzed are then calculated using the ERG distances in Table 3.3 and Figure 3.8. The affected area equals half of the area of the circle represented by the initial isolation zone plus the area of the square represented by the protective action zone. For example, for daytime/nighttime small spills, the affected area is $0.5\pi(0.0093)^2+(0.1)^2 = 0.0101 \text{ mi}^2$. The affected areas for other release scenarios are provided in Table 3.4.

Table 3.3. The U.S. DOT ERG recommended distances for the chemical considered.

Time of Day	Spill Size			
	Small		Large	
	Initial Isolation Distance (meters)	Protective Action Distance (miles)	Initial Isolation Distance (meters)	Protective Action Distance (miles)
Daytime	30	0.1	60	0.3
Nighttime	30	0.1	60	0.5

Table 3.4. The affected areas for the release scenarios and the chemical considered.

Time of Day	Spill Size	
	Small	Large
Daytime	0.0101 mi ²	0.0905 mi ²
Nighttime	0.0101 mi ²	0.2505 mi ²

In the next step, I performed an overlay analysis of the affected area and the population density using the GIS software to obtain the consequences of a release. A spatial buffer was created over route segments to represent the exposure area, which is defined as the area within the radius from track center that is equal to the U.S. DOT ERG maximum evacuation distance for the worst-case release scenario (d_{max}) of the hazardous material considered. From Table 3.3, the d_{max} is 0.5 miles, therefore, a buffer having a radius of 0.5 miles from track center was created in GIS accordingly (Figure 3.9). This represents the exposure area along the shipment route, where people might be subjected to evacuation or sheltering in place due to hazardous material release.

Finally, the buffer was then overlaid on the census tract data layer obtained from ESRI Data & Maps DVD-ROM (ESRI, 2005). The track-segment-specific population density is determined by taking the weighted average of all different population densities of the census tracts that are coincident with the affected area corresponding to each track segment. In this study, I did not quantitatively consider the effect of time-of-day-dependent population density, but this can be factored into the model if the particular risk question warrants it, and the data are available.

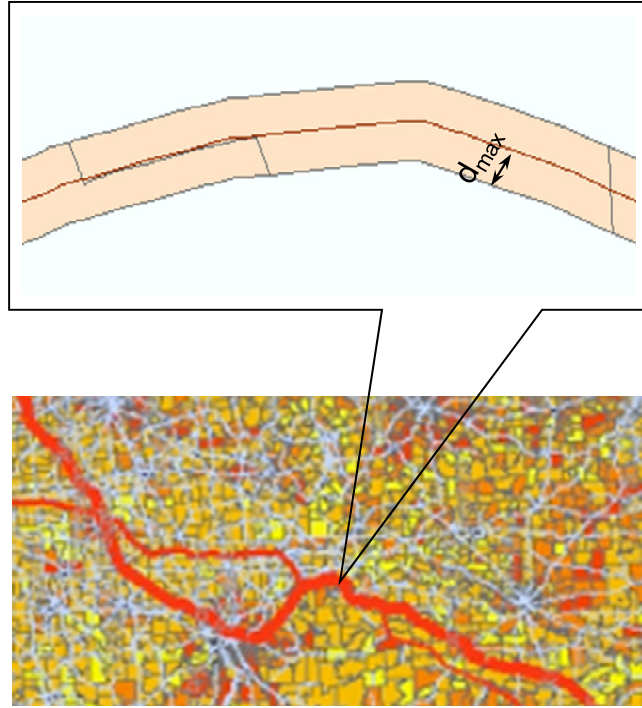


Figure 3.9: Shipment Route and Spatial Buffer Creation Using GIS

3.6 Route Rationalization Model

In this section, the parameters affecting risk described in the previous section are incorporated into the objective function of the model in Eq. (3.1), so that minimization of the risk metric is the objective function. Accordingly, the route rationalization model can be formulated as follows:

$$\text{Minimize total annual risk } S = \sum_i \sum_o \sum_d \sum_k \sum_t \sum_r Z_{iod}^r V_{od}^t L_{iod}^r K_k^t W^t D_{iod}^r A_k^t \quad (3.10)$$

Subject to:

$$\sum_r \sum_o V_{od}^t = M_d^t, \quad \forall d, \forall t \quad (3.11)$$

$$\sum_r \sum_d V_{od}^t = M_o^t, \quad \forall o, \forall t \quad (3.12)$$

and

$$V_{od}^t : \text{non-negative integer}, \quad \forall o, \forall d, \forall t \quad (3.13)$$

where:

- S = total annual risk associated with the shipments on the particular network considered
- Z_{iod}^r = the tank car derailment rate for track segment i on route r from origin o to destination d
- V_{od}^{rt} = shipments (carloads) of a hazardous material type t on route r from origin o to destination d
- L_{iod}^r = the length of track segment i of the route r from origin o to destination d
- K_k^t = the conditional probability that a specific scenario k will occur given that there is a hazardous material type t release from a derailed tank car
- W^t = the conditional probability of release given that a tank car carrying hazardous material type t is derailed in an accident
- D_{iod}^r = average population density in an affected area corresponding to track segment i of the route r from origin o to destination d
- A_k^t = affected area where people need to be evacuated or sheltered in place for a specific scenario of release k of hazardous material type t
- M_d^t = total shipments (carloads) of hazardous material type t to destination d
- M_o^t = total shipments (carloads) of hazardous material type t from origin o

The objective function of the route rationalization model integrates three major elements in risk analysis: the frequency of derailment, the frequency of release, and the consequence of release. All parameters in the objective function can be pre-determined, except the number of shipments for each O-D pair. Thus, the model can be solved using the linear programming.

The route rationalization model can be modified depending on the particular purpose of the analysis. For example, if only release rate is of interest, the consequence term in the risk equation may be omitted. If risk control is required for any particular O-D pair, the maximum risk level can be specified as a constraint in the model, so that the risk for that particular route will not exceed the prescribed level. Furthermore, this approach can be used to determine

whether risk reduction options that affect the frequency of a derailment (Zhao et al., 2007; Schafer and Barkan, 2008), the frequency of release (Barkan, 2007; Barkan et al., 2007), or the consequence of release would alter the optimal route structure. Therefore, the route rationalization model provides flexibility in the decision criteria that could be used to inform policy and planning questions and objectives.

3.7 Alternate Flow Structures

I use the route rationalization model to determine the set of optimal traffic flows for the case study, using minimization of three different objective functions: car-miles, release rate, and annual risk (Tables 3.5). The optimal flows for minimization of release rate and risk are shown in Figures 3.10a and 3.10b, respectively.

Table 3.5. Comparison of the effect of different objective functions on the different annual risk metrics considered.

Metrics	Baseline Traffic Flow	Objective Function Minimized		
		Car-miles	Release Rate	Annual Risk
Total Car-miles	142,339	96,121 (32.5%)	96,722 (32.0%)	96,140 (32.5%)
Derailment Rate	0.01765	0.01289 (26.7%)	0.01280 (27.3%)	0.01288 (26.7%)
Release Rate	0.00122	0.00089 (27.0%)	0.00088 (27.5%)	0.00089 (27.1%)
Annual Risk	0.12877	0.10581 (17.8%)	0.10814 (16.3%)	0.10558 (17.8%)

(Numbers in parentheses indicate percentage reduction from baseline.)

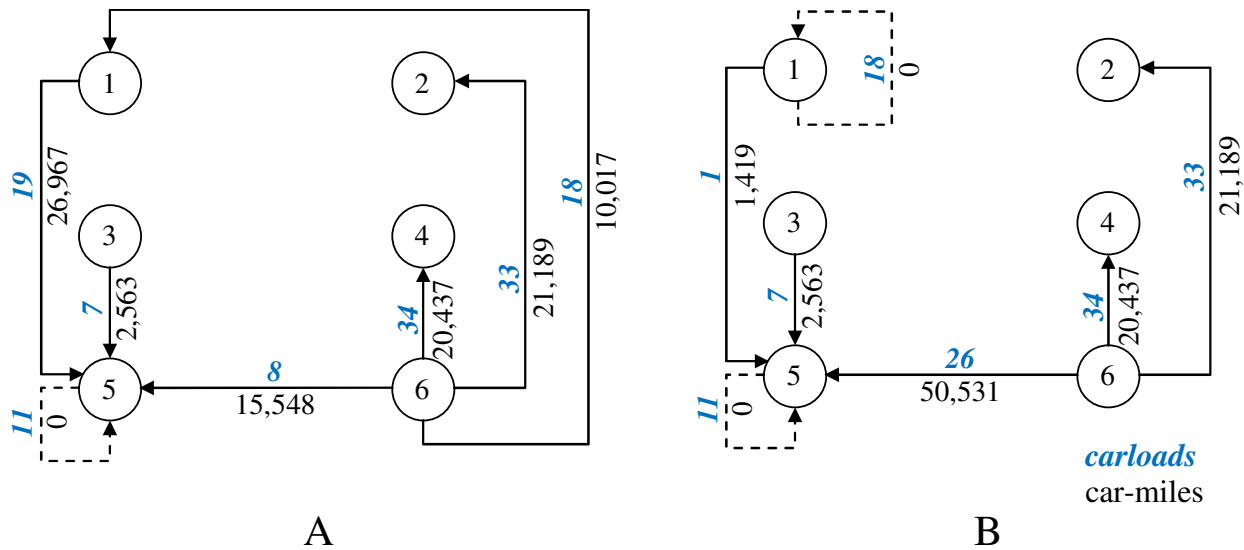


Figure 3.10: Schematic Diagram of Traffic Flow When (A) Release Rate is Minimized and (B) Risk is Minimized

Minimizing the release rate reduced car-miles by 32.0% and risk by 16.3%, whereas the minimization of risk reduced car-miles by 32.5% and risk by 17.8%. In this study, a single car design was assumed, so that the flow with the derailment rate minimized is the same as the flow with the release rate minimized. If a mix of cars with different CPRs were used on different routes, then these two flows would not be equivalent. For the particular hazardous material studied, the traffic flow patterns for the rationalized route structure, which are based on the minimization of the three objective functions, differ in some of the details. However, the values of the metric associated with each of the optimal flows did not differ by much.

3.8 Comparison of Results Using Risk Profiles

In addition to the expected risk estimates, an understanding of the distribution of risk outcomes is often useful for risk management decisions. This is particularly true regarding routing questions because routing is one of the few risk reduction strategies with the potential to affect the consequence level of a release as well as the frequency. The risk profiles (also known as "F-N curves") provide information on the frequency distribution of risk outcomes and enable a better understanding of the changes in the frequency of incidents of various magnitudes as a result of changes in the factors affecting risk, such as population exposure. Risk profiles were first

developed by listing all pairwise combinations of the frequency of a specific scenario of release and the consequence, and then sorting by the latter in a descending order and plotting the cumulative frequency against the consequence.

The use of risk profiles allows for the comparison of the distribution of frequency of release incidents corresponding to the magnitude of consequence for the baseline traffic flow to the rationalized traffic flows, based on the three different objective functions (Figure 3.11).

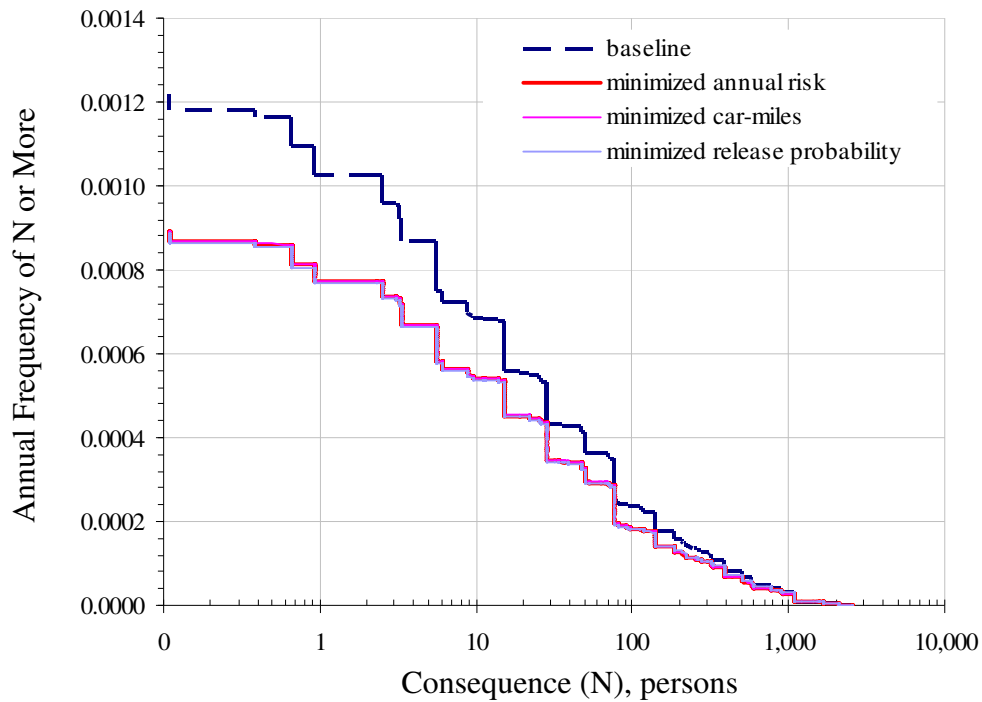


Figure 3.11: Risk Profiles for the Baseline Case Compared to the Rationalized Route Structures Optimized Using Three Different Objective Functions

As was the case with the expected risk estimates, the risk profiles for the different objective functions do not differ much from one another, but all are lower than the baseline case. This difference is true across nearly the entire range of N, but the extent of the difference declines as N increases. The differential risk profile (Figure 3.12) suggests that rationalizing the route structure for this particular hazardous material has a greater effect on reducing traffic in less populated areas of the route structure relative to the more highly populated portions. At the very highest values of N, there is no difference between the baseline and rationalized route structures, indicating that for this hazardous material, exposure to the most densely populated segments is not eliminated by route rationalization. Nevertheless, there is an overall reduction in

risk. The degree of difference resulting from the use of various objective functions may depend on the characteristics of the route structure of the material.

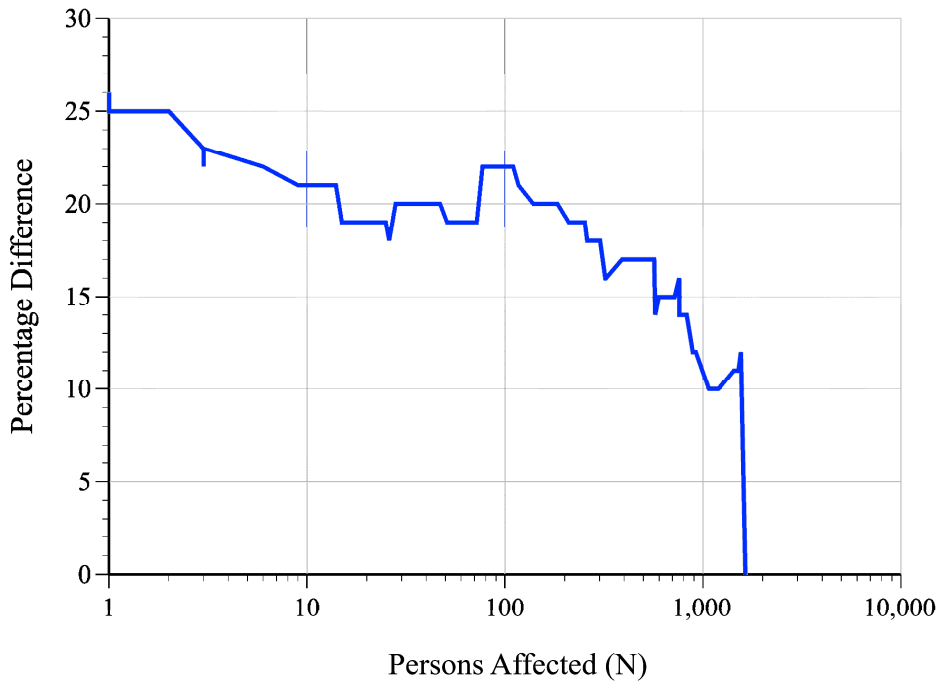


Figure 3.12: Percentage Reduction in the Frequency of N or More Persons Affected in the Rationalized Route Structure in which Risk is Minimized Compared to the Baseline Case

3.9 Discussion

The application of the route rationalization model allows several elements to be integrated and simultaneously considered. In the case study, the average reduction in risk ranged from approximately 16% to 18%, depending on which objective function was being minimized, whereas the mileage reduction was about 32%. It is interesting that the risk reduction percentage was less than the mileage reduction. This is consistent with the result that the rationalized route structure for this particular hazardous material tended to disproportionately reduce exposure to lower population density segments, compared to the baseline route structure. This is probably due to the particular nature of the route structure of the material analyzed in the case study. In general, the opportunities for risk reduction will vary depending on the route structure of the particular hazardous material being considered. More studies need to be carried out in order to understand the generality of the results presented here, the degree of variability for different product-specific route structures, and the principal factors affecting the optimal route structure.

The route rationalization problem presented in this chapter is based on a simplified distributional restriction. It works as if there is only one single railroad carrier who operates the network and is willing to change traffic patterns accordingly. However, the objective of this simplification is to provide an idea on how much risk of transporting a particular product could be reduced by rationalizing the entire shipment structure, which represents an ideal case. In practice, such change may involve several railroad operators that may not be willing to cooperate. Customers may not have control over the route to be chosen between O-D pairs. If information is available, additional constraints may be imposed by setting the distance of an infeasible route to a large value or by setting the variable to zero.

Several businesses may be involved, each working with a particular supplier, so that the rail carriers do not have the authority to change the sources of material for a given destination based on the minimum risk objective. The route rationalization problem illustrates the shipment of one particular product. However, the model is structured to accommodate shipments of multiple commodities. The model neglects flow capacity and delivery time constraints. The case study assumes that the tank cars coming back empty to the origin at the end of the planning horizon. These simplifications may be modified in future improvements of the model framework to enhance its applicability for actual transportation problems.

3.10 Conclusions

In this chapter, I describe a mathematical model for the evaluation of route rationalization as a means of reducing the risk from rail transportation of hazardous materials. The purpose is to introduce and illustrate the concept and explore the potential benefits that may be possible. I consider a simple case study based on the route structure of a TIH transported in railroad tank cars. The results indicate that for the product evaluated, route rationalization can reduce mileage, accident rate, release rate, population exposure, and risk. In general, the extent of risk reduction possible will depend on the characteristics of the traffic pattern and other constraints of the particular optimization problem. For purposes of illustration and brevity, I relaxed some constraints in this study, neglecting the possibility of schedule conflicts or track unavailability, and did not account for possible temporal variation in production capacity or demand. However, the model was structured so that it can be adapted to incorporate these and other factors, thereby enhancing its general applicability.

CHAPTER 4

EFFECTS OF TRAIN SPEED ON HAZARDOUS MATERIALS TRANSPORTATION ROUTE RISK ANALYSIS

Adapted from Kawprasert, A., and C.P.L. Barkan. Effect of Train Speed on Railroad Hazardous Materials Transportation Route Risk Analysis. In *Transportation Research Record: Journal of the Transportation Research Board*, No. 2159, TRB, National Research Council, Washington, D.C. 2010a, pp. 59–68.

4.1 Introduction

Train operating speed is one of the factors affecting the likelihood of a release in railroad accidents involving tank cars transporting hazardous materials. The higher the speed of a derailment, the more cars are likely to derail, and of these the higher the probability that one or more will suffer a release (Barkan et al., 2003). Nevertheless, previous studies have generally simplified this aspect of railroad hazardous materials transportation risk analysis by using a single value for the conditional probability of release (CPR) that does not account for variation in train speed (Saat and Barkan, 2006; Glickman et al., 2007; Kawprasert and Barkan, 2008; Verma, 2009). Use of a single value of CPR, independent of train speed, simplifies risk analysis but also implies an average speed of derailment (Kawprasert and Barkan, 2009a). Since this average CPR speed may be higher than the actual operating speed in some situations and lower in others, using it will have the effect of overestimating release probabilities in lower speed sections and underestimating release probabilities in higher speed sections of the route.

The relationship between speed and CPR has previously been considered (Nayak et al., 1983; CCPS, 1995; Treichel et al., 2006). The most recent study by Treichel et al. provides estimates for both average-speed and speed-dependent CPR of the tank cars, but only the average-speed CPR accounts for specific safety design features. Earlier works were not specific to tank cars (Nayak et al., 1983) or did not enable the application of speed-dependent effects to specific tank car designs (CCPS, 1995). In this study, I explicitly consider the effects of train speed on hazardous materials transportation risk analysis and develop a technique that enables estimation of speed-dependent CPR for specific tank car designs using published data on safety performance of tank cars in accidents (Treichel et al., 2006), which permits one to apply adjustment factors derived from a group of car types to a specific car type.

Use of tank car design enhancements as options to reduce risk has become more prevalent over the past decade, and the model introduced here provides flexibility that enables the effect of these enhancements to be considered using the most up-to-date published data available. Furthermore, the effect of tank car safety design can be integrated with other options.

In the first part of this chapter, I specifically consider the interaction of infrastructure quality, train speed, and tank car performance to understand the effect on risk estimates using speed-dependent CPR. A case study is presented using a representative hazardous material transportation route. The results of a risk analysis in which average-speed CPR is used are compared to one using speed-dependent CPR.

In the second part of this chapter, I highlight the importance of using CPR adjusted for speed by further considering its utility as part of an assessment of the effect of track-class upgrade on risk. Upgrading track has been shown to be correlated with the reduction of certain types of accidents and consequently with risk (Nayak et al., 1983). However, if the upgrade is also intended to allow increased operating speeds, it may increase the probability of release if an accident does occur (Barkan et al., 2003; Treichel et al., 2006). CPR and accident rate are the two principal elements in hazardous materials transportation risk analysis. Considering each as a function of speed enables more accurate estimation of route-specific risk. This also facilitates proper consideration of the benefit of infrastructure improvement. Two scenarios were analyzed: track upgrade without a speed increase and upgrade with a speed increase. The degree of risk reduction varies with these options, and consideration is given to which option offers the greatest safety benefit for the problem analyzed.

4.2 Review of Risk Analysis Methods

Hazardous materials transportation risk can be quantitatively expressed as the frequency of a release incident multiplied by the consequence of that release. In this study, frequency is a product of the annual per-car-mile rate of tank car involvement in an FRA-reportable derailment on mainline track, the number of shipments, the total mileage from origin to destination, and the conditional probability of release given that a tank car derails. The consequence of a release incident is the impact of the released material and is affected by product characteristics, quantity and rate of spillage, atmospheric conditions, and the population density along the route analyzed.

The consequence can be expressed using several metrics. In this study, I used the number of persons who might potentially be affected due to a hazardous material release from a tank car in accordance with the product-specific recommendations in the U.S. Department of Transportation (DOT) Emergency Response Guidebook (ERG) (PHMSA, 2008; Brown et al., 2009). The consequence can be estimated by multiplying the affected area, using the ERG recommended evacuation distances, by the population density within the affected area.

The risk metric calculated using the method previously described is the annual expected number of persons who might be evacuated or sheltered in place due to a hazardous materials release. Specifically, risk is calculated from the product of accident rate, traffic volume (measured in car-miles), tank car CPR, the probability distribution of release sizes, the affected area corresponding to the release size, and the population density in the affected area, summed over all segments on the route. The risk model in Eq. (4.1) incorporates these segment-specific parameters and gives the estimate of risk associated with shipments of hazardous materials on the route.

$$S = \sum_{i=1}^n \sum_{j=1}^k Z_i V_i L_i R_i P_j A_j D_i \quad (4.1)$$

- where
- S = annual risk (persons affected per year)
 - Z_i = rate of tank car involvement in an FRA-reportable derailment (cars derailed per car-mile)
 - V_i = annual shipments (carloads per year)
 - L_i = length of track segment (mile)
 - R_i = conditional probability of release given that a tank car derails
 - P_j = conditional probability of a specific scenario j given that there is a hazardous material release from a derailed tank car
 - A_j = affected area corresponding to a specific release scenario per the U.S. DOT ERG recommendation (square mile)
 - D_i = average population density along track segment (persons per square mile)
 - i = track specific segment
 - n = total number of segments along the route considered
 - j = specific release scenario (e.g. spill size, fire involvement, time of day)
 - k = total number of scenarios considered

4.3 Case Study

I consider a typical, representative route as part of the distribution network of a particular hazardous material on the North American rail network. The distance from origin to destination is 1,400 miles and is comprised of 598 segments with an average segment length of 2.34 miles. These track segments correspond to links in the FRA rail transportation network obtained from the Bureau of Transportation Statistics (BTS, 2007). I assumed 100 annual carloads over the entire route, using a non-insulated, DOT-111A100W1 tank car with 7/16 inch tank thickness and no special safety design features beyond the DOT minimum requirements.

For some materials, the consideration of multiple release scenarios may be appropriate. However, based on the expert opinion of the manufacturer of the product and the objectives of this study, use of a single release scenario was satisfactory. Thus, the major factors affecting risk in this analysis are product characteristics, track-class-specific accident rate, shipment volume, tank car safety design, operating speed, and population exposure along the route.

The case study is used to analyze the effects of train speed on the route risk estimate and the contribution of various other factors to the risk, including population density and FRA track class. In addition, the case study is used to illustrate the merit of using speed-dependent CPR in an assessment of the effect of track infrastructure upgrade on risk reduction. These will be discussed in more detail in the subsequent sections.

4.4 Estimation of Parameters Affecting Risk

FRA track-class-specific accident rates were used in this study (Anderson and Barkan, 2004). Track speed reflects FRA track class, which has been shown to be correlated with railroad accident rates (Nayak et al., 1983). I used railroad timetable speeds to infer the FRA track class and other local operating restrictions for all segments along the route. The next step is to estimate CPR given that a tank car is derailed in an accident. The relationships developed by Treichel et al. (2006) were used to determine the CPR of the particular design of tank car considered in this study. Since CPR is also affected by train accident speed (Nayak et al., 1983; CCPS, 1995; Barkan et al., 2003; Treichel et al., 2006), I adjusted it according to the timetable speed for each track segment. The speed-dependent CPR was calculated using the procedure described in the following section.

To estimate the consequences of a release, I used Geographic Information System (GIS) software, ArcGIS Desktop 9.2, to create the shipment route using the U.S. DOT national rail network (BTS, 2007). An overlay analysis of the population distribution along the rail network was conducted using census tract data from the ESRI Data & Maps, Electronic Database (ESRI, 2005). A buffer representing the exposure area was created. This was the area within the radius from track center equal to the U.S. DOT ERG maximum evacuation distance for the material considered. Then, the average population density of the affected area corresponding to each track segment was determined.

The procedure used to estimate and measure risk is similar to that described in the previous chapter, but this chapter focuses on refining the method to understand the effect of speed-dependent CPR.

4.5 Speed-dependent Conditional Probability of Release

Treichel et al. (2006) described lading loss probability based on the four major cause-specific loss events as:

$$P = P(E_h \cup E_s \cup E_t \cup E_b) \quad (4.2)$$

- where P = the probability of an event that a tank car releases its contents given that it derailed in an accident
- E_h = an event that contents lost is attributed to head damage
- E_s = an event that contents lost is attributed to shell damage
- E_t = an event that contents lost is attributed to top fitting damage
- E_b = an event that contents lost is attributed to bottom fitting damage

The cause-specific loss events have very low correlations (Treichel et al., 2006), so it is assumed that E_h , E_s , E_t , and E_b are independent. Therefore:

$$\begin{aligned} P &= 1 - P^c \\ &= 1 - P(E_h^c \cap E_s^c \cap E_t^c \cap E_b^c) \\ &= 1 - P(E_h^c)P(E_s^c)P(E_t^c)P(E_b^c) \\ &= 1 - [1 - P(E_h)][1 - P(E_s)][1 - P(E_t)][1 - P(E_b)] \end{aligned} \quad (4.3)$$

- where c = the complement of an event

Let R equal the conditional probability of release given that a tank car derails in an accident, and let R_h , R_s , R_t , R_b equal the CPR attributed to head, shell, top fitting, and bottom fitting, respectively, with all variables unadjusted for speed, so that:

$$R = 1 - (1-R_h)(1-R_s)(1-R_t)(1-R_b) \quad (4.4)$$

where R = tank car CPR, unadjusted
 R_h = CPR from head, unadjusted
 R_s = CPR from shell, unadjusted
 R_t = CPR from top fittings, unadjusted
 R_b = CPR from bottom fittings, unadjusted

Speed-dependent CPR was calculated by multiplying the unadjusted CPR by the speed-adjustment factors. This adjustment can be made to the CPR associated with each specific source of release, i.e.,

$$R' = 1 - (1-R_h J_h)(1-R_s J_s)(1-R_t J_t)(1-R_b J_b) \quad (4.5)$$

where R' = tank car CPR, adjusted for speed
 J_h = speed-adjustment factor for CPR from head
 J_s = speed-adjustment factor for CPR from shell
 J_t = speed-adjustment factor for CPR from top fittings
 J_b = speed-adjustment factor for CPR from bottom fittings

To determine the speed-adjustment factors in Eq. (4.5), I first developed the relationships between train speed and CPR for each release source, using the proportion of tank cars losing lading from each source. I used statistical software, SAS 9.1, to fit a simple linear regression equation with zero intercept to the published data on tank car safety performance (Treichel et al., 2006) (Figure 4.1). A simple linear regression was used without weighting it by the number of observations at each speed, consistent with a similar analysis by Treichel et al. (2006). The fitted functions are provided (Eqs. 4.6 – 4.9), and the corresponding test statistics are summarized in Table 4.1.

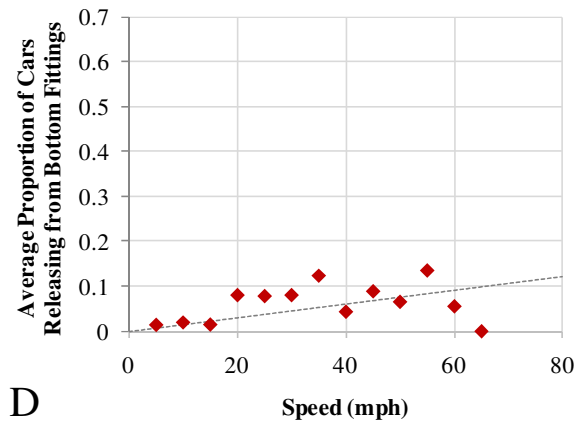
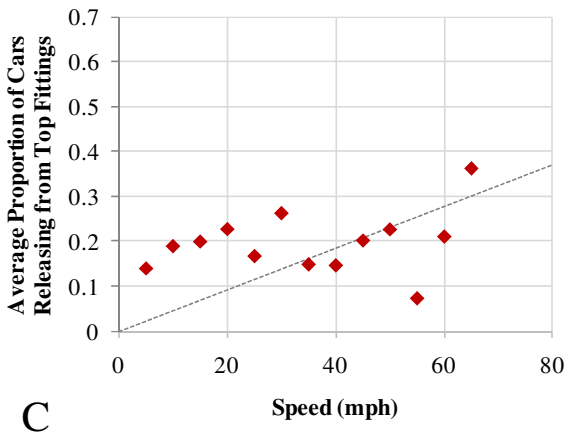
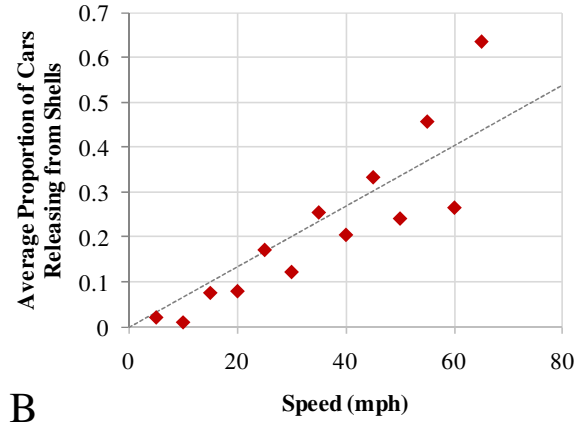
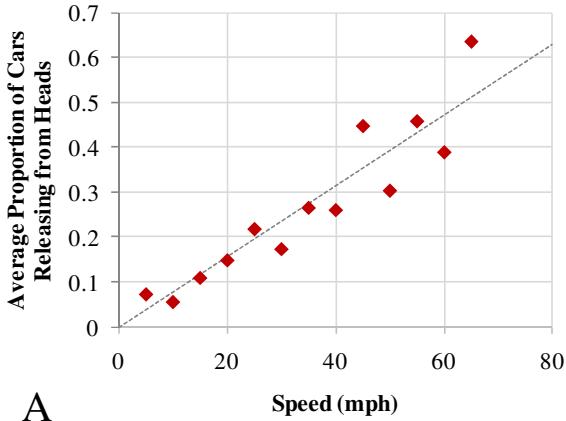


Figure 4.1: Proportion of Cars Releasing vs. Speed for Releases From (A) Heads, (B) Shells, (C) Top Fittings, and (D) Bottom Fittings

$$Y_h = 0.00786X \quad (4.6)$$

$$Y_s = 0.00674X \quad (4.7)$$

$$Y_t = 0.00460X \quad (4.8)$$

$$Y_b = 0.00150X \quad (4.9)$$

where Y_h = proportion of non-pressure cars releasing from heads, corresponding to train speed X

Y_s = proportion of non-pressure cars releasing from shells, corresponding to train speed X

Y_t = proportion of non-pressure cars releasing from top fittings, corresponding to train speed X

Y_b = proportion of non-pressure cars releasing from bottom fittings, corresponding to train speed X

X = train speed (mph)

Table 4.1. Parameter estimates of the linear speed-CPR models.

Model	Estimate of Regression Coefficient, β	Standard Error	t-value	Pr > t	R^2
$Y_h = \beta_h X$	0.00786	0.00044925	17.49	<0.0001	0.9622
$Y_s = \beta_s X$	0.00674	0.00061609	10.94	<0.0001	0.9089
$Y_t = \beta_t X$	0.00460	0.00072981	6.30	<0.0001	0.7677
$Y_b = \beta_b X$	0.00150	0.00031975	4.69	0.0005	0.6468

In the next step, I used the data in Treichel et al. (2006) to calculate the weighted average train speeds for releases from tank head, shell, top fittings and bottom fittings, which were, 38.5, 41.2, 28.7, and 35.5 mph, respectively. These average speeds were then substituted into Eqs. (4.6) through (4.9) to determine the proportion of cars releasing from each source, at the average speed (denoted by subscript “a”), yielding the following values for the non-insulated 111A100W1 considered here: $Y_{ha} = 0.30260$, $Y_{sa} = 0.27753$, $Y_{ta} = 0.13178$, and $Y_{ba} = 0.05330$.

Speed-adjustment factors were then determined by dividing the proportion of non-pressure cars releasing at a particular speed by the proportion of cars releasing corresponding to weighted average speed, e.g. $J_h = Y_h/Y_{ha}$ and so on. The speed-adjustment factors applicable to non-pressure cars were:

$$J_h = 0.02597X \quad (4.10)$$

$$J_s = 0.02429X \quad (4.11)$$

$$J_t = 0.03491X \quad (4.12)$$

$$J_b = 0.02814X \quad (4.13)$$

The cause-specific CPRs for the particular tank car considered were estimated using the data from Treichel et al. (2006) as: $R_h = 0.0799$, $R_s = 0.1092$, $R_t = 0.1577$, and $R_b = 0.0625$. Using Eq. (4.4), the average-speed (unadjusted) CPR for this tank car is 0.3527. Substituting the values of cause-specific CPRs into Eq. (4.5), the speed-dependent CPR was estimated as follows:

$$R' = 1 - [(1 - 0.0799J_h)(1 - 0.1092J_s)(1 - 0.1577J_t)(1 - 0.0625J_b)] \quad (4.14)$$

Figure 4.2 shows the speed-dependent CPRs, compared to the average-speed CPR of the non-insulated 111A100W1 tank car considered. This method can be adapted for any other type of tank car for which suitable data are available (Treichel et al., 2006).

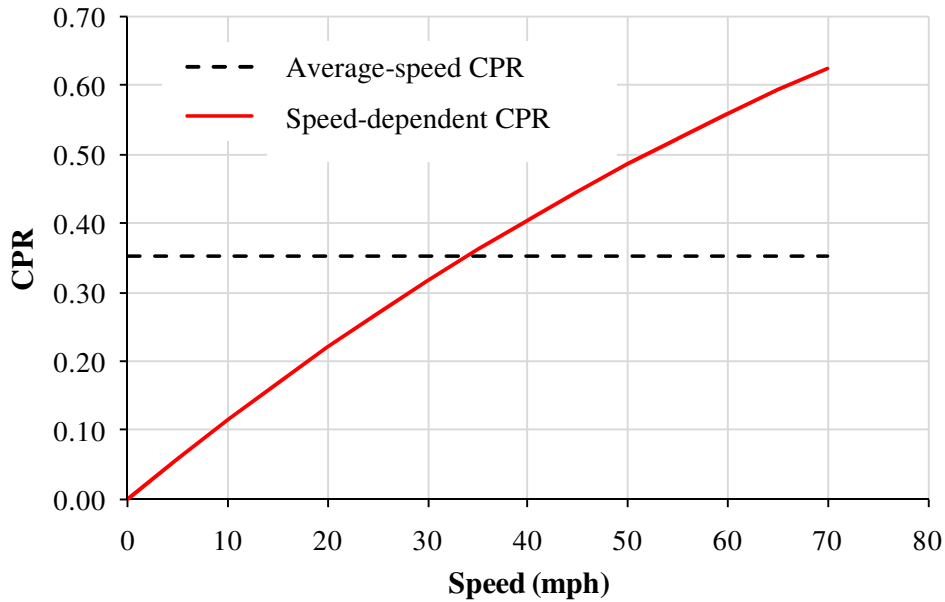
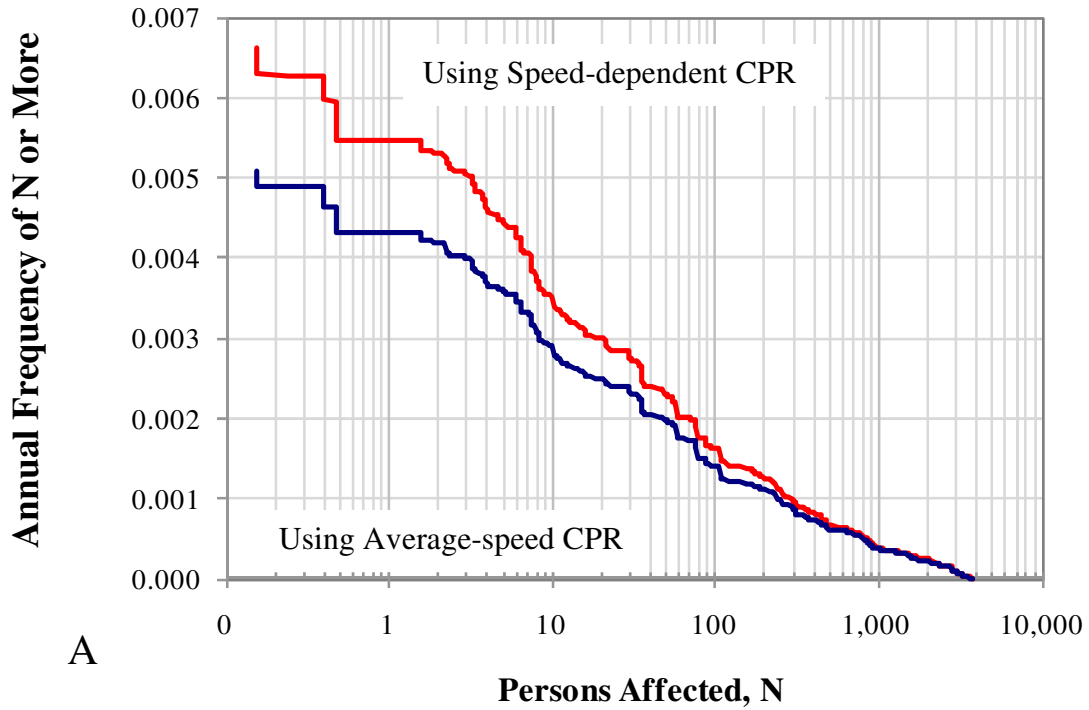


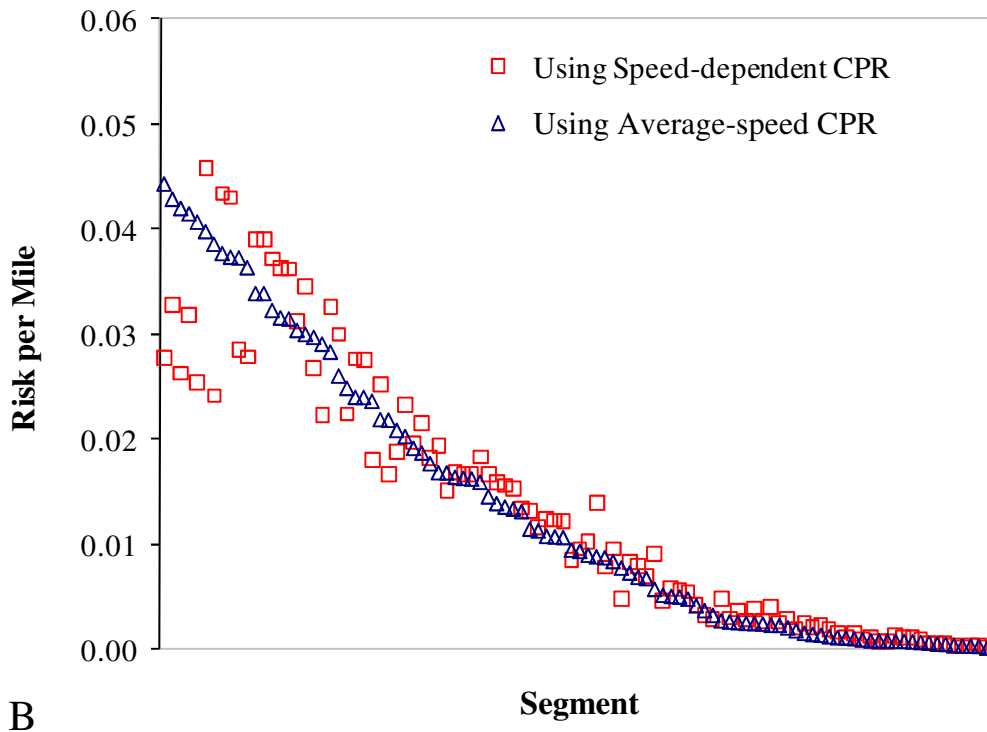
Figure 4.2: Estimated Conditional Probability of Release Dependent on Speed for the Tank Car Considered (DOT-111A100W1)

4.6 Effects of Train Speed on Risk

I evaluated the effects of train speed by comparing risk estimates calculated using speed-dependent CPR with the baseline case in which average-speed CPR was used. Use of speed-dependent CPR yields an annual risk of 1.428 persons affected per year, compared to 1.291 if average-speed CPR is used, which is an 11% difference. Further detail regarding the effect of speed-dependent CPR can be seen by comparing the risk profiles calculated using speed-dependent CPRs to those calculated using average-speed CPRs (Figure 4.3a). The differences in estimated risk when speed-dependent CPR is used are specific to the characteristics of the particular route analyzed in this case study. In general, the effect on risk estimates will depend on the distribution of speeds along a route. Specifically, routes with a larger percentage of higher-than-average-speed trackage will tend to have increased risk estimates when speed-dependent CPR is used, and those with a lower percentage will tend to have reduced risk estimates.



A



B

Figure 4.3: Comparison of Route-specific Results when Speed-dependent CPR is Used (A) Risk Profiles (F-N Curves) and (B) Top 100 Segments with the Highest Risk per Mile

A large percentage of risk along a route was attributable to a small percentage of its length (Kawprasert and Barkan, 2009a). In the case study described here, the 100 segments with the highest risk per mile (Figure 4.3b) accounted for 18% of the route length but 92% of the risk. Of these segments, all but 22 had a higher estimated risk when speed-dependent CPR was used compared to when average-speed CPR was used. Interestingly, these 22 segments were among the very highest risk segments in the entire analysis, accounting for 2% of the route length but 23% of the total risk. By contrast to the overall risk analysis results for the route, use of the speed-dependent CPR for these segments resulted in lower risk estimates than when average-speed CPR was used.

It is not surprising that use of speed-dependent CPR resulted in higher overall risk estimates in the case study considered because the segments with higher-than-average speeds comprised a majority of the overall route length, i.e. 1% for 11-25 mph (track class 2), 16% for 26-40 mph (track class 3), 39% for 41-60 mph (track class 4), and 44% for 61-70 mph (track class 5) (Tables 4.2, 4.3).

Table 4.2. Distribution of route lengths by population density and track class.

Group	Population Density		Route Length Corresponding to Speed (Track Class) and Population Density Groups (miles)				Total Length (miles)
	Class	Persons per Square Mile	11-25 mph (Track Class 2)	26-40 mph (Track Class 3)	41-60 mph (Track Class 4)	61-70 mph* (Track Class 5)	
1	Remote	Less than 60	5.1	48.6	269.2	411.4	734.3
2	Rural	61 to 550	0.0	55.1	151.0	91.4	297.5
3	Suburban	551 to 2,000	0.8	81.0	91.0	90.5	263.3
4	Urban	2,001 to 6,500	3.2	23.8	28.0	16.2	71.2
5	High	More than 6,500	1.4	21.1	5.7	1.7	29.8
Total Length (miles)			10.5	229.6	544.8	611.2	1396.1

*70 mph is a maximum speed for the route studied

Table 4.3. Percentage of route lengths by population density and track class.

Group	Population Density		Percentage of Route Length Corresponding to Speed (Track Class) and Population Density Groups (miles)				Percentage of Total Length
	Class	Persons per Square Mile	11-25 mph (Track Class 2)	26-40 mph (Track Class 3)	41-60 mph (Track Class 4)	61-70 mph* (Track Class 5)	
1	Remote	Less than 60	0.4	3.5	19.3	29.5	52.6
2	Rural	61 to 550	0.0	3.9	10.8	6.5	21.3
3	Suburban	551 to 2,000	0.1	5.8	6.5	6.5	18.9
4	Urban	2,001 to 6,500	0.2	1.7	2.0	1.2	5.1
5	High	More than 6,500	0.1	1.5	0.4	0.1	2.1
Percentage of Total Length			0.8	16.4	39.0	43.8	100.0

*70 mph is a maximum speed for the route studied

FRA regulations permit the operation of freight trains up to 80 mph on class-5 track (FRA, 2003); however, 70 mph is a more typical maximum speed and was the case for the route studied. The maximum speed for "Key trains", which operate according to a special set of operating practices defined by the AAR, is 50 mph (AAR, 2009), but the particular hazardous material considered in this study does not affect Key train status. For the purposes of this study, maximum permissible speeds from railroad timetables were used to infer FRA track class and were assumed to represent the operating speeds on each track segment.

A potential drawback of using timetable speeds to infer track class is that some segments may actually have higher quality track and correspondingly lower accident rates than would be assumed based on inferences from timetable speed. In some circumstances, railroads may be maintaining trackage to a higher standard than required by the track safety regulations for the particular speed shown in the timetable. If information is available on actual maintenance standards and operating speed, this can be formally incorporated into the risk model, allowing more accurate estimates of the accident rate for these segments.

Even in the absence of such information, the use of speed-dependent CPR instead of average-speed CPR provides more accurate risk estimates because it better reflects the particular operating characteristics of a route and their effect on risk. Such refinement is particularly important for the comparison of the risk associated with different route alternatives, e.g. a shorter route passing through urban areas with lower train speed versus a longer route that passes through less populated areas where trains may operate at higher speeds. Such considerations are germane to railroads and the U.S. DOT when considering the results of route risk assessments as required under HM-232E (U.S. DOT, 2008).

4.7 Risk Contribution by Population Density and Track Classes

I analyzed the contributions to risk by different population density groups, using both average-speed and speed-dependent CPRs, to understand their effects on risk estimates with respect to different population densities. The U.S. Census Bureau does not stipulate the classification of population census tract by density levels (see U.S. Census Bureau, 2002), thus for the purpose of this analysis I considered a population density classification used in the previous research (Saat and Barkan, 2006).

Track segments that are located in highly populated areas contribute a large proportion of route risk. For example, those segments located in areas where population density exceeds 6,500 persons per square mile represent the smallest proportion of the total route length. On the other hand, those in remote areas where population density is 60 persons per square mile or less represent more than half of the total length. The majority of the route is class 4 and 5, while class-2 track represents the smallest proportion (less than 1 percent) of the total route length (Tables 4.2, 4.3).

Although the segments in the highest density areas represent only 2% – the smallest proportion of route length compared to other groups – they account for the largest percentage of the risk, which is more than 50% of the total risk (Tables 4.4 and 4.5).

Table 4.4. Distribution of route risks by population density.

Group	Population Density		Route Length (miles)	Percentage of Route Length	Average-speed CPR		Speed-dependent CPR		Difference in Risk (persons/yr)*	Percentage Difference in Risk*
	Class	Persons per Square Mile			Risk (persons/yr)	Risk : Length	Risk (persons/yr)	Risk : Length		
1	Remote	Less than 60	734.3	52.6	0.006	0.0000	0.008	0.0000	0.002	41
2	Rural	61 to 550	297.5	21.3	0.024	0.0001	0.031	0.0001	0.008	32
3	Suburban	551 to 2,000	263.3	18.9	0.191	0.0007	0.230	0.0009	0.038	20
4	Urban	2,001 to 6,500	71.2	5.1	0.359	0.0050	0.397	0.0056	0.038	11
5	High	More than 6,500	29.8	2.1	0.712	0.0239	0.762	0.0256	0.050	7
Total			1,396.1	100.0	1.291		1.428			

*using speed-dependent CPR compared to average-speed CPR

Table 4.5. Percentage of route risks by population density.

Group	Population Density		Route Length (miles)	Percentage of Route Length	Average-speed CPR		Speed-dependent CPR		Difference in Percentage of Total Risk*
	Class	Persons per Square Mile			Percentage of Total Risk	% Risk : % Length	Percentage of Total Risk	% Risk : % Length	
1	Remote	Less than 60	734.3	52.6	0.4	0.0	0.6	0.0	0.121
2	Rural	61 to 550	297.5	21.3	1.8	0.1	2.2	0.1	0.362
3	Suburban	551 to 2,000	263.3	18.9	14.8	0.8	16.1	0.9	1.259
4	Urban	2,001 to 6,500	71.2	5.1	27.8	5.4	27.8	5.5	0.028
5	High	More than 6,500	29.8	2.1	55.1	25.8	53.4	25.0	(1.770)
Total			1,396.1	100.0	100.0		100.0		

*using speed-dependent CPR compared to average-speed CPR

In this case study, the use of speed-dependent CPR yields higher risk estimates for all population density groups compared to the use of average-speed CPR. The difference between the magnitudes of the risk estimates based on the two CPRs is the largest for the highest population density group (group 5) and the smallest for the lowest population density group (group 1). However, when the differences are expressed in percentages, the segments in the lowest population density group are associated with the highest percentage difference in risk (Table 4.4). When risk contribution is expressed as a percentage of total route risk instead of as an absolute estimate, the use of speed-dependent CPR results in a lower risk contribution for the highest population density group and a higher contribution for other population density groups, relative to average-speed CPR (Table 4.5). Both tables also show that the ratio of risk to track length is the greatest for the highest population density group.

Apart from the numerical results in these tables, I developed the illustrations to represent these results graphically (Figure 4.4). For the route considered, use of speed-dependent CPR yields higher risk estimates for all population density groups (solid line) compared to use of average-speed CPR (dashed line) (Figure 4.4a). The difference between risk estimates for the two CPRs is largest for the highest density group and smallest for the lowest density group. However, when the contribution is expressed as a percentage of total route risk instead of as an absolute estimate, the use of speed-dependent CPR results in a lower contribution for the highest population density group, relative to average-speed CPR (Figure 4.4b).

In the case study, some urban-area segments do not experience the reduction in estimated risk when speed-dependent CPR is used because these segments had speeds higher than average. On the other hand, some segments in non-urban areas had lower risk when speed-dependent CPR was used because of the speed restrictions on these segments. Figures 4.4a-b also show that the majority of the representative route is class-4 and class-5 track. Most of these segments are located in moderate to low population density areas. Class 3-segments, however, are more evenly distributed over different population classes, from the lowest to the highest density.

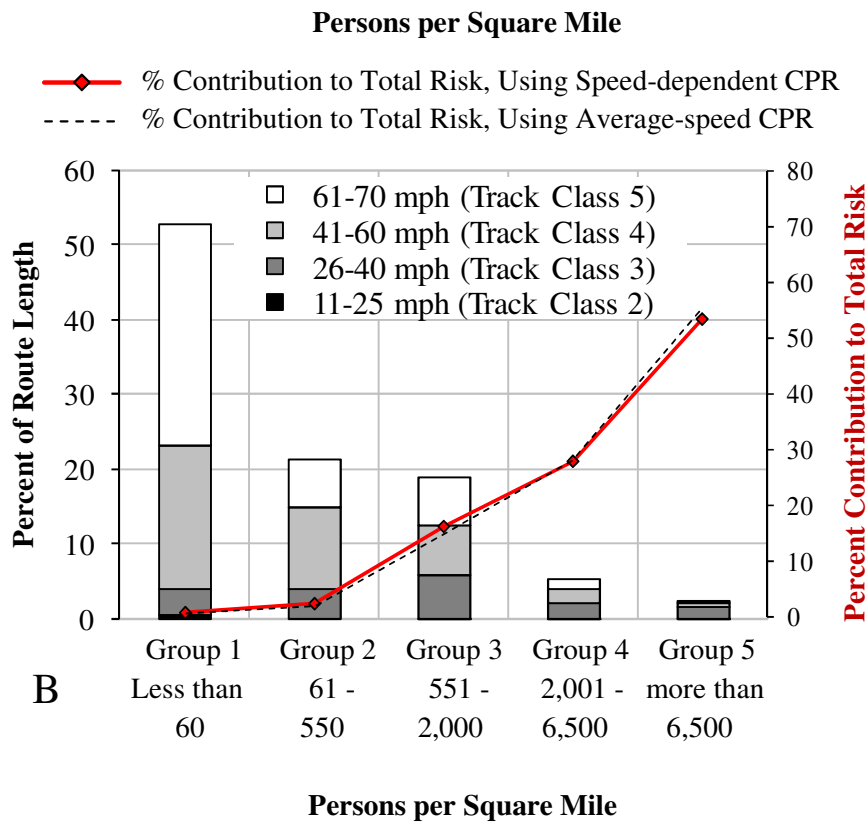
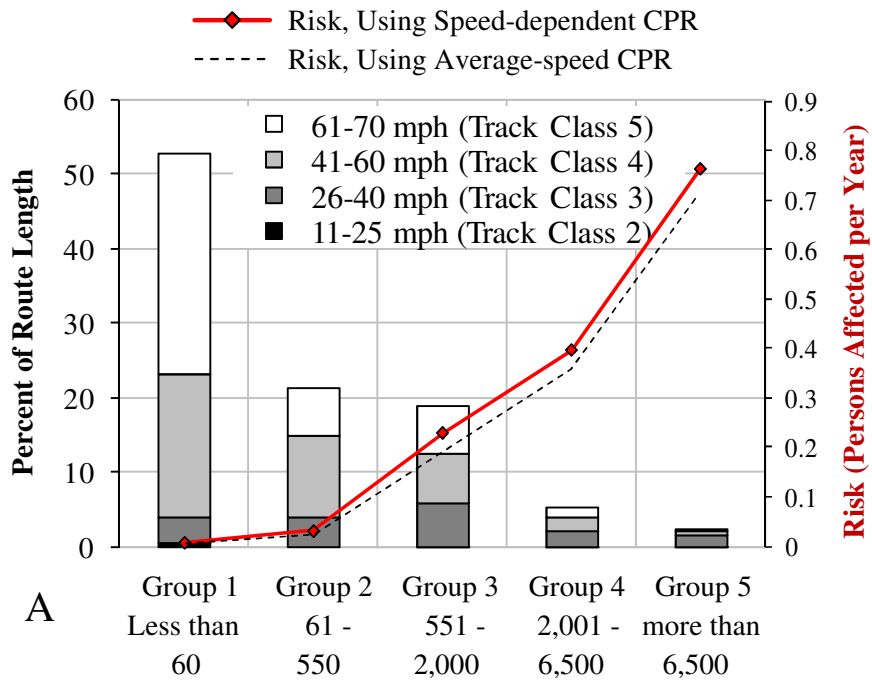


Figure 4.4: Percentage of Route Length and Contribution to Route Risk
(A) Population Density vs. Risk, (B) Population Density vs. Percentage of Total Risk

The numerical results in Tables 4.6 and 4.7 and the corresponding illustrations in Figure 4.5 show that the higher-track-class segments do not contribute much risk, despite their greater percentage of route length. By contrast, the lower-track-class segments contribute a larger percentage of total route risk, despite the lower CPRs due to a combination of the accident rate and population densities associated with them.

Table 4.6. Distribution of route risks by track class.

FRA Track Class	Route Length (miles)	Percentage of Route Length	Average-speed CPR		Speed-dependent CPR		Difference in Risk (persons/yr)*	Percentage Difference in Risk*
			Risk (persons/yr)	Risk : Length	Risk (persons/yr)	Risk : Length		
2	10.5	1	0.152	0.0145	0.112	0.0107	(0.040)	(26)
3	229.6	16	0.946	0.0041	1.013	0.0044	0.067	7
4	544.8	39	0.146	0.0003	0.221	0.0004	0.075	51
5	611.2	44	0.046	0.0001	0.082	0.0001	0.035	77
Total	1,396.1	100	1.291		1.428			

*using speed-dependent CPR compared to average-speed CPR

Table 4.7. Percentage of route risks by track class.

FRA Track Class	Route Length (miles)	Percentage of Route Length	Average-speed CPR		Speed-dependent CPR		Difference in Percentage of Route Risk*
			Percentage of Route Risk	% Risk : % Length	Percentage of Route Risk	% Risk : % Length	
2	10.5	1	11.8	11.8	8.6	8.6	(3)
3	229.6	16	73.3	4.6	70.9	4.4	(2)
4	544.8	39	11.3	0.3	14.9	0.4	4
5	611.2	44	3.6	0.1	5.6	0.1	2
Total	1,396.1	100	100		100		

*using speed-dependent CPR compared to average-speed CPR

Using the speed-dependent CPR yields a lower estimate of risk on class-2 track but higher estimates for classes 3, 4, and 5 (Figure 4.5a). When the percentage contribution to total risk is considered (Figure 4.5b), the use of the speed-dependent CPR results in a smaller percentage of risk on track classes 2 and 3 and larger percentages on classes 4 and 5, compared to the use of average-speed CPR. This analysis, based on the representative route, illustrates that the use of speed-dependent CPR takes into account the effect of differential operating speeds on risk for each categorical variable considered: population density and track class.

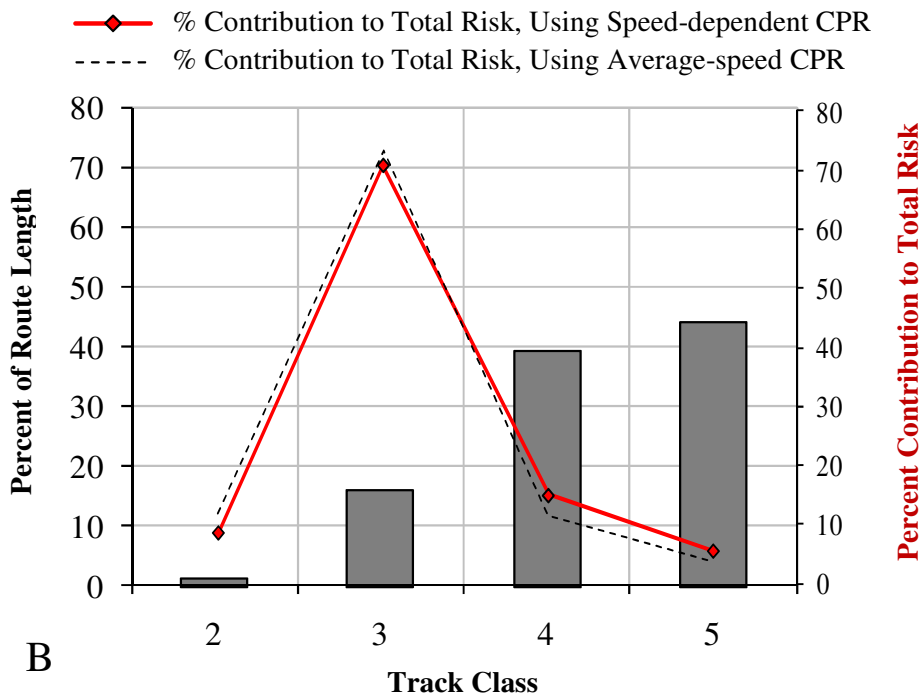
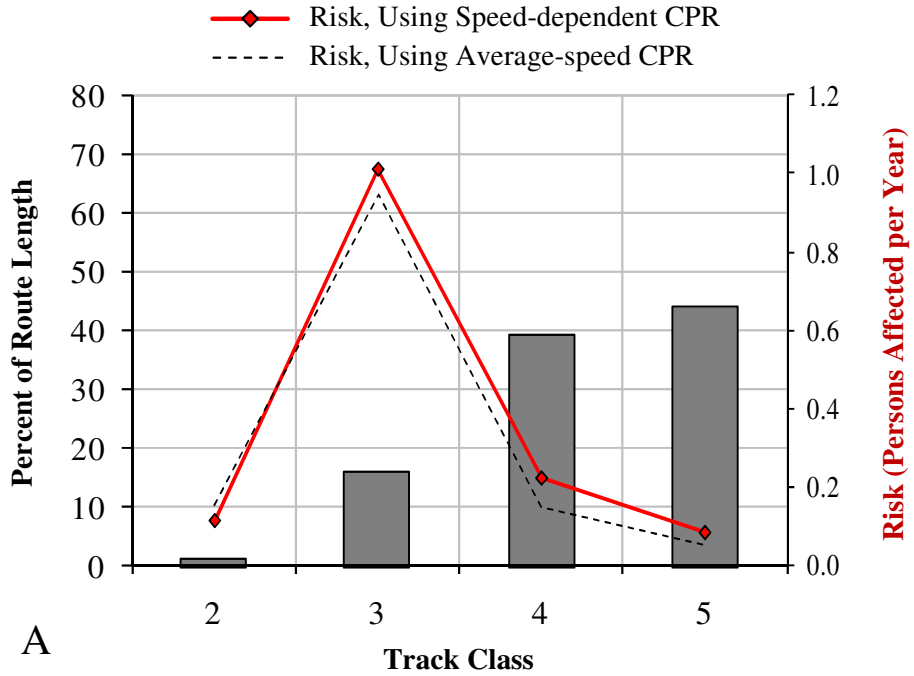


Figure 4.5: Percentage of Route Length and Contribution to Route Risk
(A) Track Class vs. Risk, (B) Track Class vs. Percentage of Total Risk

In the context of this discussion, it is useful to consider the ratio of the percentage of total risk to the percentage of route length. For the route analyzed, this risk:route length ratio, based on speed-dependent CPR, was 8.6, 4.4, 0.4, and 0.1, for track classes 2, 3, 4, and 5, respectively (Table 4.7). Although class-2 track has the highest risk contribution per track mile, the overall contribution from class 2 is not as high as that of class 3 due to the small percentage of class-2 track on the route. Since class-3 track contributes the largest percentage of risk on this route, measures to reduce this risk are likely to have the greatest overall effect. In the next section, I consider the effects of infrastructure upgrade on risk and illustrate how the use of speed-dependent CPRs enables better assessment of the safety benefits of track infrastructure upgrade.

4.8 Effects of Infrastructure Upgrade

In the case study, I considered the effect on risk of upgrading all class-2, class-3, and class-4 segments to the next higher class, i.e. to classes 3, 4, and 5, respectively, as three distinct upgrade options. I first considered the effect of track-class upgrade strictly as a means of reducing accident rate and consequently risk and, therefore, assumed that operating speeds were held constant after track upgrades. Upgrading classes-2, 3, and 4 track to the next higher class yielded a 5%, 53%, and 7% reduction in risk, respectively. Upgrading class-3 segments offered the greatest reduction in risk, primarily because of the relatively large reduction in accident rate combined with a fairly large percentage of the route.

Track upgrade principally affects track-caused accidents; however, not all track-related accidents are affected in the same way by track-class upgrades. Furthermore, there are a wide variety of potential accident causes (FRA, 2003). Non-track-related causes may have no relationship, or only an indirect one, with track class. Some accident causes, notably certain ones attributable to equipment failures such as broken wheels or axles, may actually increase with track-class upgrades if the operating speed also increases. Hence, increasing track class only affects the likelihood of some types of accidents, and the functional relationship between each of these accident causes and track class varies. When one also considers that different accident causes have differing relationships with the likelihood of a derailed hazardous materials car suffering a release (Barkan et al., 2003), it further complicates calculation of the effect of track-class upgrades on risk reduction. Further research on both the statistical and causal relationships between track class and accident frequency and severity is needed to improve the

quantitative assessment of the effect of changes in infrastructure quality on safety and risk. Until such research is completed and comprehensive data on critical infrastructure parameters is generally available, track class remains the best proxy statistic for estimating track quality, derailment rate, and ultimately risk.

4.9 Combined Effects of Infrastructure and Train Speed

In this section, the relationships between track class, accident rate, and speed-dependent CPRs are examined. It was assumed that train speeds increase in accordance with track-class upgrades. That is, trains are assumed to operate at the maximum normal operating speed corresponding to the upgraded track classes. Therefore, for each segment, the accident rate will be reduced due to the track-class upgrade, but tank car CPR will increase because of the higher speed. The overall release rate, which is the product of accident rate and CPR (a non-insulated 111A100W1 in this example), is dominated by the former, and thus it also declines. The difference in the magnitude of the release rate between consecutive track classes is the smallest for track classes 4 and 5 (Figure 4.6).

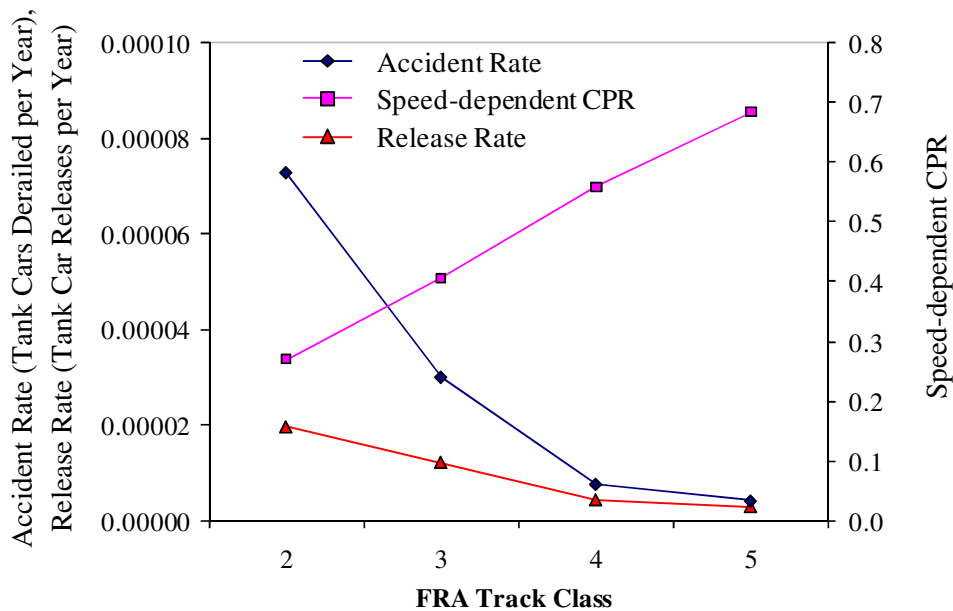


Figure 4.6: Relationship between Track Classes, Accident Rates, Speed-dependent CPRs, and Release Rates for the Tank Car Considered (DOT-111A100W1)

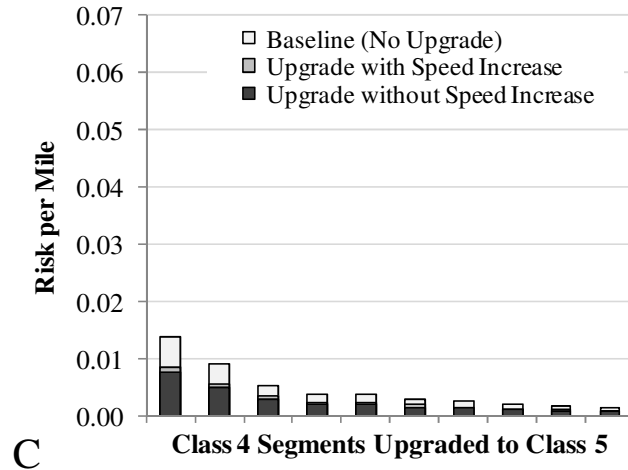
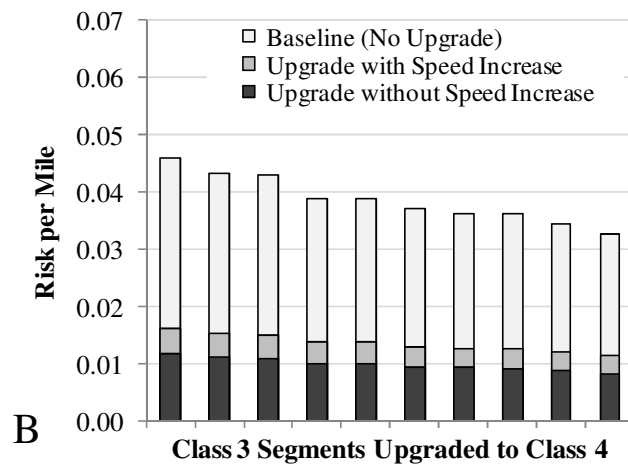
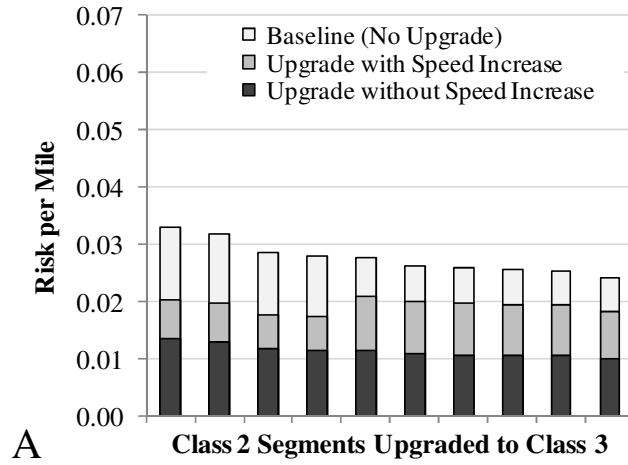


Figure 4.7: Effects of Infrastructure Upgrade and Speed on Risk Reduction for the Top 10 Segments with the Highest Risk per Mile
(A) Class 2 Upgraded to Class 3, (B) Class 3 Upgraded to Class 4, and (C) Class 4 Upgraded to Class 5

I examined each individual segment to understand the change in risk as a result of track infrastructure upgrade and speed increase. Figure 4.7 shows the distribution of segment-specific risk per mile for three cases for each track class: 1) the baseline case (no upgrade), 2) upgrade to a higher class without increase in speed, and 3) upgrade to a higher class with a speed increase. Speed-dependent CPRs were used in all scenarios. Track class is correlated with accident rates (Nayak et al., 1983), i.e. a higher track class is associated with a lower accident rate. However, in the second scenario train speed is assumed to remain the same, with no effect on accident rate, for the purpose of illustrating the use of speed-dependent CPR. For clarity, only the top ten segments with the highest risk per mile, ordered by the baseline risk, are shown. These charts indicate, for the representative route, that upgrading class-3 segments to class 4 yields the largest reduction in risk, while upgrading class-4 track to class 5 offers little reduction in risk. Furthermore, the difference between the segment risk per mile when speed is held constant and the segment risk per mile when speed is increased is the highest for the case in which class-2 segments are upgraded to class 3. The magnitude of difference varies because of the different initial operating speeds on each segment (Figure 4.7a). Overall, use of speed-dependent CPR enables individual consideration of both of the factors affecting risk in this case, the reduction in accident rate due to the upgraded track class and the increase in CPR due to the higher operating speed.

4.10 Discussion

When risk estimates for each of the scenarios analyzed in the case study are summarized, several results can be discerned (Table 4.8). First, in the consideration of track infrastructure upgrades, there are different opportunities for risk reduction based on the distribution of track classes on the route and the differential effects on risk reduction of each track class. Upgrading the lowest track class provides the highest risk reduction per track mile. However, it represents the smallest proportion of the route, thus offering little opportunity to reduce risk. On the other hand, upgrading class-3 track segments to class 4 provides the highest overall risk reduction, despite the fact that these segments do not represent the largest percentage of the route compared to other track classes.

Table 4.8. Summary of estimates using average-speed vs. speed-dependent CPRs.

Before Track Upgrade (Baseline)

Accident Rate (Cars Derailed per Year)	Release Rate (Releases per Year)		Annual Risk (Persons Affected per Year)	
	Using Average- speed CPR	Using Speed- dependent CPR	Using Average- speed CPR	Using Speed- dependent CPR
	0.0144	0.0051	0.0066	1.2913

After Track Upgrade

Track Class Considered for Upgrade to One Higher Class	Total Distance Upgraded (Miles)	Accident Rate (Cars Derailed per Year)	Release Rate (Releases per Year)			Annual Risk (Persons Affected per Year)		
			Using Average- speed CPR	Using Speed-dependent CPR		Using Average- speed CPR	Using Speed-dependent CPR	
				Without Speed Increase	With Speed Increase		Without Speed Increase	With Speed Increase
Class 2	11	0.0140	0.0049	0.0065	0.0066	1.2018	1.3621	1.3881
Class 3	230	0.0093	0.0033	0.0046	0.0050	0.5879	0.6753	0.8003
Class 4	545	0.0125	0.0044	0.0056	0.0059	1.2248	1.3276	1.3484
Percent Reduction from Baseline								
Class 2	11	3.1	3.9	1.5	0.7	6.9	4.6	2.8
Class 3	230	35.5	35.3	30.3	24.2	54.5	52.7	44.0
Class 4	545	13.2	13.7	15.2	10.6	5.1	7.0	5.6
Percent Reduction per Mile Upgraded								
Class 2	11	0.28	0.36	0.13	0.06	0.63	0.42	0.25
Class 3	230	0.15	0.15	0.13	0.11	0.24	0.23	0.19
Class 4	545	0.02	0.03	0.03	0.02	0.01	0.01	0.01

Second, the use of speed-dependent CPR properly accounts for speed effects on different routes, whereas the use of average-speed CPR does not. Furthermore, speed-dependent CPR is necessary for proper evaluation of the effect of track-class upgrades on risk, with or without speed increase.

Third, for the representative route, the use of speed-dependent CPR yields annual risk estimates slightly higher than the use of average-speed CPR. This is because the majority of the route has higher-than-average track speeds. This result will vary depending on route-specific characteristics.

Fourth, upgrading track class with the corresponding speed increase actually reduces risk relative to the baseline case. This is because the incremental effect of the lower accident rate due to the higher track class more than offsets the slight increase in CPR due to the higher speed.

Completing the analyses used to illustrate the effect of speed-dependent CPR on risk estimates required several assumptions. As mentioned, for track-class upgrades with speed increase, it was assumed that trains would operate at the maximum allowable speed corresponding to the upgraded track class. This will result in higher speed estimates than would actually be used on some segments, thus overestimating risk for these segments. Inferring track class based on timetable speed may not always represent actual maintenance conditions for some track segments, which also results in an overestimation of risk. For both of these circumstances, if data for actual operating speed are available, they can be incorporated into the model, and the use of speed-dependent CPR will make such adjustments more accurate. Additionally, the relationships developed to estimate speed-dependent conditional probability of release in this study do not account for other possible speed-dependent effects, such as number of cars derailed or spill size distribution; but, these factors can also be incorporated into the model if suitable data are available.

The intent of this research was to develop a general method to calculate speed-dependent CPR using published data on railroad tank cars. I used a case study to compare several different scenarios that affect or are affected by speed in order to gain insight into the effect of using speed-dependent CPR on estimates of safety and risk. Analysis of these scenarios is not meant to suggest that these are necessarily the most cost-effective approaches to risk reduction. Instead, the methodology presented here is intended to describe and illustrate the utility of speed-dependent CPR and how to incorporate it into safety and risk analysis calculations.

The scenarios considered here include upgrading track class both with and without speed increases. Either scenario would entail considerable additional capital and maintenance expense (Zarembski and Resor, 2004). Rational consideration of these options would require data on their incremental cost and, ideally, information on the cost-effectiveness of other options that might also affect risk. This would enable informed decisions about when and where risk reduction options should be implemented and which are the most cost-effective.

4.11 Conclusions

In this chapter, I present a technique to incorporate the effects of different train speeds on accident rate and CPR and incorporate both of these into a hazardous materials transportation risk analysis model. The relationship was developed to estimate speed-dependent CPR, thereby allowing more accurate estimates of route risk. Although previous work has addressed various aspects of this question (Nayak et al., 1983; CCPS, 1995; Barkan et al., 2003; Treichel et al., 2006), the method for calculating speed-dependent CPR described here can be used to develop estimates for specific tank car designs, which was not previously possible. Additionally, the statistics and methodology presented here are based on the most up-to-date, published data on tank car performance in accidents. The utility of speed-dependent CPR is illustrated using a case study of track infrastructure upgrades in which I analyze the effects of train speed and track improvement independently and in combination to assess their effect on route risk. Different options in a track infrastructure upgrade problem are considered to determine the option that may provide the greatest reduction in risk for the particular route studied.

Previous work has not explicitly considered the nature or extent of the effect on risk estimates of using average-speed CPR versus speed-dependent CPR. Although the use of average-speed CPR may often be appropriate for national or system wide estimates of risk, it does not satisfactorily account for differences in operating characteristics when comparing routes. Different routes will almost certainly have differing speed distributions and population exposure. The use of average-speed CPR can lead to both underestimate and overestimate of overall risk along the route and at specific locations along the route. Both of these may affect risk management decisions; therefore, the ability to more accurately calculate them is important. In addition, the use of speed-dependent CPR affects the ability to quantitatively assess the effect of certain types of track infrastructure upgrade, as illustrated in the case study. The speed-dependent CPR calculation methodology and its application to risk analysis models should enable more accurate risk calculations, not only for route risk comparisons, but also for assessment and evaluation of the benefits of infrastructure improvements that affect operating speed.

CHAPTER 5

OPTIONS FOR ROUTE INFRASTRUCTURE IMPROVEMENT FOR RISK REDUCTION

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Presented in part as Kawprasert, A., and C.P.L. Barkan. *Options for Rail route Infrastructure Improvement to Reduce Hazardous Materials Transportation Risk*. ASME-IEEE-ASCE-AREMA-TRB Joint Rail Conference, University of Illinois at Urbana-Champaign, Urbana, IL, April, 27 – 29, 2010b.

5.1 Introduction

Approaches towards reducing risk include improving transportation packaging, rerouting of hazardous materials traffic, track infrastructure improvement and speed management. Previous chapters considered routing and the effect of speed on risk. In this chapter, I introduce an alternative approach, i.e. track infrastructure improvement for hazardous materials transportation risk reduction and develop an approach to quantifying its effect and optimizing upgrade decisions.

Considerable prior work focused on rerouting of hazardous materials (e.g. Glickman, 1983; Glickman et al., 2007; Kawprasert and Barkan, 2008, and Chapter 3) and improving transportation packaging (Barkan et al., 1991; Barkan, 2008; Saat, 2009). In many circumstances, hazardous materials rerouting may not be practical and by definition will involve transferral of risk from one corridor to another. On the other hand, improving tank car safety designs reduces the conditional probability of release (CPR) given an accident and consequently the level of consequence (Saat and Barkan, 2006b). However, this measure does not reduce accident rates.

Track upgrade usually requires substantial capital investment and increased operating and maintenance expense. Therefore, such investment must be as efficient and effective as possible. Given a hazardous materials transportation network, the most effective strategy will be to upgrade segments that provide the greatest safety benefit given some budget constraints (Kawprasert and Barkan, 2009a). The objective of this chapter is to provide a quantitative framework to consider track infrastructure improvement as a means of reducing risk and to help identify the most cost-effective options to maximize the safety of rail transportation of hazardous materials.

The organization of this chapter is divided into two parts. In the first part, I introduce a mathematical framework to evaluate track infrastructure improvement as a means of reducing risk. In the second part, I illustrate an application of framework to several track upgrade decision problems.

The quantitative framework in this chapter is intended to help risk managers determine the locations where track segments should be upgraded to obtain the greatest benefit from investment. In this regard, I introduce an optimization model, the *route infrastructure improvement selection model* – a framework to formally consider route infrastructure improvement as an alternate measure for hazardous materials transportation risk reduction. A generalized version of the model is then developed using mixed integer programming (MIP). This includes a single-objective route infrastructure improvement selection model to minimize risk given a constrained upgrade cost, and a bi-objective route infrastructure improvement selection model to minimize both risk and track maintenance cost.

The first model aims at determining possible locations for track infrastructure improvements that provide the greatest reduction in risk given a resource constraint. The second model incorporates a cost element using a bi-objective optimization framework that simultaneously considers the tradeoff between reduction in risk and increase in investment cost. The bi-objective model is used to suggest the best strategy for track infrastructure management that minimizes both risk of transporting hazardous materials and annual track maintenance cost. The route infrastructure improvement selection models account for the combined effects of: segment-specific accident rate, conditional probability of release from a tank car in an accident, and population density adjacent to the rail route. In addition, the effect of train speed on risk is also considered, using the relationships described in Chapter 4 (Kawprasert and Barkan, 2010a). The models presented are structured in a way that they can be easily modified and adapted to accommodate other objectives or applications of interest. Overall, the mathematical framework serves as a tool to enable the risk-based decision making on investments in route infrastructure improvement.

In the second part of this chapter, I describe an application of the model and discuss various aspects of track infrastructure improvement problems.

First, I illustrate the model application using a case study in which I consider several strategies for track upgrade that minimize route risk under different policies and objective functions to allow flexibility for risk management and planning. In particular, the alternative approaches to allocating resources for the single-objective route infrastructure improvement selection model to minimize risk consist of: upgrade track segments of any class to the next higher class in any location on the route, upgrade track segments of a particular class to the next higher class at any location, and upgrade consecutive like-track track class segments to the next higher class. The degree of risk reduction due to these upgrade strategies is systematically evaluated and compared.

Second, I conduct a sensitivity analysis of investment in track upgrades to determine the effect on safety over various levels of investment. This enables a better understanding of how track class upgrade offers safety benefits for a given investment level. For the three upgrade scenarios above, I assume a constant track upgrade cost per mile to complete the analysis. I also conduct a sensitivity analysis of these cost assumptions. Although the parameter estimates used in the analysis may still require further refinement, this does not interfere with the principal objective of this chapter, which is to provide a general framework to evaluate the most cost-effective approaches for track infrastructure improvement to obtain the greatest safety benefit.

Third, I illustrate two variations of track infrastructure improvement problems. A bi-objective route infrastructure improvement selection model is adapted to determine the potential locations where 1) track infrastructure improvement (track-class upgrade) or 2) track infrastructure management (track-class upgrade or downgrade) should be considered to minimize both risk and track maintenance cost. In this part, track-class specific upgrade cost is considered to account for an increase in ordinary and renewal track maintenance costs.

Fourth, the route infrastructure improvement problems rely on transportation network data comprising track segments applicable for track-segment-specific risk analysis and optimization. Variation of rail segment lengths in transportation networks may affect the accuracy of segment-specific risk analyses and the optimization results for infrastructure

improvement. The last part of this chapter attempts to analyze the effect of track segment lengths in segment-specific risk estimation and optimization. In particular, I illustrate how optimality of track infrastructure improvement is achieved and compare the Pareto efficient frontier when uniform and non-uniform route segmentation is considered. This brings up a new issue on the development of a better route-segmentation approach for track-segment-specific risk analysis and optimization.

5.2 Previous Studies on Route Infrastructure Improvement for Risk Reduction

Saat and Barkan (2006b) analyzed the marginal benefit of improving tank car safety design in reducing hazardous materials transportation risk compared to improving railroad infrastructure. They developed a simple cost-benefit model to compare the safety benefit from tank car replacement vs. infrastructure improvement and determined the conditions when one is more effective than the other. While track improvement generally reduces the overall system-wide derailment probability, enhanced tank cars could change the level of possible consequences. They also showed that the marginal benefit expressed in terms of the percentage reduction in likelihood of release is proportional to the investment level for the tank car design enhancement approach, while the track improvement results in a diminishing marginal return.

Lai et al. (2010) developed an optimization framework to determine the optimal assignment of track class based upon the track characteristics, traffic demand and maintenance budget. Their model takes into account the trade-off between track infrastructure maintenance cost and transportation cost. Nevertheless, their framework does not consider the safety aspect in that the differential accident rates associated with track classes were not incorporated, i.e. it does not account for the benefit from reduction in accident rates as a result of track infrastructure improvement.

Liu et al. (2010) developed a benefit-cost analysis framework to consider the trade-off between reduced accident rates and increased costs in evaluating track infrastructure improvement as a risk reduction strategy. They also developed a model for estimating track-class-specific upgrade costs. Upgrading track class 3 to class 5 yields higher annual derailment reduction benefit than that of upgrading class 3 to class 4 and class 4 to class 5 but at higher cost. Track improvement is more cost-justified for the lines with higher traffic densities. Their

framework, however, does not provide a means to identify the locations in the network where such improvement should take place to obtain the greatest benefits.

Kawprasert and Barkan (2009a) developed a mathematical model to determine the locations where track segments should be upgraded to yield the most reduction in risk. This model, however, neglects the differential track upgrade costs for different track classes and uses a single, constant value of CPR that is independent of train speed.

In this chapter, I propose a new formulation in which speed-dependent CPR is incorporated for a more accurate evaluation of the benefits of track infrastructure improvement on risk reduction (Kawprasert and Barkan, 2010a; and Chapter 4). In addition, the new model accommodates track-class-specific infrastructure upgrade costs. In particular, the bi-objective model simultaneously considers both risk and investment costs in determining route infrastructure improvement strategy, given a resource constraint.

5.3 Route Infrastructure Improvement Selection Model

5.3.1 Model Formulation

In this section I introduce a new optimization model to determine the upgrade locations of track segments to minimize hazardous materials transportation risk based on the recent development of speed-dependent CPR by Kawprasert and Barkan (2010a).

This new model formulation considers segment-specific parameters to estimate annual risk. The new model also improves the prototype model previously developed by Kawprasert and Barkan (2009a) in that it is designed to: 1) account for train speed in estimating risk, 2) handle multiple release scenarios, and 3) incorporate use of multiple tank car types, and 4) accommodate track-class-specific upgrade cost. Since the new optimization model incorporates the effect of train speed in risk estimation, it enables a more accurate risk calculation and thus facilitates a proper evaluation of the benefits of infrastructure improvements.

Multiple release scenarios may include one or more combinations of these scenarios: time of day, fire involvement, and quantity spilled. When prior information is unavailable, one may assume the probability distribution as appropriate. For example, Kawprasert and Barkan (2008)

assumed equal probability of daytime and nighttime spills. The probability of fire involvement for specific materials may be determined from either past release incident statistics or industry expert opinion (Kawprasert and Barkan, 2010a). Treichel et al. (2006) provided the probability distribution of various spill sizes expressed by the percentage of quantity of product lost in an accident. If multiple scenarios are considered in the analysis, the affected areas may also vary depending on the corresponding scenarios considered. Since the U.S. DOT ERG (PHMSA, 2008) recommended release-scenario-specific evacuation distances for determining the area affected by a release, the consideration of a specific scenario of release is necessary for the mathematical framework that is based on the ERG hazard exposure model.

Shippers may use more than one type of container for transporting a particular product. Thus, the model formulation should be structured to accommodate shipments by multiple car types. In particular, the model must be capable of accounting for different speed-dependent CPRs corresponding to each specific tank car type. However, one may simplify the computation by using the aggregate conditional probability of release, which is the CPR normalized by the percentage of each car type in the fleet (Kawprasert and Barkan, 2008), or by using the maximum CPR to represent the worst case scenario.

The resource constraint of the model sets the maximum level of resource to be used for track infrastructure improvement. Depending on information available, a single unit cost may be assumed to represent an average infrastructure improvement cost. Hence, the upgrade length may be used as a proxy variable for track upgrade cost. Nevertheless, for more accurate cost estimation, the model should be able to handle track class specific infrastructure upgrade cost as a function of track type and traffic density (Zarembski and Resor, 2004; Lai et al., 2010; Liu et al., 2010).

The generalized formulation for route infrastructure upgrade problem is given as follows:

$$\text{Minimize Annual Risk, } S = \sum_{i=1}^n S_i \quad (5.1)$$

subject to

$$\sum_{i=1}^n C_i L_i \leq X \quad (5.2)$$

where

$$S_i = R_i - C_i d_i, \quad \forall i \quad (5.3)$$

and

$$\begin{aligned} C_i &= 1 && \text{if upgrade} \\ &= 0 && \text{otherwise} \end{aligned} \quad (5.4)$$

where

- S_i = segment risk (persons affected per year)
- C_i = decision variable for track segment i (1 if upgrade, 0 otherwise)
- L_i = length of the track segment (miles)
- X = maximum upgrade length (miles)
- R_i = baseline segment risk (before upgrade) (persons affected per year)
- d_i = reduction of segment risk if track segment i is upgraded to a higher class (persons affected per year)
- n = total number of segments in the route
- i = track segment ID

The baseline segment risk can be computed from the following equation.

$$R_i = \sum_{j=1}^o \sum_{k=1}^p V_{ik} T_i L_i W_{ik} P_{ij} D_i A_j \quad (5.5)$$

The reduction of segment risk as a result of upgrade can be determined from the following equations.

$$d_i = \sum_{j=1}^o \sum_{k=1}^p V_{ik} M_i L_i W_{ik} P_{ij} D_i A_j \quad (5.6a)$$

or

$$d_i = R'_i - \sum_{j=1}^o \sum_{k=1}^p V_{ik} Z_i L_i Q_{ik} P_{ij} D_i A_j \quad (5.6b)$$

where

- V_{ik} = annual shipments (carloads) on track segment i made by tank car type k
- T_i = rate of tank car involvement in an FRA-reportable derailment on track segment i , before upgrade (tank cars derailed per car-mile)
- L_i = length of the track segment i (miles)
- W_{ik} = conditional probability of release given that a tank car derails, adjusted for speed on track segment i for tank car type k
- P_{ij} = probability distribution of a specific release scenario j occurring on track segment i
- D_i = average population density along track segment i (persons per square mile)
- A_j = affected area for the material considered as per the U.S. DOT ERG recommendation, corresponding specific release scenario j (square mile)
- M_i = absolute difference between the original annual rate of tank car involvement in an FRA-reportable derailment of track segment i before upgrade and the new rate in which track segment i is upgraded to a higher class (tank cars derailed per car-mile)
- R'_i = segment risk after upgrade (persons affected per year)
- Z'_i = rate of tank car involvement in an FRA-reportable derailment given that segment i is upgraded to a higher class (tank cars derailed per car-mile)
- Q_{ik} = conditional probability of release given that a tank car type k derails, adjusted for maximum speed on the upgraded track segment i
- o = total number of release scenarios considered
- p = total number of tank car types used to transport the product(s)

The objective function in Eq. (5.1) gives the estimate of annual risk after track infrastructure improvement. The estimate can be compared with the baseline risk. Thus, the route infrastructure improvement selection model implies the maximum possible safety benefit in terms of risk reduction that can be obtained from track infrastructure improvement. Eq. (5.2) stipulates that the total upgrade length cannot exceed the specified level X . Eq. (5.3) computes a track segment-specific risk. Eq. (5.4) defines a binary decision variable: $C_i = 0$ (no upgrade), and

$C_i = 1$ (segment i upgraded). Eq. (5.6a) is used if one assumes the same operating speed on a segment after upgrade. If a speed increase is assumed after upgrade, e.g. assuming the train operates at maximum track speed on the upgraded segment, Eq. (5.6b) can be used. The generalized route infrastructure improvement selection model determines locations for track upgrade that minimize risk subject to a resource constraint. One advantage of formulating the route infrastructure improvement problem in the MIP form is that the problem can be easily solved using robust solvers provided that all the risk parameters are pre-determined.

5.3.2 Route Infrastructure Improvement Selection Model Incorporating Cost Parameters

The previous section considers length of track upgraded as a proxy variable for investment cost. In this section, I illustrate how the route infrastructure improvement selection model can be adapted to accommodate costs associated with track infrastructure improvement. Then, I use the modified model to conduct a sensitivity analysis of investment level on the safety benefit of track infrastructure improvement for hazardous materials transportation.

5.3.2.1 Identification of Cost Parameters

First, I consider a unit cost for railroad track infrastructure upgrade to be incorporated into the model. In practice, this cost may vary with location in the network and the level of upgrade, which depends on the existing track infrastructure and the desired condition. Therefore, in general, the unit costs will be different for upgrading different track classes. To accommodate the infrastructure upgrade cost, the resource constraint of the route infrastructure improvement selection model can be modified as follows:

$$\sum_{i=1}^n O_i C_i \leq E \quad (5.7)$$

where

O_i = cost of upgrading track segment i to a higher class (\$)

E = total budget allocated for route infrastructure improvement (\$)

Next, I attempt to quantify the benefit from the investment in track improvement. Several metrics can be considered: risk reduction compared to baseline, risk reduction per unit investment, or benefit-cost ratio (BCR). The objective is to maximize these metrics.

To express risk monetarily (i.e., risk cost), the consequence term can be decomposed into several elements representing the cost of the consequence. Depending on the degree of accuracy required and availability of information, the consequence costs may comprise: evacuation cost, clean up cost, train-delay cost, track and equipment damage costs, cost of materials loss, etc. These costs are dependent on various, different parameters. For example, evacuation cost could be a function of persons subject to evacuation or sheltering in-place, environmental cleanup cost is likely to be a function of the quantity, type and location of materials spilled (Anand 2006, Yoon et al., 2009). For simplicity, I divide the consequence of release into two parts: that which is a function of persons affected representing evacuation cost, and that which is a single average value representing the consequence costs other than evacuation cost. To accommodate these cost components, the risk equation can be modified as follows:

$$\text{Annual Risk Cost, } K = \sum_{i=1}^n \sum_{j=1}^o \sum_{k=1}^p V_{ik} Z_i L_i W_{ik} (P_{ij} D_i A_j Y_i + G) \quad (5.8)$$

where

- K = annual risk cost (\$)
- Y_i = consequence cost per person affected for track segment i (\$ per person)
- G = average consequence cost per incident (\$)

If the BCR is to be considered as criteria for evaluating the effectiveness of track infrastructure improvement, then the safety benefit per investment, B , can be computed as follows:

$$B = \frac{\Delta K}{E} \quad (5.9)$$

where

- ΔK = safety benefit, defined as the reduction in annual risk (\$) = $K' - K$
- K' = baseline risk (before improvement) (\$)
- K = risk after improvement (\$)

$$\begin{aligned}
 E &= \text{investment on track infrastructure improvement converted into present value (\$)} \\
 &= \frac{E}{(1+r/100)^t}
 \end{aligned}
 \tag{5.10}$$

where

- E = total budget allocation for track infrastructure improvement (\$)
- r = discount rate (%)
- t = time period considered (years)

To obtain the baseline risk K' , the value of E in Eq. (5.7) can be set to zero. After all parameters are estimated, the route infrastructure improvement selection model incorporating infrastructure upgrade and consequence costs can be solved in a similar manner as before.

In the following section, I discuss the estimation of parameters required for the modified route infrastructure improvement selection model incorporating track upgrade costs.

5.3.2.2 Track Infrastructure Upgrade Cost

A critical piece of information required to evaluate the cost-effectiveness of track infrastructure improvement is the track upgrade cost as it is affected by existing and alternative infrastructure condition. It may also be subject to geographic conditions and labor/equipment costs. Depending on the particular purpose for consideration, track infrastructure upgrade may refer to track-class upgrade or track rehabilitation. Here, track-class upgrade is defined as an improvement of track maintenance and renewal standards from existing track class to a higher class, while track rehabilitation (sometimes referred to as track upgrade) may involve a renewal or replacement of rail, ties and improvement of geometry and embankment to accommodate higher traffic load while not necessarily improving track class. In this section, I review various estimates of track improvement cost.

Saat and Barkan (2006b) used data from a class-1 railroad to estimate track improvement cost. Their analysis assumed a value of \$600,000 per mile accounting for upgrading class-4 mainline track to class 5 including: upgrading rail to new 136 lb/yd continuous welded rail, 33% crosstie replacement, ballasting, surfacing, shoulder and drainage improvement, and miscellaneous work.

ZETA-TECH (2000) estimated the rehabilitation costs for a complete upgrade of a mile of track for a U.S. short line or regional railroad to be \$516,066. This includes a complete replacement of rail, ties, ballast, turnout and surfacing to accommodate 286,000 lb. gross rail load cars (Resor et al., 2001).

Casavant and Tolliver (2001) considered the minimal cost per mile for upgrading branch lines to accommodate heavy axle loads (286,000 lb. maximum GRL) to be in the range of \$250,000 to \$300,000 per mile based on a use of 115 lb. or 132 lb. curve-worn rail. The lower cost of this estimate is probably due, in part, to use of used rail, rather than new rail.

In the assessment of the estimated infrastructure needs for Texas short line railroads to support 286,000 lb. GRL, Warner and Terra (2006) used a figure of \$406,252 per mile as the upgrade cost, accounting for new 115 lb. rail and wooden crosstie, ballast, and surfacing.

Babcock and Sanderson (2006) provided an estimate for track upgrade cost of \$207,770 per mile. This estimate represents an average of the costs for shortline railroads to upgrade mainline track to support 286,000 lb. axle loads. The average is based on 115 lb. and 132 lb. curve-worn rail used for upgrade.

Zarembski (2010) calculated the cost of track renewal using a specialized train to be \$491,330 (including rail, concrete ties, labor and equipment) compared to the cost of a tie gang at \$544,688 per mile. Estimates are also provided for new track construction of \$445,984 and \$459,888 using new track construction train and conventional gang, respectively.

Based to the cost information above, the unit cost of track improvement ranges from \$200,000 to \$600,000, with an average of \$400,000 per mile. For purpose of illustration, an upper value of \$600,000 per mile is assumed to represent one time investment cost on track infrastructure upgrade in the cost-effectiveness analysis.

5.3.2.3 Consequence Costs

Consequence costs can be decomposed into several elements. Saat (2009) considered three major cost components in expressing the total expected consequence cost for accident involving spills of hazardous material: evacuation cost (PHMSA, 2008), environmental cleanup cost (Schaeffer

et al., 2008; Yoon et al., 2009), and extra train-delay cost (Schafer and Barkan, 2008; Schafer, 2008) due to the presence of hazardous material in an accident.

A different set of consequences or parameter values may be appropriate for materials with different hazards such as Toxic Inhalation Hazard (TIH) materials or flammable gases. In this analysis, I assumed an evacuation period of 72 hours (3 days) but this can be adjusted to reflect the hazardous nature of the particular material analyzed and the spill quantities. I assumed an evacuation cost of \$200 per person per day (PHMSA, 2008b) so the estimated consequence cost is \$600 per person affected based on evacuation cost alone.

To estimate the fixed consequence cost, I analyzed data from the Incident Reports Database maintained by the U.S. DOT, Pipeline and Hazardous Materials Safety Administration (PHMSA, 2010). These data contain information regarding various consequence costs such as response cost, remediation cleanup cost and other damage costs associated with a particular hazardous material incident. For the material considered, I determined the average consequence cost per incident to be \$1,434,000 based on the PHMSA data.

The route infrastructure improvement selection model framework is developed based on the U.S. DOT ERG hazard exposure model (PHMSA, 2008) so the consequence estimate is a function of persons affected. An alternative approach would be to use the value of statistical life (VSL) (Viscusi and Aldy, 2003; U.S. DOT, 2008) to represent the consequence cost. If VSL is used for consequence calculation, the rate of injuries and fatalities would need to be estimated.

5.3.2.4 Discount Rate

According to the Office of Management and Budget (OMB, 1992), the discount rate is the interest rate used in calculating the present value of expected yearly benefits and costs. The OMB has provided guidelines for benefit-cost analysis of federal programs, public investments, and regulatory programs that provide benefits and costs to the general public. The discount rates are updated periodically based on the expected interest rates for the first year of the budget forecast (OBM, 1992). For the year 2009, the nominal discount rate was 4.7% and 4.5% for 20-year and 30-year maturity, respectively. In 2008, the rate was 4.9% for both maturities. In this study, I use a discount rate of 5%.

5.3.2.5 Life Cycle Cost

The project life cycle is required to calculate the present value of the investment in track infrastructure improvement. According to OMB (1992), the life cycle cost is the overall estimated cost for a particular program alternative over the time period corresponding to the life of the program, including direct and indirect initial costs plus any periodic or continuing costs of operation and maintenance. Here I consider the investment in track infrastructure upgrade as a one-time cost that represents the overall life cycle cost of track infrastructure. That is, maintenance cost and other costs during the lifetime of track are not incorporated in this analysis.

According to Daniels (2008), the life cycle of the system ranges from 20 to 30 years, and the average track life cycle may be assumed to be on the order of 25 years. In this study, I assume track service life of 30 years.

5.3.3 Bi-objective Route Infrastructure Improvement Selection Model

5.3.3.1 Bi-objective Model Formulation

In the previous section, I discussed the single-objective mathematical models for determining the strategy for track infrastructure upgrade that provides the greatest reduction in risk given constrained resource. A single-objective approach is appropriate if a single unit cost is applied to all types of infrastructure upgrade. However, in practice, each type of upgrade will require different investment amounts. More specifically, the cost associated with track upgrade can be a function of traffic density, types of crosstie, degrees of curvature, and track class (Resor and Patel, 2002; Larsson, 2004; Zarembski and Resor, 2004; Lai et al., 2010; Liu et al., 2010). Based on different cost requirements, a risk manager may be interested in investment strategies that provide the greatest safety benefit, while requiring the minimal amount of investment. This makes the route infrastructure improvement a multi-objective problem.

This section deals with the bi-objective optimization problem of route infrastructure improvement. The bi-objective optimization model allows one to simultaneously consider two conflicting objectives associated with the problem. In the context of track infrastructure improvement, the bi-objective optimization model minimizes hazardous materials transportation

risk and the cost of infrastructure upgrade, while costs are constrained not to exceed a specified level. Accordingly, the development of the bi-objective route infrastructure improvement selection model here serves two purposes. One is to provide information regarding the strategies of infrastructure improvement that maximize safety benefits and minimize investment cost. The second is to illustrate the effect of track-class specific upgrade costs on infrastructure improvement decisions.

The bi-objective route infrastructure improvement selection model can be formulated in the form of a mixed-integer programming problem in which a binary decision variable represents a particular investment decision made for each specific segment. The bi-objective model presented here considers all possible track class upgrades, i.e. class 2 to 3, 2 to 4, 2 to 5, 3 to 4, 3 to 5, and 4 to 5. The model is described as follows:

$$\begin{aligned} \text{Minimize Total Cost } Q = & \sum_{h=2}^5 \sum_{i=1}^{I_2} C_{2i}^h (\lambda S_{2i}^h + \gamma T_{2i}^h) + \sum_{h=3}^5 \sum_{i=1}^{I_3} C_{3i}^h (\lambda S_{3i}^h + \gamma T_{3i}^h) \\ & + \sum_{h=4}^5 \sum_{i=1}^{I_4} C_{4i}^h (\lambda S_{4i}^h + \gamma T_{4i}^h) + \sum_{h=5}^5 \sum_{i=1}^{I_5} C_{5i}^h (\lambda S_{5i}^h + \gamma T_{5i}^h) \end{aligned} \quad (5.11)$$

subject to

$$\sum_{h=2}^5 \sum_{i=1}^{I_2} C_{2i}^h T_{2i}^h + \sum_{h=3}^5 \sum_{i=1}^{I_3} C_{3i}^h T_{3i}^h + \sum_{h=4}^5 \sum_{i=1}^{I_4} C_{4i}^h T_{4i}^h + \sum_{h=5}^5 \sum_{i=1}^{I_5} C_{5i}^h T_{5i}^h \leq X \quad (5.12)$$

$$\sum_{h=2}^5 C_{gi}^h = 1 \quad \text{for } g=2, \text{ and for all } i \in I_2 \quad (5.13)$$

$$\sum_{h=3}^5 C_{gi}^h = 1 \quad \text{for } g=3, \text{ and for all } i \in I_3 \quad (5.14)$$

$$\sum_{h=4}^5 C_{gi}^h = 1 \quad \text{for } g=4, \text{ and for all } i \in I_4 \quad (5.15)$$

$$\sum_{h=5}^5 C_{gi}^h = 1 \quad \text{for } g=5, \text{ and for all } i \in I_5 \quad (5.16)$$

and

$$C_{gi}^h = \text{binary} \quad (5.17)$$

Where

Q = total cost (risk plus track upgrade cost) (\$)

S_{gi}^h = risk cost of transporting hazardous materials on segment i of previous class g given that the segment is upgraded or maintained at track class h standard (\$)

- T_{gi}^h = cost of upgrading segment i from class g to class h (\$)

 = 0 if $h = g$
- C_{gi}^h = binary decision variable that equals 1 if segment i

 with existing track class g is to be maintained at class h
- λ, γ = weighting coefficients
- E = total budget allocation for track infrastructure improvement (\$)
- g = existing track class of segment i
- h = desired track class of segment i to be maintained to, $h \geq g$
- I_g = set of segments of current track class g
- i = segment ID

The model above considers four groups of segments, i.e. class-2 segments ($g = 2$), class-3 segments ($g = 3$), class-4 segments ($g = 4$), and class-5 segments ($g = 5$) in the route as described by four summation terms in the objective function (Eq. 5.11), the budget constraint (Eq. 5.12) and decision constraints (Eq. 5.13 – 5.16). All possible upgrades are considered for each track class, except class-5 track.

The objective function in Eq. (5.11) gives the minimized sum of weighted risk and infrastructure upgrade cost. Note that the weighting coefficients (λ and γ) between 0 and 1 is meaningful when the two conflicting objectives have similar values. Since the magnitude of risk cost and track improvement cost is much different, a larger weight is required for risk objective (see section 5.4.3.2).

The budget constraint in Eq. (5.12) stipulates that the total investment in track infrastructure improvement must not exceed the resource available.

The decision constraints in Eq. (5.13) – (5.16) require a single action on each segment for each class group. That is, if segment i has class $g = 3$, the decision can only be one of the following: upgrade to class $h = 4$ ($C_{3i}^4 = 1$), or $h = 5$ ($C_{3i}^5 = 1$), or maintain it at the same class, $h = g$ ($C_{3i}^3 = 1$). Downgrade of track segment is not allowed, i.e. $h \geq g$.

The binary constraint in Eq. (5.17) sets the value of decision variable C to be either zero or one.

To determine the segment-specific risk cost, Eq. (5.8) can be adapted as follows:

$$S_{gi}^h = \sum_{j=1}^o \sum_{k=1}^p V_{ik} Z_i^h L_i W_{ik}^h (P_{ij} D_i A_j Y_i + G) \quad (5.18)$$

Where

Z_i^h = annual rate of tank car involvement in an FRA-reportable derailment on track segment i upgraded or maintained to class h standards (tank cars derailed per car-mile)

W_{ik}^h = conditional probability of release given that a tank car type k derails, adjusted for maximum speed on track segment i that is upgraded or maintained to class h standards

To maintain track infrastructure, U.S. railroads use ordinary and renewal maintenance techniques (Grimes and Barkan, 2006). The costs associated with these are dependent on track class, traffic density, types of crosstie and curvature (Resor and Patel, 2002; Larsson, 2004; Zarembski and Resor, 2004; Lai et al., 2010; Liu et al., 2010). Liu et al. defined track class upgrade cost as an increase in maintenance cost (ordinary plus renewal costs) from that of an existing class to an upgraded class. Using the relationship developed by Liu et al. (2010), the annual track upgrade cost can be estimated as follows:

$$T_{gi}^h = \{ \alpha_h - \alpha_g + (\beta_h - \beta_g) M_i \} L_i \quad (5.19)$$

Where

α_h = base year fixed cost of maintaining segment under the standards for a higher, upgraded track class h (\$ per mile)

α_g = base year fixed cost of maintaining segment under the standards for current track class g (\$ per mile)

β_h = base year marginal variable cost of maintaining segment under the standards for a higher, upgraded track class h (\$ per million gross ton-miles)

β_g = base year marginal variable cost of maintaining segment under the standards for current track class g (\$ per million gross ton-miles)

M_i = traffic density on segment i (million gross tons)

L_i = length of the track segment i (miles)

5.3.3.2 Estimation of Track Class Specific Upgrade Costs

One of the critical elements of the bi-objective route infrastructure improvement selection model is the estimates of track class specific upgrade cost. Lai et al. (2010) and Liu et al. (2010) provide parameter estimates for track infrastructure upgrade cost in Eq. (5.19). These estimates vary with track class, types of tie and degree of curvature. However, information about type of tie and curvature is not available in the GIS data. Thus, I assume that a route uses wooden ties and has light curvature, which is most representative of the majority of the U.S. railroad network infrastructure.

The variable cost in Eq. (5.19) is a function of traffic density. Segment-specific traffic density can be determined using the national transportation network data from the U.S. DOT Bureau of Transportation Statistics (BTS). To account for variation in traffic over the route network, a segment-specific traffic density can be considered. For illustration, I considered the weighted average density of the entire route. Using BTS (2007) data, the average traffic density on the route considered is 86 million gross tons (MGT).

Using Liu et al. (2010) parameter estimates, annual track upgrade costs for the base year (2008) applicable for wooden tie track with light curvature and annual traffic density of 86 MGT are determined (Table 5.1).

Table 5.1. Estimated track upgrade cost for the route considered.

Track Upgrade Unit Cost (\$ Per Mile) *			
Existing Track Class	Desired Track Class		
	3	4	5
2	10,989	22,566	31,365
3	-	11,577	20,376
4	-	-	8,799

* Assume wooden tie, light curvature,
and traffic density of 86 MGT

5.4 Case Studies of Route Infrastructure Improvement

5.4.1 Route Infrastructure Improvement to Minimize Risk Given Constrained Resources

I developed a case study of track infrastructure upgrade, assuming speed increase after track upgrade and using the same representative route and traffic as described in Chapter 4 to verify the route infrastructure improvement selection model described in Section 5.3.1. A single release scenario is considered for 100 shipments made by a DOT-111A100W4 insulated tank car without a bottom outlet (Table 5.2). The upgrade is constrained to class-3 track upgrade to class 4 at any location on the route under a budget allocation equivalent to an upgrade of 50 miles of track. I used GAMS/CPLEX to solve the MIP model. The optimal strategy involves an upgrade of 68 class-3 segments to class 4 for a total upgrade length of 49.6 miles. The annual risk is reduced from the baseline of 0.779 to 0.471 persons affected per year, a 39% reduction.

The numerical solution obtained from the optimization problem alone may not be sufficient in the context of risk management and planning. Risk managers may prefer to visualize the quantitative results, in particular, the location of the segments to be upgraded along with the magnitude of risk reduction and the changes in the distribution of route risk. Kawprasert and Barkan (2009a) discussed several risk communication techniques to present this information more effectively. Figure 5.1 is a graphical representation of the change in risk distribution along the route together with cumulative route risk (before and after upgrade) based on the output from the optimization process. Chapter 9 provides additional illustration of means to communicate risk analysis results.

Table 5.2. Input parameters for route infrastructure improvement selection model.

Parameter	Value	Unit
Number of Carloads (<i>V</i>)	100	Carloads
Length of Track Segment ¹ (<i>L</i>)	Varies	Mile
Speed-dependent Conditional Probability of Release ² (<i>R</i>)	Varies	No Unit
Segment-specific Population Density ³ (<i>D</i>)	Varies	Persons/Sq.Mi.
Affected Area ⁴ (<i>A</i>)	0.785	Square-mile
Maximum Total Upgrade Length (<i>X</i>)	50	Miles
Track Class-specific Derailment Rates ⁵ (<i>T</i>)		
Class 2 Track	726x10 ⁻⁹	Per Car-mile
Class 3 Track	300x10 ⁻⁹	Per Car-mile
Class 4 Track	77x10 ⁻⁹	Per Car-mile
Class 5 Track	42x10 ⁻⁹	Per Car-mile
Maximum Reduction in Derailment Rate due to Upgrade (<i>M</i>)		
Class 2 Track Upgraded to Class 3	(726-300)x10 ⁻⁹	Per Car-mile
Class 3 Track Upgraded to Class 4	(300-77)x10 ⁻⁹	Per Car-mile
Class 4 Track Upgraded to Class 5	(77-42)x10 ⁻⁹	Per Car-mile
Maximum CPR on the Upgraded Track (<i>Q</i>)		
Class 4 Track (60 mph max.)	0.2940	No Unit
Class 5 Track (70 mph max.) ⁶	0.3307	No Unit

¹ Use BTS (2007) data

² Use Kawprasert and Barkan (2010a) speed-dependent CPR, based on timetable speeds

³ Use ESRI (2005) data

⁴ per the U.S. DOT ERG's Recommendation (PHMSA, 2008)

⁵ from Anderson and Barkan (2004)

⁶ Regulations permit operation of freight trains up to 80 mph (FRA, 2003)
but for the representative route, maximum speed was limited to 70 mph.

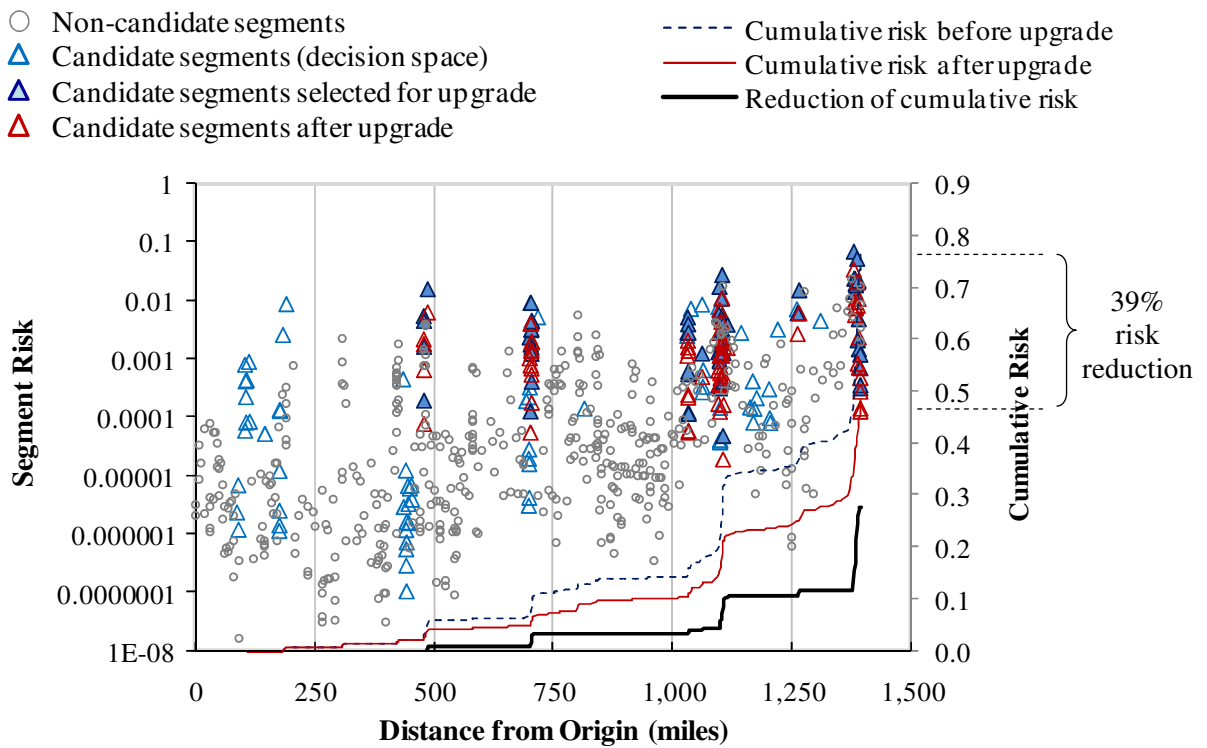


Figure 5.1: Distribution of Segment-specific Risks When 50 Miles of Class-3 Segments Were Upgraded to Class 4 (Upgrade Segments in Any Location to Minimize Risk)

5.4.1.1 Route Infrastructure Improvement Strategies

Risk managers may wish to consider several different strategies to reduce route risk so that they can choose the one that offers the greatest benefit given constrained resources. Likewise, for track infrastructure improvement, there are several possible approaches. In this section, I illustrate the effect of different upgrade strategies on the magnitude of risk reduction. Previously, I considered class-3 segments upgrade because this offers the highest opportunity for risk reduction for the route considered (Kawprasert and Barkan, 2010a). The alternate strategies considered here include: 1) upgrade consecutive class-3 segments, and 2) upgrade any segments of class 4 or lower at any location along the route.

Upgrade Consecutive Class-3 Segments to Minimize Risk

This scenario considers upgrading consecutive class-3 track segments to class 4 along the route given a budget allocation for a 50-mile track upgrade. In this particular case, I used a simulation that was developed using Visual Basic for Application (VBA) to enumerate possible locations and obtain the optimal solution that gives the maximum reduction in risk. The algorithm

performs a one-way search from origin to destination for segments to be upgraded provided that the budget does not exceed an allowable limit. The objective is to measure the safety benefit that this scenario would offer compared to the previous scenario. For a 50-mile upgrade of class-3 segments to class-4, the best solution obtained involves an upgrade of 17 class 3-segments to class 4 with the total upgrade length of 49.8 miles. The route risk decreases from 0.779 to 0.600 persons per year, a 23% reduction.

Figure 5.2 shows the distribution of segment risk before and after upgrade. The previous upgrade scenario (Figure 5.1) gives a higher reduction in risk because of the greater flexibility in choosing segments for upgrade. This scenario with constrained location may favor a more practical upgrade in which consecutive segments having the same class are upgraded such that the risk reduction opportunities are greatest. For this particular case study, the segments chosen for upgraded are located in one area near the end of the route where the risk concentration is relatively high.

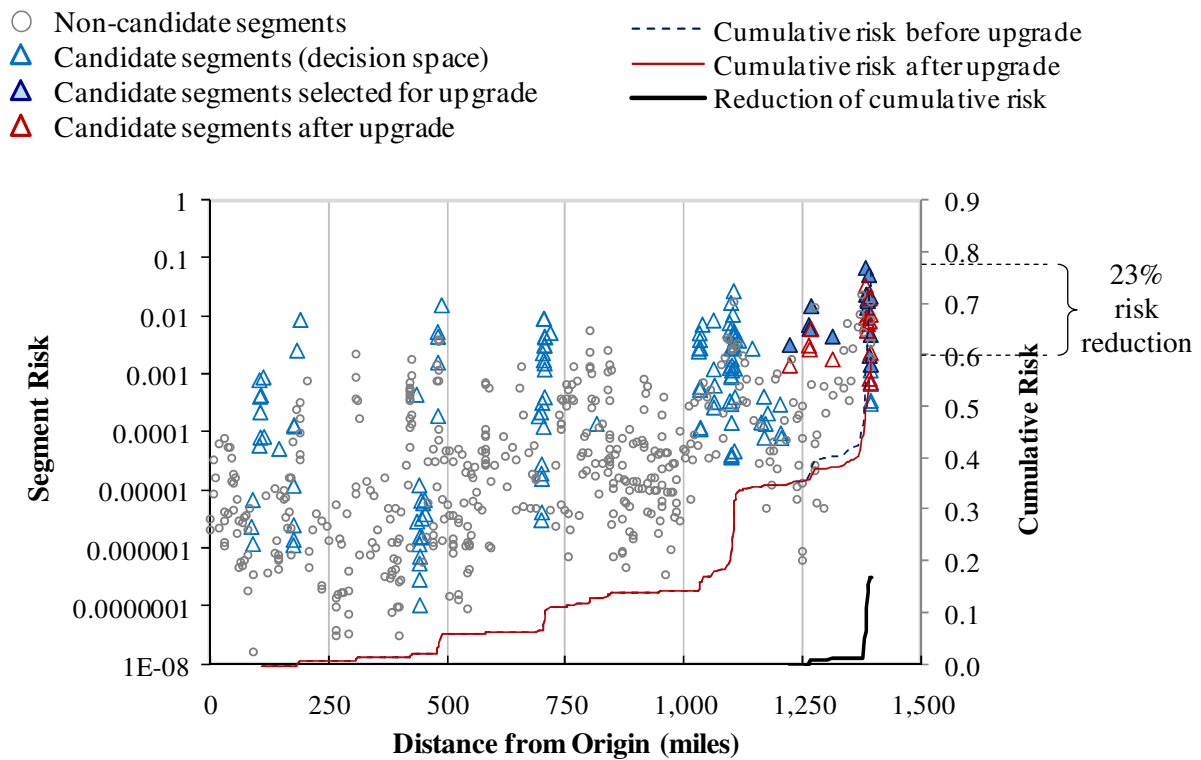


Figure 5.2: Distribution of Segment-specific Risks When 50 Miles of Class-3 Segments Were Upgraded to Class 4 (Upgrade Consecutive Class-3 Segments to Minimize Risk)

Upgrade Any Segment in Any Location

This scenario represents the case with the most flexibility in choosing track segments and locations for upgrade. That is, any segment of class 4 or lower at any location can be chosen for upgrade. Compared to the first upgrade scenario, the magnitude of reduction in risk in this case is only 4% higher (Figure 5.3). Although the model selected some class-2 track segments for upgrade, there is relatively little risk reduction because this track class represents a small proportion of the network. In addition, for the level of investment considered the model did not select any class-4 segments for upgrade because they give smaller reduction in risk compared to upgrading lower-track-class segments.

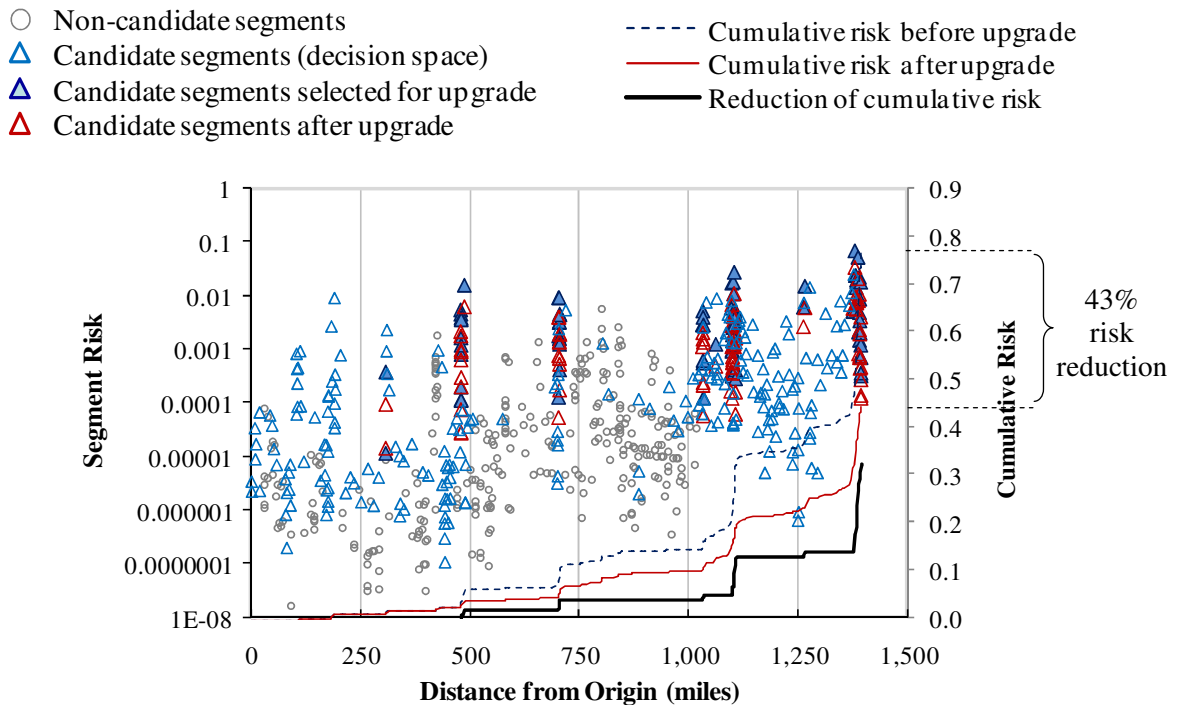
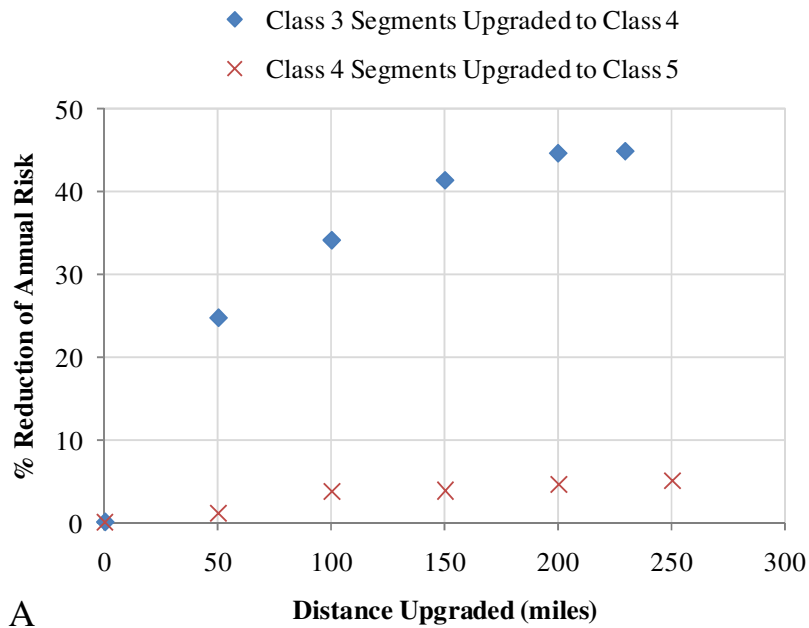


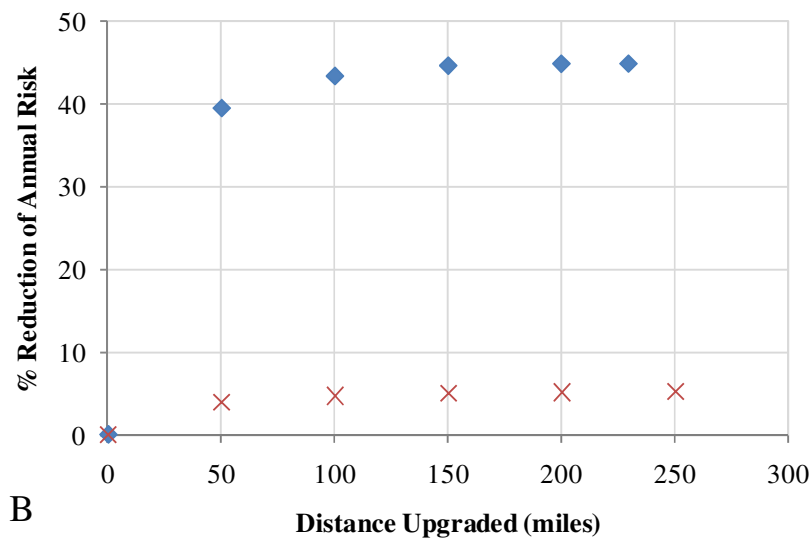
Figure 5.3: Distribution of Segment-specific Risks When 50 miles of Segments of Class-4 or Lower Were Upgraded to One Higher Class

5.4.1.2 Effect of Level of Investment on Risk Reduction

To determine how various levels of investment in track upgrades affect risk, I conducted a sensitivity analysis by varying the total upgrade length to represent different levels of investment in track improvement. I considered the upgrades of classes 3 and 4 because these represent the major proportion of the route. Figure 5.4 shows the percentage risk reduction versus investment level.



A



B

Figure 5.4: Effect of Level of Investment on Risk Reduction

(A) Upgrade Segments in Any Location to Minimize Risk and (B) Upgrade Consecutive Segments to Minimize Risk

From these results, upgrading the higher class track (i.e., class 4 to class 5) has much less effect on risk reduction compared to upgrading lower track classes. This is consistent with the results of Kawprasert and Barkan (2009a; 2010a) and Chapter 4 of this dissertation, that upgrading class-3 segments to class 4 is likely to be a more effective strategy that offers higher

risk reduction. Moreover, there are diminishing returns for investment in infrastructure improvement for risk reduction, as previously shown by Saat and Barkan (2006b). For example, Figure 5.4b shows that at 50 mile increments for distance upgraded, the change in risk reduction is less than 20% after 200 miles of track have been upgraded from class 3 to class 4, and after 100 miles of track have been upgraded from class 4 to class 5. This kind of analysis may be helpful in considering an appropriate level of investment for track infrastructure upgrade to minimize hazardous materials transportation risk.

5.4.1.3 Sensitivity Analysis of Investment Level on Safety Benefit of Track Infrastructure Improvement

The one-time investment level, the discount rate, and the service life are used to calculate the present value of the investment. For example, if $E = \$30$ million, $r = 5\%$, and $t = 30$ years, then $E = \$6.94$ million from Eq. (5.10). The scenario considered is class-3 track upgraded to class 4 applied anywhere on the route. Table 5.3 summarizes the parameters used in this analysis.

Figure 5.5 shows the possible safety benefits for various levels of investment and traffic volume as measured by two metrics: annual reduction in risk cost, and annual reduction in risk cost per investment on track infrastructure improvement, based on the assumptions made.

Table 5.3. Parameters used in the sensitivity analysis.

Parameter	Value
Budget Allocation (E) (million \$)	Varies
Discount Rate (r)	5%
Infrastructure Life Cycle (t)	30 years
Consequence Cost (Y)	\$600 per person affected
Track Upgrade Cost (O)	\$600,000 per mile upgraded

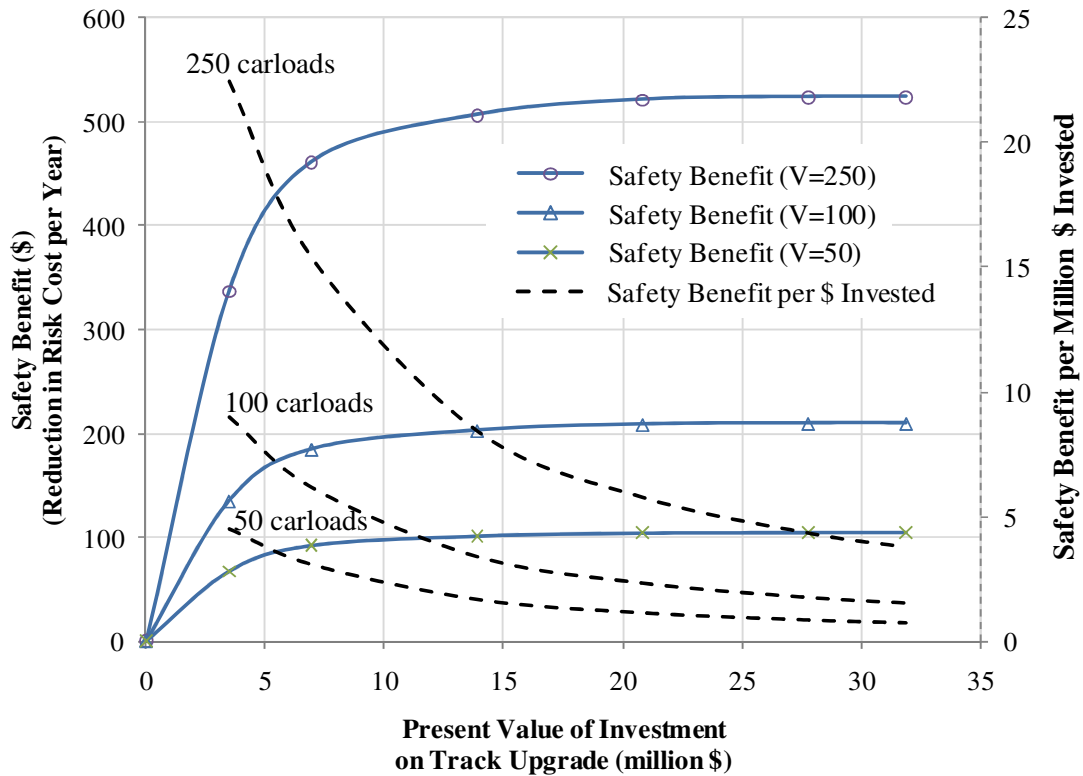


Figure 5.5: Safety Benefit of Route Infrastructure Improvement As Measured by Reduction in Risk Cost per Year

For different levels of investment, safety benefit increases rapidly with the initial investment. However, as investment increases the rate of risk reduction declines with benefit. Similarly, the safety benefit per unit of investment is the highest for the initial levels of investment, then decreases with the level of investment. This represents diminishing marginal returns of route infrastructure improvement. The result is consistent with the finding in Section 5.5 that risk initially decreases rapidly as the high-risk segments (that comprise a small percentage of route length) are upgraded. Since the segments identified for upgrade are rank-ordered, there are diminishing benefits as more are upgraded. Consequently, risk is reduced at a decreasingly lower rate as the lower-risk segments that constitute most of the route are upgraded.

For any given level of investment, track infrastructure improvement provides a safety benefit that is basically a linear function of hazardous material traffic volume on each affected track segment. The more carloads on a track segment, the greater the benefit from track infrastructure improvement. The graph also shows that the sensitivity of the safety benefit per

unit investment is directly related to the traffic. This leads to the intuitive result that investment in track infrastructure improvement is worth more for portions of the network with higher hazardous materials traffic compared to those with less traffic (Liu et al., 2010). In general, the incremental change in hazardous materials traffic is unlikely to affect track deterioration rate and maintenance cost. These costs will be strongly affected by overall tonnage on a route and this must be properly factored into the cost-effectiveness of segment specific upgrades.

The utility of the metric used to quantify risk may vary depending on the type and context of risk management decisions. Figure 5.6 is an alternative representation of the results, using a reduction in annual number of persons subject to evacuation or sheltering in-place as the metric for the benefit. This is equivalent to the difference in annual risk after track infrastructure improvement, compared to baseline risk.

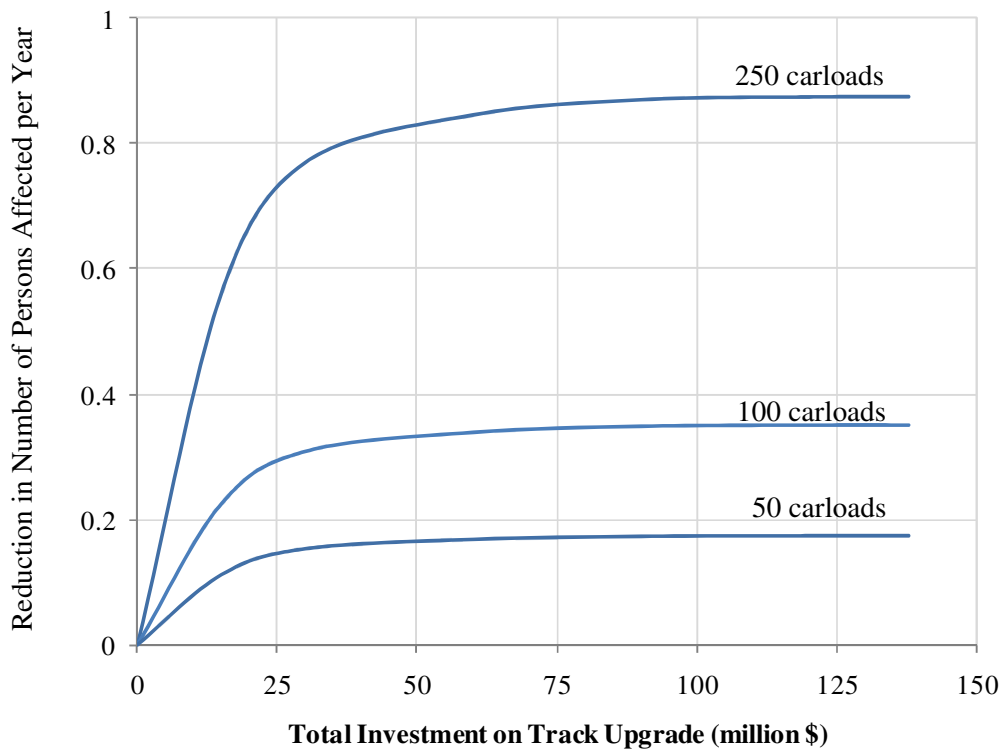


Figure 5.6: Safety Benefit of Route Infrastructure Improvement As Measured by Magnitude of Reduction in Number of Persons Affected per Year

5.4.1.4 Sensitivity Analysis of Track Infrastructure Upgrade Cost

Due to uncertainty associated with the cost estimate of track infrastructure improvement, this section examines how safety benefit changes with the variation in the unit cost of track upgrade. Assuming 100 carloads of the same material over the same route considered before, the unit cost of track upgrade is varied from \$200,000 to \$600,000 per mile at \$100,000 increment. Figure 5.7 shows the result of sensitivity analysis of track upgrade cost. At the same investment level, a lower unit upgrade cost provides a higher benefit. The higher the unit cost, the greater the total budget required to obtain the highest possible reduction in risk. However, the difference in safety benefit is the greatest in the initial levels of investment, i.e. within the range between \$5,000,000 and \$10,000,000.

Apart from cost estimate, there is uncertainty error associated with other risk parameters such as track-class-specific accident rates, CPR and consequence that may affect a quantitative analysis of the benefit of track infrastructure improvement. This issue is discussed in later part of this chapter.

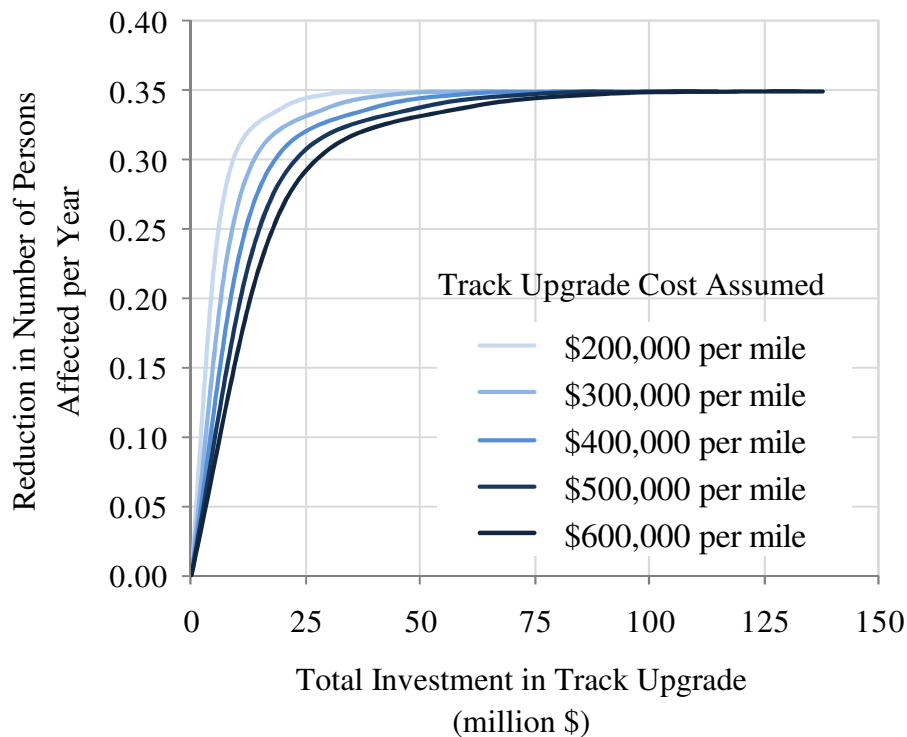


Figure 5.7: Sensitivity Analysis of Track Infrastructure Upgrade Costs

5.4.2 Route Infrastructure Improvement to Minimize Both Risk and Cost

Previous analyses consider one-time investment on track infrastructure improvement. Another approach is to consider track-class-specific upgrade cost defined as an increase in annual track renewal and maintenance cost. Using the cost model of track-class upgrade developed by Liu et al. (2010) and assuming wooden tie, light curvature, and annual traffic of 100 million gross tons, the annual track class upgrade cost is estimated to be \$13,243 per mile.

In Section 5.4.1 a one-time investment cost of \$600,000 per mile is assumed for upgrade cost. If this is equally distributed over the track lifetime of 30 years, then the annual upgrade cost is \$20,000 per track mile. An average cost of \$400,000 per mile would result in annual average cost of \$13,333 per mile, which is closer to Liu et al.'s model estimate. While the capital cost is depreciated over time period, the maintenance cost will be incurred each year. In the next section, I introduce a variation of track infrastructure improvement selection problem that strictly considers track-class upgrades using Liu et al. (2010) cost estimates.

A case study using the same representative route data as Section 5.4.1 was considered. However, the tank car type considered was changed to a more common non-insulated DOT-111A100W1 tank car with 7/16 inch tank thickness without special safety design features beyond the DOT minimum requirements. The average consequence cost previously estimated in Section 5.3.2.3 is incorporated into the model for a more complete cost-benefit analysis of track infrastructure improvement. Instead of using a one-time track upgrade cost, an annual saving in ordinary and renewal track maintenance costs is considered (Liu et al., 2010). In addition to parameters used in Table 5.4, all other input parameters for this case study are the same as those described in Table 5.2.

Table 5.4. Input parameters for bi-objective route infrastructure improvement selection model.

Parameter	Value	Unit
Maximum CPR on the Upgraded Track ¹		
Class 3 Track (40 mph max.)	0.2182	No Unit
Class 4 Track (60 mph max.)	0.2940	No Unit
Class 5 Track (70 mph max.)	0.3307	No Unit
Consequence Costs		
Fixed Cost ²	1,434,000	\$ per incident
Variable Cost	600	\$ per person affected
Annual Investment Budget	1,000,000	\$ per year
Track Upgrade Unit Cost ³	Varies (Table 5.1)	\$ per mile

¹ Use Kawprasert and Barkan (2010a) speed-dependent CPR for particular tank car considered

² Based on PHMSA hazardous material incidents data (see discussion in Section 5.3.2.3 and Chapter 6)

³ Use Liu et al. (2010) cost model for track class upgrade

For each segment, risk and improvement costs can be predetermined for all possible upgrade strategies considered. Therefore, for ease of coding, I developed corresponding risk and cost matrices, each of size of 598x7 (number of segments times number of strategies considered). Wherever, any strategies are not applicable, a large number is assigned as an upgrade cost to prevent the model from choosing impossible strategies while zero is assigned as the corresponding risk value (Table 5.5).

The baseline risk cost (without any upgrades) was determined to be \$10,335. Solving the bi-objective route infrastructure improvement selection model with weighting coefficient λ of 1.0 applied to risk cost in the objective function (Eq. 5.11) under various budget levels yields the optimal solutions shown in Figure 5.8 and Table 5.6.

Table 5.5. Example of risk and cost matrices for the bi-objective model.

Segment-specific Risk Matrix								
Segment Number	Track Class	Strategy						
		Do Nothing	Upgrade from Track Class:					
			2 to 3	2 to 4	2 to 5	3 to 4	3 to 5	4 to 5
1	2	S^2_{21}	S^3_{21}	S^4_{21}	S^5_{21}	0	0	0
2	3	S^3_{32}	0	0	0	S^4_{32}	S^5_{32}	0
3	4	S^4_{43}	0	0	0	0	0	S^5_{43}
4	5	S^5_{54}	0	0	0	0	0	0
...

Segment-specific Upgrade Cost Matrix								
Segment Number	Track Class	Strategy						
		Do Nothing	Upgrade from Track Class:					
			2 to 3	2 to 4	2 to 5	3 to 4	3 to 5	4 to 5
1	2	0	T^3_{21}	T^4_{21}	T^5_{21}	\mathcal{M}	\mathcal{M}	\mathcal{M}
2	3	0	\mathcal{M}	\mathcal{M}	\mathcal{M}	T^4_{32}	T^5_{32}	\mathcal{M}
3	4	0	\mathcal{M}	\mathcal{M}	\mathcal{M}	\mathcal{M}	\mathcal{M}	T^5_{43}
4	5	0	\mathcal{M}	\mathcal{M}	\mathcal{M}	\mathcal{M}	\mathcal{M}	\mathcal{M}
...

\mathcal{M} = large positive number

S^h_{gi} = risk cost of transporting hazardous materials on segment i of previous class g given that the segment is upgraded or maintained at track class h standard (\$)

T^h_{gi} = cost of upgrading segment i from class g to class h (\$)

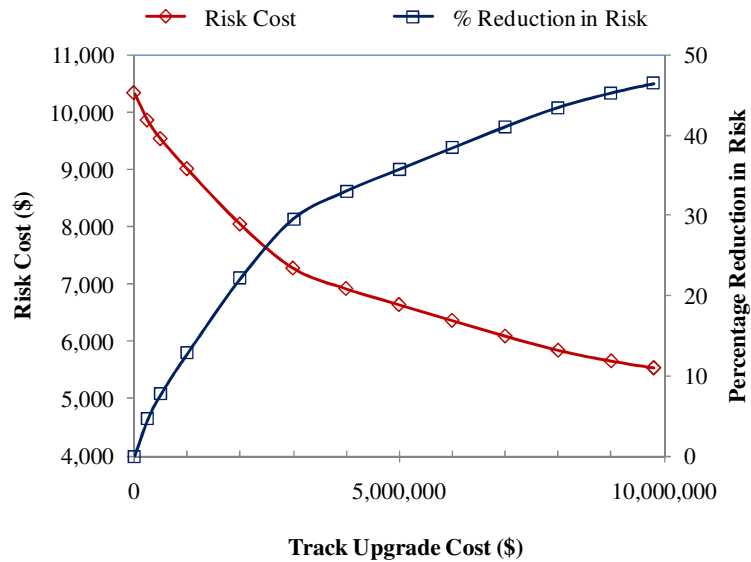


Figure 5.8: Risk vs. Track Upgrade Cost at Optimal Investment Levels

Figure 5.8 indicates that risk decreases at a more constant rate with track infrastructure improvement, compared to the diminishing pattern found in previous analyses (Section 5.4.1.3). This is because of a fixed consequence cost assumed in Eq. (5.18) outweighs the variable component of the consequence cost (Table 5.4).

A maximum possible risk reduction for the scenario considered is 46.5%, corresponding to the investment in track infrastructure improvement of \$9.8 million. There is a noticeable change in rate of risk reduction beyond the investment level of \$3 million.

Table 5.6 shows optimal track infrastructure improvement strategies at each level of budget allocation in more detail. From a budget up to \$3 million, the model suggests upgrading classes 2 and 3; in particular, upgrading class-2 segments to class-4 and class-3 segments to class 4. From a budget of \$4 million, the model suggests upgrading more class-4 track segments. All class-2 segments (11 miles total) are to be upgraded to the highest class 5 at a budget level of \$6 million, while all class-3 segments (230 miles total) and class-4 segments (545 miles total) are to be upgraded to class 5 at \$8 million and \$9.8 million, respectively. With an annual budget of \$9,801,435, all segments in the route can be upgraded or maintained at class-5 track standards. This gives a maximum possible reduction in annual risk of 46.5% from the baseline route risk.

Risk managers may be interested in the basis underlying for how the model prioritizes the investment among different upgrade options. Table 5.6 implies that upgrading classes-2 and -3 track segments to class 4 are the most favorable options for a budget under \$4 million. Above this level, the better strategies (that give a higher reduction in risk) would be upgrading all classes 2, 3 and 4 to class 5. Class 4 track segments have the highest proportion of total route length, but converting them to class 5 results in less reduction in risk per mile upgraded, compared to upgrading other classes. Thus, above \$4 million investment, the rate of risk reduction declines.

It may be useful to consider how each upgrade option offers benefit while requiring a different level of investment. Table 5.7 shows the magnitude of reduction in accident rates due to upgrading different track classes. It is obvious that the safety benefit in term of accident rate reduction per mile upgraded is the highest for the lowest track class upgrades and the lowest for the highest track class upgrades. Thus, the model would favor upgrading lower class track before choosing higher classes.

Table 5.6. Optimal track infrastructure improvement strategies.

Baseline Risk Cost = \$10,335

Budget Level (\$)	Objective Function (\$)	Budget Used (\$)	Reduction in Risk (%)	Metric	Track Upgrade from Class:					
					2 to 3	2 to 4	2 to 5	3 to 4	3 to 5	4 to 5
0	10,335	0	0.0	(\$)	0	0	0	0	0	0
				(miles)	0	0	0	0	0	0
250,000	9,859	249,992	4.6	(\$)	0	45,035	0	204,956	0	0
				(miles)	0	2	0	18	0	0
500,000	9,534	499,989	7.8	(\$)	71	103,697	0	396,220	0	0
				(miles)	0	5	0	34	0	0
1,000,000	9,009	999,963	12.8	(\$)	0	103,844	0	896,119	0	0
				(miles)	0	5	0	77	0	0
2,000,000	8,043	1,999,988	22.2	(\$)	0	103,844	0	1,896,144	0	0
				(miles)	0	5	0	164	0	0
3,000,000	7,274	2,999,969	29.6	(\$)	0	237,276	0	2,515,390	241,305	5,998
				(miles)	0	11	0	217	12	1
4,000,000	6,917	3,999,999	33.1	(\$)	0	114,704	170,366	1,821,032	1,473,239	420,658
				(miles)	0	5	5	157	72	48
5,000,000	6,636	4,999,997	35.8	(\$)	0	114,704	170,366	993,804	2,929,195	791,929
				(miles)	0	5	5	86	144	90
6,000,000	6,362	5,999,999	38.4	(\$)	0	0	329,795	298,463	4,153,024	1,218,717
				(miles)	0	0	11	26	204	139
7,000,000	6,088	7,000,000	41.1	(\$)	0	0	329,795	13,981	4,653,724	2,002,499
				(miles)	0	0	11	1	228	228
8,000,000	5,840	7,999,945	43.5	(\$)	0	0	329,795	0	4,678,331	2,991,819
				(miles)	0	0	11	0	230	340
9,000,000	5,653	8,999,999	45.3	(\$)	0	0	329,795	0	4,678,331	3,991,873
				(miles)	0	0	11	0	230	454
10,000,000	5,533	9,801,435	46.5	(\$)	0	0	329,795	0	4,678,331	4,793,308
				(miles)	0	0	11	0	230	545

Table 5.7. Benefit of reducing accident rates by upgrading different track classes.

Reduction in Accident Rates (Cars Derailed per Billion Car-miles)*				Track Upgrade Cost : Reduction in Accident Rate Ratio			
Existing Track Class	Upgraded Track Class			Existing Track Class	Upgraded Track Class		
	3	4	5		3	4	5
2	426	649	684	2	26	35	46
3	-	223	258	3	-	52	79
4	-	-	35	4	-	-	251

*Based on Accidents Rates from Anderson and Barkan (2004)

The right hand side of Table 5.7 shows the values of track upgrade unit cost divided by the corresponding reduction in accident rates. For example, one mile of class-4 track upgrade would require \$251 to reduce the annual number of cars derailed by one per billion car-miles. Thus, for the same amount of benefit in reducing accident rates, upgrading higher track classes requires a higher investment, especially upgrading class 4 to 5.

This analysis provides important ideas regarding the prioritization of the investment strategies. There are several other factors involved in the optimization process; for example, a different magnitude of speed increase and consequently the CPR corresponding to each upgrade strategy. For the same track-class upgrade, the locations affect the decision because of different exposure level to population and environment. The optimization model framework takes into account and integrates all these aspects thereby providing an efficient tool to facilitate a risk-based decision making on track infrastructure improvement.

Another useful tool is a graphical illustration of the optimal strategies selected. The techniques described by Kawprasert and Barkan (2009a) (Chapter 9) can be applied to show the locations along the route where different strategies would be applied. Such illustrations will complement the numerical results shown in Table 5.6 and provide additional useful information to risk managers.

5.4.3 Additional Case Studies Using Uniform Segment Length

In this section, I develop additional case studies using uniform track-segment length. The effect of segment length on the risk reduction optimization problem is formally analyzed in the later part of this chapter. The purpose of this analysis is to show the distribution of risk of upgraded segments when segment length is uniform and to consider additional variation of route infrastructure improvement problems using equal-length route segments.

For this particular study, I consider a set of track segments, each having a length of two miles (Figure 5.9), the percentage distribution of track class by length is: class-2 track 1%, class-3 track 20%, class-4 track 35%, and class-5 track 44%. I assume 100 annual carloads of a particular hazardous material made using a non-insulated DOT 111A100W1. The speed-dependent CPR is computed using the relationship developed in Chapter 4, assuming that the train is operated at maximum track class speeds and not exceeding 70 miles per hour on class-5 track.

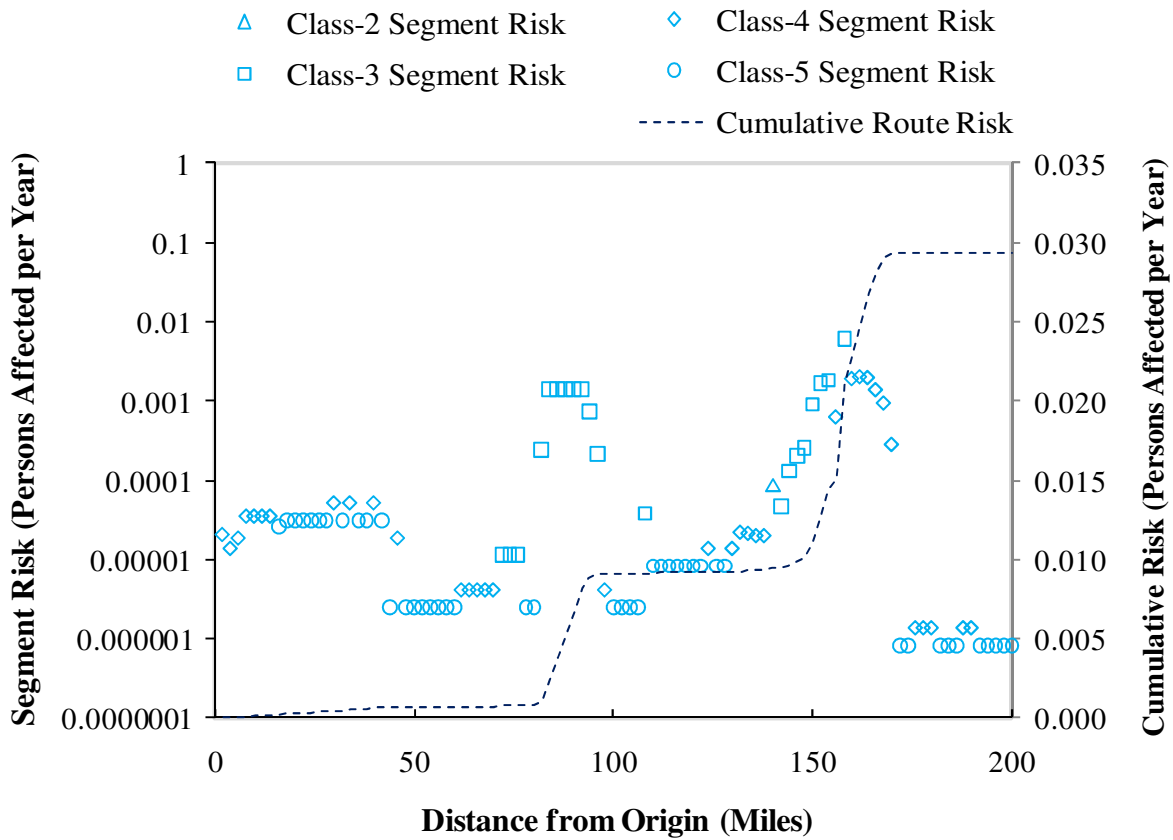


Figure 5.9: Baseline Risk of the Hypothetical Shipment Route Comprising 100 Segments of Equal Length

5.4.3.1 Single Objective Problem of Minimizing Risk

I apply the route infrastructure improvement selection model to determine the optimal locations for upgrade that provide the greatest reduction in risk. In this analysis, I consider track-class-specific upgrade cost, defined as the difference between annual track maintenance and renewal costs of baseline and upgraded tracks per Liu et al. (2010). Assuming annual traffic density of 50 MGT throughout the route having wooden ties and light curvature, Liu et al. (2010)'s estimate yields track-class-specific upgrade costs as shown in Table 5.8.

In this optimization problem, both location and track class are not constrained so upgrades can be made on any segment along the route. Furthermore, a track segment can be upgraded to any higher classes (e.g. class-2 segments can be upgraded to class 3, 4 or 5). The optimization accounts for a tradeoff between an increase in CPR and a reduction in accident rate due to track class upgrade, so a train is assumed to operate at the maximum authorized track speed for the upgraded track class.

Table 5.8. Estimated track upgrade cost for the hypothetical route considered.

Existing Track Class	Track Upgrade Unit Cost (\$ Per Mile)*		
	Desired Track Class		
	3	4	5
2	6,921	14,214	19,773
3	-	7,293	12,852
4	-	-	5,559

*Assume wooden tie, light curvature,
and annual traffic density of 50 MGT

Under a budget of \$500,000, the optimal upgrade strategy and the magnitude of risk reduction are shown in Table 5.9 and Figure 5.10. Route risk is reduced from the baseline of 0.02937 to 0.01068 persons affected per year, a 63.6% reduction. This scenario requires an upgrade budget of \$495,282.

The segment length is the same throughout the route and the objective is to minimize risk, so the model simply chose segments with the highest risk for upgrade to achieve the greatest risk reduction given the budget available. Much of the risk reduction is achieved by upgrading class-3 track to class 5 (Table 5.9). Following the upgrade, lower track-class segments were converted into higher class, thus risk was reduced on what had previously been on low-class segments. If it is assumed that operating speed will increase commensurate with the upgrade in track class, then CPR will be increased while accident rate will be reduced resulting in an overall reduction in risk. In this particular example the segments selected for upgrade are located in populated areas where operating speeds should be limited. Therefore, if information regarding a local speed restriction is known in advance, it could be incorporated into the model for a more accurate estimation of risk. Depending on circumstances, it may be better to assume that speed is maintained the same after upgrade.

Table 5.9. Optimal upgrade strategy that minimizes risk under a \$500,000 investment.

Track-class Upgrade	Length, Miles (% of Total)	Risk, Persons (% of Total)
Before Upgrade		
Class-2 Segments	2 (1)	0.00009 (0.3)
Class-3 Segments	40 (20)	0.01940 (66)
Class-4 Segments	70 (35)	0.00944 (32)
Class-5 Segments	88 (44)	0.00045 (1.5)
Total	200 (100)	0.02937 (100)
After Upgrade		
Class-2 Segments (No Upgrade)	0 (0)	0.00000 (0.0)
Class-2 Segments Upgraded to Class 3	0 (0)	0.00000 (0.0)
Class-2 Segments Upgraded to Class 4	2 (1)	0.00002 (0.2)
Class-2 Segments Upgraded to Class 5	0 (0)	0.00000 (0.0)
Class-3 Segments (No Upgrade)	8 (4)	0.00007 (0.7)
Class-3 Segments Upgraded to Class 4	4 (2)	0.00006 (0.6)
Class-3 Segments Upgraded to Class 5	28 (14)	0.00413 (39)
Class-4 Segments (No Upgrade)	56 (28)	0.00050 (4.7)
Class-4 Segments Upgraded to Class 5	14 (7)	0.00545 (51)
Class-5 Segments (No Upgrade)	88 (44)	0.00045 (4.2)
Total Class-2 Segments	0 (0)	0.00000 (0.0)
Total Class-3 Segments	8 (4)	0.00007 (0.7)
Total Class-4 Segments	62 (31)	0.00058 (5.4)
Total Class-5 Segments	130 (65)	0.01003 (94)
Grand Total	200 (100)	0.01068 (100)

- △ Baseline Segment Risk (Class-2)
- Baseline Segment Risk (Class-3)
- ◇ Baseline Segment Risk (Class-4)
- Baseline Segment Risk (Class-5)
- ▲ Class-2 Segment Selected for Upgrade
- Class-3 Segment Selected for Upgrade
- ◆ Class-4 Segment Selected for Upgrade
- △ Class-2 Segment After Upgrade to Class-4
- Class-3 Segment After Upgrade to Class-4
- Class-3 Segment After Upgrade to Class-5
- ◇ Class-4 Segment After Upgrade to Class-5
- Cumulative Route Risk Before Upgrade
- Cumulative Route Risk After Upgrade

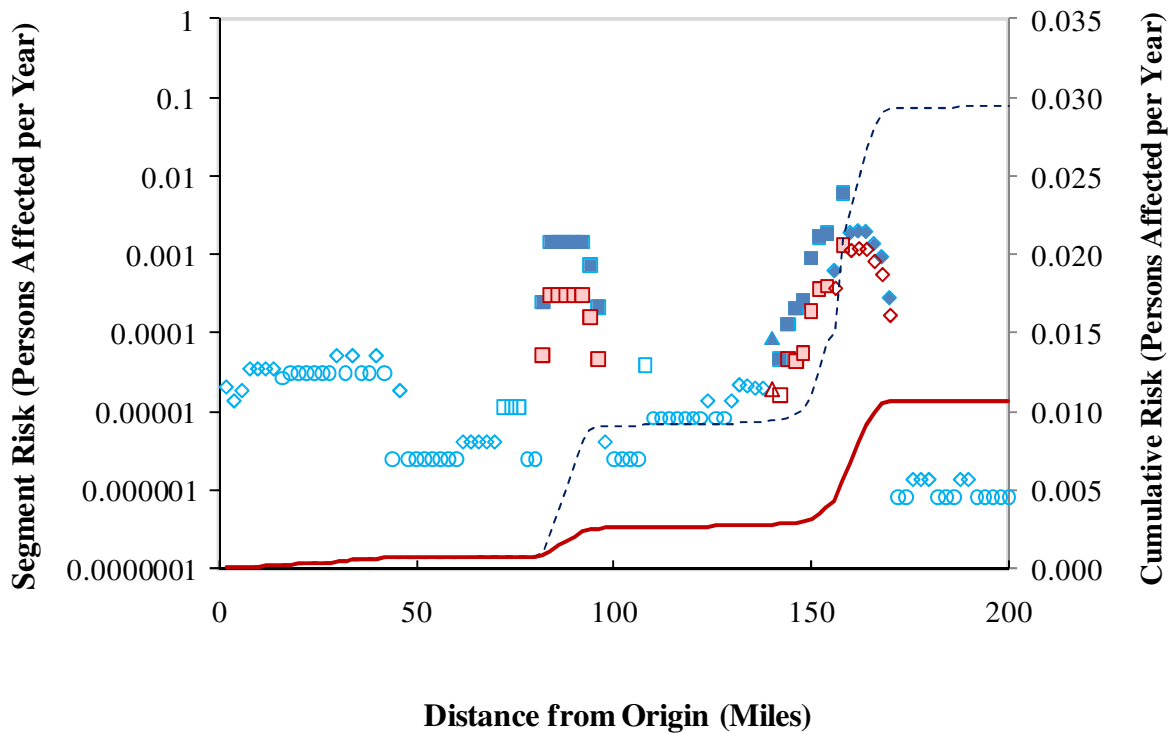


Figure 5.10: Optimal Upgrade Strategy that Minimizes Risk Under a \$500,000 Investment

5.4.3.2 Bi-objective Problem of Minimizing Risk and Cost

The route infrastructure improvement selection problem can be adapted to accommodate different objectives of interest. A possible variation is to minimize both risk and upgrade cost using the bi-objective optimization described earlier in Section 5.3.3. However, there are two issues regarding the bi-objective route infrastructure improvement problem: lack of an accurate estimate of consequence cost and a difference in magnitude of risk cost and track infrastructure improvement cost.

To address the first problem, I used information from the Pipeline and Hazardous Materials Safety Administration (PHMSA) incident reports database, together with some additional estimates from other sources to develop average consequence cost. However, if better information were available, a more accurate estimate could be developed and incorporated into the hazardous materials transportation decision framework.

The second issue is more problematic since the risk cost is outweighed by infrastructure improvement cost so that the bi-objective optimization will never choose track segments for upgrade. For example, for the case study presented in Figure 5.9, I calculated the baseline risk to be 0.02937 persons per year and baseline annual track maintenance cost to be \$9,379,844. Track maintenance cost here refers to track-specific ordinary maintenance and renewal costs (See Liu, 2010). If the consequence cost is \$1,000,000 per incident and risk is expressed in a monetary value, the bi-objective model would choose do nothing because track-upgrade cost outweighs risk cost. A weighting coefficient may be applied to risk cost and upgrade cost in the objective function with a much greater magnitude of weight applied to risk. Another method is to normalize risk and investment costs by appropriate constants. For example, by normalizing each cost element in the objective function by its baseline value, an optimal solution can be obtained (Figure 5.11).

Compared to the case of minimizing risk (Figure 5.10), the optimal upgrade strategy for minimizing the total cost comprising risk and track upgrade costs is slightly different. The latter involves upgrading 4%, 11% and 7% of route length from class 3 to class 4, class 3 to class 5, and class 4 to class 5, respectively, a total upgrade length of 44 miles. Route risk is reduced from 0.02937 to 0.01087 persons affected, a 63% reduction. This scenario requires an annual budget for track renewal and maintenance to increase from \$9,379,844 to \$9,798,758, an increase of \$418,914 or 4.5% from baseline. Further improvements than the optimal would cause the total cost in the objective function to increase.

- △ Baseline Segment Risk (Class-2)
- Baseline Segment Risk (Class-3)
- ◇ Baseline Segment Risk (Class-4)
- Baseline Segment Risk (Class-5)
- ▲ Class-2 Segment Selected for Upgrade
- Class-3 Segment Selected for Upgrade
- ◆ Class-4 Segment Selected for Upgrade
- △ Class-2 Segment After Upgrade to Class-4
- Class-3 Segment After Upgrade to Class-4
- ◇ Class-3 Segment After Upgrade to Class-5
- ◇ Class-4 Segment After Upgrade to Class-5
- Cumulative Route Risk Before Upgrade
- Cumulative Route Risk After Upgrade

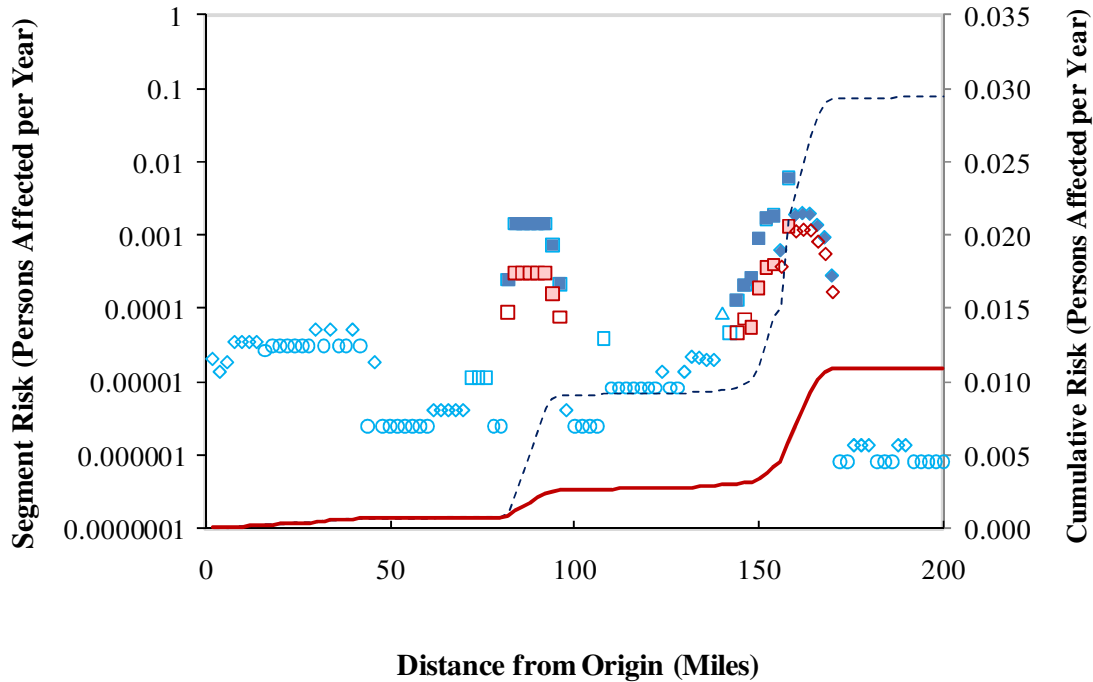


Figure 5.11: Optimal Upgrade Strategy that Minimizes Risk and Improvement Costs Under a \$500,000 Investment

5.4.3.3 Managing Route Infrastructure to Minimize Risk and Cost

Another variation of the route infrastructure improvement selection problem is to determine the optimal track classes to be maintained considering a tradeoff between annual risk and track maintenance cost. A similar problem with consideration of transportation and track maintenance costs was previously addressed by Lai et al. (2010) without integrating risk elements. In the context of hazardous materials transportation, track classes could be managed in such a way that total annual risk and cost of track maintenance are minimized. The route infrastructure improvement selection model can readily accommodate this variation of track infrastructure improvement. Using the same case study, the model determines the optimal track classes as

shown in Figure 5.12. The annual track maintenance cost is reduced from the baseline cost of \$9,379,844 to \$8,535,764 per year, a 9% reduction, while the annual risk is reduced from 0.02937 to 0.01186 persons per year, a 59.6% reduction.

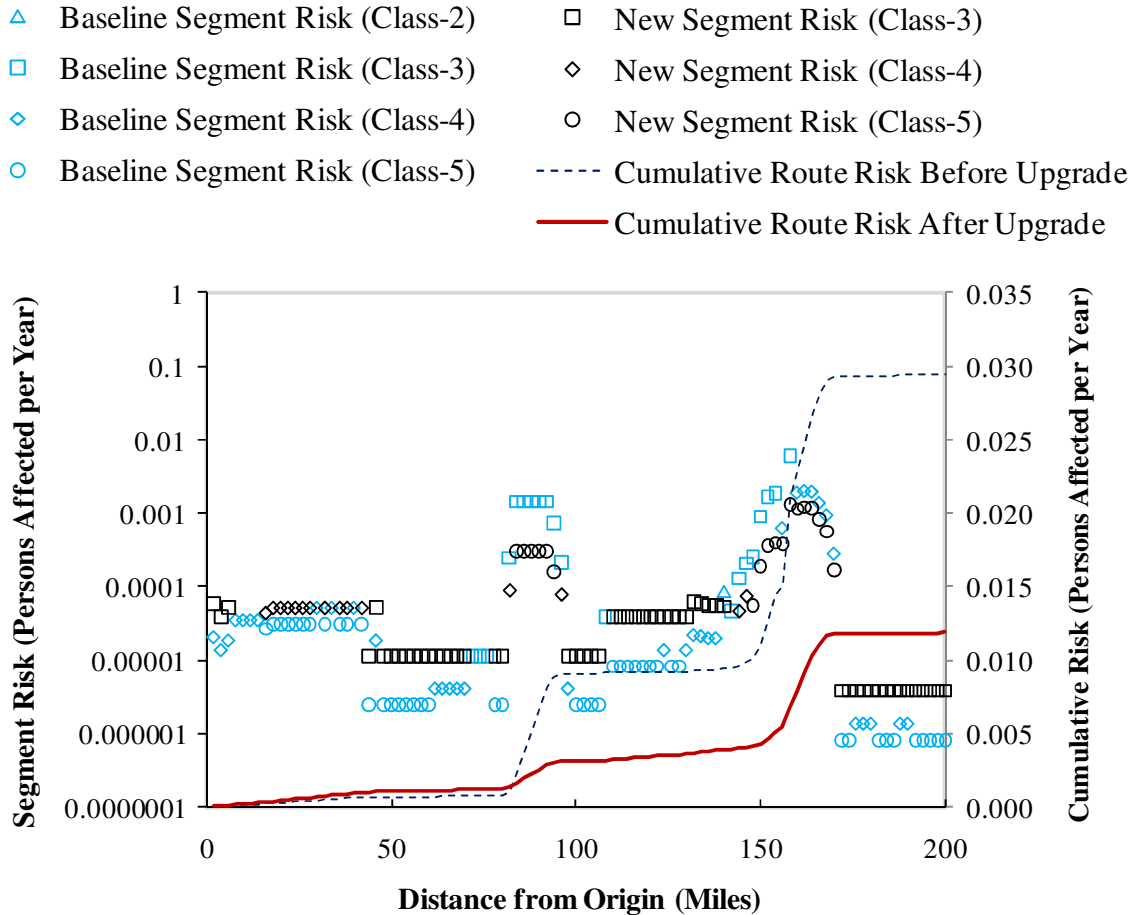


Figure 5.12: Optimal Track Classes that Minimizes Risk and Track Maintenance Costs

5.5 Effect of Track Segment Lengths in Risk Estimation and Optimization Problems

Hazardous materials transportation risk analysis often involves examination of network infrastructure and operating characteristics to determine opportunities for safety improvement. These may be performed at different levels ranging from relatively short, individual track segments, to shipment route, up to the network level. Segment-specific level analysis involves a detailed process in which each individual track segment is examined for each pertinent characteristic. Estimation of route risk typically involves analysis of a group of segments that comprise the route. The granularity of the route risk analysis affects, and will be affected by, the

length of the individual segments, with more detailed or finer grained analyses requiring shorter segments. However, segment length may or may not be able to be controlled by the risk analyst. In particular, the necessary database will often drive the granularity that is feasible in a route risk analysis. Consequently, it is important to understand how this affects route risk estimation, and in the context of this research, segment-specific risk estimation and optimization of infrastructure upgrade.

Prior studies have used the transportation network data provided by the Bureau of Transportation Statistics (BTS) of the U.S. Department of Transportation (DOT) (e.g. Saat and Barkan, 2006a; Kawprasert and Barkan, 2008; 2009a; 2010a). The BTS transportation network database offers a convenient basis for analysis because the data are available online in Geographic Information System (GIS) format that facilitates various aspects of hazardous materials transportation risk analysis. GIS software can be used to aid the risk estimation process, in particular, the consequence analysis that involves estimation of population exposure. The GIS database makes estimation of segment-specific risk relatively simple because rail lines are divided into segments or links defined by the Federal Railroad Administration (FRA) transportation network structure.

Examination of the U.S. rail transportation network structure (BTS, 2007) shows that lengths of these rail segments vary, ranging from a minimum of 0.002 miles, to a maximum of 56 miles, with an average of 1.3 miles and a standard deviation of 2.5 miles. These values will vary depending on the particular network considered. Railroads may develop their own proprietary databases with different segmentation, but the BTS rail network data will often be used by government, public sector, academic researchers and risk analysts who may not have access to proprietary data. In any case, variation of rail segment lengths can affect the results of quantitative risk analysis and risk optimization. The principal objective of this study is to address potential effects of track segment length in hazardous materials transportation risk analysis and certain risk optimization problems so as to obtain a better understanding of how the segment length affects risk and optimization results, and consequently, decision-making. Discussion of uncertainties in risk estimates and potential improvements in track-segment-specific risk analysis are also presented.

5.5.1 Effect of Segmentation on Track-segment-specific Risk Analysis

Using appropriate segment lengths in hazardous materials transportation risk analysis may help improve the accuracy of risk estimates, in particular, estimation of the consequences of a hazardous material release. Consequence analysis at the track-segment-specific level involves estimation of the number of persons potentially affected by a hazardous material release. Recent studies have used population census tract data from the U.S. Census Bureau and simplified the consequence analysis by considering a weighted average population density within an exposure area (Kawprasert and Barkan, 2008; 2009a). There is uncertainty associated with this process of estimating the consequences due to variation in population density of census tracts coincident with each individual track segment. Figure 5.13 represents different patterns of population distribution along a track segment that are generally found in the population census tract database.

Figure 5.13A shows a track segment with a uniform population density in the exposure area, so there is a minimal error associated with the weighted average of population density.

Figure 5.13B is the case in which a rail line is shared between two population census tracts with different densities, one on each side of the track segment. This case may be associated with an error in estimation of the number of persons affected, depending on the shape of the affected area considered and the prevailing wind direction.

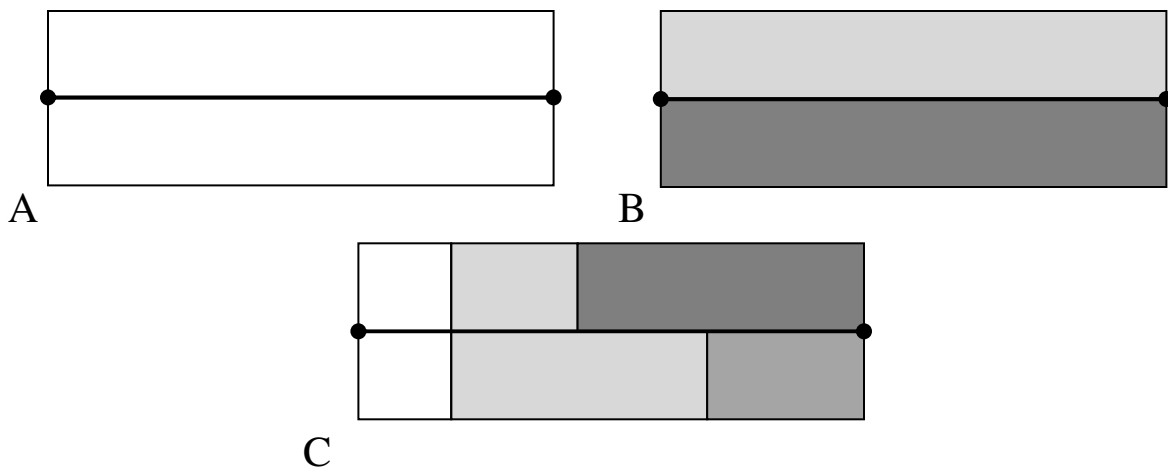


Figure 5.13: Illustration of a Track Segment with Different Population Distributions (A) Uniform Population Density, (B) Different Population Densities on Each Side of Track, and (C) Non-uniform Population Density Along the Track

The U.S. DOT recommends either a semicircle with an adjoining square (Figure 3.8 in Chapter 3) or a circle (Figure C.1 in Appendix C) for an affected area, depending on the products considered (PHMSA, 2008). Considering wind direction, there would be no problem caused by averaging population densities of census tracts if the affected area is a circle along the rail line. This is the case for most analyses in this dissertation. For some other products that require a semicircle with an adjoining square, there is an uncertainty due to wind direction. That is, when the wind direction forms an angle with the rail line, the weighted average population exposure would be prone to error. This requires a probabilistic technique to account for variation of wind directions.

Figures 5.13A and 5.13B show the patterns of population census tract density that are often found in rural or remote areas where the variation in density is less and segment lengths tend to be longer compared to urban areas. As long as a similar pattern of population distribution exists, use of a shorter segment length would not be beneficial for either case. Figure 5.13C represents a typical case for urban areas in which population census tracts are smaller in size with a greater variation in population density along the track segment. The larger the difference in population census tract densities, the greater the uncertainty associated with the weighted average population density assigned to each track segment, especially when a track segment is long. By contrast to cases 5.13A and 5.13B, using shorter segments may help reduce the error in local risk estimates in this case. Therefore, using a uniform segment length may not always be an ideal option in the context of segment-specific risk estimation.

While using finer segmentation (i.e., shorter segments) may offer greater accuracy in risk estimates, it also increases the computational effort, in particular, for geoprocessing in GIS. Use of equal segment length may not be the best option unless one can determine a single, optimal length that minimizes total error in consequence estimation. This is rather difficult because the optimal length also varies with the particular route or transportation network considered. Certain conditions in the frequency analysis of hazardous material releases further complicate the determination of optimal segment length.

Apart from uncertainties in the consequence analysis, there are uncertainties associated with the frequency analysis of a hazardous material release that contribute to error in risk estimation. First, there is no information regarding the FRA track classes in the national

transportation network database. Thus, maximum speeds from timetables are generally used to assign track class in segment-specific risk analyses of hazardous material transportation (Kawprasert and Barkan, 2009a; 2010a). This process involves coordinating mileposts in timetables with route segments in a GIS database and assigning track class to each segment based on maximum track speed. The problem is that track speed delineation in timetables may not correspond to links in the national transportation network structure. A long segment in a GIS transportation database may comprise track sections with different characteristics such as operating speeds or track maintenance standards. Such differences could be sufficient to introduce differences in track classes within a segment and consequently confound the accident rates that should be assigned. One approach is to assign a single speed and track class to each segment that represents the worst-case scenario to avoid breaking a long segment into shorter ones. This will result in an overestimate of track-class-specific accident rates and consequently release frequency for part of the segment. Using industry data with actual maintenance and operating characteristics to define segments may help reduce such uncertainties when calculating accident rates and speed-dependent conditional probability of release. However, some error will persist due to other sources of heterogeneity in track segment characteristics. For example, a train may actually be operated at different speeds along track segments with the same maintenance standard, and track segments are also subject to heterogeneity in population density along the route.

Another difficulty is assigning operating speeds to track segments in the case of multiple-track sections along the route. Route sections may involve different operating speeds (such as main tracks and sidings). Actual operating conditions are usually not available for detailed analysis at segment-specific level. For example, a train may slow down and stop on a siding track at intermediate stations en-route for crew changes, fueling or meets and passes, or it may take the mainline track and pass through without stopping. In timetables, main and siding tracks are sometimes associated with different maximum permissible speeds, which may signify different track conditions. Operating speeds and actual track conditions may be different enough so that each track type should be assigned a different accident rate. In the risk calculations in this dissertation, I assumed that hazardous material trains would take the main track at maximum track speed.

Similar to the case of consequence analysis mentioned earlier, using a uniform segment length may not be as efficient as variable segment lengths in light of route risk estimation unless one can determine the optimal length that minimizes overall heterogeneity within each segment so as to reduce the total errors in the frequency analysis. That is, use of variable segment lengths in which each single segment has the same infrastructure and operating characteristics throughout the segment may be more appropriate. Determining a single, optimal segment length for use in hazardous materials transportation route risk analysis remains a challenge. For the transportation network considered, the optimal segment length must minimize errors and uncertainties in both frequency and consequence analyses to provide the most accurate estimate of risk.

5.5.2 Effect of Segmentation on Risk Optimization

This section discusses the effect of segment length in risk optimization problems, in particular, optimization of route risk reduction by track infrastructure improvement. Variation in track segment lengths considered in such problems may affect the result of the optimization. Although the route infrastructure improvement selection model focuses on track-segment-specific level analysis, the same model structure is applicable to analysis at the route or network level. The following discussion and analyses are based on a segment-specific level.

To understand the effect of segment length in the track infrastructure upgrade problems, I considered a single track segment and the same segment divided into two shorter sections with equal length (Figure 5.14). In some situations, there is a chance that the route infrastructure improvement selection model will not pick up a long segment (Figure 5.14A) if it causes an investment cost to exceed the budget level specified. Instead, the model may select a shorter segment (Figure 5.14B) if it fits within the budget for upgrade despite its lower risk due to its shorter length. This situation can arise even if the risk reduction per mile of upgrade for longer and shorter segments is the same or lower and it would arise as we approach the budget limit, that is, it may not occur in general. Also, it is more likely with larger differences in segment length.



Figure 5.14: Illustration of a Track Segment
(A) Without Division and (B) With Equal Divisions

Recall that in the optimization result for the route infrastructure improvement selection problem shown in Figure 5.1, many high risk segments were not selected for upgrade. For this case, upgrade of those segments would cause the budget to exceed a maximum allowable level. When Figure 5.1 is re-plotted using segment risk per mile in the primary vertical axis on the left hand side, it is evident that the route infrastructure improvement selection model generally seeks the track segments with the highest risk per-mile that altogether give the greatest reduction in risk provided that the total investment cost is within the limit (Figure 5.15).

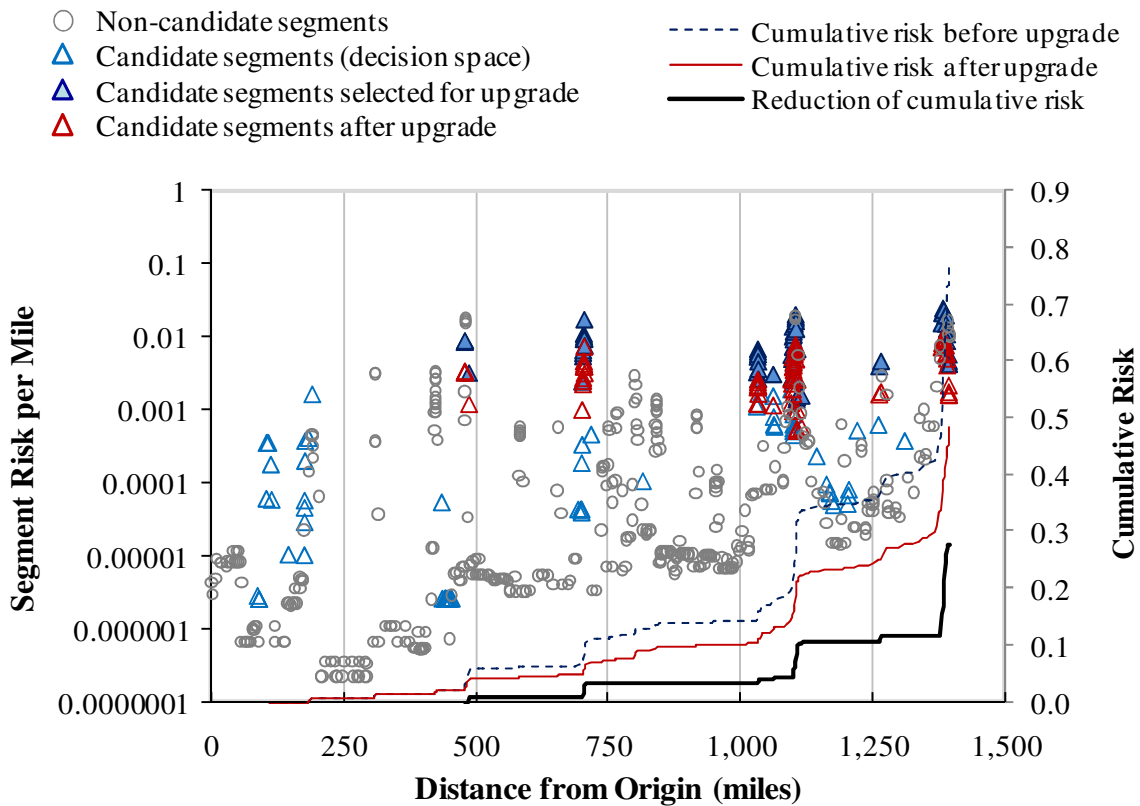


Figure 5.15: Distribution of Segment Risk per Mile When 50 miles of Optimal Segments Were Upgraded to Next Higher Class

5.5.3 Optimality of Route Infrastructure Investment Selection Problem

The route infrastructure improvement selection model aims at identifying segments for upgrade to minimizing risk given that upgrade cost does not exceed the budget limit. The set of optimal solutions depends on upgrade strategies and assumption about the costs. The graphical representation (Figure 5.15) depicts a set of segments corresponding to an optimal solution to facilitate risk communication. However, it does not illustrate how the optimality is reached. To provide better understanding, I consider a small set of segments to assess the decision rules of three scenarios for track infrastructure improvement with the objective of minimizing risk: 1) upgrade any track class at any location to the next higher class, 2) upgrade a certain track class anywhere to the next higher class, and 3) upgrade consecutive segments of the same track class to the next higher class. Then, I illustrate how optimal decision of track infrastructure improvement is reached using a Pareto efficient frontier. Another purpose is to illustrate how track segmentation would affect the optimal decisions and use of resources.

5.5.3.1 Decision Rules of Route Infrastructure Improvement Problems of Minimizing Risk

In this section I elaborate on the decision rules applied to the route infrastructure improvement problems considered in Section 5.4.1 and 5.4.1.1. A set of ten segments with particular classes shown below is used for illustration.

Segment	1	2	3	4	5	6	7	8	9	10
Track Class	2	3	3	3	4	4	3	4	5	3

The decision space for upgrade of any track classes anywhere along the route to a next higher class would comprise any possible combination of all of the above segments except segment 9, which is class-5. Thus, there are 511 different combinations in total.

The decision space for upgrade of class-3 segments anywhere to the next higher class would comprise any possible combination of segments 2, 3, 4, 7 and 10, a total of 31 different combinations.

The decision space for upgrade of consecutive class-3 segments along the route to a next higher class would comprise any possible combination of segments 2, 3, 4, 7 and 10 but the

candidate segments must be consecutive to each other. For example, if the budget allows for upgrade of three segments, possible choices would be upgrading segments 2, 3, 4, or 3, 4, 7, or 4, 7, 10, whichever provides the greatest reduction in risk.

5.5.3.2 Illustration of Pareto Optimality of Route Infrastructure Improvement

The optimal upgrade decision discussed in Section 5.4 is the output from the solver. This section illustrates how the Pareto efficient set of upgrades is identified.

Table 5.10 shows segment risk data and possible upgrade decisions for a general case of route infrastructure improvement, i.e. upgrade any track classes anywhere with the objective of minimizing risk. The Pareto efficient frontier is shown by the dashed line (Figure 5.16) and indicates a set of non-dominated solutions, i.e. upgrade decisions that offer the greatest reduction in risk with increasing cost.

Table 5.10. Segment risk data and decision space for upgrading any track class anywhere along the route.

Baseline Segment	Length (Mi.)	Risk (Persons Affected)
1	1	0.0468
2	2	0.2111
3	1	0.0718
Total	4	0.3297

Decision (Segments Upgraded)	Length Upgraded (Mi.)	Upgrade Cost (Million \$)	Route Risk (Persons Affected)			
			Before Upgrade	After Upgrade	Reduction	Risk Reduction Per Million \$
1	1	0.6	0.3297	0.3006	0.0291	0.0484
2	2	1.2	0.3297	0.2075	0.1222	0.1018
3	1	0.6	0.3297	0.2881	0.0415	0.0692
1, 2	3	1.8	0.3297	0.1784	0.1512	0.0840
1, 3	2	1.2	0.3297	0.2591	0.0706	0.0588
2, 3	3	1.8	0.3297	0.1660	0.1637	0.0910
1, 2, 3	4	2.4	0.3297	0.1369	0.1928	0.0803

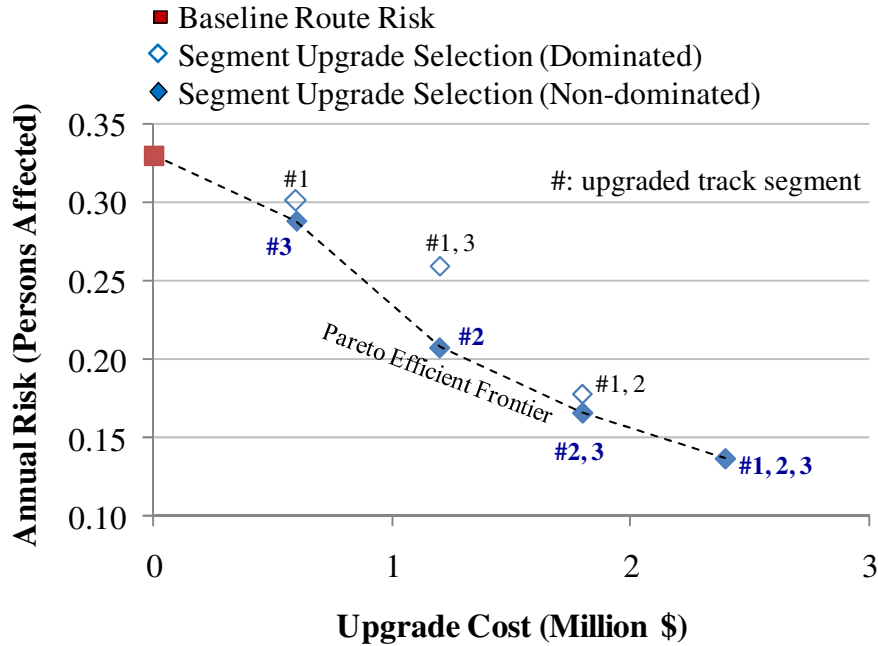


Figure 5.16: Pareto Efficient Frontier Showing Optimal Decisions for Track Upgrade to Minimize Risk

The hypothetical segment risk data in Table 5.11 illustrates the optimal solution for the case in which consecutive segments of a particular track class are upgraded with the objective of minimizing risk. The lower part of the table shows possible decisions for consecutive class-3 track segment upgrade corresponding to the decision rule described in Section 5.5.3.1. The Pareto efficient frontier (Figure 5.17) indicates the set of optimal upgrade decisions that offers the greatest reduction in risk for this particular case.

Table 5.11. Segment risk data and decision space for upgrading consecutive track segments of the same class anywhere along the route.

Baseline Segment	Length (Mi.)	Track Class	Risk (Persons Affected)
1	1	3	0.0468
2	2	3	0.2111
3	1	4	0.0302
4	1	3	0.0844
5	2	4	0.1067
6	2	3	0.2533
Total	9		0.7325

Decision (Segments Upgraded)	Length (Mi.)	Upgrade Cost (Million \$)	Route Risk (Persons Affected)		
			Before Upgrade	After Upgrade	Reduction
1	1	0.6	0.7325	0.7035	0.0291
2	2	1.2	0.7325	0.6103	0.1222
4	1	0.6	0.7325	0.6837	0.0489
6	2	1.2	0.7325	0.5859	0.1466
1, 2	3	1.8	0.7325	0.5813	0.1512
2, 4	3	1.8	0.7325	0.5615	0.1711
4, 6	3	1.8	0.7325	0.5370	0.1955
1, 2, 4	4	2.4	0.7325	0.5324	0.2001
2, 4, 6	5	3.0	0.7325	0.4148	0.3177
1, 2, 4, 6	6	3.6	0.7325	0.3858	0.3467

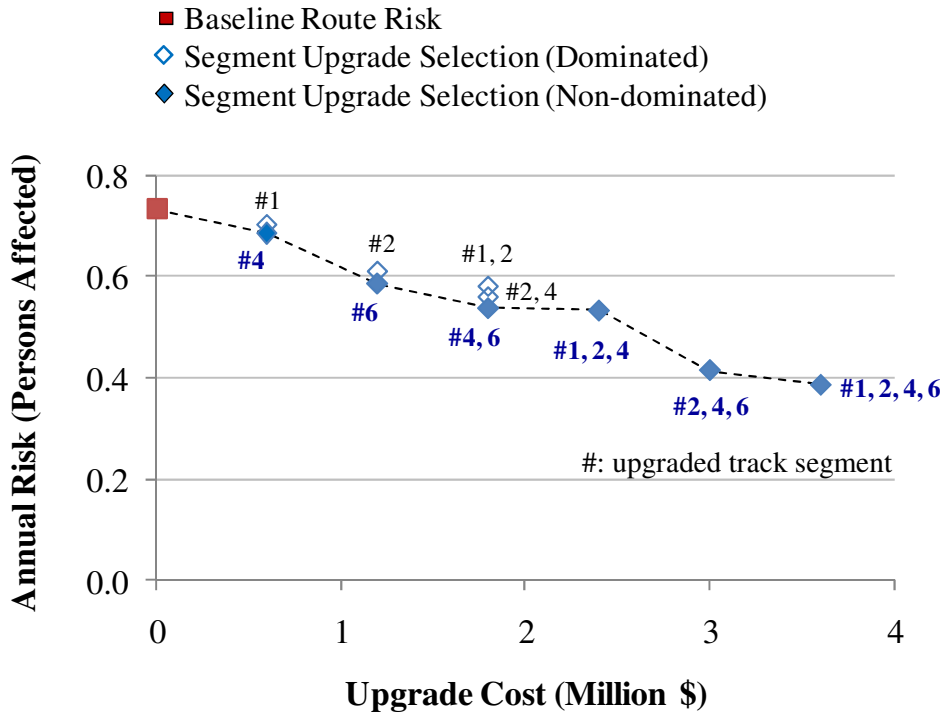


Figure 5.17: Pareto Efficient Frontier Showing Optimal Decisions for Consecutive Track Segments Upgrade to Minimize Risk

5.5.3.3 Effect of Track Segment Length on Optimality and Use of Resources

As discussed earlier, track segment lengths may affect the optimal decision in that high risk segments may be disregarded by the model if their upgrade causes the total cost to exceed maximum allowable limit. For example, Figure 5.16 shows that for a budget of \$1 million, the only possible decision is to upgrade either segment 1 or 3 requiring \$0.6 million investment with a remaining budget of \$0.4 million. Upgrading segments 1 and 3, or segment 2, is not possible because it requires \$1.2 million investment. For a better use of the budget, a route could be divided into smaller, uniform segments to enable some other feasible solutions that may offer a greater benefit and allow more efficient use of resources. To illustrate this idea, I revisit the segment data in Section 5.5.3.2 and consider alternate segmentation, i.e. uniform segment length. The new segment data is shown in Table 5.12, and the optimal upgrade decisions are shown in Figure 5.18.

Table 5.12. Segment risk data and decision space for upgrading any track class anywhere along the route, using uniform segment length.

Baseline Segment	Length (Mi.)	Risk (Persons Affected)
1	1	0.0468
2.1	1	0.1055
2.2	1	0.1055
3	1	0.0718
Total	4	0.3297

Segment Upgraded	Length Upgraded (Mi.)	Upgrade Cost (Million \$)	Route Risk (Persons Affected)		
			Before Upgrade	After Upgrade	Reduction
1	1	0.6	0.3297	0.3006	0.0291
2.1	1	0.6	0.3297	0.2686	0.0611
2.2	1	0.6	0.3297	0.2686	0.0611
3	1	0.6	0.3297	0.2881	0.0415
1, 2.1	2	1.2	0.3297	0.2395	0.0902
1, 2.2	2	1.2	0.3297	0.2395	0.0902
1, 3	2	1.2	0.3297	0.2591	0.0706
2.1, 2.2	2	1.2	0.3297	0.2075	0.1222
2.1, 3	2	1.2	0.3297	0.2270	0.1026
2.2, 3	2	1.2	0.3297	0.2270	0.1026
1, 2.1, 2.2	3	1.8	0.3297	0.1784	0.1512
1, 2.1, 3	3	1.8	0.3297	0.1980	0.1317
1, 2.2, 3	3	1.8	0.3297	0.1980	0.1317
2.1, 2.2, 3	3	1.8	0.3297	0.1660	0.1637
1, 2.1, 2.2, 3	4	2.4	0.3297	0.1369	0.1928

Figure 5.18 shows an improvement in Pareto optimality at an investment of \$0.6 million. That is, upgrading segments 2.1 or 2.2 gives a higher benefit in risk reduction at the same cost than an upgrade of segment 3. There is still an unused amount of budget when a 1-mile segment length is used. For example, if a \$1 million-budget is available, \$0.4 million still remains. Dividing a segment further into a smaller, uniform length allows better use of the entire budget amount available.

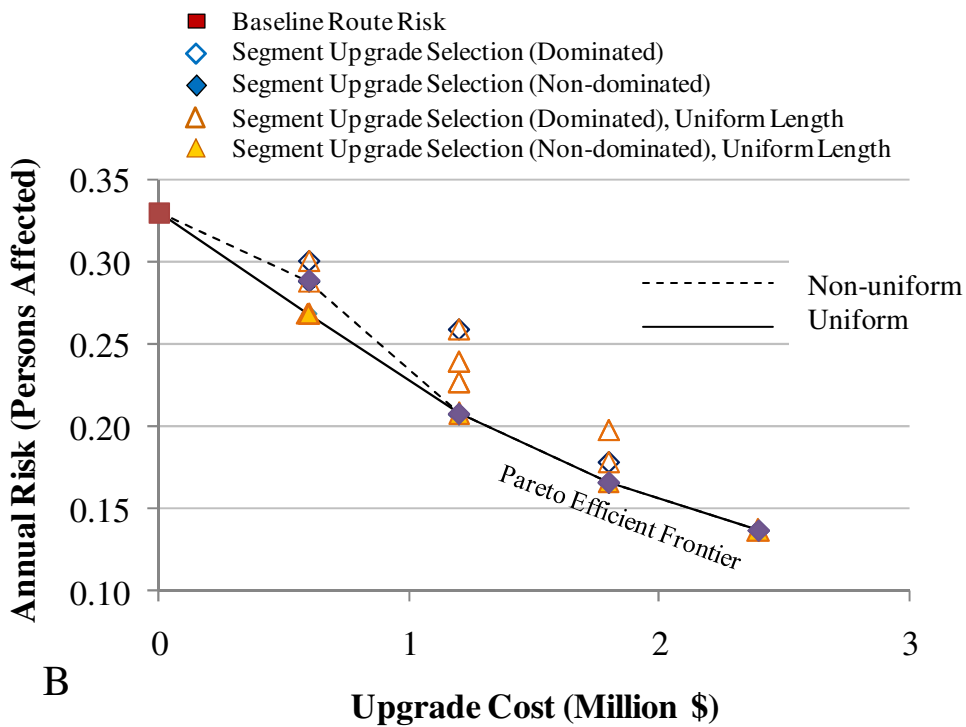
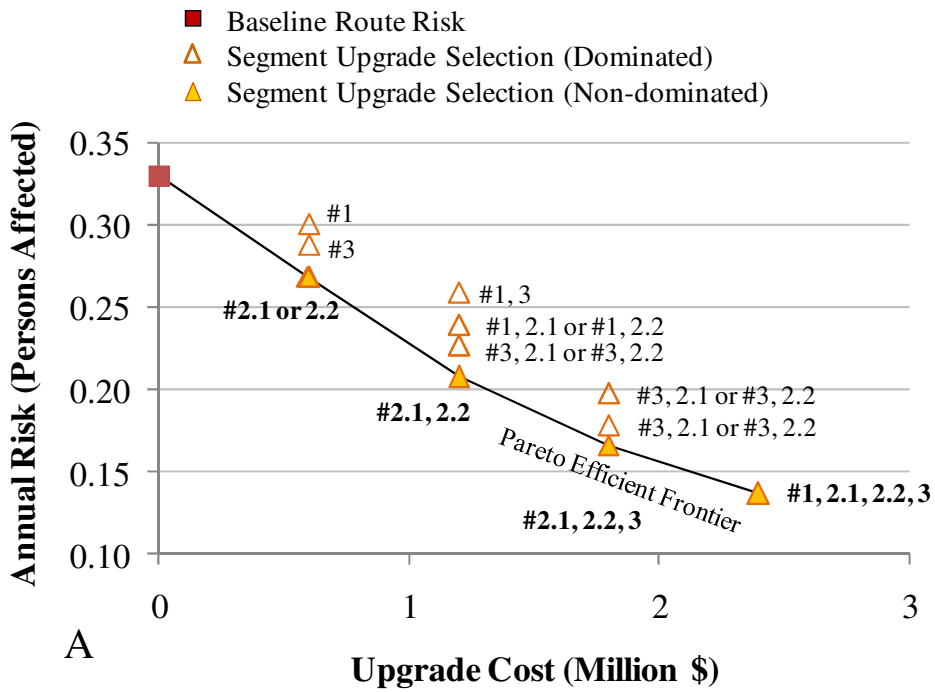


Figure 5.18: Pareto Efficient Frontier Showing Optimal Decisions for Track Upgrade to Minimize Risk (A) Using Uniform Segment Length, (B) Comparing Optimal Decisions When Uniform and Non-uniform Segment Lengths Are Used

5.5.4 Possible Directions for Future Development of Transportation Network Data for Use in Track Segment-specific Risk Analysis and Optimization

One possible improvement of track segment-specific risk analysis is to use railroad data with more accurate input information such as track classes, operating speeds of freight trains, mileposts and stations. First, track segments can be defined by track class so that a track-class-specific accident rate can be assigned to each segment. The segments can then be broken down further if operating speeds are different on each segment so that the CPR can be determined for any container type considered.

Although the uncertainty of the frequency estimate could be reduced by considering actual track classes and operating speeds, there is still error due to the track-class-specific accident rate estimate itself. Furthermore, actual accident speed and assumed speed may be different, resulting in errors when calculating the CPR. These uncertainties are discussed in more detail in Chapter 8. Further study may focus on developing statistics on average accident speed on each track class that could give a better estimate of risk than assuming a train traveling at maximum track speed. Another improvement could be made in the stage of overlay analysis of population exposure using GIS. The route layer from origin to destination can be created using a Network Analyst feature in ArcGIS together with route information from rail routing software such as PC*MILER|Rail. The route layer can then be broken down into segments using an appropriate algorithm to account for difference in track-segment-specific characteristics based on segments defined in previous stage. One possible problem is that the total route length from railroad and GIS data may not match exactly so appropriate adjustments may be necessary.

Another task which could be considered for improvement is population density estimation. An approximate method previously used is to consider proportions of different population density classes that intersect track segments or coincide with exposure area corresponding to track segments of each class. A more detailed analysis method is to calculate a weighted average population density in the exposure area corresponding to each track segment (Chapter 3). In some cases it might be inaccurate to use an algorithm to detect changes in population census tract density to create a new segment because such changes occur not only in the direction parallel to track segments but also perpendicular to the segments. It is difficult, particularly in urban areas, to create a new segment when a new population census tract is encountered because census tracts could be relatively small. In such instance a weighted average

method for estimating population density corresponding to each track segments may be a suitable approach. If the segment is very long while having the same characteristics, segmentation could be applied so that the maximum length does not exceed an average, say, two miles. Longer segments may be divided into two or more segments with equal length to: 1) appropriately capture the changes in population density especially where variation in density is high, and/or 2) avoid the bias in segment selection in track infrastructure improvement selection to minimize risk.

After track segments are adjusted, a buffer can be created using GIS. The buffer should have a radius equal to the U.S. DOT's recommended evacuation or downwind distance (PHMSA, 2008) for a material and for the specific release scenario considered. The population census tracts within that buffer should be clipped out. Finally, parts of the clipped buffer that coincide with track segments are clipped again. The weighted average population density is calculated and assigned to each track segment. This process could be automated in ArcGIS to accommodate the route segmentation considered, using either uniform or non-uniform segment lengths.

The benefit of using railroad data is that more accurate information can be incorporated into the risk analysis. Furthermore, output from optimization problems, such as optimal track segments for upgrade can be more conveniently considered by the railroad. In the case that an artificially equalized segment length is used in the analysis, some selected segments may not correspond to what the railroad actually has on their network. That is, a selected optimal segment may be shared by two track sections or more. If railroad data are not available, the BTS national transportation network data may still be used under the same procedures discussed above. Very short segments can be combined, while very long segments may be split as appropriate.

In short, improvements can be made in two ways. The first is to divide a shipment route into segments having short enough lengths to capture any change in risk parameters: track class (accident rate), operating speed and average population density. In this case, the lengths of the segments may not have to be equal. Alternatively, the route may be divided into segments with uniform length such that the length minimizes overall error in the risk parameter estimates. Both will require further developments in route segmentation technique. In particular, the latter will require automation and simulation methods to determine the optimal length.

A segment-specific risk analysis is time consuming and labor-intensive. In previous risk analysis projects, the tasks described here were performed with the aid of routing, GIS and spreadsheet applications. There is a trade-off between manual versus automated processes. The former requires more time and resources and has a potential of introducing human error. However, adjustments such as track segmentation or other location-specific requirements can be made with relative ease. On the other hand, a fully automated process can substantially reduce process time, but unexpected errors may be propagated during the process, and these are more difficult to detect. For example, Network analyst in ArcGIS which uses a shortest path algorithm, in many cases, results in a use of diverted track or a short-cut path that is not a mainline track section or is not a section that would typically be used. The routing output needs to be carefully checked and compared with the routing-software-generated route and then fixed on a case by case basis. Such errors would easily be missed if the entire process was fully automated in determining track-segment-specific risk and/or route-specific risk.

The adjustments in track-segment-specific risk analysis described in this section could help improve the accuracy of risk estimates. However, no study has been conducted to quantify the benefits of such improvement and to assess whether it significantly changes the estimates of route risk or the effect is only marginal. Further investigation of error in risk estimation may provide insights and enable comparison of risk estimates with other risk analysis tools such as the Rail Corridor Risk Management System (RCRMS) routing model.

5.6 Discussion

The purpose of this chapter is to formally consider infrastructure improvement as a means of reducing hazardous materials transportation risk. I develop an optimization model, the route infrastructure improvement selection model, to facilitate a consideration of the most effective strategy for rail infrastructure improvement to obtain the maximum safety benefit given a limited resource. Further to the work in the previous chapter, I incorporated speed-dependent CPR into the risk optimization model to take into account the combined effects of train speed and track infrastructure upgrade on route risk. This provides a more accurate result and enables a better evaluation of benefit of risk reduction due to track infrastructure improvement.

The application of the model was illustrated using a case study of the representative route. Different improvement strategies were considered, these include: 1) upgrading class 3-segments to class-4 at any location on the route, 2) upgrading consecutive class 3-segments to class-4, and 3) upgrading any segment of class-4 or lower at any location. Using a graphical technique developed by Kawprasert and Barkan (2009a), the locations for upgrade and risk distribution before and after improvement are identified. The results support the finding in the previous chapter that upgrading class-3 track to class 4 is a more effective option as it offers greater risk reduction for the representative route.

Policy on track infrastructure improvement affects the degree of risk reduction. Upgrading consecutive track segments offers a smaller risk reduction because it imposes constraint on segment selection. For the initial budget level, upgrading any segment of any class lower than class-5 does not provide much difference in the magnitude of risk reduction compared to upgrading only class-3 segments.

I illustrated how the model can be adapted to accommodate an economic analysis of railroad track infrastructure improvement. The preliminary analysis on the effectiveness of infrastructure improvement shows that: 1) at the same level of investment, track infrastructure improvement offers a higher benefit for a higher volume of traffic operated on the track, and 2) investments in track infrastructure improvement to reduce risk yield diminishing marginal returns.

Analysis shows that benefit in risk reduction alone does not outweigh track infrastructure upgrade cost (Figure 5.5). Cost justification would require hazardous material shipment volume thousand times greater than assumed. However, there is a benefit of track upgrade in reduction of accident rates for non-hazardous material traffic that has not been accounted for. The bi-objective optimization model incorporating track class-specific upgrade cost suggests the improvements of classes 2 and 3 track segments to class 4 when the budget is limited, and the upgrades of these classes into class 5 when more budget is available. The track infrastructure improvement selection framework can be adapted to accommodate other elements for a more comprehensive consideration of benefits of track upgrade, e.g. a reduction in non hazardous material car derailments and an increase in throughput in addition to a reduction in hazardous material related accidents and speed increase.

In this analysis, several assumptions were made in order to express risk in monetary units, and to develop track infrastructure upgrade and consequence costs. The consideration of more accurate, complete cost parameters should be considered in future research to further refine and improve the cost-effectiveness analysis of this risk reduction option. Furthermore, the case studies considered in this chapter are applicable for a single year investment. Further development should consider applying the model over a long time horizon to determine the optimal strategies for annual budget allocation over a multi-year investment period.

In the last parts of this chapter, I discuss the effect of track segment length and uncertainties associated with frequency and consequence estimates in quantitative risk analysis of hazardous materials transportation. Further investigation using a hypothetical case study on the route having uniform and non-uniform segment lengths shows that the route infrastructure improvement selection model identifies the highest-risk segments for upgrade such that the greatest reduction in risk is achieved while the budget limit is not exceeded. As the budget limit is approached, there is an increasing likelihood that shorter segments with lower risk will be selected to use the remaining budget. Use of uniform, shorter segment lengths will tend to minimize this possible bias and use the budget more effectively. This may not add complexity to analysis but it requires more time to process segment-specific data.

Two additional route infrastructure improvement scenarios were studied: 1) upgrading track infrastructure with the objective of minimizing risk and cost by normalizing each component by its baseline value, and 2) managing track infrastructure with the objective of minimizing risk and cost. While the former is restricted for track-class upgrades, the latter allows track segments to be upgraded, downgraded or maintained at the same level. The route infrastructure improvement selection framework can be readily adapted to accommodate these variations of track infrastructure management problems. While the case study assumes a speed increase with track-class upgrade, this is not necessarily true in practice, especially for high-risk segments in populated areas. However, the framework can be adjusted to accommodate this constraint provided that information is available.

Track infrastructure upgrade problems can be applied at various levels: segment level, route level, or network level. As an example, suppose a railroad operating a number of divisions wishes to allocate a budget to choose a few routes or divisions for track infrastructure

improvement under a limited budget, the problem would involve consideration between choosing some shorter routes or divisions that may not contribute the greatest proportion of total risk so that an investment required does not exceed the available amount. This is synonymous to the case when the route infrastructure improvement selection model chose some shorter segments with lower risk to fill up the budget level. Furthermore, considering the heterogeneity of track-segment-specific characteristics, use of non-uniform track segment lengths may not be a critical issue in hazardous materials transportation risk analysis. Yet, a technique to determine an optimal length of track segment, which minimizes the error in risk estimates caused by the heterogeneity of segment-specific characteristics, remains an interesting subject for further investigation.

I discuss several issues regarding uncertainties in segment-specific risk parameter estimates. In part, this is due to limited information that required certain assumptions to be made in the quantitative risk analysis process. The transportation network data itself also contributes uncertainties to risk parameter estimation. One approach to reducing such errors is to use railroad industry data on track infrastructure and to adjust track segment lengths in GIS database accordingly. Ideally, a new segment should be considered when there is a substantial change in any one of parameters affecting risk: track condition (accident rate), operating speed or population exposure. Further study to formally determine the optimal segment length that minimizes overall heterogeneity will be helpful for the segment-specific risk analysis process.

A new segmentation algorithm may be developed to serve two purposes. One is for route risk analysis at segment-specific level, and another is for track upgrade problems in which uniform segment is preferred. For the former, the algorithm should detect any changes in risk parameters, in particular accident rates and population census tract density coincident with track segment and break the route segments accordingly. For the latter, one may consider Montecarlo simulation to determine a uniform segment length that minimizes the error in one or more risk parameters in step-wise manner. For example, Chapter 4 indicates that accident rate is a risk parameter that dominates the conditional probability of release. Thus, for the first trial of segment length, a simulation process may determine the length that minimizes the error of route-specific accident rate compared to baseline. Once the uniform length is obtained, the second trial may divide the segment length further to determine the optimal, uniform length that minimizes the error in population density.

If the length of the segment that minimizes the heterogeneity in route characteristics is too short to be considered as a practical length in actual implementation of track infrastructure improvement, the route infrastructure improvement selection model could be modified to incorporate a constraint that ties consecutive segments together to achieve a desirable length.

There is a trade-off of using uniform and non-uniform segment lengths in route risk analysis and optimization. A uniform segment length may not be as efficient as variable segment lengths in the areas with less heterogeneity along the route, e.g. rural areas where track class, operating speed and population tend to be more uniform for longer distances. In this case, route segmentation uses unnecessary resources and can be redundant. If resources for route processing are constrained, use of variable segment lengths may be favorable. Meanwhile, the highest risk segments will not always be chosen in track infrastructure improvement problems if the segment lengths vary.

The improvements in route segmentation discussed in this chapter represent an ideal case and are subject to several challenges. First is due to the fact that there will always be heterogeneity in segment-specific properties. For example, a train may accelerate or decelerate on the segments causing variation in operating speeds for determining the CPR. Furthermore, it is not always possible to have track segments with a single population census tract density because an affected area may require a larger boundary than the length of the track. At best, one may consider a maximum track segment length that minimizes a change in average population density in the hazard exposure area considered. Second, the approach described indicates a need for a more complicated automation process that could be time consuming. Further quantitative study of how heterogeneity and uncertainties affects segment-specific or localized risk will help us better understand the extent of their effect on route risk. This would provide better understanding of whether or not the improvements in segment-specific risk analysis and route segmentation described here are worthwhile.

5.7 Conclusions

This chapter presents a mathematical model framework to help facilitate decision making regarding railroad track infrastructure improvement by identifying locations where track upgrade will provide the maximum safety benefits. By using speed-dependent CPR, the model

simultaneously takes into account the effects of reduction in accident rates and increase in CPR caused by track improvement. This allows for a more accurate estimate of route risk. Solutions show that upgrading class-3 track to class-4 yields greater benefit in risk reduction, compared to upgrading other track classes to a next higher class. The more hazardous materials traffic operated, the greater the safety benefit obtained from track infrastructure improvement. The greatest safety benefit in terms of risk reduction is obtained during the initial level of investment, and risk does not reduce much further after the high-risk segments have been upgraded. This diminishing marginal return is not apparent when the greater magnitude of fixed consequence cost is added to the cost component of the objective function. To improve the quality of the cost-effectiveness analysis of track infrastructure improvement, a more comprehensive, accurate estimate of consequence costs may be considered in future studies.

I discussed the effect of track segment length in hazardous materials transportation risk analysis and optimization. A hypothetical case study using equal segment length was used to illustrate the cases when track segment length is equal. The study shows that the route infrastructure improvement selection model generally seeks the segments with the highest risk per mile for upgrade to the highest track class so as to obtain the greatest reduction in risk. In some cases, the model will choose the lower-risk segments to use the remaining budget. An optimality analysis of route infrastructure improvement shows that use of uniform, shorter length segments may result in better use of the budget.

Due to heterogeneity in track-segment-specific characteristics and uncertainties in estimation of risk parameters, use of equal segments should be based on an optimal length that minimizes total error in the risk estimate. Future research may consider determining what optimal length should be and develop an algorithm for geo-processing of GIS transportation network database accordingly. Issues regarding uncertainties in segment-specific risk analysis have been addressed along with possible improvements to develop more accurate risk estimates. Further quantitative studies may be necessary to evaluate whether such uncertainties are significant relative to the magnitude of route risk and to what extent that they affect the decision making.

CHAPTER 6

MANAGING TRAIN SPEED TO REDUCE RISK AND OPTIMIZING HAZARDOUS MATERIAL TRANSPORTATION RISK REDUCTION OPTIONS

6.1 Introduction

Operations research methods have been used extensively in hazardous materials transportation risk analyses. In particular, optimization techniques may help suggest a more effective strategy for the management of hazardous materials transportation. Previous research on hazardous materials transportation has considered application of these techniques to a wide range of questions regarding hazardous materials transportation safety, including facility location, routing and scheduling of hazardous materials (Abkowitz and Cheng, 1988; List et al., 1991; Alumur and Kara, 2007), tank car design optimization (Saat and Barkan, 2005; Barkan, 2008; Saat, 2009), and installation of wayside defect detection systems (Ouyang et al., 2009). Another option that has gained attention from the government and the railroad industry is the management of train operating speeds to reduce risk. A recent study by Kawprasert and Barkan (2010a) indicates the potential of this option to improve hazardous materials transportation safety. I am unaware of any other formal, quantitative investigation of how speed reduction can be efficiently applied to hazardous materials transportation problems.

In this chapter, I develop an approach to formally consider speed management as an option for reducing the risk of hazardous materials transportation. The objective is to develop a mathematical framework to facilitate the consideration of speed management as a means of risk reduction, using the relationship between train speed, derailment probability, and conditional probability of release (CPR) from Chapter 4. The model is structured to handle multiple car types and products with different hazard characteristics. Application of the framework is illustrated through case studies under different scenarios using the representative route data from Chapter 5.

In addition to the speed management approach, several risk reduction options have already been developed and studied, e.g. rerouting and rationalization of hazardous material route structure (Saat and Barkan, 2006a; Kawprasert and Barkan, 2008) and upgrading railroad track infrastructure (Saat and Barkan, 2006b; Kawprasert and Barkan, 2010b). In order for these options to be considered and appropriately adapted for implementation, it is of interest to establish a general framework for the consideration of the most cost-effective options suitable for a particular purpose. Therefore, the second objective of this chapter is to provide a general framework to consider multiple risk-reduction options. This general framework is designed to identify the most appropriate option for reducing hazardous materials transportation risk given a particular set of alternatives and a shipment network. In particular, I develop a framework that considers both train-speed reduction and track-infrastructure improvement simultaneously. The framework incorporates the financial impact of risk reduction options based on track-class-specific maintenance costs and train-delay cost.

Due to the complexity of various constraints, uncertainties, and information that is difficult to quantify, several assumptions and simplifications have been made to complete the work described in this chapter. In practice, the most suitable risk reduction alternative is likely to depend on a particular situation, objectives of interest, resource, and other constraints that may vary case by case. Refinements may be necessary for the model framework to handle more realistic scenarios. Overall, this chapter provides a better understanding of the performance of speed management in hazardous materials transportation risk reduction. The framework will facilitate the consideration of the most cost-effective risk reduction strategies, thereby providing better information to private and public sector decision-makers as well as to researchers interested in this topic.

6.2 Managing Train Speed for Hazardous Materials Transportation Risk Reduction

Train accident speed affects the number of cars derailed (Barkan et al., 2003) and the likelihood of a release from a container transporting hazardous material (Nayak et al., 1983; CCPS, 1995; Treichel et al., 2006; Kawprasert and Barkan, 2010a). Therefore, reducing train speed in critical areas may help reduce the severity of damage and loss in accidents involving hazardous materials. The objective of the mathematical framework for managing train operating speed that is developed in this chapter is to determine locations where speeds may be adjusted so as to minimize transportation risk.

Reducing speed, however, requires more time for vehicles to complete the trip and may reduce asset utilization and line capacity in some cases. This brings in several potential adverse impacts, such as the possibility of elevated security risk. Optimizing train speed may be a more complicated option than track infrastructure upgrade because the former is subject to several constraints. First, speed change may be limited by infrastructure and operating constraints. Reducing speed of one particular train may also substantially affect the schedule of other trains and consequently result in an overall system delay (Dingler et al., 2009). Furthermore, arbitrary reduction in train speed (e.g. imposition of speed reductions on portions of the network) may disrupt operations. Changing from one speed to another (acceleration and deceleration) requires a certain distance, which depends on various factors including gradient, curvature, locomotive performance, and total tonnage (Hay, 1982). Thus, route sections where speed reduction is to be applied should have a length greater than this distance in order for trains to operate smoothly at the desired speed. The mathematical framework developed here simplifies this aspect by neglecting the minimum segment length that may be required for speed change. However, the model can be adjusted to accommodate this constraint.

Travel time extended from the original time required for the train to complete its trip due to speed reduction implies train delay. To account for the cost incurred by speed reduction, train-delay cost estimates developed by Schafer and Barkan (2008) are considered. This delay cost estimate includes car, locomotive, fuel, and crew labor costs that are considered together as a single cost of speed reduction in the model framework. Other cost elements can also be incorporated if information is available.

6.2.1 Train Speed Management Model Formulation

This section describes key elements of a mathematical model to determine locations where speed reduction should be applied to simultaneously minimize transportation risk of hazardous materials and delay cost. The model is referred to as the “*train speed management model for hazardous materials transportation risk reduction*” or “*train speed management model*” in short. This model is structured to incorporate the tradeoff between a reduction in hazardous materials transportation risk and the simultaneous increase in delay cost under a bi-objective optimization. First, I will discuss the equations and relationships necessary for the train speed management problem. Later, I will organize these relationships and formally introduce the model.

6.2.1.1 Risk Cost Objective Function

The first element of the train speed management model is the objective function, which has two conflicting objectives: 1) minimizing risk cost and 2) minimizing transportation (delay) cost. Using the risk expression defined in Chapter 3, the objective function of minimizing total risk cost of transporting hazardous materials can be expressed as follows:

$$\text{Minimize } S = \sum_{i \in I} \sum_{j \in J} \sum_{k \in K} \sum_{m \in M} V_{ik}^m L_i Z_i f(W'_{ik}) P_{ij}^m D_i A_j^m Y_{ij}^m \quad (6.1)$$

Where:

- S = total risk cost of transporting hazardous materials (\$)
- V_{ik}^m = shipments (carloads) of material type m by car type k on segment i
- L_i = length of segment i (miles)
- Z_i = segment-specific accident rate (cars derailed per car-mile)
- $f(W'_{ik})$ = conditional probability of release as a function of speed W' (mph) on segment i for car type k
- P_{ij}^m = conditional probability of specific scenario j occurring given release of material m on segment i

D_i = average population density along segment i (persons per square mile)

A_j^m = affected area per the U.S. Department of Transportation (DOT) Emergency Response Guidebook (ERG) recommendation for release scenario j and material m (square mile)

Y_{ij}^m = emergency response cost per person affected on segment i for specific scenario of release j and material m (\$ per person)

To accommodate the train speed management problem, the CPR in the objective function must be a function of both train speed and container-specific safety design features. As discussed in Chapter 4, several speed-dependent CPR relationships have been developed. These include the work by Nayak et al. (1983), CCPS (1995), Treichel et al. (2006), and Kawprasert and Barkan (2010). I use the equation developed by Kawprasert and Barkan (Chapter 4) to estimate speed-dependent CPR as follows:

$$f(W'_{ik}) = 1 - \prod_{q \in Q} (1 - \beta_{qk} (\gamma_{qk} W'_{ik})) \quad (6.2)$$

Where:

β_{qk} = average-speed CPR for release source q for tank car type k

γ_{qk} = constant for release source q for tank car type k

The model above handles multiple types of tank cars. The problem can be simplified by considering the weighted-average, speed-dependent CPR as a substitute, which can be expressed as:

$$\frac{\sum_i \sum_k f(W'_{ik}) n_{ik}}{\sum_i \sum_k n_{ik}} \quad (6.3)$$

Where:

n_{ik} = number of tank car type k operated on segment i

Although certain causes of accidents may be correlated with speed, the formulation above assumes that speed has a direct effect on tank car CPR but does not significantly affect the accident rate for the speed management problems to be illustrated. Figure 4.6 (Chapter 4) implies that as track-class speeds increase, accident rates decrease while CPR increases. However, if the track class remains the same, speed reduction would cause the CPR to decrease but would not increase the accident rate. Therefore, it is assumed that the speed reduction affects only the CPR and not accident rate in Eq. (6.1).

6.2.1.2 Transportation Cost Objective Function

The second objective function is to minimize the transportation cost incurred by speed reduction. Here, the delay cost is assumed to represent the transportation cost. The train-delay cost equation developed by Schafer and Barkan (2008) can be adapted and incorporated into the cost objective function as follows:

$$\text{Minimize } f(T) = TO + \sum_{b=1}^B (T - bt)O \quad (6.4)$$

Where:

- $f(T)$ = total cost of speed reduction as a function of train delay T (\$)
- T = total system delay (across all trains) due to speed reduction (hours)
- O = cost of delay per train-hour (\$233.32)
- t = time interval between each train (headway) = 53.33/MGT (hours)
- MGT = traffic density (million gross tons)
- B = number of following trains delayed = T/t

Total delay as a result of speed reduction can be determined as follows:

$$\begin{aligned} T &= \sum_i T_i \\ &= \sum_i \left[\left(\frac{L_i}{W'_i} \right) - \left(\frac{L_i}{W_i} \right) \right] \end{aligned} \quad (6.5)$$

Where:

- L_i = length of segment i (miles)
- W'_i = target speed on segment i (mph)
- W_i = original speed on segment i (mph)

Traffic density in MGT can be determined using data from the transportation network database in Geographic Information System (GIS) format (BTS, 2007). Depending on the accuracy required, segment-specific MGT may be used. Alternatively, route-specific MGT may be considered as a single, average value for the entire shipment network, i.e.:

$$\overline{\text{MGT}} = \frac{\sum_i \text{MGT}_i \times L_i}{\sum_i L_i} \quad (6.6)$$

Where:

$$\text{MGT}_i = \text{MGT on segment } i$$

This approach to calculating system delay may not be as accurate because it considers an accumulated delay over the entire trip for a particular train to which the speed reduction is applied. This assumes that all subsequent trains operating on the network are affected by this amount of delay. In practice, the impact of the delay on subsequent trains may be managed, in part, through rescheduling or operating changes. To obtain a more realistic, accurate train delay estimation, a sophisticated modeling of train delay may be necessary to determine total delay cost due to speed reduction. It is beyond the scope of this work to develop a detailed approach to this aspect of the problem, as delay mitigation approaches will often be line or network specific. Some literature on modeling of train delay that may be useful for future studies include Chen and Harker (1990), Harker and Hong (1990), Higgins et al. (1995), and Murali et al. (2009). Simulation software such as Rail Traffic Controller (RTC) may also be helpful to estimate the system delay (Dingler et al., 2009).

Another difficulty is that hazardous material shipments may be in a single train or may be distributed over multiple trains. Although modification can easily be made to accommodate multiple hazardous material trains by summing the total delay of all trains that are subject to speed reduction, this will likely result in a less accurate estimation of the delay cost. Furthermore, the scheduling and assignment of hazardous material cars to trains is managed by the carriers, and this information is not available for use in analyses.

6.2.1.3 Operating Constraints

The train speed management model considers a single decision variable, i.e. target speed, to be operated on each segment. Basically, the target speed to be determined is subject to some operating restrictions. First, the target speed cannot exceed the maximum allowable speed on the segment. This upper speed limit may represent the track speed limit in accordance with the track classification or the speed limit due to geometric conditions, such as grade and curvature. Likewise, the target speed should not be lower than the lower bound of the speed range corresponding to track class or the minimum practical operating speed applied to particular geographic conditions. The lower bound for operating speeds is necessary to prevent the optimization model from assigning zero speed to the segments in certain optimization problems. The bounds for speed also help maintain consistency with track class definitions and track-class-specific accident rate assignment.

In some situations, risk managers may want to strictly consider speed reduction throughout the entire network, i.e. not allowing an increase in speed from the original operating speeds. Therefore, depending on the scenarios, speed constraints may comprise a combination of the following equations:

$$W'_{ik} \geq W_i^{\min} \quad \forall i, \forall k \quad (6.7)$$

$$W'_{ik} \leq W_i^{\max} \quad \forall i, \forall k \quad (6.8a)$$

$$W'_{ik} \leq W_{ik} \quad \forall i, \forall k \quad (6.8b)$$

Where:

W_i^{\max} = upper speed limit (track-class speed limit) for segment i (mph)

W_i^{\min} = lower speed limit (speed limit on one lower track class) for segment i (mph)

If the objective is to *manage* speed to reduce risk, i.e. speed may be increased or decreased within the limits, Eq. (6.7) and (6.8a) are applicable. On the other hand, if the objective is to strictly *reduce* speed, then Eq. (6.7) and (6.8b) are needed.

6.2.1.4 Cost Constraints

The cost constraint stipulates that the total cost due to speed reduction does not exceed the resources available; that is:

$$f(T) \leq X \quad (6.9a)$$

Where:

$$X = \text{maximum allowable transportation cost (\$)}$$

Furthermore, the cost function may not be negative, i.e.

$$f(T) \geq 0 \quad (6.9b)$$

However, if risk managers wish to use the model to freely manage the target speed so that it can be lower or higher than the original speed, none of these constraints would be necessary. This is because the model will determine target speed on each segment within the minimum-maximum speed range. If the target speed is lower than the original speed, it will increase delay on the affected segments, and if it is higher, it will reduce delay. These positive or negative effects on delay are added up in Eq. (6.5) and converted into cost in Eq. (6.4).

The resource constraint in Eq. (6.9a) is necessary when the goal is to reduce speed to an extent not exceeding the maximum allowable delay.

The non-negativity constraint in Eq. (6.9b) is needed if the target train is required to operate at an average speed not higher than the original, average operating speed. In other words, this constraint stipulates that the total travel time after speed changes must not be less than the baseline. Therefore, in this case, the total transportation cost cannot be negative.

The multiplicative form of the speed-dependent CPR function in Eq. (6.2) leads to difficulty in solving the model because it requires nonlinear programming (NLP). Also, the inverse relationship between speed and travel time requires a division operation (Eq. 6.5), and such division must be avoided. A new variable may be considered to change a division operation to multiplication, but a similar modification would also be necessary for the speed-dependent CPR relationship in Eq. (6.1). To simplify this complication, I consider an integer programming (IP) model that can conveniently be solved.

6.3 Train Speed Management Model Using Integer Programming

The train speed management model can be formulated using an integer variable C_{iw} to represent the decision for the target operating speed on segment i . At any specific target speed $W = W'$ (mph), CPR, risk, and delay cost can be determined using Eq. (6.2), (6.1), and (6.4), respectively. Therefore, the integer variable C_{iw} is the only variable required in the simplified model.

The train speed management model in IP form is given as follows:

$$\text{Minimize } Q = \sum_{i \in I} \sum_{w \in W} C_{iw} (S_{iw} + f(T_{iw})) \quad (6.10)$$

subject to

$$\sum_{i \in I} \sum_{w \in W} C_{iw} f(T_{iw}) \leq X \quad (6.11)$$

$$\sum_{i \in I} \sum_{w \in W} C_{iw} f(T_{iw}) \geq 0 \quad (6.12)$$

$$\sum_{w \in W} C_{iw} = 1 \quad \forall i \quad (6.13)$$

and

$$C_{iw} : \text{binary} \quad (6.14)$$

Where:

- Q = total cost (\$) of transporting hazardous materials on the route
- S_{iw} = risk cost (\$) of transporting hazardous materials on segment i given that affected trains are operated at speed $W = W'$ (mph)
- $f(T_{iw})$ = delay cost (\$) of transporting hazardous materials on segment i given that affected trains are operated at speed $W = W'$ (mph)
- X = maximum allowable delay cost (\$)
- C_{iw} = decision variable for target operating speed on segment i
(1 if speed $W = W'$ is chosen for segment i , 0 if another speed is chosen)
- I = a set of track segments in the route considered
- W = a set of candidate operating speeds within minimum and maximum speed limits, W_i^{\min} and W_i^{\max} (mph)

The objective function in Eq. (6.10) minimizes both the risk and delay costs of transporting hazardous materials on the route.

Eq. (6.11) is a resource constraint that controls the maximum allowable delay or the resource allocated for speed reduction. It stipulates that the total delay cost must not exceed the specified level X (\$).

Eq. (6.12) is an optional non-negativity constraint. It stipulates that the total delay cost must not be negative and, therefore, prevents a decrease in total travel time from the baseline.

Eq. (6.13) stipulates that there must be only one target speed chosen for each segment i .

The binary constraint in Eq. (6.14) stipulates that the decision variable for speed C_{iw} shall be either zero or one. If $C = 1$, then the target speed $w = W'$ will be chosen and otherwise for $C = 0$.

I is a set of segments in the route considered.

W is a set of candidate speeds to be considered for target operating speeds. For example, using a 5 mph increment, there are 12 candidate speeds ranging from $(15, 20, 25)^{\text{class } 2}$, $(30, 35, 40)^{\text{class } 3}$, $(45, 50, 55, 60)^{\text{class } 4}$, and $(65, 70)^{\text{class } 5}$. One may choose a smaller speed increment, but this increases the number of constraints in the optimization process and the computation time.

The parameters S_{iw} , $f(T_{iw})$, and the decision variable C_{iw} are matrices having a size equal to the total number of segments times the number of candidate speeds.

The simplification of the model framework presented here is that it assumes the target speed for all car types is the same. However, the model can be modified to accommodate multiple car types operating at different speeds.

6.3.1 Variation of The Train Speed Management Model

The train speed management model is flexible so that it can be tailored to suit different objectives of interest. The mathematical model formulation described earlier determines the speed on track segments that will minimize risk and cost. Target speeds to be determined by the model are varied arbitrarily within the specified minimum-maximum speed range. In some instances, risk managers may wish to control or set the magnitude of speed reduction. In this section, I discuss a variation of the train speed management model that can accommodate a predefined magnitude of reduction in train speed. The predefined speed reduction may be one of the following: 1) a fixed, constant speed reduction, 2) a set of different magnitudes of speed

reduction for different groups of track segments (e.g. track classes), or 3) a set of different magnitudes of speed reduction for different segments. One benefit of this model is that it enables the risk manager to evaluate and compare the cost-effectiveness of different magnitudes of speed reduction.

A general IP form of the train speed management model, incorporating a fixed reduction in train speed, is given as follows:

$$\text{Minimize } Q = \sum_{i \in I} (1 - C_i) S_i + C_i S'_i + \sum_{i \in I} C_i f(T_i) \quad (6.15)$$

subject to

$$\sum_{i \in I} C_i f(T_i) \leq X \quad (6.16)$$

$$W'_i - C_i \Delta_i \geq W_i^{\min} \quad \forall i \quad (6.17)$$

and

$$C_i: \text{ binary} \quad (6.18)$$

Where

- Q = total cost (\$) of transporting hazardous materials on the route
- S_i = risk cost (\$) of transporting hazardous materials on segment i given that affected trains are operated at original speed
- S'_i = risk cost (\$) of transporting hazardous materials on segment i given that affected trains are operated at reduced speed
- $f(T_i)$ = delay cost (\$) of transporting hazardous materials on segment i given that affected trains are operated at reduced speed
- X = maximum allowable delay cost (\$)
- W'_i = target operating speed (mph) on segment i
- W_i^{\min} = minimum speed limit on segment i (mph)
- Δ_i = magnitude of speed reduction on segment i (mph)
- C_i = decision variable for target operating speed on segment i
(1 if speed reduction is to be applied on segment i ,
0 if original speed is to be maintained)
- I = a set of track segments in the route network considered

The objective function in Eq. (6.15) minimizes the risk and delay costs of transporting hazardous materials on the network. Eq. (6.16) controls the delay cost such that it does not exceed the maximum allowable level. Eq. (6.17) is a minimum speed constraint that maintains consistency with the track-class-specific speed range considered. The speed ranges may be changed to accommodate other speed restrictions or operating requirements on certain segments as appropriate. The maximum track speed constraint is not required because the target speed is always either lower than or the same as the original speed. For the same reason, the non-negativity requirement for the resource constraint is not necessary. A magnitude of speed reduction, Δ , can be set to a desired value for any specific segment to suit a particular objective of interest. For a case study to be illustrated later, Δ represents a constant for all segments i . Eq. (6.18) is a binary constraint. That is, if $C_i = 1$ then a speed reduction is to be applied on segment i , and if $C_i = 0$ then the original speed will be maintained.

6.4 Case Studies

The train speed management model enables consideration of train-speed reduction to minimize two conflicting objectives: hazardous materials transportation risk and train delay. The model introduced can be modified and adapted to accommodate various objectives of interest. In this section, I consider several case studies to verify the model structure developed and to illustrate some possible applications of the model. The following assumptions were made for all case studies:

- One product is considered.
- A single scenario of release is assumed.
- All hazardous material car shipments are in one train and using one car type.
- Only the delay of the corresponding hazardous material train is considered.
- Possible security risk due to travel time increase is not considered.
- The risk cost estimate incorporates a per-person evacuation cost (costs of remediation cleanup, material loss, and track and equipment damage are excluded).

Different speed management strategies are considered on a representative shipment route to minimize risk and delay cost. These include: 1) varying operating speeds on the network (increase or decrease within maximum-minimum track speed limits), 2) strictly reducing speeds (variable magnitudes), 3) reducing speeds by a fixed magnitude, and 4) operating the hazardous material train at minimum track speeds. Table 6.1 summarizes the scenarios considered in the case study.

Table 6.1. Speed management scenarios.

Scenario	Detail
1	Manage Target Speeds (Increase or Decrease)
1.1	- Allow Reduction in Total Travel Time
1.2	- Reduction in Total Travel Time Not Allowed
2	Reduce Speeds, Magnitude Varies
3	Apply a Fixed Magnitude of Speed Reduction
4	Operate Train at Minimum Track Speeds

The representative hazardous material transportation shipment route from Chapter 5 is used for the case study. For simplicity, I consider a single release scenario ($j = 1$), one tank car type ($k = 1$), and one product ($m = 1$). Table 6.2 summarizes the model parameters to be used.

The tank car considered in this case study is a non-insulated DOT-111A100W1 tank car with 7/16 inch tank thickness. Using the relationship developed in Chapter 4, the speed-dependent CPR function is $f(W'_i) = 1 - [(1 - 0.00208W'_i)(1 - 0.00265W'_i)(1 - 0.00551W'_i)(1 - 0.00176W'_i)]$, where $W'_i =$ speed (mph) on segment i .

Table 6.2. Route characteristics and input parameters.

Parameter	Value	Unit
Number of Carloads (V)	100	Carloads
Total Network Length	1,396	Miles
Length of Track Segment ¹ (L)	Varies	Miles
Average	2.33	Miles
Number of Segments	598	Segments
Operating Speeds ²	Varies	mph
Average	58	mph
Track Speed Limit (W^{\min}, W^{\max})	Based on track class	mph
Track class-specific Derailment Rates ³ (Z)		
Class 2 Track (25 mph maximum)	726×10^{-9}	Per Car-mile
Class 3 Track (40 mph maximum)	300×10^{-9}	Per Car-mile
Class 4 Track (60 mph maximum)	77×10^{-9}	Per Car-mile
Class 5 Track (70 mph maximum)	42×10^{-9}	Per Car-mile
Speed-dependent CPR ⁴ $f(W)$	Varies with speeds	No Unit
Probability of Specific Release Scenario (P)	1.0	No Unit
Segment-specific Population Density ⁵ (D)	Varies	Persons/Sq.Mi.
Affected Area for Specific Chemical ⁶ (A)	0.785	Square-mile
Consequence Cost ⁷ (Y)	675	\$ per persons
Train-delay Cost ⁸ (O)	233.32	\$ per train-hour

¹ BTS (2007)² Based on Timetable Speeds³ Anderson and Barkan (2004)⁴ Kawprasert and Barkan (2010)⁵ ESRI (2005)⁶ PHMSA (2008)⁷ Based on an evacuation cost of \$225 per person (PHMSA, 2008b) and an evacuation period of 3 days per industry expert opinion⁸ Schafer and Barkan (2008)

6.4.1 Manage Target Speeds and Allow Reduction in Total Travel Time

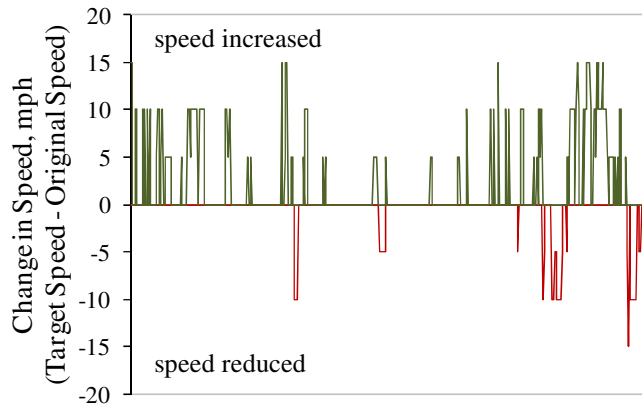
In this scenario, the train speed management model can be used to arbitrarily choose target speeds within a defined range of maximum and minimum speeds so as to minimize the risk and delay cost. The first step is to adapt the train speed management model to suit this particular problem. The computation of train-delay cost is simplified by considering the delay of only a single train, regardless of the following trains and the traffic density on the route network. That is, only the first term in Eq. (6.4) is considered.

In this scenario, the target speed on any particular segment may be increased or decreased from the original operating speed. The former results in travel time savings that are assumed to be represented by a negative delay cost, while the latter results in a positive delay cost on that segment. Since the net cost is unknown (either positive or negative), the non-negativity constraint in Eq. (6.12) is not required. Ideally, the early arrival of a train would offer track, crew, and rolling stock availability for later use, which is considered beneficial. The negative delay cost is assumed to account for this benefit under the ideal case. In practice, trains may arrive at a destination sooner but have to wait for crew or yard space, so that such a benefit could not be fully achieved. However, early arrival of trains may still offer availability for portions of the track section.

The original operating speeds on this particular route range from 20 to 70 mph and are all divisible by 5. Therefore, I consider a set of candidate target speeds for each segment from a minimum of 15 mph to a maximum of 70 mph at 5 mph increments for a total of 12 levels. The candidate speeds comprise 15, 20, and 25 mph for track class 2; 30, 35, and 40 mph for track class 3; 45, 50, 55, and 60 mph for track class 4; and 65 and 70 mph for track class 5. The risk and the delay cost parameters are computed for these speeds.

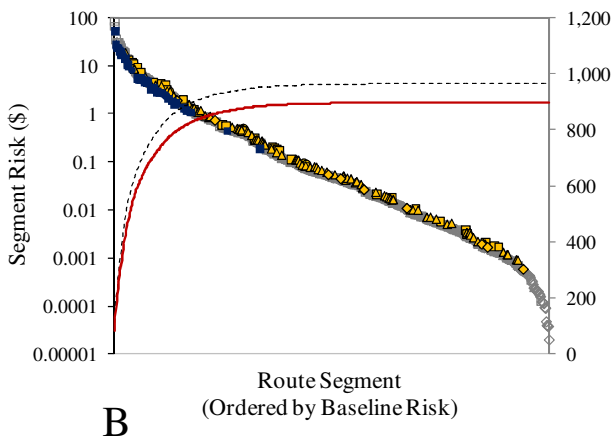
Next, I compute the value of the objective function for the baseline (prior to speed changes). This can be done by setting the speed variable equal to the original speed on each segment. Using GAMS/CPLEX, the objective function is determined to be \$964, comprising a baseline risk cost of \$964 and a delay cost of \$0. Using the original operating speeds, the train takes 25.5 hours to complete a trip on the network considered.

Solving the train speed management model to minimize both risk and delay costs yields a risk cost of \$898 (7% decrease from baseline risk cost), a delay cost of -\$294, and a total cost of \$603, which is a 37% decrease from the baseline total cost. Negative delay cost indicates that the train takes less time to complete the trip. In this case, total travel time is reduced from 25.5 hours to 24.2 hours, which is about 76 minutes faster (5% less than the original travel time). 181 segments, accounting for a total distance of 493 miles (31% of route length), are subject to speed change (increase or decrease). Figure 6.1 depicts the changes in operating speeds and the distribution of risk along the route considered.

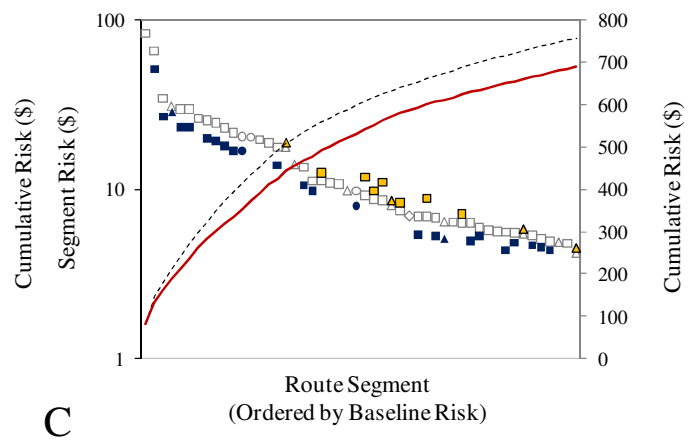


A Route Segment (from Origin to Destination)

- Baseline Risk (Class 2)
- Baseline Risk (Class 3)
- △ Baseline Risk (Class 4)
- ◇ Baseline Risk (Class 5)
- Baseline Cumulative Risk
- Cumulative Risk After Speed Management
- Speed Increase on Class 2
- Speed Increase on Class 3
- ▲ Speed Increase on Class 4
- ◆ Speed Increase on Class 5
- Speed Decrease on Class 2
- Speed Decrease on Class 3
- ▲ Speed Decrease on Class 4
- ◆ Speed Decrease on Class 5



B



C

Figure 6.1: Effects of Speed Changes (Travel Time Reduction Allowed)
(A) Speed Diagram, (B) Risk Distribution (All Segments),
and (C) Risk Distribution for Top 50 Segments with the Highest Risk

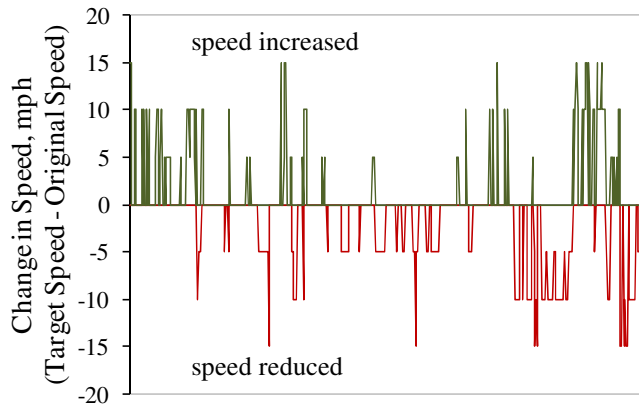
6.4.2 Manage Target Speeds without a Reduction in Total Travel Time

The previous scenario represents the case that offers the greatest reduction in total cost in which train speeds can be freely adjusted within the minimum-maximum track speed range. In this section, I introduce another train speed management strategy that allows for an increase in speed on segments but does not allow a reduction in total travel time. The purpose is to determine if there is an opportunity for speed changes in cases where a train is subject to operating conditions such that the total travel time cannot be further reduced. The train speed management model can easily be modified to accommodate this scenario by incorporating the non-negativity constraint of the delay cost. Thus, the model applicable for this specific scenario comprises Eq. (6.10) and (6.12) – (6.14).

Solving the train speed management model yields a risk cost of \$826 (14% reduction from baseline risk cost) and a delay cost of \$0, for a total cost of \$826 (14% decrease from baseline total cost). With the new speeds (Figure 6.2a), the train will spend the same amount of time to complete the trip as the baseline case. The model suggests that 258 segments, accounting for 509 miles or 36% of total route length, are subject to speed change. Under this scenario, only speed reduction is applied on high risk segments (Figures 6.2b-c), as compared to both speed increases and decreases in the previous scenario (Figures 6.1b-c).

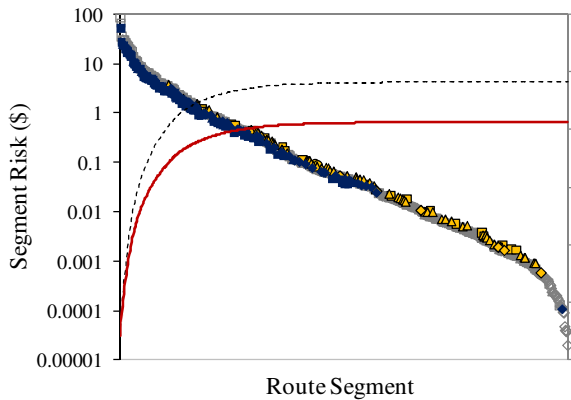
6.4.3 Manage Target Speeds with a Variable Reduction in Train Speeds

This scenario is similar to the previous scenario, except that speeds can only be reduced. Therefore, the maximum speed limit W_i^{\max} is replaced by original speeds W_i . Solving the train speed management model yields a risk cost of \$875 (9% decrease from baseline), a delay cost of \$42, and a total cost of \$916 (5% decrease). Total travel time increases by 11 minutes, and 42 segments (28 miles or 2% of total length) are subject to speed reduction (Figure 6.3).

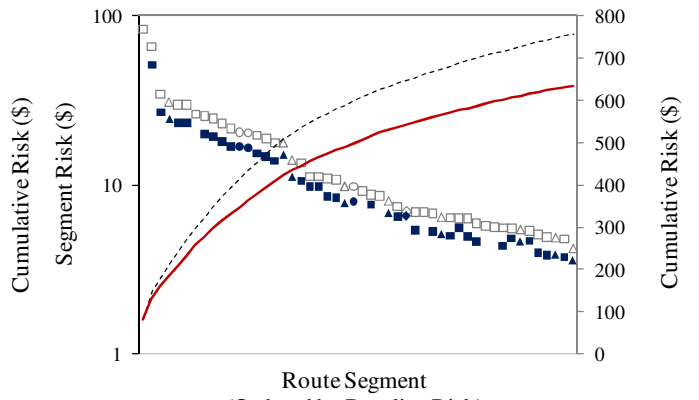


A Route Segment (from Origin to Destination)

- Baseline Risk (Class 2)
- Baseline Risk (Class 3)
- △ Baseline Risk (Class 4)
- ◇ Baseline Risk (Class 5)
- Baseline Cumulative Risk
- Cumulative Risk After Speed Management
- Speed Increase on Class 2
- Speed Increase on Class 3
- ▲ Speed Increase on Class 4
- ◆ Speed Increase on Class 5
- Speed Decrease on Class 2
- Speed Decrease on Class 3
- ▲ Speed Decrease on Class 4
- ◆ Speed Decrease on Class 5



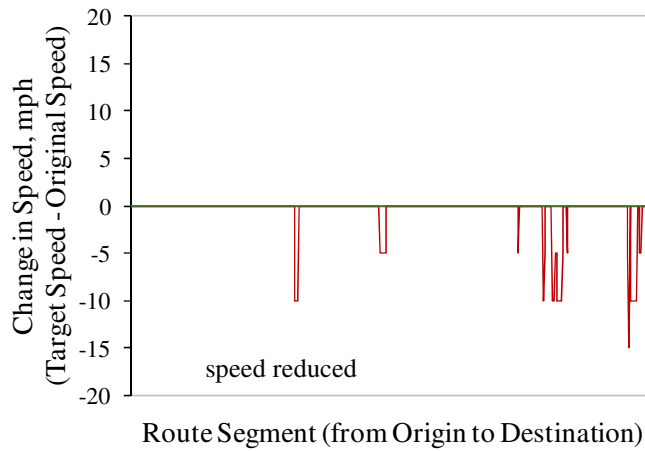
B Route Segment (Ordered by Baseline Risk)



C Route Segment (Ordered by Baseline Risk)

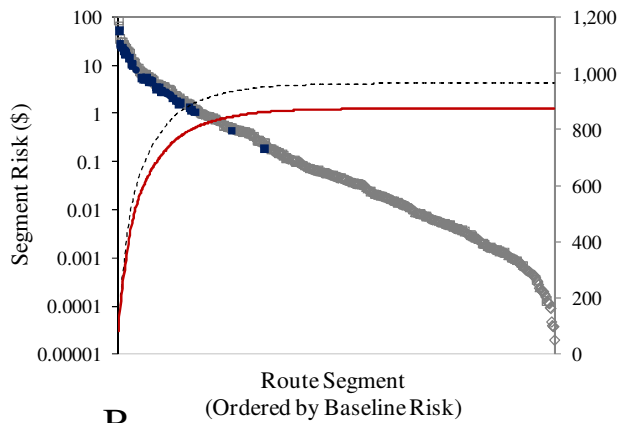
Figure 6.2: Effects of Speed Changes (Travel Time Reduction Not Allowed)

(A) Speed Diagram, (B) Risk Distribution (All Segments), and (C) Risk Distribution for Top 50 Segments with the Highest Risk

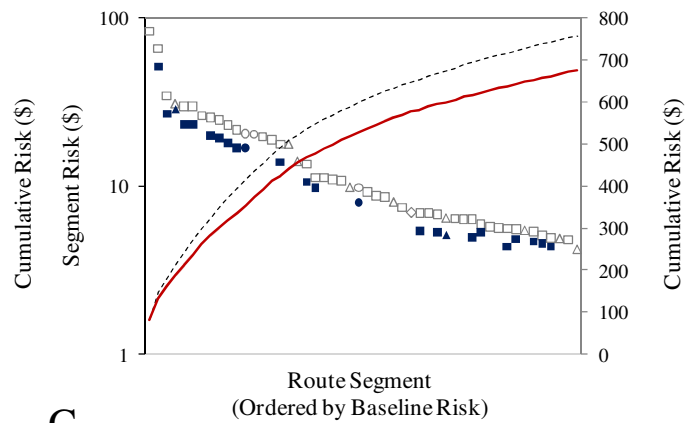


A

- Baseline Risk (Class 2)
- Baseline Risk (Class 3)
- △ Baseline Risk (Class 4)
- ◇ Baseline Risk (Class 5)
- Baseline Cumulative Risk
- Cumulative Risk After Speed Management
- Speed Decrease on Class 2
- Speed Decrease on Class 3
- ▲ Speed Decrease on Class 4
- ◆ Speed Decrease on Class 5



B



C

Figure 6.3: Effects of Speed Changes (Speed Reduced Only)
(A) Speed Diagram, (B) Risk Distribution (All Segments),
and (C) Risk Distribution for Top 50 Segments with the Highest Risk

6.4.4 Manage Target Speeds with a Fixed Reduction in Train Speeds

This scenario facilitates a consideration of speed management for any particular magnitude of reduction in train speed, given a maximum allowable train delay. Accordingly, the modified model described in Eq. (6.15) – (6.18) is used. Here, I illustrate the case of a constant reduction in speed by assuming $\Delta = 10$ mph and a maximum allowable delay of 1 hour. Segment-specific CPR, risk, and travel time are computed and used as model inputs. Solving the train speed management model yields a risk cost of \$873 (9% decrease from baseline), a delay cost of \$45, and a total cost of \$918 (5% decrease). Total travel time increases by 12 minutes, and 29 segments (23 miles or 1.6% of total length) are subjected to speed reduction (Figure 6.4).

6.4.5 Operate Train at Minimum Track Speeds

The last scenario illustrates the extreme case in which risk is minimized by operating a hazardous material train at minimum artificial track speeds. That is, the objective is to minimize the risk while neglecting the delay. The train speed management model could be modified to accommodate this scenario by relaxing the travel cost constraint and assigning the minimum track speed as a set of the candidate speed.

The model yields a risk cost of \$710 (26% decrease from baseline), a delay cost of \$1,775, and a total cost of \$2,485 (158% increase). Total travel time increases by 7.6 hours, and all 598 segments in the network are subject to speed reduction.

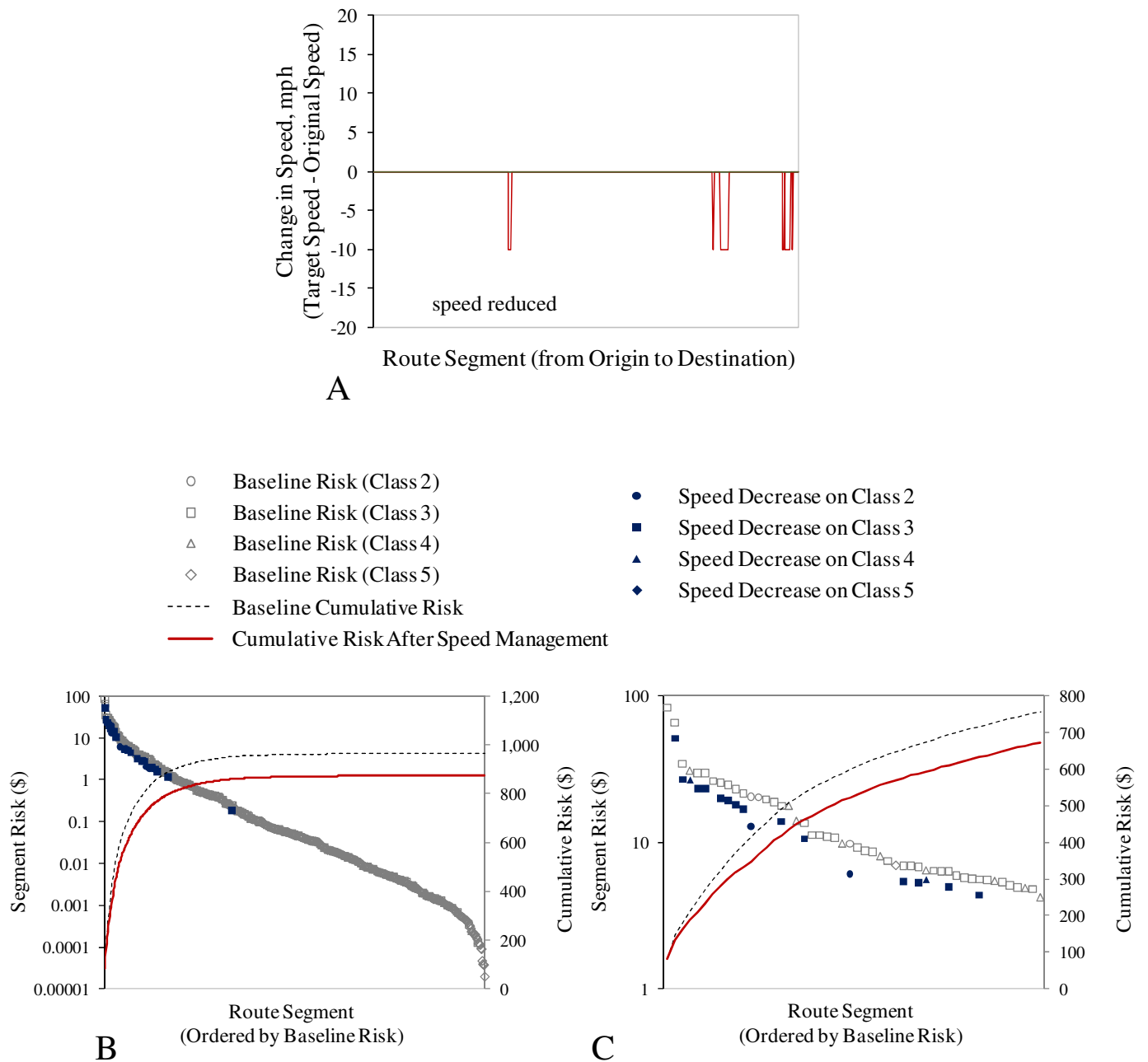


Figure 6.4: Effects of Speed Changes (Speed Reduction Fixed at 10 mph)
(A) Speed Diagram, (B) Risk Distribution (All Segments),
and (C) Risk Distribution for Top 50 Segments with the Highest Risk

6.4.6 Comparison of Results of Speed Management Scenarios

Five different scenarios for train speed management were illustrated. For all scenarios, a greater proportion of risk reduction is achieved by managing speeds on class-3 track segments, as indicated in Figures 6.1 – 6.4. These also illustrate how the train speed management model performs according to different objectives of interest. In the scenario where speeds can be arbitrarily adjusted, the model increases speeds to minimize delay and consequently the total cost. In the scenario where speeds change without reduction in travel time, the model attempts to balance speed increases and decreases to minimize risk, while maintaining the same total travel time.

For the scenario where the magnitude of speed reduction is fixed and the scenario where the magnitude of speed reduction varies, the magnitude of reduction in total cost is small. This is because a further reduction in speed would result in an increased delay and, subsequently, in total cost. Nevertheless, all scenarios considered, except that in which the train is operated at minimum track speeds, suggest a cost reduction associated with the shipments: 7% – 14% for risk cost and 5% – 37% for total cost. A graphical comparison of results is shown in Figure 6.5.

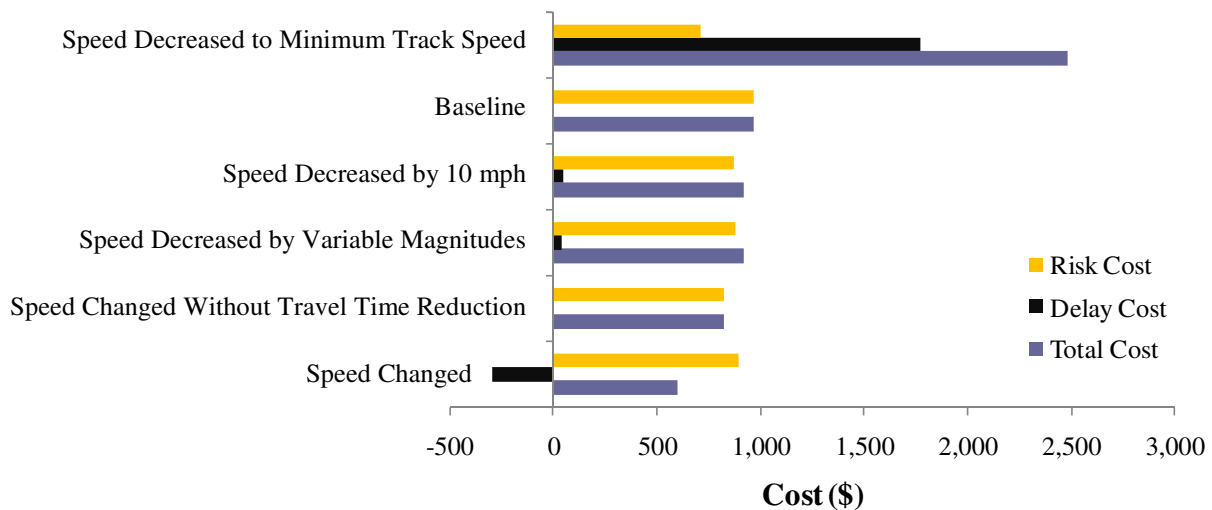


Figure 6.5: Comparison of Results of Speed Management Scenarios

6.4.7 Effects of Magnitude of Speed Reduction on Risk and Cost

A risk manager may be interested in evaluating the effects of several parameters that affect the total cost, including the effectiveness of various magnitudes of speed reduction. The train speed management model can be used for this type of evaluation. Here, I provide two illustrations of the sensitivity analysis.

Figure 6.6 shows the changes in costs along and total distance to which a speed reduction of 10 mph is applied at the optimal locations. As the speed reduction distance increases, the delay increases while the risk decreases at diminishing rate, up to the minimum level of \$825 (14% decrease), corresponding to a total cost of \$1,385 at the distance of 464 miles (not shown on graph). The problem becomes infeasible beyond this minimum risk level. The reduction in total cost, however, is possible up to the distance of 74 miles, indicated by the vertical dashed line. With an increased travel time of 0.55 hours from the baseline, corresponding to the delay cost of \$128, the total cost is maintained at the same level as that of the baseline cost of \$964, but risk cost can be reduced to \$835 (15% decrease). Beyond the 74 miles of 10-mph speed reduction, the total cost becomes greater than the baseline cost as the increase in delay cost overcomes the reduction in risk cost.

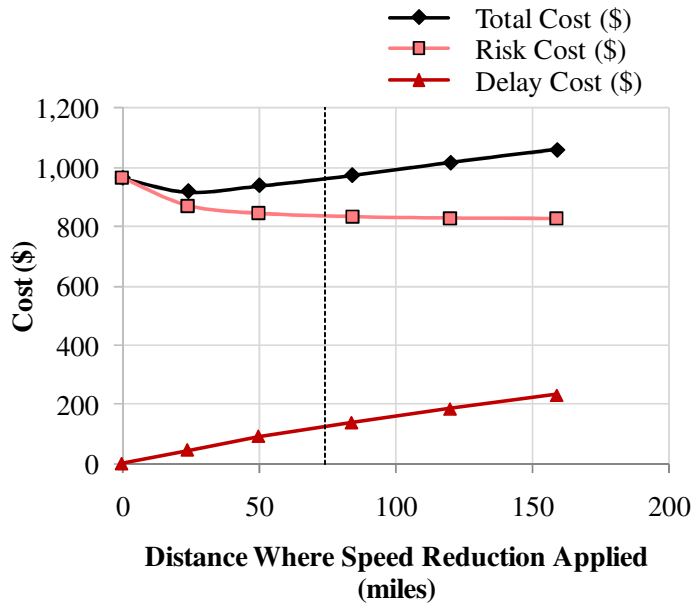


Figure 6.6: Cost vs. Distance for 10 mph Speed Reduction

Figure 6.7 shows the number of segments and the corresponding distance required for various magnitudes of speed reduction. For the same amount of delay, a speed reduction of 5 mph requires more segments and a greater distance where the speed reduction is to be applied.

Because of operating constraints, 5 mph and 10 mph reductions in train speed are not possible beyond a 2.4 hour-delay (1,245 miles and 464 miles of speed reduction, respectively), while a 15 mph speed reduction is limited to 1.4 hours of delay (252 miles of speed reduction).

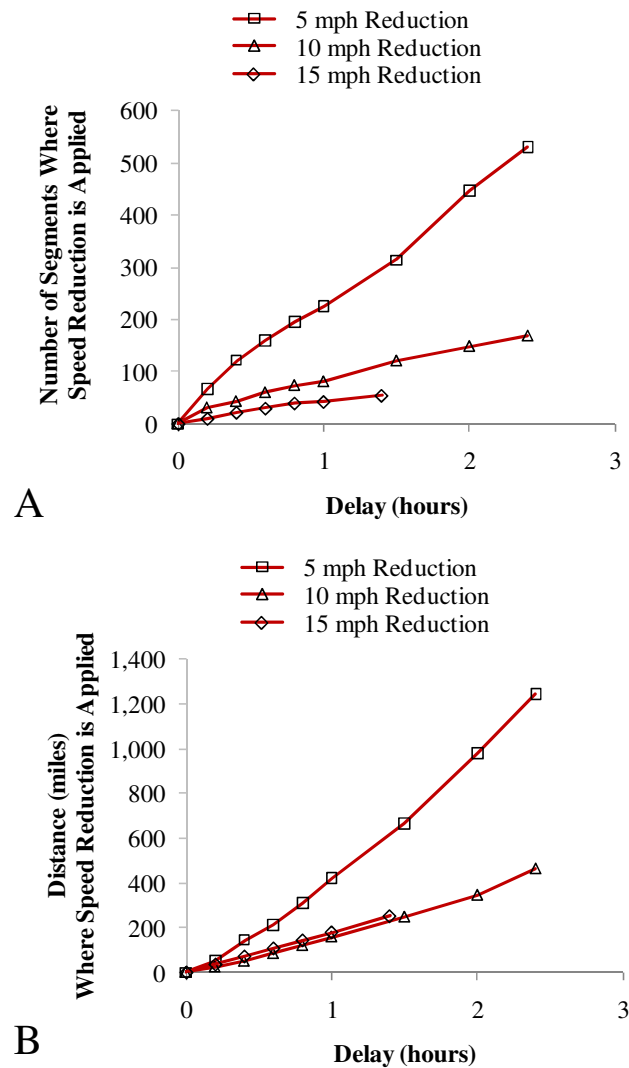


Figure 6.7: Infrastructure Requirements for Various Magnitudes of Speed Reduction
(A) Number of Segments and (B) Distance

Figure 6.8 shows the effects of different magnitudes of speed reduction on risk cost, delay cost, and total cost. Three constant magnitudes of speed reduction are evaluated: 5 mph, 10 mph, and 15 mph. Interestingly, for the same amount of delay, the highest magnitude of speed reduction results in the least reduction in risk cost and total cost, while the 10 mph speed reduction yields the greatest reduction.

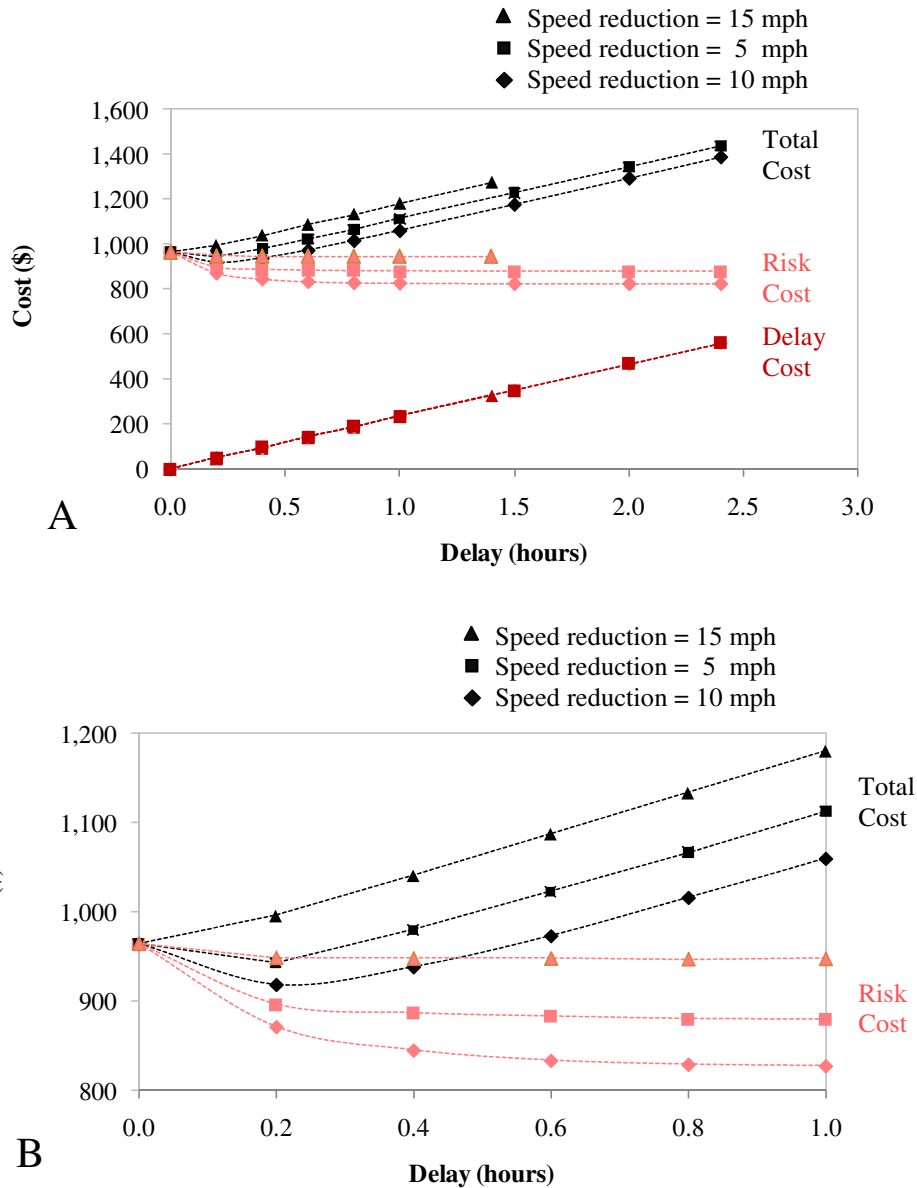


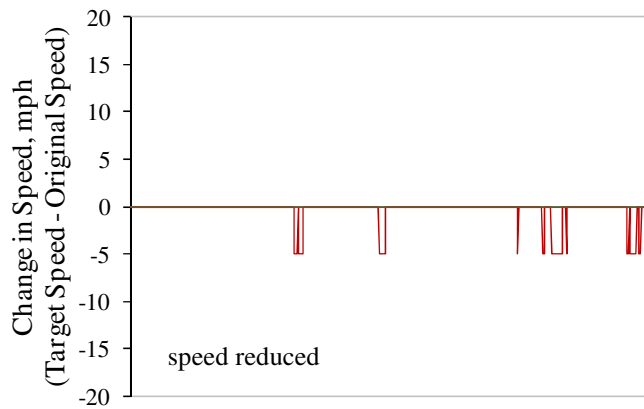
Figure 6.8: Effects of Various Magnitudes of Speed Reduction on Costs
(A) Risk, Delay, and Total Costs and (B) Risk and Total Costs for Delay of 0 to 1 Hour

It is expected that the risk reduction from a 10 mph speed reduction will be greater than from a 5 mph reduction. However, the 15 mph reduction does not result in a greater reduction in risk than the 10 mph reduction. This is because the higher the magnitude of speed reduction, the more likely the reduction will be subject to other operating constraints. Based on track-class-specific speed categories (mph) assumed in Section 6.4.1, i.e. (15, 20, 25)^{class 2}, (30, 35, 40)^{class 3}, (45, 50, 55, 60)^{class 4}, and (65, 70)^{class 5}, the track class having the widest speed range that allows for a 15 mph reduction is class-4 track. In particular, the segments that can accommodate a 15 mph reduction in speed are more limited in number for the route considered. Those segments are likely to be those where the train is originally operated at the maximum track speed, and they tend to be located in lower risk areas along the route. To formally investigate this, I examined the speed and risk distribution diagrams for fixed speed reductions of 5 and 15 mph, similar to the analysis in Figure 6.4.

Figures 6.9 and 6.10 show the optimal segments for speed reduction and the magnitude of risk reduction corresponding to a fixed speed reduction of 5 and 15 mph, respectively. For a 5 mph speed reduction, the train speed management model yields a minimum risk cost of \$911 (5% decrease from baseline), a delay cost of \$25, and a total cost of \$937 (3% decrease). Total travel time increases by 7 minutes, and 47 segments (28 miles or 2% of total length) are subject to speed reduction (Figure 6.9). For a 15 mph reduction, the minimum possible risk cost is \$963. There is only one segment that can accommodate a speed reduction of 15 mph to reduce the total cost (Figure 6.10). Thus, the magnitude of cost reduction is negligible compared to the baseline total cost. Therefore, for the route considered, the model found more opportunities to reduce risk with 5 and 10 mph reductions than with a 15 mph reduction.

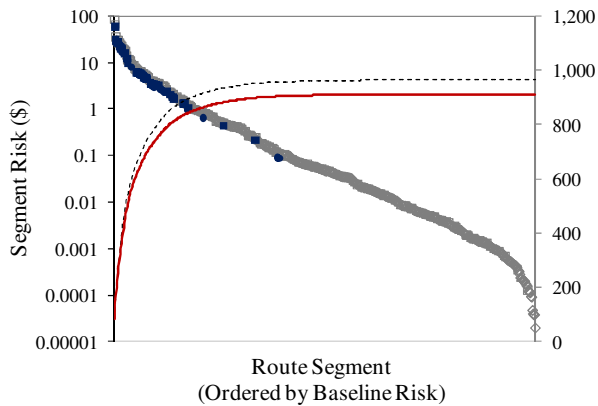
6.4.8 Effects of Weights Attached to Risk and Delay Costs

Previously, I illustrated various speed management scenarios, assuming that both risk and delay costs have the same weight. In actual decision making, preference towards risk and cost may differ depending on the parties who make the decision and their objective of interest. For example, the government may wish to place more weight on risk reduction, while transportation delay may be a more important factor for railroad carriers or shippers. The tradeoff of such preferences may affect the optimal speed management strategy. Thus, the model framework must be capable of identifying the strategy that best supports the decision maker's preference.

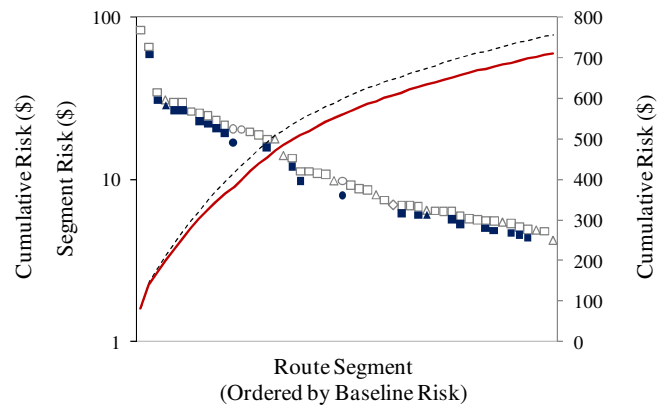


A Route Segment (from Origin to Destination)

- Baseline Risk (Class 2)
- Baseline Risk (Class 3)
- △ Baseline Risk (Class 4)
- ◇ Baseline Risk (Class 5)
- Baseline Cumulative Risk
- Cumulative Risk After Speed Management
- Speed Decrease on Class 2
- Speed Decrease on Class 3
- ▲ Speed Decrease on Class 4
- ◆ Speed Decrease on Class 5

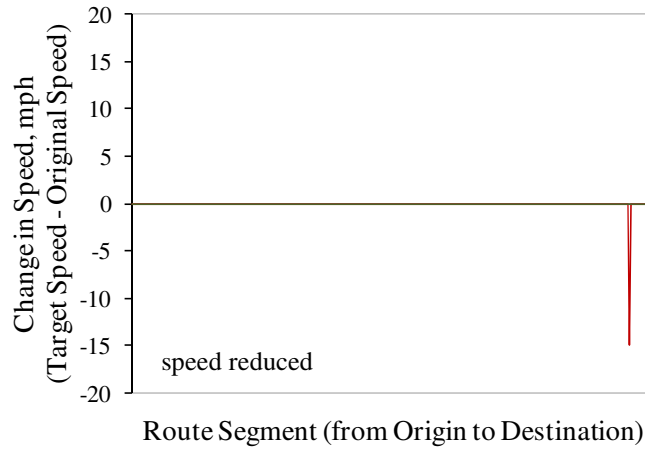


B



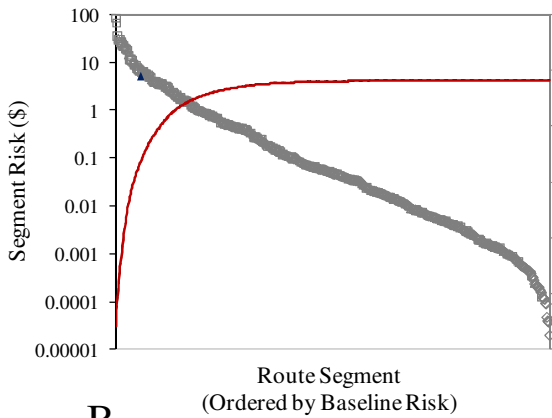
C

Figure 6.9: Effects of Speed Changes (Speed Reduction Fixed at 5 mph)
(A) Speed Diagram, (B) Risk Distribution (All Segments),
and (C) Risk Distribution for Top 50 Segments with the Highest Risk

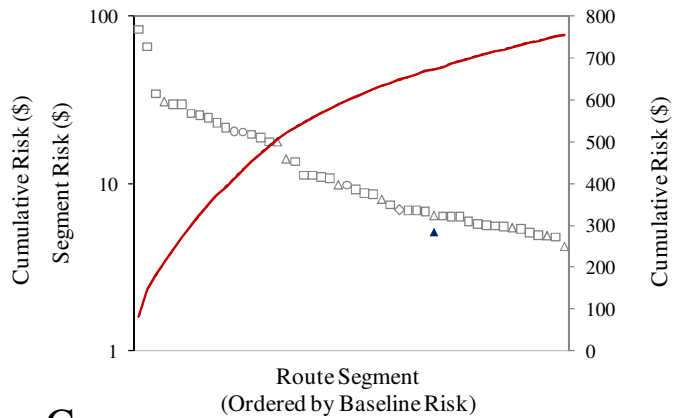


A

- Baseline Risk (Class 2)
- Baseline Risk (Class 3)
- △ Baseline Risk (Class 4)
- ◇ Baseline Risk (Class 5)
- Baseline Cumulative Risk
- Cumulative Risk After Speed Management
- Speed Decrease on Class 2
- Speed Decrease on Class 3
- ▲ Speed Decrease on Class 4
- ◆ Speed Decrease on Class 5



B



C

Figure 6.10: Effects of Speed Changes (Speed Reduction Fixed at 15 mph)
(A) Speed Diagram, (B) Risk Distribution (All Segments),
and (C) Risk Distribution for Top 50 Segments with the Highest Risk

To accommodate the tradeoff between risk and cost (i.e. risk cost and delay cost), the objective function of the train speed management models can be modified as follows:

$$\text{Minimize } Q = \sum_{i \in I} \sum_{w \in W} C_{iw} \left[\lambda S_{iw} + (1 - \lambda) f(T_{iw}) \right] \quad (6.19)$$

$$\text{Minimize } Q = \lambda \left(\sum_{i \in I} (1 - \phi_i) S_i + \phi_i S'_i \right) + (1 - \lambda) \sum_{i \in I} \phi_i f(T_i) \quad (6.20)$$

Where:

$$\lambda = \text{weighting coefficient (between 0 and 1)}$$

The objective functions in Eq. (6.19) and (6.20) above substitute Eq. (6.10) and (6.15) of the train speed management model, respectively.

To illustrate the effect of different weights attached to risk and cost components, I consider the case of a fixed reduction in speed (Δ) of 5, 10, and 15 mph. Solving the modified train speed management model, comprising Eq. (6.19) and (6.16) – (6.18), with 0.1 increments for the weighting coefficient λ , yields the results in Table 6.3.

As the weight attached to risk increases, the model chooses more segments to which it applies the speed reduction, thereby further reducing risk while increasing delay. At 0.1 increments for the weighting coefficient, speed reduction takes place when $\lambda = 0.3$ or more for $\Delta = 5$ and 10 mph, while a speed reduction of 15 mph requires $\lambda = 0.5$ or more. For all the magnitudes of speed reduction considered, the total cost is minimized when $\lambda = 0.5$.

For all values of λ , the speed reduction of 5 mph requires a greater distance of speed reduction compared to a 10 mph reduction yet gives a smaller magnitude of reduction in risk. In the case of $\Delta = 15$ mph, the model struggles to find the segments to which it can apply a speed reduction, thereby providing the least reduction in risk. For the scenarios considered, a speed reduction of 10 mph is the best option, giving the highest magnitude of risk reduction, 14%, from the baseline at $\lambda = 0.9$ (Figure 6.11).

Table 6.3. Speed management strategies based on tradeoffs between risk and cost.

Magnitude of Speed Reduction = 5 mph								
Lambda	Value of Objective Function	Risk Cost		Delay (hrs)	Delay Cost (\$)	Total Cost (\$)	Speed Reduction Applied to:	
		\$	% Reduction from Baseline				No. of Segments	Distance (Miles)
0.1	96.40	963.99	0.00	0.00	0.00	963.99	0	0
0.2	192.80	963.99	0.00	0.00	0.00	963.99	0	0
0.3	286.81	933.61	3.15	0.04	9.62	943.23	14	11
0.4	378.57	924.41	4.11	0.06	14.68	939.09	23	16
0.5	468.41	911.46	5.45	0.11	25.36	936.82	47	28
0.6	555.85	901.19	6.52	0.16	37.84	939.03	64	38
0.7	641.66	895.89	7.06	0.21	48.44	944.34	79	56
0.8	725.92	892.49	7.42	0.26	59.62	952.11	92	78
0.9	806.87	886.29	8.06	0.39	92.12	978.41	134	147

Magnitude of Speed Reduction = 10 mph								
Lambda	Value of Objective Function	Risk Cost		Delay (hrs)	Delay Cost (\$)	Total Cost (\$)	Speed Reduction Applied to:	
		\$	% Reduction from Baseline				No. of Segments	Distance (Miles)
0.1	96.40	963.99	0.00	0.00	0.00	963.99	0	0
0.2	192.80	963.99	0.00	0.00	0.00	963.99	0	0
0.3	286.06	908.06	5.80	0.08	19.49	927.55	10	10
0.4	373.82	895.87	7.07	0.11	25.79	921.66	17	14
0.5	458.88	873.07	9.43	0.19	44.68	917.75	29	23
0.6	540.57	857.24	11.07	0.28	65.58	922.82	41	28
0.7	618.56	845.45	12.30	0.38	89.15	934.60	50	44
0.8	693.38	841.48	12.71	0.43	100.96	942.44	57	55
0.9	763.05	829.30	13.97	0.71	166.75	996.06	72	111

Magnitude of Speed Reduction = 15 mph								
Lambda	Value of Objective Function	Risk Cost		Delay (hrs)	Delay Cost (\$)	Total Cost (\$)	Speed Reduction Applied to:	
		\$	% Reduction from Baseline				No. of Segments	Distance (Miles)
0.1	96.40	963.99	0.00	0.00	0.00	963.99	0	0
0.2	192.80	963.99	0.00	0.00	0.00	963.99	0	0
0.3	289.20	963.99	0.00	0.00	0.00	963.99	0	0
0.4	385.59	963.99	0.00	0.00	0.00	963.99	0	0
0.5	481.79	962.70	0.14	0.00	0.88	963.58	1	1
0.6	576.88	956.57	0.77	0.03	7.34	963.92	2	6
0.7	671.80	956.57	0.77	0.03	7.34	963.92	2	6
0.8	765.84	953.46	1.09	0.07	15.36	968.82	4	12
0.9	858.45	949.18	1.54	0.18	41.83	991.02	9	32

- ▲— Risk vs. Delay Cost (5 mph reduction)
- ◆— Risk vs. Delay Cost (10 mph reduction)
- Risk vs. Delay Cost (15 mph reduction)
- -▲- - Risk vs. Total Cost (5 mph reduction)
- -◆- - Risk vs. Total Cost (10 mph reduction)
- -■- - Risk vs. Total Cost (15 mph reduction)

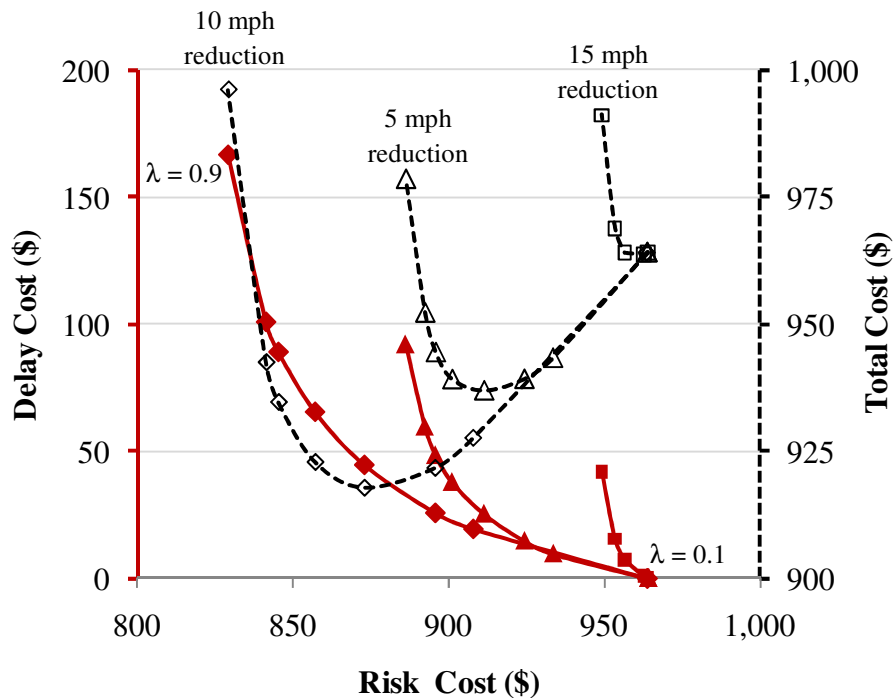


Figure 6.11: Tradeoff Curves for Different Values of The Weighting Coefficient and Speed Reduction

6.5 Consideration of Other Cost Elements

There will always be uncertainties associated with risk and delay cost elements that are difficult to accurately determine. Analyses in previous sections are based on a simplification of risk and delay cost estimation. That is, only the costs of an evacuation and a single train delayed were incorporated. In addition, artificial speed restrictions on route segments were assumed. As mentioned earlier, the objective is not to provide the best estimates but to test and illustrate various possible applications of the train speed management model developed in this chapter. In this section, I discuss some opportunities for improving the cost estimates that may be necessary for a more accurate analysis of the cost-effectiveness of train-speed reduction as a means of reducing risk.

6.5.1 Consequence Costs of Hazardous Material Release Incident

Apart from the evacuation cost per person affected in a hazardous material release incident, one may consider incorporating other costs into the mathematical model. Depending on the information available, these costs may include: remedial cleanup, track property and equipment damage, and material loss. The U.S. Department of Transportation (DOT) Pipeline and Hazardous Materials Safety Administration (PHMSA) maintains a database of hazardous material incidents. The database is available online at <https://hazmatonline.phmsa.dot.gov/IncidentReportsSearch/> (PHMSA, 2010). One may look up the incident statistics involving the hazardous materials of interest. I analyzed the PHMSA incident database for hazardous material tank car derailments in transit during the years 1998 to 2009. Only incidents involving materials of hazard classes 3 and 4, transported in non-pressure cars, which involved fire were analyzed (Table 6.4).

Table 6.4. Consequence costs from PHMSA incident reports database.

Cost (\$)	Material Loss	Carrier Damage	Property Damage	Response Cost	Remediation Cleanup Cost	Total Amount of Damages
Min	3,000	4,500	5,000	8,100	1,500	53,000
Max	849,236	2,500,000	2,300,000	350,000	950,000	3,015,000
Average	178,903	624,985	226,750	101,950	299,089	1,433,998

Notes: 1) Incident data from 1998 – 2009, accessed January 2010
 2) Incidents involved hazardous materials with DOT hazard classes 3 and 4 transported in non-pressure cars that were derailed in transit resulting in fire

Saat (2009) used the Hazardous Materials Transportation Environmental Consequence Model to estimate the chemical-specific expected cleanup costs of a spill, representing the nationwide average and accounting for different hydrogeological conditions along the rail lines. The expected costs of spills for a group of Light Non-Aqueous-Phase Liquids (LNAPL) hydrocarbon compounds ranged from approximately \$400,000 to \$900,000.

Liu et al. (2010) developed track-class-specific consequence cost using FRA-reportable accident data. The average consequence cost, accounting for track and equipment damage due to a derailment on a mainline, is \$375,000 per accident. Their estimates would include costs unrelated to hazardous materials and exclude some hazardous-material-specific costs.

The costs described here provide insight into the order of magnitude that risk cost should be. In general, the consequence cost may comprise both fixed (average) cost and variable (unit) cost. The average cost may comprise carrier and property damage costs that are independent of accident speed and severity, rolling stock, and infrastructure condition. The unit cost may comprise material loss and cleanup costs, which could be a function of spill size or volume, and emergency response or evacuation costs, which vary with the number of persons affected. The train speed management model developed in this chapter can be modified to accommodate these additional cost elements. For example, the risk cost objective function below incorporates the evacuation cost per person affected and the average consequence cost per release incident.

$$\text{Minimize } S = \sum_{i \in I} \sum_{j \in J} \sum_{k \in K} \sum_{m \in M} V_{ik}^m L_i Z_i f(W'_{ik}) (P_{ij}^m D_i A_j^m Y_{ij}^m + E^m) \quad (6.21)$$

Where:

$$E^m = \text{average consequence cost per release incident for material } m \text{ (\$)}$$

6.5.2 Multiple Train-delay Costs

Rail Traffic Controller (RTC) may be used to determine train delay for all possible magnitudes of speed change applied to each segment, but this can be quite time consuming. Previous studies using RTC often considered an average or a maximum speed for each train type to compute the delay on the network (Dingler et al., 2009) and, therefore, may not be suitable for analyses regarding speed changes that require more detail at the segment-specific level. The case studies in Section 6.4 consider the delay cost of one single train, i.e. the train carrying the hazardous material that is subject to the speed reduction. In this section, I revisit the estimation of delay cost using the relationship developed by Schafer (2008) to investigate if it is applicable for multiple-train delay in the speed management problems considered.

First, I determined traffic density for the route considered using the data provided by the Bureau of Transportation Statistics (BTS, 2007). For simplicity, I calculated a weighted-average traffic density instead of segment-specific density. The average density on the route considered is 86 million gross tons. I assumed a fixed speed reduction of 10 mph.

For each segment, I computed the delay (in hours) after a 10 mph speed reduction was applied using Eq. (6.4). Here, the headway is $t = 53.33/\text{MGT} = 53.33/86 = 0.62$ hours. The maximum delay due to speed decrease on segments T_i^{\max} is 0.15 hours. For each segment, the number of subsequent trains delayed is less than one ($B = T/t = 0.15/0.62$), so the delay cost corresponding to each segment is $T_i O + (T_i - 0.62) O$. The second term of the summation is negative because the segments in the route are not long enough for the multiple-train delay cost equation to have an effect. Therefore, I neglected the multiple-train delay cost when computing the total-train delay cost in the case studies in Section 6.4.

Another observation is about a difference in the order of magnitude of the risk and delay costs. Suppose all consequence cost elements in Table 6.4 were incorporated into the risk cost equation. The risk cost could outweigh the delay cost and thereby reduce the optimization problem to the single objective problem of minimizing risk. Although weighting factors or normalization can be applied to risk and delay costs as desired, there remain challenges to develop a more accurate, realistic estimation of both risk and delay costs.

6.6 Optimizing Risk Reduction Options: Managing Train Speed and Track Upgrade

Risk managers may be interested in choosing the most cost-effective option among a set of alternatives for reducing hazardous materials transportation risk on a particular network of interest. Previously, I discussed the model framework that can be adapted to facilitate the consideration of each individual risk reduction option: alternate routing (Chapter 3), track infrastructure improvement (Chapter 5), and speed management (Chapter 6). One approach to determining the option that offers the greatest reduction in risk with minimal cost is to solve each individual model separately and compare the benefits and costs of each option.

Another approach is to develop an integrated framework that incorporates multiple risk-reduction options into one single model. In this section, I describe a basic framework that can help risk managers choose between reducing speed, upgrading segments to higher track classes, or doing nothing. The routing problem, however, has different characteristics and requirements. In addition, there is not enough information to accurately estimate the cost of rerouting. At this stage, it may be more appropriate to consider the routing option separately.

6.6.1 Mathematical Model for Choosing Multiple Risk Reduction Strategies

In this subsection, I describe a mathematical model that simultaneously considers train speed management and track infrastructure upgrade for hazardous materials transportation route risk reduction. The mathematical framework for simultaneously considering these options for hazardous materials transportation risk reduction is referred to as the *risk reduction options selection model*, which can be written in a general BIP form as follows:

$$\text{Minimize } S = \sum_{i \in I} \phi_i S_i^N + \sum_{i \in I} \varphi_i S_i^S + \sum_{i \in I} \gamma_i S_i^U \quad (6.22)$$

$$T = \sum_{i \in I} \varphi_i T_i^S + \sum_{i \in I} \gamma_i T_i^U \quad (6.23)$$

subject to

$$\sum_{i \in I} \varphi_i T_i^S + \sum_{i \in I} \gamma_i T_i^U \leq X \quad (6.24)$$

$$\phi_i + \varphi_i + \gamma_i = 1 \quad \forall i \quad (6.25)$$

and

$$\phi_i, \varphi_i, \gamma_i : \text{binary } \forall i \quad (6.26)$$

Where:

- S = total risk cost of transporting hazardous materials on route network
- T = total cost of implementing risk reduction measures on route network
- S_i^N = baseline risk cost of transporting hazardous materials on segment i
- S_i^S = risk cost of transporting hazardous materials on segment i given that speed reduction is applied to the corresponding segment
- S_i^U = risk cost of transporting hazardous materials on segment i given that the corresponding segment is upgraded to a higher class
- T_i^S = cost of reducing train speeds on segment i
- T_i^U = cost of upgrading segment i to a higher class
- X = maximum budget allocation (\$)
- $\phi_i, \varphi_i, \gamma_i$ = decision variables corresponding to the option to be considered: do nothing, reduce speed, and upgrade track, respectively (0 if option is not selected, 1 if selected)

Baseline risk cost for segment i can be determined as follows:

$$S_i^N = \sum_{j \in J} \sum_{k \in K} \sum_{m \in M} V_{ik}^m L_i Z_i f(W_{ik}) (P_{ij}^m D_i A_j^m Y_{ij}^m + E^m) \quad (6.27)$$

The risk cost of transporting hazardous materials on segment i , given that speed reduction is applied to the corresponding segment, can be determined as follows:

$$S_i^S = \sum_{j \in J} \sum_{k \in K} \sum_{m \in M} V_{ik}^m L_i Z_i f(W_{ik} - \Delta_i) (P_{ij}^m D_i A_j^m Y_{ij}^m + E^m) \quad (6.28)$$

The risk cost of transporting hazardous materials on segment i , given that the segment is upgraded to a higher class, can be determined as follows:

$$S_i^U = \sum_{j \in J} \sum_{k \in K} \sum_{m \in M} V_{ik}^m L_i (Z_i - \Psi_i) f(W_{ik}) (P_{ij}^m D_i A_j^m Y_{ij}^m + E^m) \quad (6.29)$$

Where:

$$\Psi_i = \text{reduction in the segment-specific accident rate given that segment } i \text{ is upgraded to a higher class}$$

The cost of reducing train speeds, T^S , can be determined using Eqs. (6.4) to (6.6)

The cost of upgrading segment i to a higher class can be defined as an increase in the annual track maintenance cost that comprises the ordinary and the renewal maintenance costs (Liu et al., 2010).

$$T_i^U = F_i L_i \quad (6.30)$$

Where:

$$F_i = \text{annual cost of upgrading segment } i \text{ to a higher track class (\$ per mile)}$$

Lai et al. (2010) and Liu et al. (2010) developed an approach to estimate track-class-specific maintenance cost using information from Zarembski and Resor (2004). Information from these studies can be used for estimating annual track upgrade costs, F_i .

Depending on the objective of interest, the combined risk reduction model may be adjusted to accommodate a consideration of one particular strategy. For example, if a risk manager wishes to consider only speed reduction, then γ_i can be set to zero for all segment i . Likewise, ϕ_i can be set to zero if infrastructure improvement is the only option of interest.

All parameters of the model can be determined, thus the objective is to solve for an optimal combination of decision variables for each segment i , subject to total cost and decision constraints.

6.6.2 Case Study on Multiple Risk Reduction Strategies

To illustrate an application of the risk reduction options selection model, I considered a case study using the same hypothetical route data as that in Section 6.4. Several additional parameters were considered, together with assumptions, as shown in Table 6.5. In this particular problem, I assumed that the speeds remained the same after the track upgrade, since the objective focuses on speed reduction. However, the model also accounts for the benefit of reduced delays if a speed increase is assumed. Furthermore, I assumed that the speed reduction affects only the CPR and not the accident rate.

Table 6.5. Parameters and Assumptions for Risk Reduction Options Selection Problem.

Parameter / Assumption	Detail
<i>Average Consequence Cost</i>	Assume an average consequence cost (E) of \$1,332,000 per release incident, using data from Table 6.4 (use average value of total consequence cost, excluding response cost).
<i>Speed Reduction</i>	Assume a constant speed reduction (Δ) of 10 mph where applicable (where target speeds are not less than minimum track speeds). Use CPR from Kawprasert and Barkan (2010).
<i>Track Class Upgrade</i>	Consider upgrading existing track class to one higher class (i.e. 2 to 3, 3 to 4, or 4 to 5). Use track-class-specific accident rates from Anderson and Barkan (2004). Assume operating speeds remain the same after track upgrade.
<i>Annual Track Upgrade Cost</i>	Use Liu et al. (2010) track class upgrade cost model based on the average traffic density of 86 MGT. Upgrade Class 2 to Class 3: \$10,989 per mile Upgrade Class 3 to Class 4: \$11,577 per mile Upgrade Class 4 to Class 5: \$8,799 per mile

The corresponding baseline cost is \$9,768. The full model, comprising Eqs. (6.22) – (6.30), is solved under various levels of resource allocation: $X = \$ 0.25, 0.5, 1, 5, \text{ and } 10$ million. Since both Eq. (6.22) and (6.23) are in the same cost unit, they can be combined into a bi-objective function of minimizing risk and cost.

Solving the model yields a risk cost of \$9,050 (7% decrease from baseline), a delay cost of \$348, an upgrade cost of \$0, and a total cost of \$9,398 (4% decrease). The total travel time increases by 1.5 hours, and 116 segments (205 miles or 15% of total length) are subjected to speed reduction. As expected, the model did not choose any segments for upgrade because of the higher improvement cost compared to that of speed reduction. The delay cost estimation here accounts for only a single train delay and not the overall system delay. The resource levels are redundant because any further improvements beyond the optimal cost results in an increase in total cost.

To illustrate the effect of different budget levels, Eq. (6.23) is removed, thereby reducing the problem to risk minimization. Solving the risk reduction options selection model comprising Eq. (6.22) and Eq. (6.24) – (6.26) yields the results in Table 6.6.

Table 6.6. Combined strategies for risk reduction: speed reduction and track upgrade.

Baseline Risk Cost = \$9,768

Budget Allocation (million \$)	Risk Cost (\$)		Improvement Cost (\$)			Risk Reduction Strategies			
	Objective Function	% Reduction from Baseline Risk	Delay Cost	Track Upgrade Cost	Total Improvement Cost	Speed Reduction (miles)	Track Class Upgrade (miles)		
							2 to 3	3 to 4	4 to 5
0.25	8,376	14	550	249,432	249,982	468	1	21	0
0.5	8,079	17	535	499,461	499,996	460	6	37	0
1	7,595	22	528	999,459	999,987	456	6	80	0
5	5,603	43	239	4,999,717	4,999,956	292	11	230	253
10	5,067	48	0	7,566,935	7,566,935	0	11	230	545

From the optimization results, greater investment yields greater risk reduction. For lower levels of investment, the model prefers speed reduction to track infrastructure improvement. At higher levels of investment, the model favors track infrastructure upgrade and chooses less speed reduction. At the highest level of investment, risk is minimized through only track infrastructure upgrade.

For the route considered, the maximum possible risk reduction is 48% from the baseline, corresponding to the investment level of \$8 million. The magnitude of risk reduction diminishes over an increasing budget level (Figure 6.12).

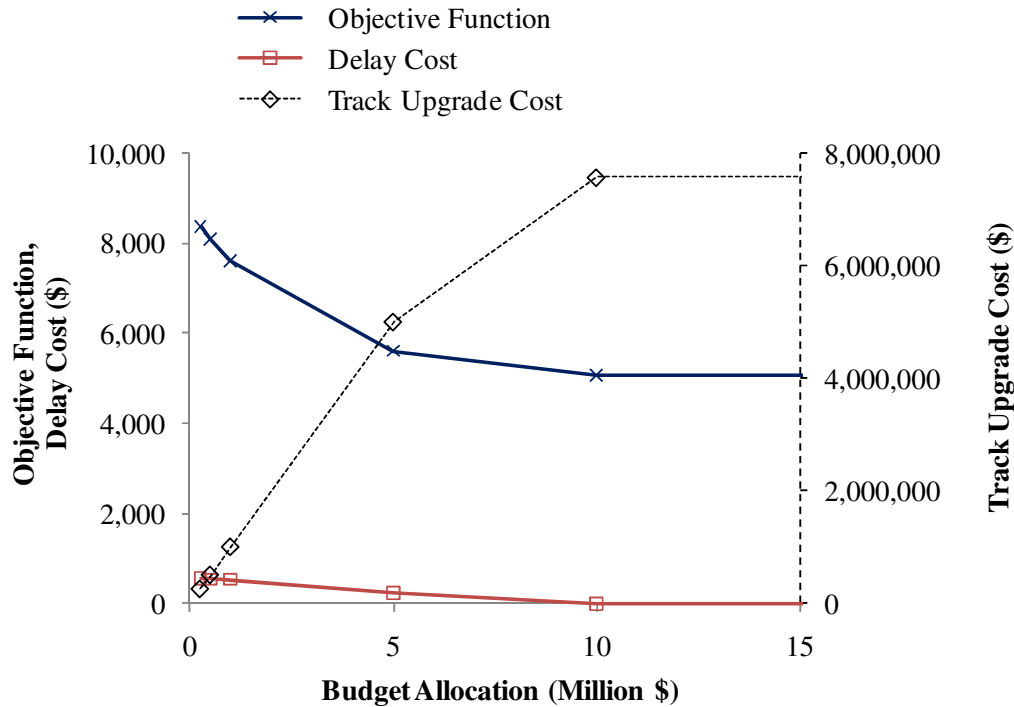


Figure 6.12: Optimal Budget Allocation Under Different Risk Reduction Strategies

Figure 6.13 is a graphical illustration of the distribution of segment risk after optimal risk reduction measures have been applied, corresponding to the investment level of \$5 million. The distribution indicates that the greatest reduction in risk is obtained by upgrading class-3 segments to class 4 (32% reduction), followed by upgrading class-4 segments to class 5 (6.4% reduction), reducing speed by 10 mph on class-4 segments (2.3% reduction) and upgrading class-2 segments to class 3 (1.9% reduction), for a total reduction in risk of 42.6% from baseline risk.

With appropriate assumptions, this type of analysis using the risk reduction options selection framework suggests a combination of risk reduction strategies given the available resources and helps inform decision-makers regarding investments to improve railroad hazardous materials transportation safety. Further development may consider packaging and/or routing as additional risk reduction options (e.g. Lai et al., 2011) to enhance the utility of the framework for the consideration of multiple risk-reduction options.

- Baseline Risk (Class 2) ▲ 10 mph Speed Reduction on Class 4
- Baseline Risk (Class 3) ● Class 2 Upgraded to Class 3
- △ Baseline Risk (Class 4) ■ Class 3 Upgraded to Class 4
- ◇ Baseline Risk (Class 5) △ Class 4 Upgraded to Class 5
- Baseline Cumulative Risk
- Cumulative Risk After Risk Reduction Applied

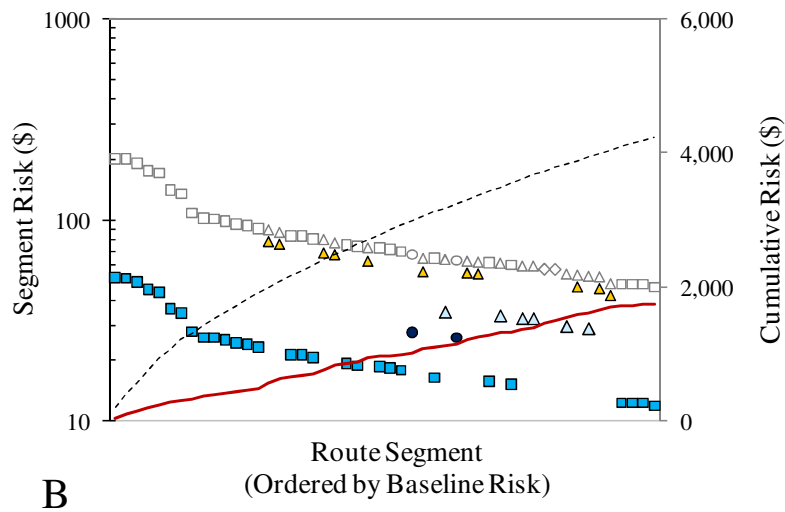
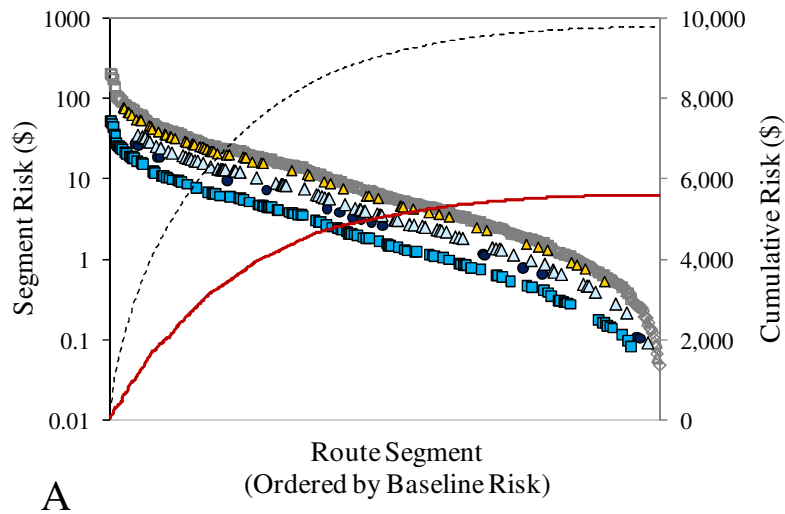


Figure 6.13: Distribution of Segment Risk When Optimal Risk Reduction Strategies Applied Under Budget of \$5,000,000

(A) All 598 Segments and (B) Focus on 50 Segments with the Highest Risk

6.7 Discussion

This chapter describes a mathematical framework that considers train speed as a management option for hazardous materials transportation risk reduction. Using representative shipment route data, a case study is developed to illustrate an application of the train speed management model under various scenarios. This allows for a better understanding of how this option performs and how it offers benefit as a possible means of risk reduction in addition to the other measures discussed in previous chapters.

The mathematical model framework developed is intended to help risk managers determine a more cost-effective strategy to reduce the risk of hazardous materials transportation by appropriately managing train speeds on a particular network given resource constraints. The case study highlights a flexibility of speed management that can be applied under various scenarios that are most feasible and useful to the concerned parties. All scenarios considered in the case study suggest a possible reduction in route risk compared to baseline.

Apart from train speed management, this chapter also introduces a general framework that integrates several different risk reduction options and considers them simultaneously in one single model. This integrated framework helps risk managers choose the most cost-effective strategy among a set of route risk reduction options. In particular, the integrated framework incorporates train-speed reduction and track infrastructure improvement. The case study, using the same representative route data, suggests that the risk could be reduced by half with a budget of \$8 million for risk reduction measures. The model framework presented here may serve as a decision support tool that could be further adapted to accommodate a particular problem of interest regarding hazardous materials transportation risk reduction.

There remains a challenge in developing a more accurate estimate of risk and system delay costs. These are critical elements in the mathematical framework for train speed management that is presented in this chapter. Simplification of these estimates serves the purpose of illustrating the application of the model. However, actual implementation of this means of reducing risk will require more realistic benefit and cost estimates for decision making.

6.8 Conclusions

This chapter makes use of recent developments in speed-dependent conditional probability of release (Kawprasert and Barkan, 2010), train-delay cost estimation (Schafer, 2008), and track infrastructure upgrade cost estimates (Liu et al., 2010) to develop a mathematical modeling framework that formally considers train speed management as a means of hazardous materials transportation risk reduction. The case study illustrates the flexibility of the train speed management model to accommodate various speed management scenarios. It also indicates a potential for risk reduction through the speed management of trains transporting hazardous materials over the route. In addition, an integrated model to consider combined risk reduction strategies is also developed as a tool to facilitate risk-based decision making for hazardous materials transportation. A case study suggests that speed reduction is the more favorable approach to risk reduction when lower levels of investment are available, while track infrastructure improvement may serve as a longer term measure when a larger budget is available. Overall, the study indicates that train speed management could be a feasible means of reducing hazardous materials transportation risk.

CHAPTER 7

PROBABILISTIC MODEL FOR ROUTE RISK ESTIMATION

7.1 Introduction

Definition of “risk” varies with the context of its application. According to Langlois and Cosgel (1993), early interpretation of risk involves “situations in which one could assign probabilities to outcomes and by uncertainty situations in which one could not” (Knight, 1921; Friedman, 1976). In safety engineering, risk is “a combination of three attributes: What can go wrong?, How bad could it be?, and How often might it happen?” (CCPS, 2007). In the context of transportation risk, it is defined as “a measure of human injury, environmental damage, or economic loss in terms of both the incident likelihood and the magnitude of the loss or injury” (CCPS, 2008). To describe risk (qualitatively or quantitatively), the process of risk analysis is carried out. This involves engineering evaluations and the use of mathematical techniques for combining estimates of the likelihood and the consequence of the event (NTSB, 1971; CCPS, 1995). The likelihood of an event is a measure of the *frequency* or the *expected probability* of that event that may be expressed as a frequency, such as the number of events per year, or a probability of an occurrence during some time interval (CCPS, 1995).

Risk analysis models often adopt a certain probability distribution (such as the Poisson distribution) to estimate the likelihood of an accident based on the statistical inference on historical data of accident statistics (e.g. Glickman and Rosenfiled, 1984; Abkowitz and Cheng, 1988; Purdy, 1993; Erkut and Verter, 1995). The risk model using this approach will be referred to as *a probabilistic risk model*. Another approach is based on a direct multiplication of the frequency, or rate of accident, from the historical data with other probabilities and consequence estimates in the risk model to obtain the numerical value of risk (e.g. CCPS, 1995; Bubbico et al., 2000; Saat and Barkan, 2006a). The risk model under the frequency-based or simplified approach is referred to as *a simplified risk model*. The objective of this chapter is to investigate the assumptions and simplifications behind the simplified risk model and compare the estimate of the likelihood of a hazardous material release event to that using the probabilistic approach.

First, I describe the use of a probability distribution to determine the likelihood of an accident. The probabilistic model is then developed using a Poisson process (Ross, 2002). The numerical estimates of risk using the probabilistic approach are compared with those from a simplified approach. Then, I discuss the interpretations of risk estimates obtained by these two approaches and evaluate the difference in their magnitudes.

The probabilistic approach may be useful because it enables a calculation of the probability of any specific number of incidents on a route. Depending on the rate used in the probabilistic risk model, the probability of any number of train accidents or tank car derailments can be determined. For example, if the accident rate is known, one can compute the probability of a particular number of accidents on a route; if derailment rate is known, the probability of any number of derailments can be determined. The probabilistic approach may further facilitate the consideration of multiple levels of consequences that are a function of the number of accidents or the number of tank cars derailed.

Similar work was previously conducted by Erkut and Verter (1998) and Erkut and Ingolfsson (2005) for highway hazardous materials transportation risk modeling. Here, I adapt it to accommodate rail hazardous materials transport, to incorporate more specific parameters affecting risk, and to illustrate the effects of multiple shipments on model estimates.

7.2 Risk Model Formulation Revisited

In this section, I describe the model formulation for both probabilistic and simplified risk models in detail.

7.2.1 Probabilistic Risk Model

I assume that the occurrence of an accident is a random event with a known rate, Z , which can be modeled using the Poisson distribution (Glickman and Rosenfield, 1984; Hauer, 1986; Erkut and Ingolfsson, 2005). Bedford (2005) discussed the merits of assuming a Poisson process for the calculation of the likelihood of the event of an accident. Under a Poisson process, the number of events occurring in any fixed interval of length L is assumed to be a Poisson random variable with mean ZL , and the events occurring in the non-overlapping intervals in the length L are

assumed to be independent of one another. The probability of t accidents on an interval of length L , $P\{N(L) = t\}$, can be expressed as follows:

$$P\{N(L) = t\} = \frac{\exp(-ZL)(ZL)^t}{t!} \quad (7.1)$$

where $N(L)$ = the number of accidents on a segment of length L
 t = 0, 1, 2...
 Z = the accident rate per unit length of segment

Let A be the event that at least one accident occurred, and A_i that event occurring on segment i . Using Eq. (7.1), I express the probability that at least one accident occurred on segment i , $P(A_i)$, as follows:

$$\begin{aligned} P(A_i) &= 1 - P\{N(L_i) = 0\} \\ &= 1 - \exp(-Z_i L_i) \end{aligned} \quad (7.2)$$

The probability of an accident on a route, comprising n segments, using a non-homogeneous Poisson process, is then described as follows:

$$P(A) = 1 - \exp\left(-\sum_{i=1}^n Z_i L_i\right) \quad (7.3)$$

$P(A)$ in Eq. (7.3) above can be interpreted as the probability that there will be at least one accident on the route, or in short, the probability of an accident occurring. In the context of hazardous materials transportation, a focus is usually made on the event of tank cars being derailed in an accident. Thus, $P(A)$ can also represent the probability that there will be at least one tank car derailed on the route, provided that Z represents the tank car derailment rate (i.e., cars derailed per car-mile).

The probability of a hazardous material release on segment i , $P(R_i)$, can then be expressed as follows:

$$P(R_i) = P(R_i|A_i)P(A_i) + P(R_i|A_i')P(A_i') \quad (7.4)$$

where $P(R_i|A_i)$ = the conditional probability of a hazardous material release (CPR) given an accident on segment i

A_i' = the event that there will be no accident on segment i

Simplification can be made by considering only an accident-caused release, thus the term $P(R_i|A_i')P(A_i')$ in Eq. (7.4) can be neglected. Depending on the accuracy required, $P(R_i|A_i)$ in Eq. (7.4) can be either average-speed CPR or speed-dependent CPR. For each, one may consider the CPR that is weighted by the number of different tank car types in the fleet, if the relationship used for calculating the CPR accounts for specific safety design features. Table 7.1 summarizes the models available for the estimation of the CPR that is appropriate for different objectives of analysis.

Table 7.1. Possible relationships and detail levels for estimation of CPR.

Level of Consideration	Safety-Design-Specific CPR		Non-safety Design Specific CPR
	Normalized by Number of Each Tank Car Type	Individual Tank Car Type (Non-normalized)	
CPR based on average accident speed	Treichel et al. (2006)		Nayak (1983), CCPS (1995),
Speed-dependent CPR	Kawprasert and Barkan (2010a)		Treichel et al. (2006)

For any particular hazardous material, the level of consequence depends, in part, on the quantity of material released to the environment, which may vary with the severity of the accident, the atmospheric conditions, and the chemical properties of the material itself. To account for different release scenarios, such as a large quantity spilled or a release involving fire, I consider the probability of an event of a specific scenario of release k for a track segment i , $P(I_{ki})$, as follows:

$$P(I_{ki}) = P(I_i|R_i, A_i)_k P(R_i|A_i)P(A_i) \quad (7.5)$$

where $P(I_i|R_i, A_i)_k$ = the conditional probability that a specific scenario k will occur given that there is a hazardous material release due to an accident on segment i

The conditional probability of hazardous material car involvement in an accident is excluded from Eq. (7.5) since only a hazardous material shipment (carload) is considered.

For the consequence part of the risk model, I express it in terms of number of persons exposed to possible evacuation, which can be estimated from the product of the affected area due to a hazardous material release and the average population density in that area. So, the consequence of a specific release scenario k for track segment i , C_{ki} , is written as:

$$C_{ki} = E_k D_i \quad (7.6)$$

where E_k = affected area where people need to be evacuated or sheltered in place for a specific scenario of release k

D_i = average population density in an affected area corresponding to segment i

For the chemical and release scenario of interest, the affected area can be determined in accordance with the recommendations provided in the U.S. Department of Transportation (DOT) Emergency Response Guidebook (ERG) (PHMSA, 2008; Brown et al., 2009). The population density corresponding to segment i can be approximated by considering the weighted average number of people in the census tracts coincident with the affected area. Use of Geographic Information System (GIS) analysis can aid this process (Kawprasert and Barkan, 2008; 2009a).

The expected risk associated with the shipment of hazardous materials along the route comprising n segments from origin to destination is described by Erkut and Verter (1998) and Erkut and Ingolfsson (2005) as follows:

$$S = P_1 C_1 + (1 - P_1) P_2 C_2 + (1 - P_1)(1 - P_2) P_3 C_3 + \dots + (1 - P_1)(1 - P_2) \dots (1 - P_{n-1}) P_n C_n$$

or

$$S = \sum_{i=1}^n \prod_{j=1}^{i-1} (1 - P_j) P_i C_i \quad (7.7)$$

where S = risk associated with the trip

P_i = probability of a release incident on a segment i

C_i = consequence of a release incident on a segment i

n = number of segments on the route

Figure 7.1, adapted from Erkut and Verter (1998), illustrates the partial probability tree in accordance with Eq. (7.7).

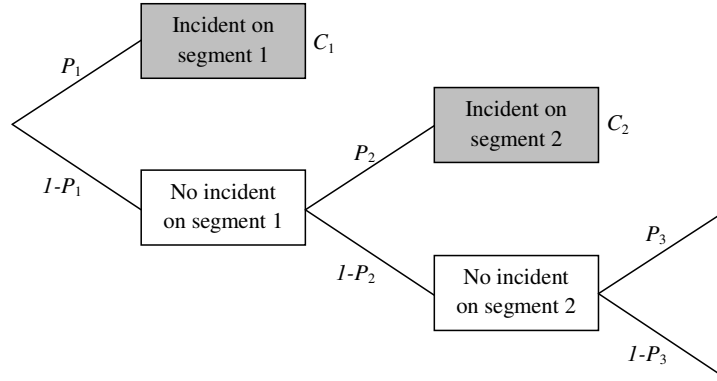


Figure 7.1: Partial Probability Tree Showing Possible Outcomes of Hazardous Materials Transportation along the Route

Using model elements as defined earlier, the equation used to estimate the risk associated with hazardous material shipments on a rail route is as follows:

$$S = \sum_{k=1}^m \sum_{i=1}^n \prod_{j=1}^{i-1} \left(1 - P(I_j | R_j, A_j)_k P(R_j | A_j) \{ 1 - \exp(-Z_j L_j Q_j) \} \right) \left(P(I_i | R_i, A_i)_k P(R_i | A_i) \{ 1 - \exp(-Z_i L_i Q_i) \} \right) E_k D_i \quad (7.8)$$

Eq. (7.8) above is referred to as the *probabilistic risk model*.

7.2.2 Simplified Risk Model

In railroad hazardous materials transportation risk analyses, the probability terms in the risk model are sometimes simplified by considering the product of the accident rate per car-mile and the hazardous material car-miles to determine the probability of an accident occurring, $P(A)$.

Under this simplification, the product gives the frequency of an accident rather than the probability, and, consequently, Eq. (7.5) is considered to be the frequency of a release incident.

In this section, I describe how the simplified risk model can be derived from the probabilistic risk model.

First, the product of segment-specific probability P_i and P_j in Eq. (7.7) is assumed to be very small, so that the term $\Pi(1 - P_j)$ can be neglected (Erkut and Verter, 1998; Erkut and Ingolfsson, 2005). Eq. (7.7) is then simplified to:

$$S = \sum_{i=1}^n P_i C_i \quad (7.9)$$

where P_i = frequency of a release incident on a segment i

Eq. (7.2) can be simplified by considering the first-order approximation. Using Taylor's series expansion, the exponential term in Eq. (7.2) can be written as:

$$\exp(-Z_i L_i) = 1 + (-Z_i L_i) + \frac{(-Z_i L_i)^2}{2!} + \frac{(-Z_i L_i)^3}{3!} + \dots \quad (7.10)$$

Due to the very low railroad accident rate, the product of Z_i and L_i is very small, so that the higher-order terms in the series can be neglected, i.e. $\exp(-Z_i L_i) \cong 1 - Z_i L_i$. Therefore, Eq. (7.2) is simplified to:

$$\begin{aligned} F_i &\cong 1 - (1 - Z_i L_i) \\ &= Z_i L_i \end{aligned} \quad (7.11)$$

And the frequency of an accident on a route comprising n segments is:

$$F = \sum_{i=1}^n Z_i L_i \quad (7.12)$$

The corresponding equation incorporating hazardous material shipments, Q , and other risk components is then written as follows:

$$S = \sum_{k=1}^m \sum_{i=1}^n P(I_i | R_i, A_i)_k P(R_i | A_i) Z_i L_i Q_i E_k D_i \quad (7.13)$$

I refer to Eq. (7.13) as the *simplified risk model*.

It is important to understand the difference in the magnitude of the numerical estimates obtained from both approaches as well as the difference in the interpretation of those estimates. This is the principal objective of this chapter and will be discussed in more detail in the following section.

7.3 Comparison of Probabilistic and Simplified Risk Models

7.3.1 Interpretation of Probability/Frequency Term

The probability/frequency terms in each of the risk models have different interpretations. To elaborate this, I define an accident event as the derailment of a railcar carrying a hazardous material on a mainline track. Assuming a constant derailment rate of $Z = 100 \times 10^{-9}$ per car-mile and a constant traffic volume of $Q = 1,000$ shipments on a route of length of $L = 1,000$ miles, the probability of an accident on this route can be computed as follows:

$$\begin{aligned} P(A) &= 1 - \exp(-Z \times L \times Q) \\ &= 1 - \exp(-100 \times 10^{-9} \times 1,000 \times 1,000) \\ &= 0.095163 \text{ or } 9.52\% \text{ chance} \end{aligned}$$

The figure represents the probability that there will be at least one derailment (car derailed) on the route.

Using the simplified approach, the frequency of an accident can be calculated by multiplying Z , L , and Q together, i.e.

$$\begin{aligned} F &\cong Z \times L \times Q && (7.14) \\ &= 100 \times 10^{-9} \times 1,000 \times 1,000 \\ &= 0.1 \text{ (or 1 car derailed in 10 years)} \end{aligned}$$

The difference between the exact probability and the frequency is 0.48%. The latter approach enables consideration in terms of the frequency of an accident rather than the probability. The interpretation of F is *the expected number of derailments* (cars derailed) on the route, which equals 0.1 cars derailed per year. An equivalent interpretation is the frequency of a derailment on this route is 1 car derailed in every 10 years. Hence, for these two approaches, there is a difference not only in the magnitude of the estimate but also in the interpretation of the estimate.

The advantage of the probabilistic approach based on the Poisson process is that it can be used to calculate the exact probability of any specific number of accidents (cars derailed) given hazardous material traffic and the accident rate. For example, I consider the same parameters as before: a constant derailment rate of $Z = 100 \times 10^{-9}$ per car-mile, a constant traffic volume of $Q = 1,000$ shipments, and a route length of $L = 1,000$ miles. The probability of multiple car derailments on this route can be computed using Eq. (7.1). The result is shown in Table 7.2.

It is important to note that the numbers of cars derailed in Table 7.2 do not necessarily represent the number of tank cars derailed in the same accident. For example, consider one train comprising two carloads from origin to destination; the number of multiple cars derailed that are described here indicate the number of tank car derailments in separate accidents along the route (Figure 7.2a) rather than the number of cars derailed in one single accident (Figure 7.2b).

Table 7.2. Probabilities of multiple car derailments.

Number of Accidents (Cars Derailed)	Probability
0	0.904837
1	0.090484
2	0.004524
3	0.000151
4	0.000004
At least 1	0.095163

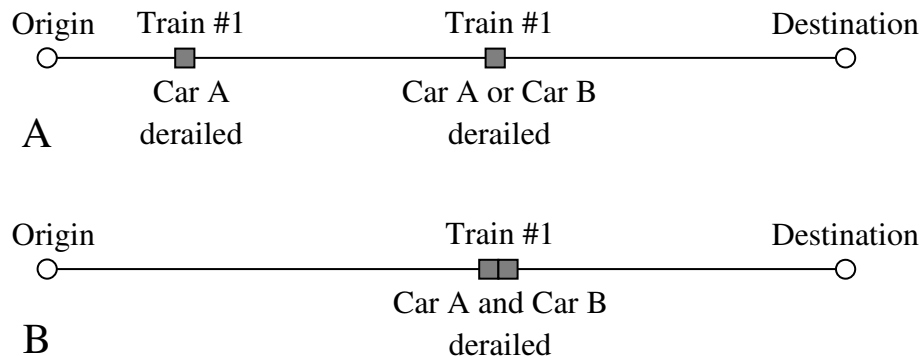


Figure 7.2: Illustration of Multiple Derailments along the Route

(A) Multiple Car Derailments in Separate Accidents and (B) Multiple Car Derailments in the Same Accident

The expectation of the probabilities in Table 7.2 can be computed as follows:

$$\begin{aligned} \sum t P\{N(L) = t\} &= 0 \times P\{N(L) = 0\} + 1 \times P\{N(L) = 1\} + 2 \times P\{N(L) = 2\} + \dots \\ &= 0(0.904837) + 1(0.090484) + 2(0.004524) + \dots \\ &= 0.1 \end{aligned}$$

This represents the expected number of cars derailed and is exactly the same result as that obtained using the simplified risk model. The results are shown graphically in Figure 7.3.

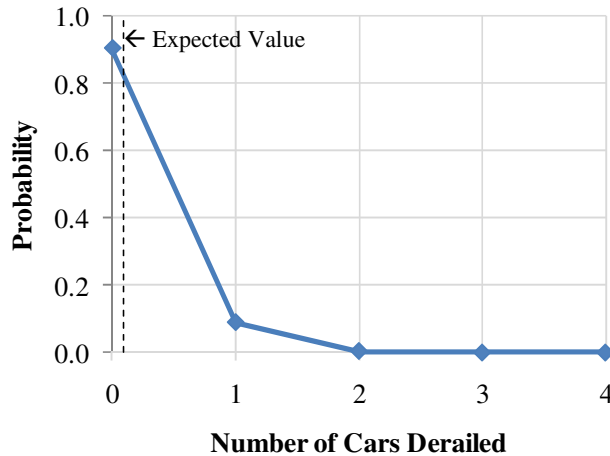


Figure 7.3: Probability of Multiple Derailments and Expected Value

In this way, the Poisson process can be used to evaluate the exact probability of any specific number of derailments (none, single, or multiple cars derailed) as well as the expectation of the event of the expected number of cars derailed along the route, given accident rates and car-miles of hazardous materials traffic. Nevertheless, in hazardous material transportation risk analysis, there is much more interest in the probability of multiple cars being derailed in the same accident. Further development of such probability is necessary to facilitate a particular analysis of the risk involved with multiple-car derailment in the single accident.

7.3.2 Comparison of the Numerical Results of the Probability/Frequency Term

It is of interest to understand how the difference in the magnitudes of $P(A)$ and F changes under different levels of Z , L , and Q . To visualize this, I performed a sensitivity analysis to quantify the difference in the estimates obtained from both approaches. Different route lengths were considered with the maximum length of $L = 5,000$ miles under three different levels of traffic: $Q = 1, 100,$ and 500 carloads. Two levels of accident rate are assumed: $Z = 300 \times 10^{-9}$

and 700×10^{-9} per car-mile. Figure 7.4 shows the values of $P(A)$ and F for various levels of Z , L , and Q . It is evident that $P(A)$ converges to 1.0 as car-miles increase when the probabilistic expression is used. On the other hand, F , based on the simplified expression, increases proportionally with the car-mile and eventually exceeds 1.0, clearly illustrating that F is not a probability.

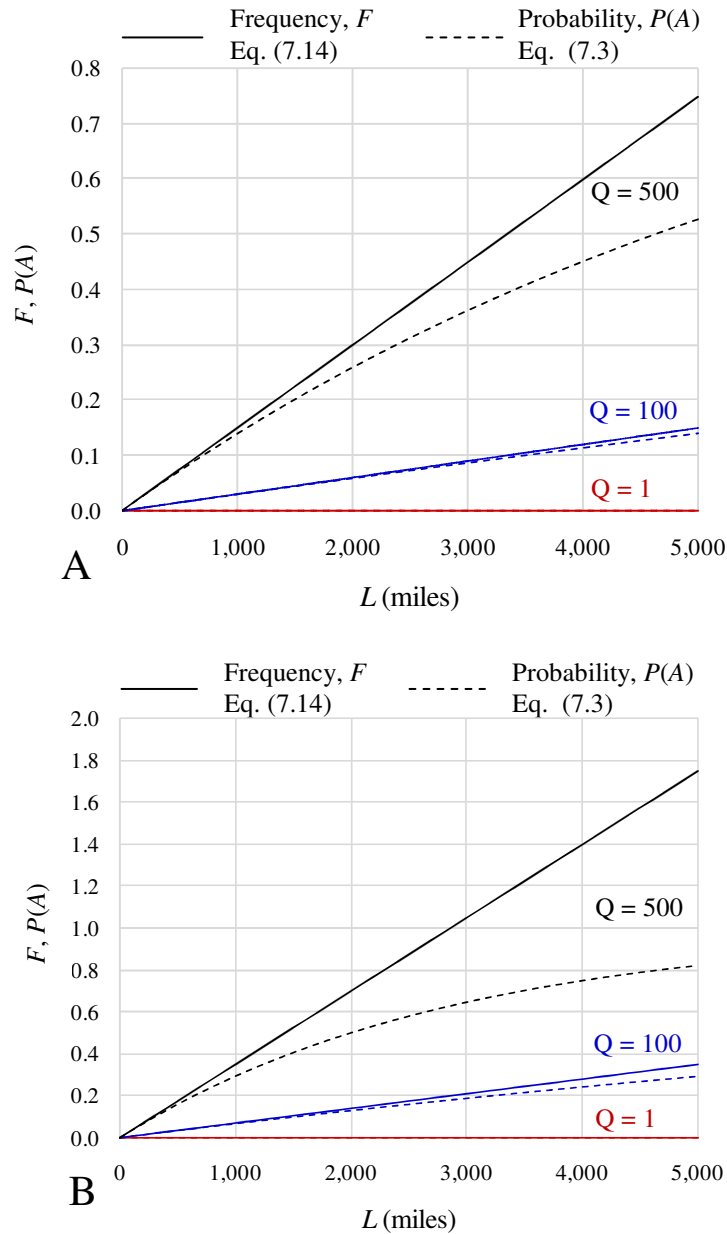


Figure 7.4: Comparison of Accident Probability vs. Frequency
 (A) $Z = 300 \times 10^{-9}$ and (B) $Z = 700 \times 10^{-9}$

Figure 7.5 shows the percentage difference between $P(A)$ and F for various levels of Z , L , and Q . At $L = 3,000$ miles and $Q = 100$ carloads, the two approaches result in about 5% for $Z = 300 \times 10^{-9}$ (Figure 7.5a) and 10% for $Z = 700 \times 10^{-9}$ (Figure 7.5b), respectively. For a single shipment, the difference in the magnitudes of $P(A)$ and F is less than 0.001 for both levels of Z considered. The difference is very small, so that the lines overlap with the horizontal axis on this graph. Thus, the simplified approach approximates well the probability for $Q = 1$. The difference, however, becomes larger as car-miles increase. For example, F is no longer the probability at $L = 3,000$ miles and $Q = 500$ carloads for $Z = 700 \times 10^{-9}$ (Figure 7.4b).

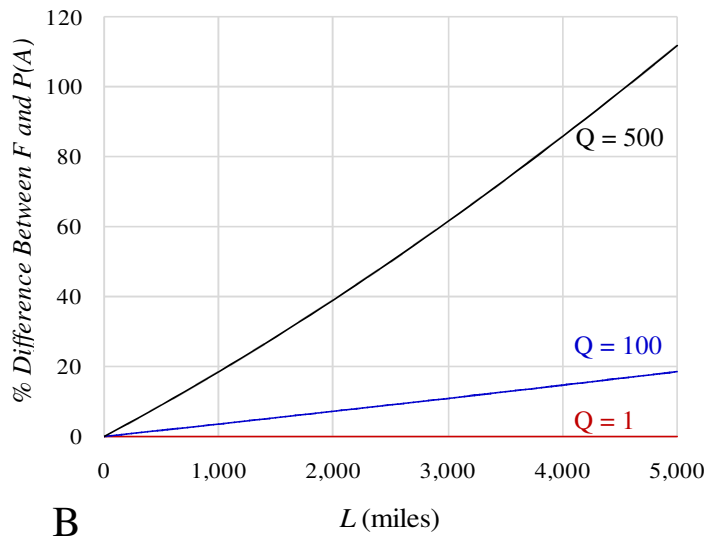
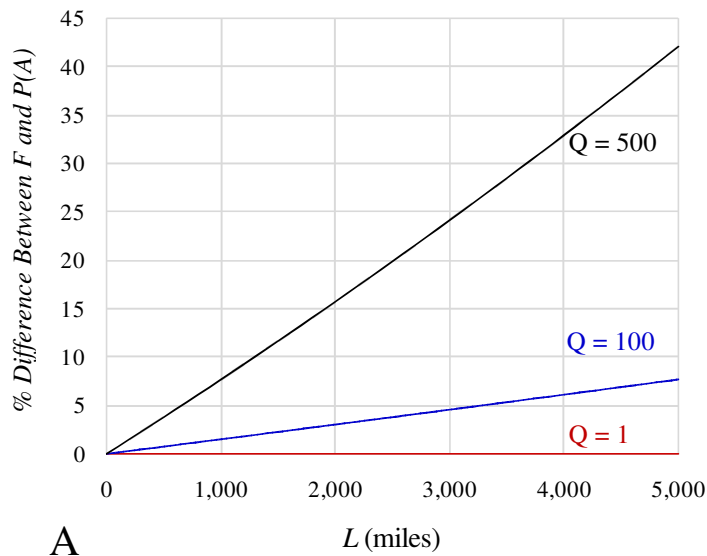


Figure 7.5: Percentage Difference of Accident Probability vs. Frequency
 (A) $Z = 300 \times 10^{-9}$ and (B) $Z = 700 \times 10^{-9}$

The difference between frequency and probability estimates, Δ , can be mathematically expressed as $\Delta = J - 1 + 1/\exp(J)$, where $J = Z \times L \times Q$. The first term, J , increases proportionally while the last term decreases exponentially with car-miles. Since hazardous material shipments are usually made within an average distance of about 1,000 miles, and the majority of the routes is of higher track classes in which accident rates do not vary much, the key variable affecting the difference between frequency and probability estimates is traffic level, Q . Assuming an average accident rate of 100×10^{-9} per car-mile, the difference, Δ , remains modest at 1,000 miles, i.e. only 2.5%.

7.3.3 Comparison of Risk Estimates

In this section, I compare risk estimates based on the two approaches described earlier. In addition, I also illustrate the effect of segmentation on the risk estimate. Route segmentation is the division of route length into several segments to facilitate segment-specific risk analysis. For this analysis, I assumed the risk parameters shown in Table 7.3.

Table 7.3. Parameters considered for comparison of risk estimates.

Parameter	Value
Probability of Specific Release Scenario, $P(IRS, A)$	1.0 (single scenario)
Conditional Probability of Release, $P(RIA)$	0.10
Accident Rate, Z	300×10^{-9} cars derailed per car-mile, 700×10^{-9} cars derailed per car-mile
Route Length, L	Varies up to 5,000 miles
Shipments, Q	1, 100, and 500 carloads
Affected Area, E	1 square-mile
Average Population Density, D	10 persons per square-mile
Number of Segments, n	5 and 500 segments

Figure 7.6 shows the comparison of the risk estimates made using the different expressions of risk given in Eqs. (7.8) and (7.13) for different levels of Z , L , Q , and n .

Figure 7.7 shows the magnitude of the difference in the risk estimates. By dividing the route into segments, the difference in the risk estimates from these two approaches is substantially reduced compared to the difference shown in the previous section. The greater the number of segments, the smaller the difference in the risk that is calculated using the probabilistic and simplified approaches for the route considered. At the highest level of Z , L , and Q , the difference in the risk estimates is less than 10% (Figure 7.7d).

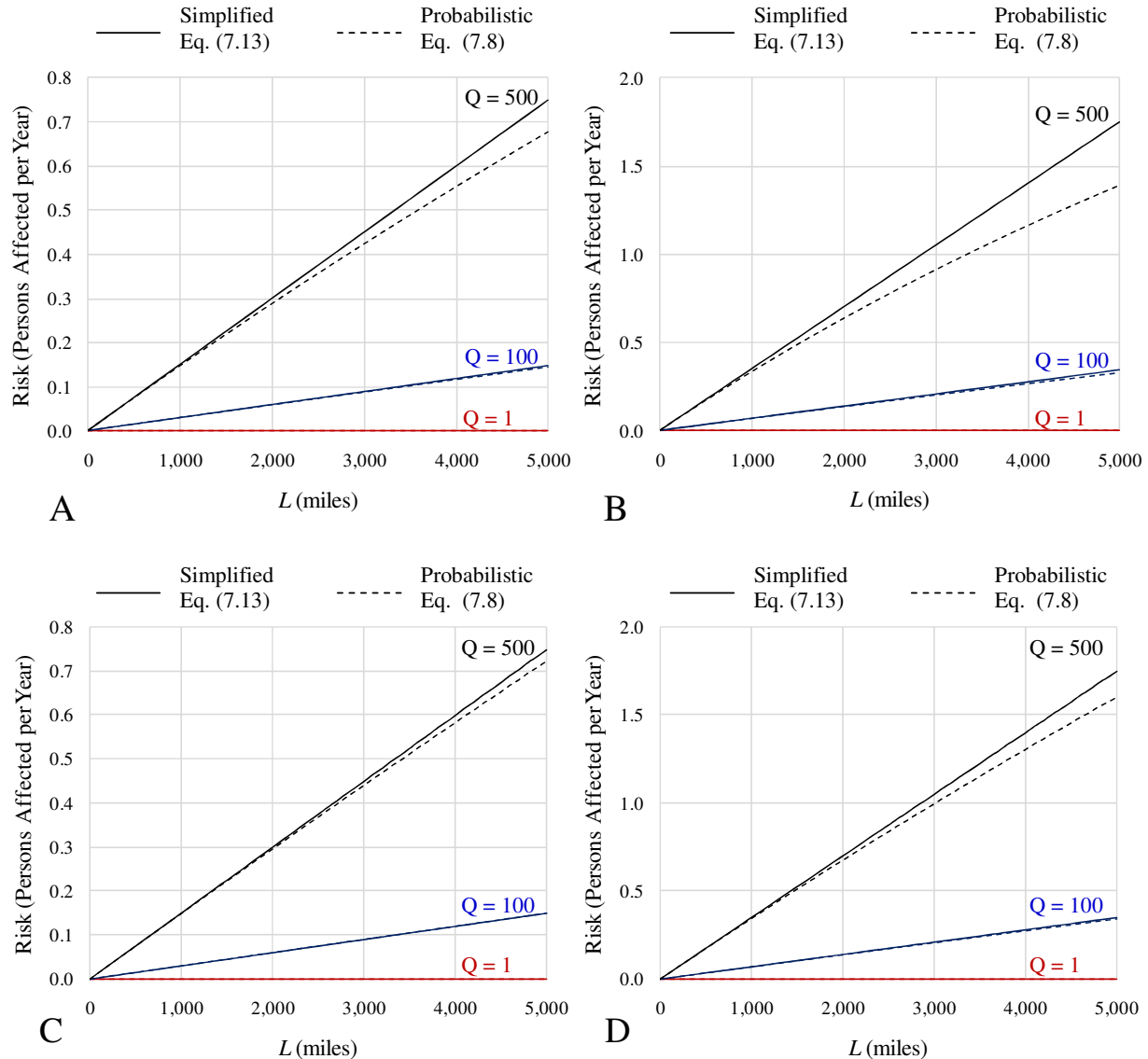


Figure 7.6: Comparison of the Risk Estimates Made Using Probabilistic and Simplified Risk Models (A) $Z = 300 \times 10^{-9}$, $n = 5$; (B) $Z = 700 \times 10^{-9}$, $n = 5$; (C) $Z = 300 \times 10^{-9}$, $n = 500$; and (D) $Z = 700 \times 10^{-9}$, $n = 500$

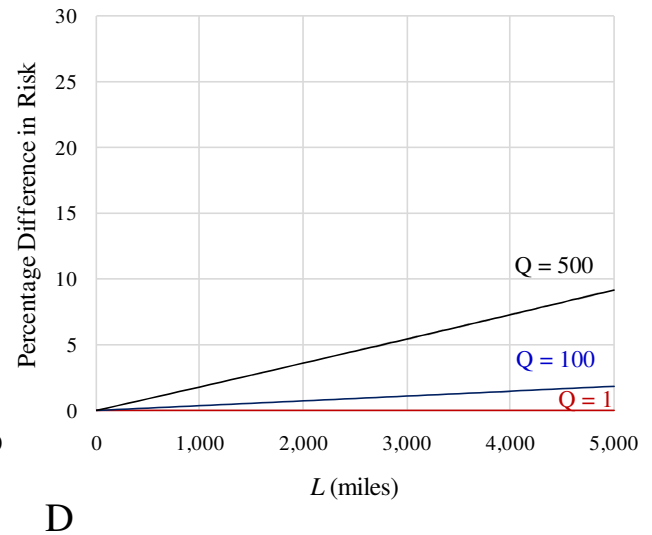
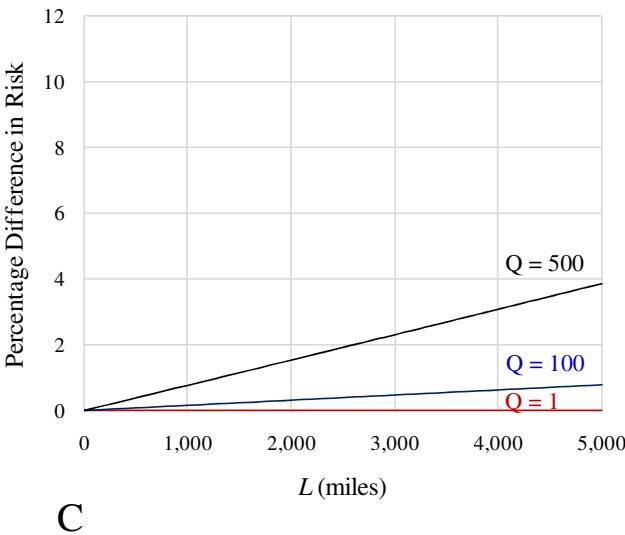
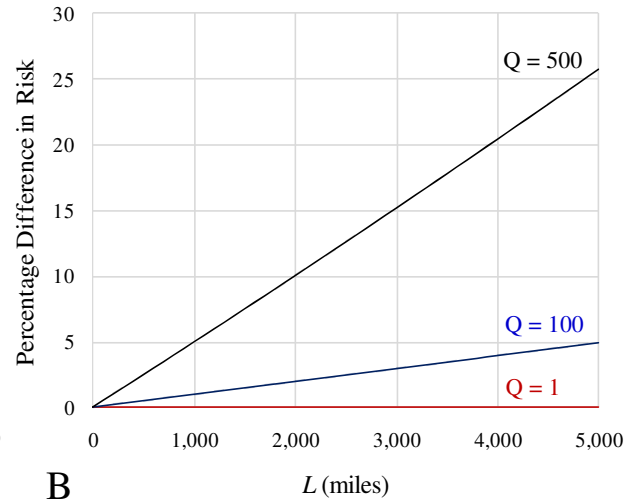
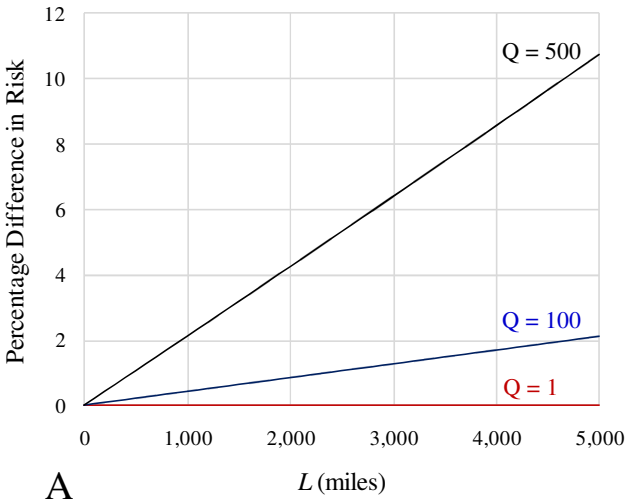


Figure 7.7: Percent Difference in Risk between Probabilistic and Simplified Risk Models
(A) $Z = 300 \times 10^{-9}$, $n = 5$; (B) $Z = 700 \times 10^{-9}$, $n = 5$; (C) $Z = 300 \times 10^{-9}$, $n = 500$;
and (D) $Z = 700 \times 10^{-9}$, $n = 500$

The difference in the risk estimates reduces as n increases because L in Eq. (7.8) becomes smaller, so that the first-order approximation, i.e. Eq. (7.11), is not much different from its original expression in an exponential form in Eq. (7.2). Note that the risk estimates given by the simplified expression do not change with n . It is possible to further reduce the difference in the risk estimates by dividing the route into more and shorter segments, thereby increasing n . The use of shorter segments may reduce errors in estimating the risk parameters, due to the heterogeneity of the route. However, this will require more time and resources for the risk analysis process.

Previous research on hazardous materials transportation route risk analyses (Kawprasert and Barkan, 2008; 2009a; 2010a) used the FRA national rail network database (BTS, 2007). Route data from these studies indicate that segment lengths in the railroad hazardous materials shipment network vary from 0.005 miles to 28 miles, with an average segment length of 2 miles and a standard deviation of 3 miles. Consequently, a typical hazardous material shipment route 1,000 miles in length comprises over 400 segments.

Using a simulation, the difference between the risk estimates from the probabilistic and simplified approaches is only 3.5% for a 1,000-mile route with $Z = 700 \times 10^{-9}$, $Q = 1,000$, and $n = 400$. Thus, with proper route segmentation, the simplified approach would reduce computation effort while still providing reasonable accuracy.

One potential drawback of using the railroad segments defined in the GIS database is that the segment lengths are not uniform. Consequently, the risk estimate associated with a particular segment varies with the length of that segment. For example, some particular segments may have high risk, not due to a high accident rate or a high population density but due to long length. To account for this, a normalized segment risk (e.g. segment risk per mile) is sometimes considered instead of absolute segment risk (Kawprasert and Barkan, 2009a). According to Gheorghe et al. (2005), "Route segment is a part of a traffic segment, where the risk is expected to change very little (maintain a nearly constant level). Therefore, it should have a length of at least a few hundred meters, yet not exceeding a few kilometers." It is of interest, yet beyond the scope of this study, to determine an optimal segment length that properly balances the tradeoff between the computational effort and the accuracy of using a uniform segment. This may be a useful subject for future risk analysis and research.

An analytical system may give different risk results for different numbers or lengths of track segment used in the analysis. This is not fundamentally flawed because segment definition also depends on the available information, the desired level of accuracy, resources, and other constraints. While the underlying reality remains the same, the numerical estimate of risk produced by the QRA is still associated with uncertainties for each of the parameters and, thus, reflects a certain degree of belief based on the state of knowledge. The QRA methodology and analytical models discussed here serve as an analysis framework that encourages a consistent approach toward hazardous materials transportation risk analysis.

7.4 Risk Model Based on Expected Frequency of Incident

In the previous sections I showed that the probabilistic risk model produces slightly different risk results compared to those based on frequency when route segmentation is applied. It is possible to eliminate this difference to obtain consistent results for rail hazardous materials transportation risk analysis by quantifying risk as the product of the *expected frequency* of a release incident and the consequence of the release incident. That is, from Eq. (7.9)

$$S = \sum_{k=1}^m \sum_{i=1}^n Y_{ik} C_{ik} \quad (7.15)$$

where Y_{ik} = expected frequency of a release scenario k on a segment i

The expected frequency of accidents (derailments) can be computed as follows:

$$\begin{aligned} E[t] &= \sum_{t:p\{t\}>0} t P\{t\} \\ &= \sum_{t:p\{t\}>0} t \frac{\exp(-ZLQ)(ZLQ)^t}{t!} \\ &= ZLQ \end{aligned} \quad (7.16)$$

For example, for $Z = 700 \times 10^{-9}$; $L = 1,000$; $Q = 1,000$; the expected number of derailments equals $100 \times 10^{-6} \times 1,000 \times 1,000 = 0.7$.

The point here is that the difference between the probability and the expected frequency of accidents gets larger as the product of Z , L , and Q becomes large. Thus, Eq. (7.16) no longer approximates the probability for higher values of Q . For example, for $Z = 700 \times 10^{-6}$, the difference between the probability of accident $P\{t \geq 1\}$ and the expected frequency of accident $E[t]$ is 1.05%, 3.54%, and 39.05% for 30,000; 100,000; and 1,000,000 car-miles, respectively. To overcome this discrepancy, the risk model for rail hazardous material transportation may be formulated using the expected frequency of a release incident rather than the probability of a release incident. For the probabilistic risk model in Eq. (7.8), both P_i and P_j are very small, so that their product is approximately zero. By considering the expected frequency of an accident instead of the probability of an accident, the probabilistic risk model is then rewritten as:

$$S = \sum_{k=1}^m \sum_{i=1}^n P(I_i | R_i, A_i)_k P(R_i | A_i) Z_i L_i Q_i E_k D_i$$

which is exactly the same as the simplified risk model in Eq. (7.13).

7.5 Discussion

A probabilistic risk model, based on the assumption that accident occurrence follows a Poisson process, is discussed. One of the benefits of using a Poisson distribution to describe the event of a tank car derailment is that the exact probability of any number of derailments (tank cars derailed) along the route can be computed, given the level of traffic and the accident rate. In this study, I show how a simplified risk model is derived from the probabilistic model.

I compare the estimates of accident risk that are made using both models. For a single carload, the difference in the risk estimates from these two models is negligible. The difference becomes larger as the car-miles and the accident rate increase. However, with appropriate route segmentation, the difference in risk estimates from the two approaches can be reduced. The magnitude of reduction depends on the number of divisions (segments), the car-miles and the accident rate considered.

Although the simplified risk model has an advantage in terms of its simplicity, it is important to properly define the corresponding risk component as the frequency and not the probability when analysis is carried out using the simplified approach. Each approach is associated with different interpretations and may give substantially different results under some circumstances, particularly when longer distances or multiple shipments are involved.

7.6 Conclusions

The probabilistic approach enables an estimation of risk for any specific number of derailments along the route, while the simplified risk model has an advantage in terms of its simplicity of computation. The latter still offers acceptable accuracy for a route with a moderate number of car-miles, when proper segmentation is applied, compared to the probabilistic approach that requires more complicated analysis. The simplified model can be made more accurate by the use of more segments along a route, but this makes the analysis more complex and requires intensive data processing and management. Previous studies (Kawprasert and Barkan, 2008; 2009a; 2010a) indicate that the number of segments of hazardous materials transportation rail routes given by a GIS database will often be sufficient so that the difference in risk estimates using both approaches will not be substantial. When the risk model considered is based on the expected frequency of an accident, one should avoid the incorrect usage of the term “probability” in the context that it may be misleading the results due to the differences in both the magnitude and the interpretation of probability versus frequency.

CHAPTER 8

ROUTE RISK COMPARISON TECHNIQUES

Presented in part as Kawprasert, A. and C.P.L. Barkan. *Statistical Comparison of Railroad Hazardous Materials Transportation Route Risks*. ASME-IEEE-ASCE-AREMA-TRB Joint Rail Conference, University of Illinois at Urbana-Champaign, Urbana, IL, April, 27 – 29, 2010c.

8.1 Introduction

In hazardous materials transportation routing decision problems, risk managers may be faced with situations in which the differences in single-point estimates of risk associated with routing alternatives are difficult to distinguish. This is because the differences are relatively small, difficult to observe, or involve various trade-offs. Single-point estimates of risk are the simplest to calculate and present, but these often mask the additional information risk-managers need to address critical questions. At the very least they can complicate or confound risk-based decision-making, and at worst may result in decisions that are inconsistent with the objectives of the decision maker. One alternative for route risk comparison is to consider the distribution of risk levels using risk profiles or F-N curves. These offer a richer measure for risk assessment because they expand the point estimate of the expectation to enable consideration of the entire distribution (Erkut et al., 2007).

Nevertheless, risk profiles also have limitations that prevent one from observing certain changes in route risk in detail and thus do not allow a complete understanding of the differences in risk distribution. For example, it is not easy to compare the risk profiles with one another to justify or rank which alternative represents higher risk because they may have a similar shape but are differ in the details (HSL and HSE, 2009). In certain circumstances, the conventional approaches for route risk comparison based on either single-point estimates of risk or risk profiles would fail to adequately identify differences that are needed for risk management decision-making or would not be able to sufficiently distinguish between the risks associated with two routes.

The objective of this chapter is to address these issues and to discuss several potential techniques for comparison of route risks that may be useful for risk-based decision making regarding routing problems. These new approaches include risk profiles incorporating a point estimate of risk (expected consequence) and statistical methods for risk comparison. The latter offers an enhancement in risk-based decision-making capability for risk managers by providing additional information and confidence in decision-making. In addition, I consider the use of graphical techniques to help visualize changes or differences that might otherwise not be discernable. This approach will be discussed in more detail in Chapter 9.

The statistical methods have the potential to help risk managers quantitatively distinguish among risk management alternatives regarding routing decisions or other risk management alternatives when resources are limited so that the risk analysis could not be completed for the entire route or network. The principal idea of using statistical methods to facilitate a comparison of route risks is to examine whether the risk distribution of alternatives differs significantly from the baseline route risk distribution based on random sample segments rather than analyzing the whole routes. The work is intended to facilitate the consideration of statistically robust methods to formally test the significance of differences between two distributions. There are several possible statistical approaches; each with differing assumptions, advantages and limitations. This study is among the first to consider this aspect of railroad hazardous materials transportation route risk analysis and comparison.

8.2 Comparison of Route Risks Using Risk Profiles and Point Estimates of Risk

The results from quantitative risk analysis (QRA) of hazardous materials transportation route risk analysis nearly always include a single-point estimate of risk, and sometimes also a risk profile or F-N curve. The single-point estimate of risk is a single statistic that is the expected consequence of a hazardous material release for a particular set of transport conditions. It is the direct output of QRA that is easiest to calculate and the simplest to present and, in principle, to understand. Risk profiles are plots of cumulative frequency (F) of release incidents that exceed increasing levels of consequence measured by some numerical (N) metric of the impacts such as number of fatalities or number of people evacuated (CCPS, 1995; Erkut et al, 2007). Therefore, they basically portray the distribution of release frequency for various possible magnitudes of impact. The conventional approach for route risk comparison is generally based on use of these

two QRA outputs. In this section, I introduce a modified version of a risk profile in which both the distribution and the expected value of the release consequence are incorporated into one single graphic. Then, I elaborate the typical patterns of the risk profiles one may obtain from route risk analyses and discuss some issues regarding the efficiency of risk profiles in communicating route risk analysis results.

8.2.1 Risk Profiles Incorporating Expected Consequence

Conventional risk profiles provide the frequency distribution for incidents over a range of possible magnitudes of consequence; however, they do not show the corresponding single-point estimates of route risk. The risk profile incorporating expected consequence (Figure 8.1) enables visual comparison of both the frequency distribution of occurrence and the expected value of consequences in a single graphic. This is useful for route risk comparison, in particular, when two routes are compared. The risk profile incorporating expected consequence simultaneously provides information on the point estimate of risk and the distribution of release outcomes.

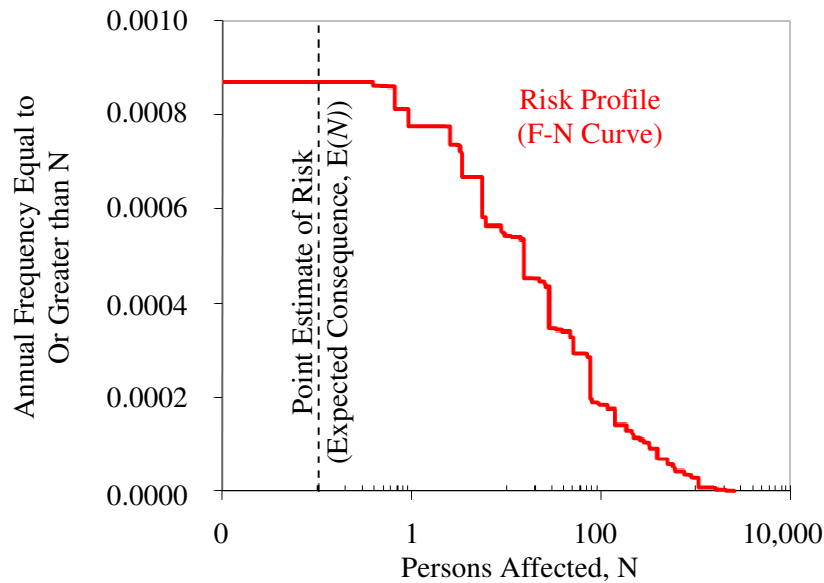


Figure 8.1: Risk Profiles Incorporating Point Estimate of Risk

8.2.2 Typical Cases of Route Risk Comparison

In railroad hazardous materials transportation risk analysis, the typical patterns of risk comparison of two (or more) routes often include one of the scenarios described in Table 8.1. To illustrate these graphically, I developed hypothetical risk profiles using the technique described in the previous section (Figure 8.2).

Table 8.1. Typical cases for hazardous materials transportation route risk comparison.

Scenario	Point Estimate of Risk	Frequency Distribution of Consequence
Figure 8.2a	Point estimate of risk of one route is substantially larger or smaller than that of another route.	The frequency distribution of consequence for one route is substantially higher or smaller than that of another route over the entire range of possible magnitudes of consequence.
Figure 8.2b	Point estimate of risk of one route is substantially larger or smaller than that of another route.	The frequency distribution of consequence for one route is about the same as that of another route over a lower range of consequence. The difference of the frequency distributions becomes evident at a higher level of consequence.
Figure 8.2c	Point estimate of risk of one route is apparently larger or smaller than that of another route.	The frequency of distribution of consequence for one route is apparently larger or smaller than that of another route up to a certain magnitude of consequence and vice versa beyond that magnitude.
Figure 8.2d	The difference in point estimates of risk is marginal and is difficult to discern.	The difference in the frequency of distributions of consequence is marginal and is difficult to discern.

The first scenario (Figure 8.2a) represents the simplest case in risk-based routing decision making because the estimated risks for two routes differ substantially in both their point estimate and the distribution of risk outcomes. In this case, risk managers should generally have little difficulty choosing one route over the other, and either the point estimates or the risk profiles would provide sufficient information.

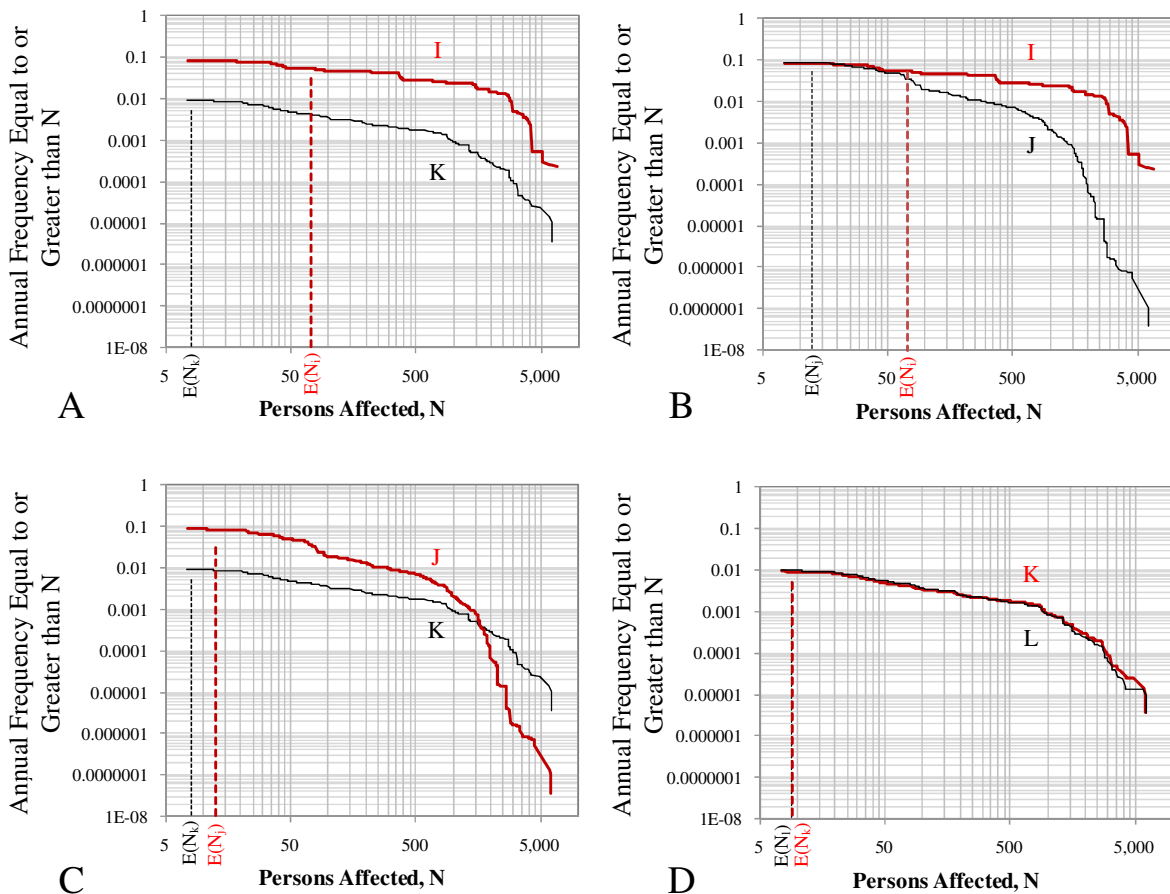


Figure 8.2: Typical Cases for Hazardous Materials Transportation Route Risk Comparison

The second scenario (Figure 8.2b) represents the case in which two routes have approximately the same frequency of release at the lower level of consequence. Beyond a certain magnitude of consequence, the difference in the frequency distributions becomes larger. The point estimates of risk of the two routes are also substantially different; therefore, choosing one route over the other is not difficult. However, unlike the previous case, risk managers may want to observe both the point estimate of risk and the risk profiles to understand more details of how the two routes will differ.

The third scenario (Figure 8.3c) represents a dilemma in routing decision making. One route has a higher frequency of incident in the lower consequence range, and lower in the higher consequence range. In this particular comparison, route *J* is the high frequency – low consequence route, while route *K* represents the low frequency – high consequence route. The decision to choose one route over the other is more difficult than the previous two cases since this may involve conflicting objectives. For example, a local authority may want to minimize the likelihood of a release event resulting in the highest range of magnitudes of consequence, while a carrier may prefer minimizing the overall frequency of release incidents regardless of its impact. Under this scenario, risk managers may need a decision analysis or other kinds of subjective evaluation tool to help facilitate decision making.

The fourth scenario (Figure 8.2d) involves the situation in which the risk distributions of two alternatives are quite similar. Thus, simple visual analysis of the single point estimate or the risk profile does not enable one to know if the difference in route-specific risks is significant. In such situations, appropriate statistical methods could be used to formally test if the difference between two is significant. This will provide greater confidence in a decision to choose one route over the other.

8.2.3 Limitations of Point Estimate of Risk and Risk Profiles

Although point estimates of risk and risk profiles can be used to facilitate risk-based decision-making, their major drawback is that, in many cases, both hide some critical information on how risk is actually distributed along the route. In some cases, this could be a critical issue in risk-based decision-making.

One such special case is where both risk profiles and point estimate of risk would fail to adequately describe the changes in risk distribution along a route. This particular case is the case associated with a shift in location of the distribution (Figure 8.3). In this case, represented by the solid line in Figure 8.3a, risk was concentrated at location X. After some type of change, the risk was shifted to location Z, while the risk at location Y remained the same (dashed line). For this situation, before and after improvements are associated with the same single point estimate of risk and the risk profile (Figure 8.3b).

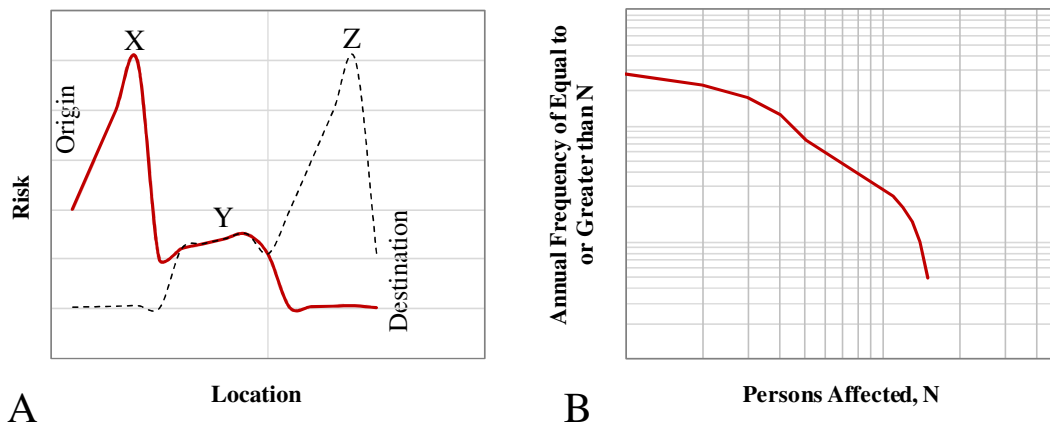


Figure 8.3: Illustration of a Location Shift in Risk Distribution
(A) Risk Distribution Plot with Respect to Locations,
and (B) Frequency Distribution Plot with Respect to Consequences (Risk Profiles)

Since neither point estimates of risk nor risk profiles distinguish the difference in the distributions of risk at particular locations, there is a need for techniques that are able to identify such changes. One technique is a graphical approach that enables visualization of the changes in risk distribution with respect to the locations along the route. This approach will be elaborated in Chapter 9.

An alternative is to use a statistical approach. This may be considered as a formal procedure to determine whether the risks of the two routes are significantly different, when a complete analysis of route-specific risk is not possible. In the following sections, I will discuss the potential of statistical methods to facilitate route risk comparison.

8.3 Statistical Methods for Route Risks Comparison

Statistical methods serve as a tool for risk managers by providing more information regarding the difference in the distributions of route risks. These methods are most useful when resources are limited and a complete analysis of the entire routes is not possible. They enable objective assessment of the confidence in the difference among routes thereby enhancing the quality of decision making. Several techniques are potentially useful for route risk comparison. However, assumptions and objectives of these tests may be different and therefore need to be understood prior to applying them to hazardous materials transportation routing decision problems.

In this study, the statistical methods considered for route risk comparison include: chi-square test for goodness of fit, Kolmogorov-Smirnov two-sample test, Wilcoxon rank-sum test, Kruskal-Wallis test, Wilcoxon signed rank test, and Fisher sign test. It is important to note that these techniques usually provide only numerical indices that help enhance the confidence in the decision making, but do not portray route risk distribution details. For effective risk communication, risk analysts may need to use both statistical test results and appropriate visual techniques (such as risk profiles or other forms of graphical representation). Moreover, each test method often has its own assumptions, advantages and drawbacks. In some situations, two test methods may lead to different conclusion so that one may have to conduct several tests to understand what the most appropriate decision would be.

This study focuses on comparison of median risk and distribution of segment risk based on random sample segments. Future work could investigate other risk parameters such as total route risk, variance of segment risk and statistical techniques that are applicable for the whole route analysis for these additional parameters. Examples include a comparison of expected and variability of risk outcomes (Markowitz, 1987) and stochastic dominance of risk distribution (Yitzhaki, 1982).

8.3.1 Review of Selected Statistical Methods

8.3.1.1 The Tests Based on Chi-square Statistics

A chi-square test is any statistical hypothesis test in which the sampling distribution of the test statistic is a chi-square distribution when the null hypothesis is true, or any in which this is asymptotically true (Snedecor and Cochran, 1989). The chi-square test of goodness of fit can be used quantitatively to assess the discrepancies between observed and expected frequencies. The null hypothesis of the chi-square test is that the observations are randomly drawn from a specified theoretical distribution.

There are general rules regarding proper use of the chi-square test. According to Cochran (1954), “no expected frequency should be less than one for each class considered. Two expected frequencies may be near one provided that most of the other expected frequencies are greater than five. Classes with expected frequencies below one should be combined, and the number of

classes to be used is that after the combinations have been made”. For the validity of the test results, the data to be tested should conform to these rules.

It is important to note the typical errors in using the chi-square test. According to Lewis and Burke (1949), these errors include: “lack of independence among the single events, small theoretical frequencies, neglect of frequencies of non-occurrence, failure to equalize the sum of the observed frequencies and the sum of the theoretical frequencies, and use of non-frequency data”. These need to be carefully reviewed to minimize the errors or inaccuracies that may invalidate the test results.

One of the major advantages of the chi-square test is that it can be used with either a continuous or discrete theoretical distribution. Therefore, it is applicable to the probabilistic risk model based on the discrete probability distribution, i.e. Poisson distribution, described in the previous chapter. Nevertheless, the chi-square test has some drawbacks. According to Law and Kelton (2000), the chi-square test in general can be considered as a formal comparison of observed histogram data versus the probability mass function of the hypothesized distribution. This technique requires the data to be grouped into classes so information on the distribution within classes is ignored by the test. The process of specifying an appropriate interval for class can be troublesome, and it is difficult to determine appropriate values for width of the class, and, consequently, the number of classes to be used. A technique to determine the number of classes is available for continuous hypothesized distributions but not for discrete case (Williams, Jr., 1950). Thus, the width of class chosen may possibly affect the results.

The chi-square test for goodness of fit requires the same total number of observed and expected frequencies, and is generally considered less powerful than the tests that are based on the empirical distribution function (EDF) such as Kolmogorov-Smirnov test (Moore, 1986). Example of a use of the chi-square test in rail safety is the work of Dick (2001), who used it in a screening level analysis of the parameters affecting rail service failures.

8.3.1.2 Tests Based on Empirical Distribution Function Statistics

The test statistics based on the empirical distribution function (EDF) are generally more powerful than the Pearson chi-square statistic (Massey, Jr. 1951; Steele and Chaseling, 2006). The EDF is a step function calculated from the sample that estimates the population distribution function (Stephens, 1986) and a well-known example is the Kolmogorov-Smirnov (K-S) test (Kolmogorov, 1933; Smirnov, 1939; Massey, Jr. 1951). This test compares an empirical distribution function with a hypothesized distribution function. Unlike the chi-square test, the K-S test does not require data grouping so no information is lost. It also eliminates the problem of interval specification and is valid for any sample size (Law and Kelton, 2000). The K-S test is based on the assumptions that a sample is random. If the hypothesized distribution function is continuous then the test is exact, otherwise it is conservative (Conover, 1971).

The drawback of the K-S test is that it assigns the same weight to differences from anywhere in the distributions of the empirical function and the hypothesized function (Law and Kelton, 2000). Therefore, it tends to be more sensitive near the center of the distribution. In the case in which two distributions differ primarily in the tails, the Anderson-Darling (A-D) test (Anderson and Darling, 1952; 1954) may be preferable (NIST/SEMATECH, 2003). Similar to the K-S test, the A-D test also assumes a continuous hypothesized distribution. However, the A-D test is applicable only for a few specific continuous distributions (NIST/SEMATECH, 2003) thus it is not considered in this study.

8.3.1.3 Nonparametric Tests

According to Hollander and Wolfe (1999), nonparametric statistical methods are preferred alternatives for data analysis because they do not require restrictive distributional assumptions about the underlying populations from which the data are drawn. Moreover, nonparametric methods are often incorporated in modern statistical packages so that computations can be readily performed.

In this chapter, I provide discussion and illustrations of the following nonparametric tests: Wilcoxon rank-sum or Mann-Whitney U test (Wilcoxon, 1945; Mann and Whitney, 1947), Kruskal-Wallis test (Kruskal and Wallis, 1952), Wilcoxon signed rank test, and Fisher sign test.

The important assumptions of the Wilcoxon rank-sum test are 1) the two samples being compared are mutually independent, 2) the observations in these two samples are independent and identically distributed, and 3) the samples are random samples from continuous populations. The null hypothesis tests whether the two samples have the same probability distribution, and the alternative hypothesis tests whether one sample tends to be larger or smaller than another (Hollander and Wolfe, 1999).

The Kruskal-Wallis test focuses on comparing the relative locations (medians) of three or more populations. The basic assumptions of the test are the same as that of the Wilcoxon rank-sum test. The null hypothesis is that there are no differences among the treatment effects, i.e. the underlying distributions being compared are the same. The alternative hypothesis tests if at least two of the treatment effects are not equal.

The signed rank test and the sign test are applicable for one-sample data or the data with paired replicates that represent pre-treatment and post-treatment observations. Both tests examine if there is a significant shift in location of the distribution due to the treatment (Hollander and Wolfe, 1999).

In general, these non-parametric statistical methods based on ranks offer the advantage of both simplicity and power (Lehmann, 2006). In the next sections, I consider a case study to illustrate the afore-mentioned statistical techniques. I will also provide the formulae for test procedures and graphical illustrations of the hypothesis to be tested as appropriate. The statistical analysis software, SAS 9.1 (SAS, 2003) was used for most of the statistical tests considered.

8.3.2 Illustrations of the Statistical Methods for Route Risk Comparison

8.3.2.1 Case Study for Statistical Comparison of Route Risks

To illustrate an application of statistical methods considered, I consider a hypothetical set of 200 segments representing random sample segments from two different routes as part of a particular transportation network. In actual application, segments may be randomly selected from each route to be compared. This can be done in a spreadsheet by dividing the route into segments with unique identification (ID). The number of segments in the route depends on how the route is segmented, i.e. using a smaller or a larger number of segments according to the granularity of the

route risk analysis. To avoid bias due to variation of segment lengths, segment risk to be compared may be normalized by segment length, or one may consider using uniform segment length in route segmentation for better results. The number of samples may depend on the total number of segments in the route, percent confidence interval and desired accuracy. Various sampling techniques can be considered for choosing appropriate number of sample segments. Generally, the number of samples is a function of Z-value, percentage picking a choice, and confidence interval. One may use an online sample size calculator. For this analysis, I consult the table provided by California Department of Resources Recycling and Recovery (2010), which suggests the number of samples for a given population size. Accordingly, a sample of 200 segments from a typical route of 1,000 miles having about 500 segments in total would be sufficient. To randomly choose segments, a random number is assigned to each individual segment ID and sorting data by random numbers. The first 200 segments are then selected. Table 8.2 and Figure 8.4 show the characteristics and risk profiles of the two samples representing two different routes.

Table 8.2. Characteristics of the sample segments.

Characteristics	Sample	
	A	B
Number of Samples	200 segments	200 segments
Total Length	489 miles	447 miles
Average Segment Length	2.4 miles	2.2 miles
Annual Carload	1 carload	1 carload
Total Annual Risk	0.0033 persons	0.0070 persons
Maximum Number of Persons Affected	3,054 persons	4,885 persons
Total Population Potentially Exposed	161,690 persons	128,124 persons

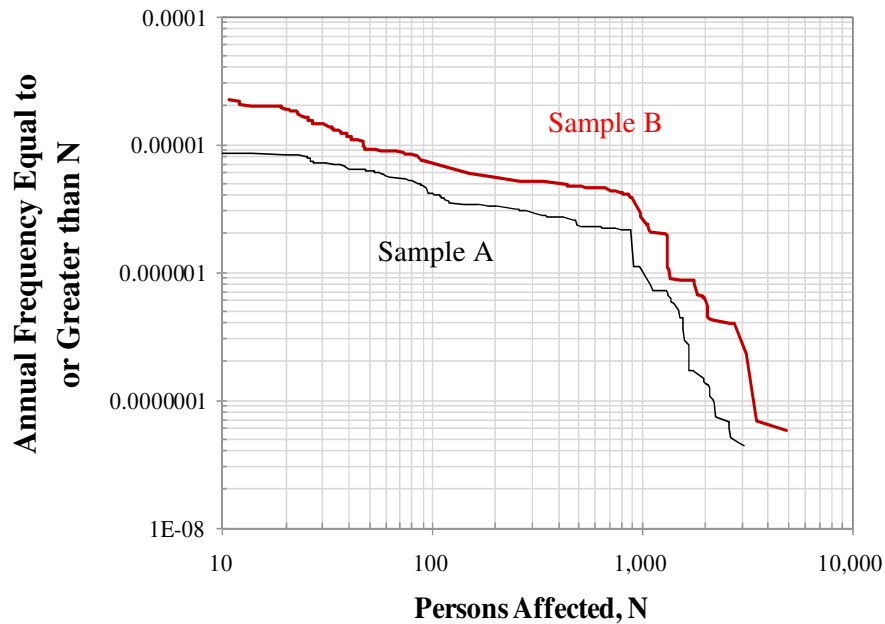


Figure 8.4: Risk Profiles (F-N Curves) of the Sample Segments

8.3.2.2 Tests for Independence

Many statistical tests often require that two assumptions be satisfied: 1) the independence of each individual observation within the same group, and 2) the independence of samples between the two groups to be compared. These are applicable to route risk comparison in which the segment risks being compared must not be correlated data, either within or across the groups. In the previous chapter, I described how the Poisson process assumes that events occurring in non-overlapping intervals are independent of one another. Nevertheless, there could be some shared contributing risk factors among route segments to be compared. For example, the two samples may come from different parts of the same railroads, with the same maintenance standards or operator training, or each individual sample in the same group comes from the segments located near each other on the same route with similar maintenance standards, geography and/or traffic volume. Therefore, to maximize the degree of independence, sample segments could be randomly selected along the route or across the network to minimize correlations. In addition, a formal procedure could be carried out to test whether the data sets are free of autocorrelation. In this section, I discuss several tests that may be considered for detecting non-randomness in sample data to ensure independence prior to conducting other statistical tests.

One of the tests applicable for detecting a randomness of the data set is the Wald–Wolfowitz runs test (Wald and Wolfowitz, 1940). However, it is more appropriate for large samples (Knuth, 1998; Law and Kelton, 2000). For the case study here, I first examine the lag plot and autocorrelation plot (NIST/SEMATECH, 2003), then I perform a formal test for autocorrelation to detect randomness within each data set. To test for independence of the data across the two groups (i.e. each pair of segment risks from the two samples), I use the distribution-free tests for independence: Spearman’s rank correlation (Spearman, 1904) and Kendall’s tau rank correlation (Kendall, 1938; 1948).

Lag Plot

The lag plots of segment risk are shown in Figure 8.5. There are a few extreme risk values due to variation of segment lengths in the data set (Figures 8.5a and 8.5c). The lower risk segments are exaggerated in Figures 8.5b and 8.5d.

Autocorrelation Plot and Test for White Noise

The autocorrelation plot indicates the degree of correlation with past values of the series as a function of the number of periods in the past (i.e., the lag) at which the correlation is computed. The test for white noise is “an approximate statistical test of the hypothesis that none of the autocorrelations of the series up to a given lag are significantly different from zero” (SAS, 2003). In addition to lag plots, I conducted a formal test for autocorrelation using the SAS ARIMA Procedure. Outputs for various lags for one sample are shown in Table 8.3, which comprises two parts. The first part is the autocorrelation plot, and the second part is the test for white noise (randomness). The autocorrelation plot in Table 8.3 shows how values of the series are correlated with past values of the series. The asterisks show the correlation values graphically, and the dot indicates two standard errors.

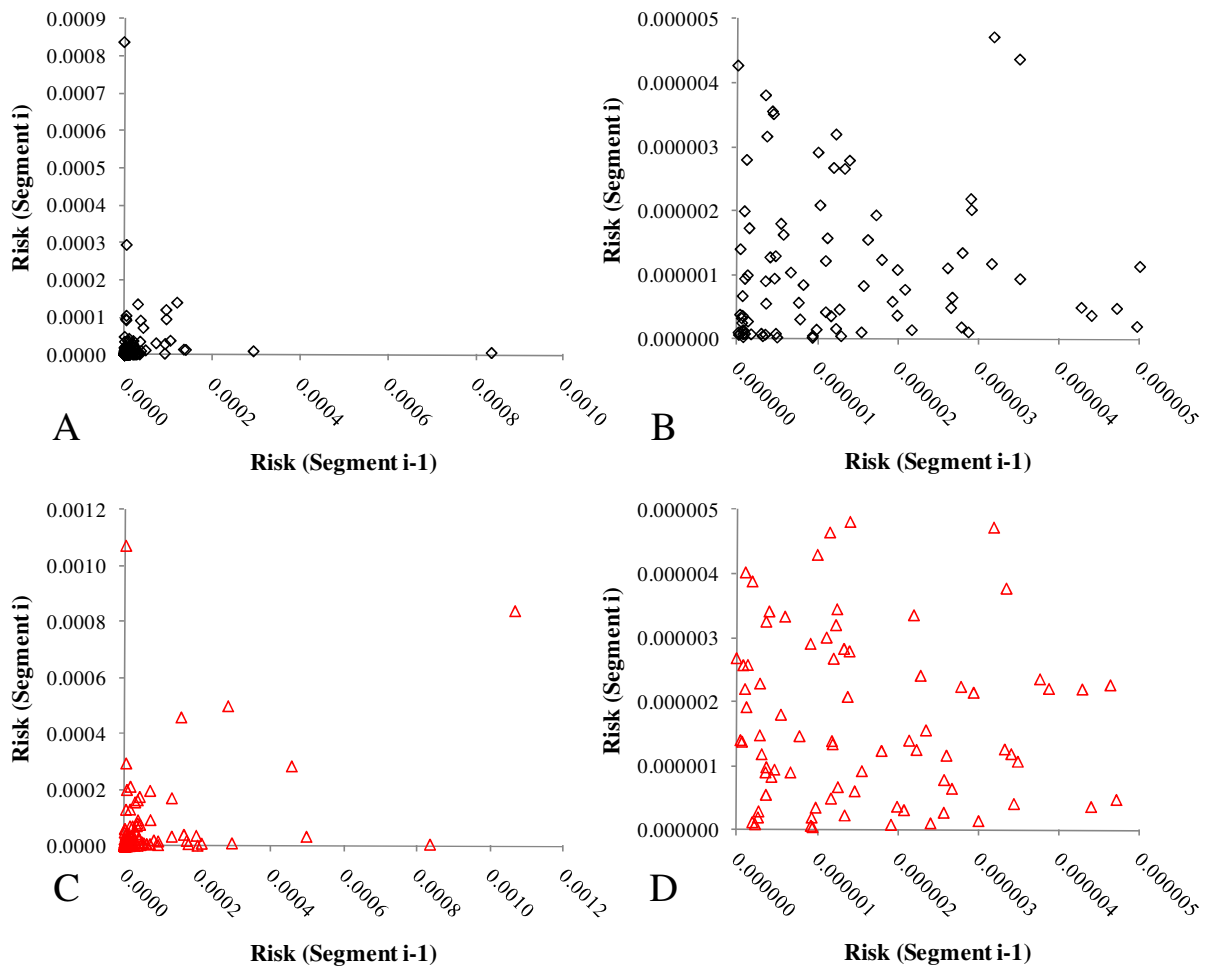


Figure 8.5: Lag Plots of Absolute Segment Risk Using Lag of 1
(A) Sample A (All Segments), (B) Sample A (Focus on Segment Risk of 0.000005 or Less),
(C) Sample B (All Segments), and (D) Sample B (Focus on Segment Risk of 0.000005 or Less)

The lag plots do not indicate a serious pattern of autocorrelation. However, use of different metrics (e.g. normalized or absolute value) may lead to different results. Table 8.3 is an alternative test for autocorrelation. By observing the value of autocorrelations in the first part of the table, there is a mild pattern that the autocorrelations tend to be positive at low lags and slightly negative at high lags but the magnitude of autocorrelations is very small. The p -values corresponding to various lags show that the autocorrelations are not significant except those up to lag 6 in which p -value is 0.01. Presence of mild autocorrelations at certain lag indicates that the data set may not be perfect, however, it will be used to illustrate the statistical tests.

Table 8.3. SAS output showing the results of the test for autocorrelations.

The SAS System 13:20 Tuesday, October 6, 2009

The ARIMA Procedure

Name of Variable = RISK A

Mean of Working Series 0.000017
 Standard Deviation 0.000066
 Number of Observations 200

Autocorrelations

Lag	Covariance	Correlation	-1	9	8	7	6	5	4	3	2	1	0	1	2	3	4	5	6	7	8	9	1	Std Error
0	4.29303E-9	1.00000												*****										0
1	2.0577E-10	0.04793										.	*	.										0.070711
2	9.8832E-11	0.02302										.	.	.										0.070873
3	1.19798E-9	0.27905										.	*****											0.070910
4	3.1891E-11	0.00743										.	.	.										0.076204
5	3.9769E-11	0.00926										.	.	.										0.076207
6	1.2732E-10	0.02966										.	*	.										0.076213
7	6.7586E-11	0.01574										.	.	.										0.076270
8	1.5457E-10	0.03601										.	*	.										0.076287
9	3.5226E-10	0.08205										.	**											0.076372
10	-4.421E-11	-.01030										.	.	.										0.076811
11	-2.453E-11	-.00571										.	.	.										0.076818
12	-2.714E-11	-.00632										.	.	.										0.076820
13	-9.175E-11	-.02137										.	.	.										0.076823
14	-4.144E-11	-.00965										.	.	.										0.076853
15	-1.329E-11	-.00310										.	.	.										0.076859
16	-5.044E-11	-.01175										.	.	.										0.076859
17	-9.044E-11	-.02107										.	.	.										0.076868
18	-1.081E-10	-.02519										.	*	.										0.076897
19	8.3522E-11	0.01946										.	.	.										0.076938
20	-5.723E-11	-.01333										.	.	.										0.076963
21	-7.054E-11	-.01643										.	.	.										0.076974
22	-1.052E-10	-.02449										.	.	.										0.076992
23	-1.286E-10	-.02996										.	*	.										0.077031
24	-1.077E-10	-.02508										.	*	.										0.077089

"," marks two standard errors

The SAS System 13:20 Tuesday, October 6, 2009

The ARIMA Procedure

Autocorrelation Check for White Noise

Route A

To Lag	Chi-Square	DF	Pr > ChiSq	-----Autocorrelations-----					
6	16.76	6	0.0102	0.048	0.023	0.279	0.007	0.009	0.030
12	18.54	12	0.1002	0.016	0.036	0.082	-0.010	-0.006	-0.006
18	18.93	18	0.3959	-0.021	-0.010	-0.003	-0.012	-0.021	-0.025
24	19.60	24	0.7191	0.019	-0.013	-0.016	-0.024	-0.030	-0.025

The next step is to examine if there is a correlation across the two groups of segment risk data to be compared. The objective is to determine whether the observation pairs between the two groups are mutually independent and identically distributed. Accordingly, I conducted a test for independence using Spearman's and Kendall's tau rank correlation, using the SAS CORR

Procedure. The results (Table 8.4) show small values of correlation coefficients with the p -values above 0.3. Thus, the results indicate no evidence of correlation between segment risks from samples *A* and *B*.

Table 8.4. SAS output showing the results of the test for independence.

```

The SAS System 13:20 Tuesday, October 6, 2009

The CORR Procedure

Spearman Correlation Coefficients, N = 200
Prob > |r| under H0: Rho=0

                SEGMENTRISK_      SEGMENTRISK_
                SAMPLEA           SAMPLEB
SEGMENTRISK_   1.00000           0.07145
SAMPLEA        0.3147
SEGMENTRISK_   0.07145           1.00000
SAMPLEB        0.3147

Kendall Tau b Correlation Coefficients, N = 200
Prob > |r| under H0: Rho=0

                SEGMENTRISK_      SEGMENTRISK_
                SAMPLEA           SAMPLEB
SEGMENTRISK_   1.00000           0.04730
SAMPLEA        0.3200
SEGMENTRISK_   0.04730           1.00000
SAMPLEB        0.3200

```

8.3.2.3 Comparison of Risk Distributions Using Chi-square Test for a Goodness of Fit

The idea of route risk comparison is to determine whether there is a significant difference in the distributions of risks of the two (or more) routes. One potential method is to use the chi-square test for a goodness of fit. This may be useful in the case where the observed difference in the point estimates of risk is not apparent and the risk manager wishes to take an initial step to investigate if there is a statistical difference in the risk distributions before further examination of the distributions in detail.

First, I assumed one route as a baseline, with a hypothesized distribution of risk, and then conducted a test to determine whether the risk distribution of the alternative route significantly differs from the hypothesized risk distribution. In this case, the sample with a higher point estimate of risk (i.e. sample B) is chosen to represent the baseline route. In actual application, the selection of baseline route may reflect the objective of comparison. For example, the baseline route may represent the route being used for shipments, and the alternate route may be the different one to avoid highly populated areas. This is to facilitate understanding of the effects

when the baseline represents the status quo and the alternative reflects risk reduction option under consideration. However, the test results will have the same p -value with any case as the baseline.

The chi-square test requires that the data be grouped into classes. Therefore, I constructed a frequency table showing the distribution of the number of segment counts over different classes of magnitude of segment risk for the baseline route. To ensure that the frequency distribution in each class conforms to the practical rules mentioned earlier, I used the SAS FREQ Procedure to sort the segment risks in ascending order and determine the cumulative frequency (Table 8.5). Then, I chose the risk levels corresponding to the cumulative percent of: 5%, 25%, 50%, 75%, 95%, and 100% as the upper levels for each class (Table 8.6). In this way, I could ensure that the frequency in each class conforms to the rules (i.e. no expected frequency of less than five in each class).

Table 8.5. Partial frequency table of the baseline segment risk data.

The SAS System		22:55 Tuesday, November 17, 2009			
		The FREQ Procedure			
SEGMENTRISK_	SAMPLEB	Frequency	Percent	Cumulative Frequency	Cumulative Percent
	4.65E-8	1	0.50	1	0.50
	6.68E-8	1	0.50	2	1.00
	8.23E-8	1	0.50	3	1.50
	9.08E-8	1	0.50	4	2.00
	1.048E-7	1	0.50	5	2.50
	1.135E-7	1	0.50	6	3.00
	1.22E-7	1	0.50	7	3.50
	1.394E-7	1	0.50	8	4.00
	1.948E-7	1	0.50	9	4.50
	1.978E-7	1	0.50	10	5.00
	...				
	0.000170473	1	0.50	190	95.00
	0.000175068	1	0.50	191	95.50
	0.000196677	1	0.50	192	96.00
	0.000199985	1	0.50	193	96.50
	0.000211404	1	0.50	194	97.00
	0.000283813	1	0.50	195	97.50
	0.000294145	1	0.50	196	98.00
	0.0004579	1	0.50	197	98.50
	0.000497914	1	0.50	198	99.00
	0.000835905	1	0.50	199	99.50
	0.001068819	1	0.50	200	100.00

Figure 8.6 shows the histograms of the distributions of the segment risk to be compared. The final step is to perform the chi-square test. I used the percentages in column 5 of Table 8.6 as the test percentages representing the hypothesized distribution, and used the SAS FREQ

Procedure to compute the test statistic X^2 (Table 8.7), which equals 32.66 with 5 degrees of freedom. The probability of chi-square greater than the calculated X^2 is less than 0.0001. The critical value of chi-square with 5 degree of freedom at 0.05-level ($\chi^2_{0.05, 5}$) is 11.07. Therefore, the null hypothesis is rejected, and it can be concluded that the risk distributions of the two samples are different at the 0.05-level.

Table 8.6. Classification of segment risks of the baseline route.

Class	Baseline Segment Risk (Persons Affected per Year) Interval	Frequency (Segments)	Cumulative Frequency	Percent	Cumulative Percent
1	$0 - 1.98 \times 10^{-7}$	10	10	5%	5%
2	$1.98 \times 10^{-7} - 1.25 \times 10^{-6}$	40	50	20%	25%
3	$1.25 \times 10^{-6} - 4.17 \times 10^{-6}$	50	100	25%	50%
4	$4.17 \times 10^{-6} - 1.57 \times 10^{-5}$	50	150	25%	75%
5	$1.57 \times 10^{-5} - 1.70 \times 10^{-4}$	40	190	20%	95%
6	$1.70 \times 10^{-4} - 1.07 \times 10^{-3}$	10	200	5%	100%

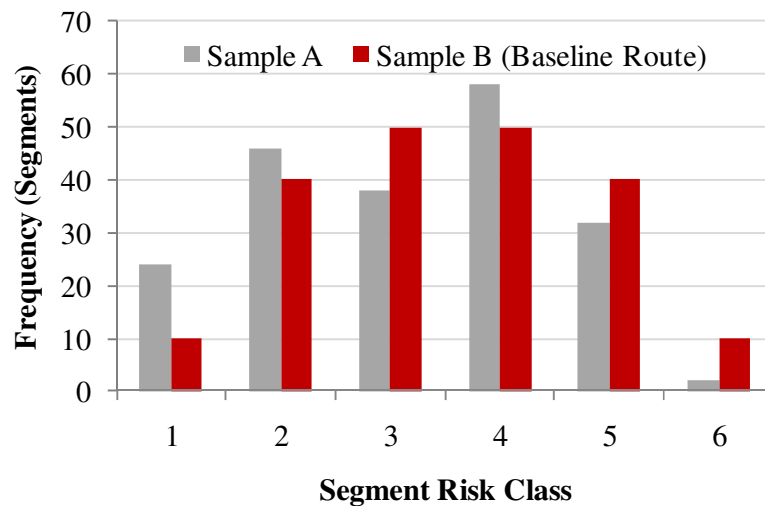


Figure 8.6: Histograms of Segment Risk to be Compared

Table 8.7. SAS output showing the results of the chi-square test.

```

The SAS System
The FREQ Procedure

SAMPLEA_RISKCLASS Frequency    Percent    Test
-----
1                24         12.00      5.00
2                46         23.00     20.00
3                38         19.00     25.00
4                58         29.00     25.00
5                32         16.00     20.00
6                 2          1.00      5.00

Chi-Square Test
for Specified Proportions
-----
Chi-Square          32.6600
DF                   5
Pr > ChiSq          <.0001

Sample Size = 200
```

According to Law and Kelton (2000), one of the major weaknesses of the chi-square test is that information regarding the distribution within classes is lost and thus the test may not properly evaluate the differences in case of a relocation of the distribution (Figure 8.3). Furthermore, the widths of classes chosen may possibly affect the test results. The test requires the same total number of observed and expected frequencies, and it is generally considered less powerful than the tests based on an empirical distribution function (EDF).

8.3.2.4 Comparison of Risk Distributions Using Wilcoxon Rank-sum Test

According to Hollander and Wolfe (1999), the Wilcoxon rank-sum test (aka Mann–Whitney U test) is a non-parametric test for assessing whether two independent samples of observations come from the same distribution. The null hypothesis of the test is that the two samples are drawn from a single population and, therefore, have the same probability distribution but that the common distribution is not specified. The alternative hypothesis is that one population group tends to be larger or smaller than another. In other words, two population groups are the same except that one is shifted by the amount Δ , which is called the location shift or the treatment effect. Figure 8.7 (Wild and Seber, 2000), illustrates the test hypotheses for Wilcoxon rank-sum test.

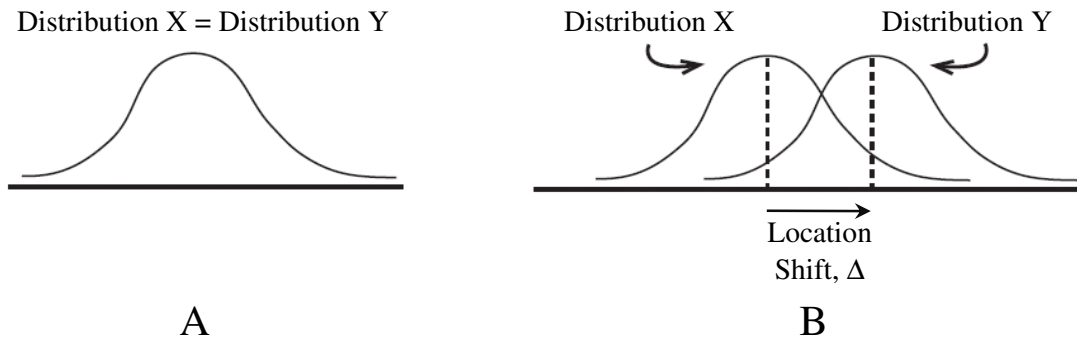


Figure 8.7: Illustration of Wilcoxon Rank-sum Test Hypotheses

(A) $H_0: X = Y$, vs. (B) $H_a: Y > X$

The Wilcoxon rank-sum test assumes that: the two samples under investigation are independent of each other, the observations within each sample are independent, and the observations are comparable. Its advantage is that the method is applicable for arbitrary sample sizes. In this section, I illustrate an application of Wilcoxon rank-sum test to determine if the median segment risks of the two samples significantly differ from one another (Figure 8.8). The null hypothesis is that the medians of the distributions of segment risks of samples A and B are the same, and the alternative hypothesis is that the median risk for B (baseline route) is higher.

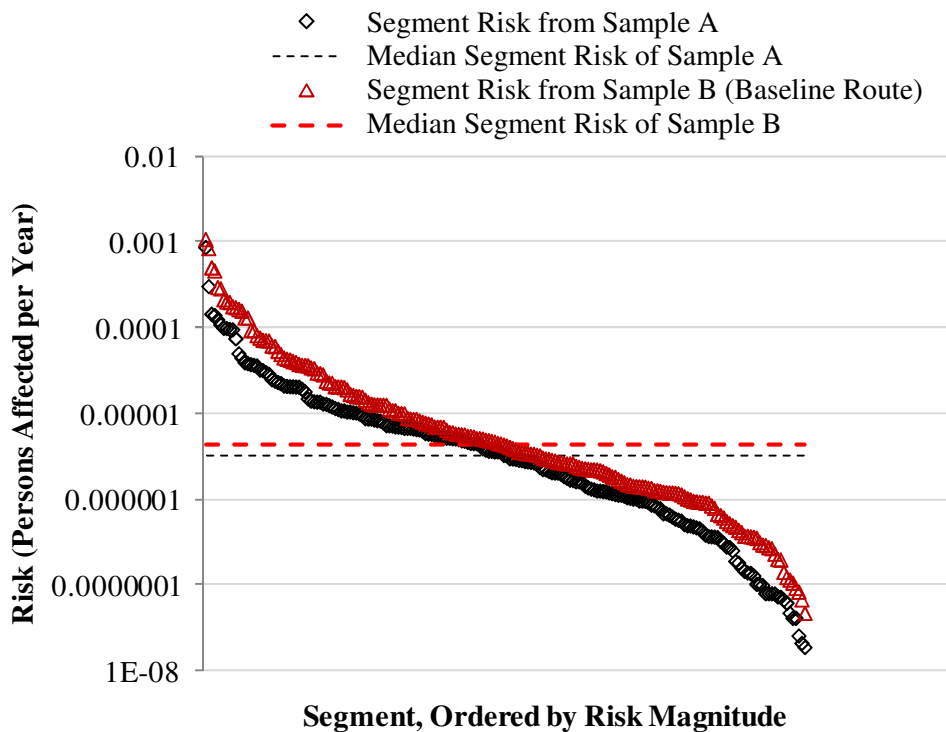


Figure 8.8: Distribution of Segment Risks to be Compared

I conduct the test using the SAS NPAR1WAY Procedure. SAS output (Table 8.8) indicates the p -value of 0.0087 (one-sided). Therefore, the null hypothesis is rejected. That is, the baseline segment risks tend to be larger.

Table 8.8. SAS output showing the results of Wilcoxon rank-sum test.

```

The SAS System          18:19 Friday, November 13, 2009

                The NPAR1WAY Procedure

Wilcoxon Scores (Rank Sums) for Variable SegmentRisk_
Classified by Variable Sample_

Sample_      N      Sum of      Expected      Std Dev      Mean
-----      -      Scores      Under H0      Under H0      Score
-----      -      -----      -----      -----      -----
A            200      37348.0      40100.0      1156.14215      186.740
B            200      42852.0      40100.0      1156.14215      214.260

Average scores were used for ties.

Wilcoxon Two-Sample Test

Statistic                37348.0000

Normal Approximation
Z                        -2.3799
One-Sided Pr < Z        0.0087
Two-Sided Pr > |Z|      0.0173

t Approximation
One-Sided Pr < Z        0.0089
Two-Sided Pr > |Z|      0.0178

Z includes a continuity correction of 0.5.

```

8.3.2.5 Comparison of Risk Distributions Using Kolmogorov-Smirnov Two-sample Test

The Wilcoxon rank-sum test focuses on detecting the change in the location of the distributions but other differences between the two populations are still possible. For example, the two distributions may have the same general form but different shape or scale parameters as illustrated in Figure 8.9 (Hollander and Wolfe, 1999).

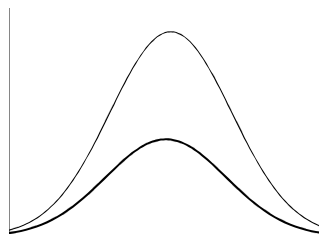


Figure 8.9: Probability Distributions with the Same General Form and Equal Medians but Different Scale

Therefore, instead of testing whether two distributions are different in location, a broader test would consider any general differences including both location and shape of the distributions. One nonparametric test for detecting such general differences in two populations is the Kolmogorov-Smirnov (K-S) test (Kolmogorov, 1933; Smirnov, 1939).

According to Hollander and Wolfe (1999), the K-S test assumes that the observations in each group are a random sample from a continuous distribution, i.e. the observations are mutually independent and identically distributed within each group. It also assumes the independence between the two groups. These assumptions are similar to those required by the Wilcoxon rank-sum test described earlier. The objective of the test is to consider the null hypothesis, H_0 , that the two probability distributions are the same versus the alternative hypothesis, H_a , that there are any differences between the two distributions.

First, I created a cumulative distribution plot of segment risks of the two groups to be compared (Figure 8.10). The cumulative distribution plot portrays the cumulative distribution function (CDF) (also referred to as the empirical distribution function or EDF). The plot in non-logarithmic scale (Figure 8.10a) indicates that the segment risk data are not normally distributed. The nonparametric methods discussed are applicable to this kind of data provided that their assumptions are met.

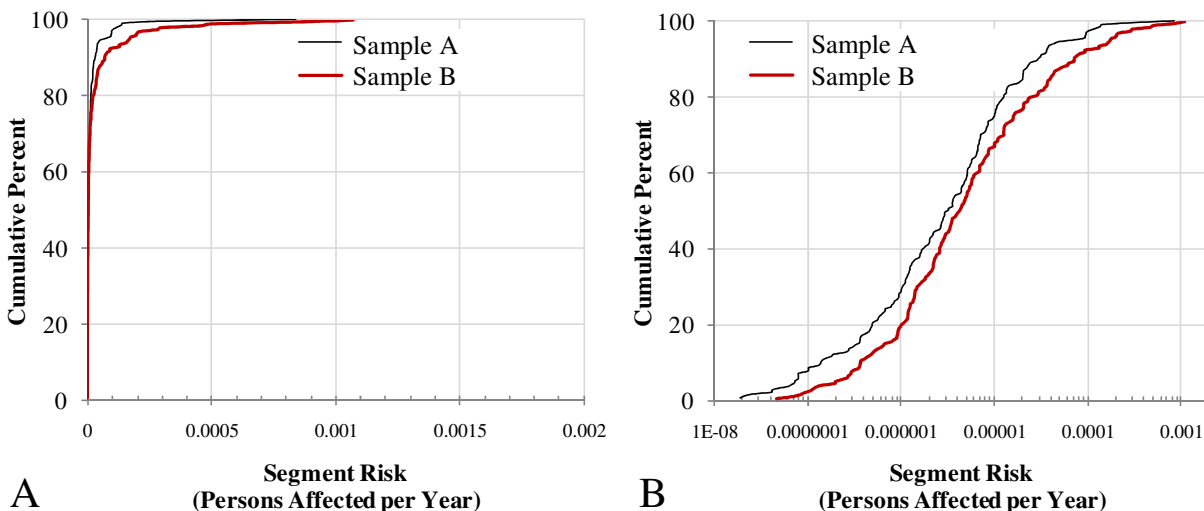


Figure 8.10: Cumulative Distribution Function of Segment Risks with Horizontal Axis in (A) Equal Intervals and (B) Logarithmic Scale

A logarithmic scale is applied to the horizontal axis to better visualize the differences between the two CDFs (Figure 8.10b). The plot shows that the cumulative percentage of segment risk data of sample B (baseline route) is generally less than that of sample A for most of the values of segment risk. At the same cumulative percentage, the segment risk of the sample B tends to be higher.

The K-S test considers the maximum vertical deviation between the two CDFs as the statistic and tests whether the two probability distributions are identical, or there are any possible differences between them.

To illustrate the K-S test for route risk comparison, I use the SAS NPAR1WAY Procedure to compute the two-sided two-sample Kolmogorov-Smirnov statistic. The test statistic obtained from SAS is based on large-sample approximation. Hollander and Wolfe (1999) suggested that the smallest significance level at which to reject H_0 is 0.0551 under large-sample approximation.

From Table 8.9, the asymptotic p -value for the K-S test is 0.142, which does not favor rejection of the null hypothesis at 0.05-level. Thus, the apparent differences between the distributions of segment risks for the two samples are not statistically significant.

Table 8.9. SAS output showing the results of Kolmogorov-Smirnov test of general differences in the distributions of segment risk.

```

The SAS System          16:58 Wednesday, November 18, 2009

                The NPAR1WAY Procedure

      Kolmogorov-Smirnov Test for Variable SegmentRisk_
      Classified by Variable Sample_

Sample_      N      EDF at      Deviation from Mean
              N      Maximum      at Maximum
-----
A             200     0.32500     0.813173
B             200     0.21000    -0.813173
Total        400     0.26750

```

Maximum Deviation Occurred at Observation 36

Value of SegmentRisk_ at Maximum = 1.15E-6

Kolmogorov-Smirnov Two-Sample Test (Asymptotic)

```

KS      0.057500      D      0.115000

KSa     1.150000      Pr > KSa  0.1420

```

The results of the K-S test give a different conclusion than that using the Wilcoxon rank-sum test. It is important to note the issues regarding the efficiency of the two-sample K-S test. According to Hollander and Wolfe (1999), the power of the test against specific subclasses of alternatives such as location shifts or differences in dispersions is sacrificed to guard against all possible differences between the distributions. For certain distributions, the K-S test has the highest rates of committing type-II error, i.e. the test may fail to detect a difference when there is one. Thus, the power of K-S test is less than Wilcoxon rank-sum test when sample sizes are equal. The latter still performs well for long-tailed samples or samples with outliers.

Depending on the objective of the test, the K-S test is more likely to be valid in case one wishes to test the general differences in both location and shape of risk distributions that may be more useful for route risk comparison. However, the Wilcoxon Rank-sum test is a more powerful test for detecting the difference in only location of risk distribution (i.e. comparing median risk). In addition, it is suitable for non-normal data or the case in which the underlying distribution is unknown (Chen and Xie, 2007).

8.3.3 Comparison of Multiple Routes

In the previous sections, I discussed the statistical techniques applicable for a comparison of two routes. For multiple alternatives of three or more routes, the test must be capable of handling multiple comparisons of route risk distributions. This section deals with a comparison of multiple route risks and describes potential statistical tests.

8.3.3.1 Comparison of Multiple Risk Distributions Using Kruskal-Wallis Test

The distribution-free, Kruskal-Wallis test for general alternatives (Kruskal and Wallis, 1952) is a non-parametric test of equality of population medians among groups and is an extension of the Wilcoxon rank-sum test for three or more groups. The test assumes an identically-shaped and scaled distribution for each group, except for any difference in medians.

As explained by Hollander and Wolfe (1999), the null hypothesis of the Kruskal-Wallis test is that there is no difference in locations (medians) among the groups in which one of them represents a control population. The alternative hypothesis is that at least one of the other groups are different from this control group. The test is based on the same assumptions as described

earlier. That is, the samples in each group under investigation are a random sample from a continuous distribution, and the random variables within each group are mutually independent.

To illustrate the test method, I considered another route alternative in addition to those in the previous case study. Another random sample of 200 segments is drawn to represent the third alternate route. The route characteristics and the risk profiles are shown in Table 8.10 and Figure 8.11, respectively.

Table 8.10. Sample segments for multiple-route risk comparison.

Characteristics	Sample		
	A	B	C
Total Length	489 miles	447 miles	405 miles
Number of Segments	200 segments	200 segments	200 segments
Average Segment Length	2.4 miles	2.2 miles	2.0 miles
Annual Carload	1 carload	1 carload	1 carload
Total Annual Risk	0.0033 persons	0.0070 persons	0.0016 persons
Maximum No. of Persons Affected	3,054 persons	4,885 persons	6,064 persons
Total Population Potentially Exposed	161,690 persons	128,124 persons	147,359 persons

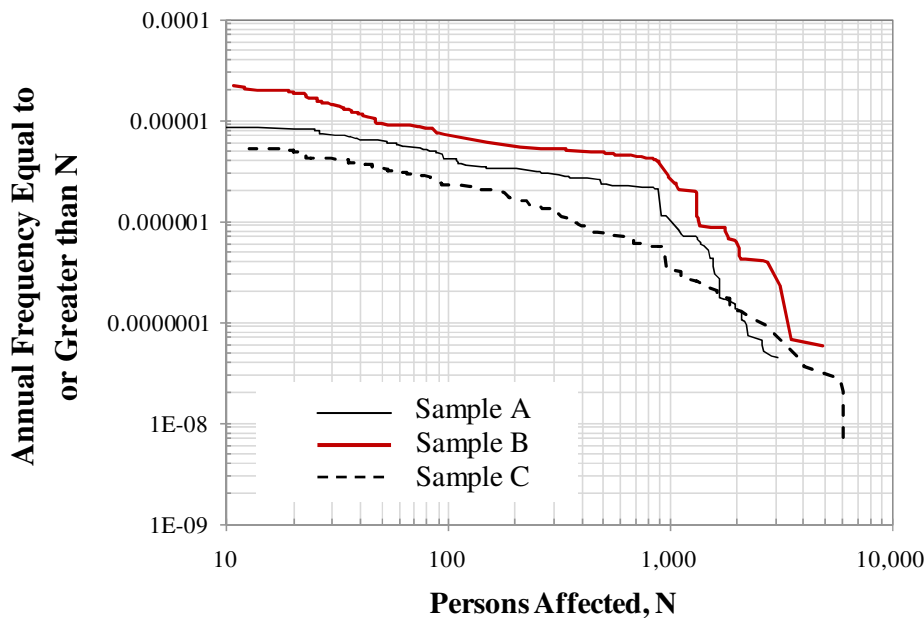


Figure 8.11: Risk Profiles (F-N Curves) for Multiple-route Comparison

To test for the difference in median segment risks, I used the SAS NPARIWAY Procedure. An asymptotic chi-square distribution with 2 degrees of freedom from the test is 28.179 (Table 8.11).

Table 8.11. SAS output showing the results of Kruskal-Wallis test.

```

The SAS System          17:13 Sunday, November 22, 2009

                                The NPARIWAY Procedure
Wilcoxon Scores (Rank Sums) for Variable SegmentRisk_
Classified by Variable Group_

Group_      N      Sum of      Expected      Std Dev      Mean
-----      -      Scores      Under H0      Under H0      Score
1 (A)      200      60708.0      60100.0      2001.66550      303.5400
2 (B)      200      68983.0      60100.0      2001.66550      344.9150
3 (C)      200      50609.0      60100.0      2001.66550      253.0450

Average scores were used for ties.
Kruskal-Wallis Test
Chi-Square      28.1791
DF              2
Pr > Chi-Square <.0001

```

The p -value is less than 0.0001, thus there is a significant difference in segment risks of at least two routes under this comparison.

Although this technique is applicable for a comparison of more than two routes, it only tests whether there is a difference among the groups but does not indicate which one is different from which. Therefore, its utility on risk-based decision making regarding route selection is still limited.

There are some other tests that may better suit the multiple-route comparison. For example, Fligner (1985) developed a pair-wise ranking test procedure analogue of the Kruskal-Wallis statistic (see Hollander and Wolfe, 1999). In particular, the Dwass, Steel, Critchlow-Fligner two-sided multiple comparisons based on pair-wise rankings can accommodate a decision on individual differences between pairs of population groups in comparison. These pair-wise multiple comparisons are not included in this study and could be explored further to obtain a better understanding regarding statistical methods that would be most useful to the risk-based decision making in addition to the techniques presented in this chapter.

8.4 Statistical Methods to Assess the Effectiveness of Risk Reduction Measures

Risk managers may wish to evaluate the effectiveness of safety improvement measures applied to a particular route; for example, whether track infrastructure improvement results in a significant reduction in route risk. Previously, I discussed various statistical techniques for a comparison of two or more routes. This particular case of evaluating the changes in risk associated with one single route (or network) requires tests that can handle the paired replicates data. Accordingly, the baseline represents the route without any improvements, and the alternative is the same route but with application of certain risk reduction measures. Thus, the comparison involves two data sets: pre-treatment observations and post-treatment observations. The objective of the test is to detect the shift in location of a population (i.e., segment risks) due to the application of the treatments (i.e., risk reduction measure).

In this section, I will consider the paired replicates analyses based on signed ranks (Wilcoxon signed rank test) and that based on signs (Fisher sign test). Both are analogous to the paired t -test, but these are non-parametric tests so that they are applicable for the case that the distribution of differences between paired replicates is not normal.

8.4.1 Wilcoxon Signed Rank Test

According to Hollander and Wolfe (1999), the Wilcoxon signed rank test assumes the differences of each individual paired observation are mutually independent. The test also assumes that these differences come from a continuous population that is symmetric about the common median, θ , referred to as the treatment effect. The test, however, does not require that individual observations are independent of each other. The null hypothesis, H_0 , asserts that there are zero shifts in location due to treatment ($\theta=0$). The alternative hypothesis, H_a , for the two-sided test is that the treatment effect is not zero ($\theta \neq 0$).

8.4.2 Fisher Sign Test

The Fisher sign test requires the same assumptions as those of the signed rank test except that the symmetry assumption on the differences between paired observations is relaxed. While the requirement of the Fisher sign test is less stringent, the statistical power may be less than that of the paired-sample t -test and Wilcoxon signed-rank test.

8.4.3 Tests for Effectiveness of Track Infrastructure Improvement

To illustrate the test methods described, I consider upgrading track segments along a route, accounting for 25 percent of the total route length. In this upgrade, class-3 track segments are upgraded to class 4. An average-speed CPR corresponding to the tank car considered is used. The risk of baseline sample segments before upgrade is 0.0016 persons affected per year and that after upgrade is 0.0014, a 12 percent reduction (Figure 8.12).

I use SAS UNIVARIATE Procedure to conduct sign and signed rank tests whether the median segment risk after upgrade significantly differs from that before upgrade. The results of sign and signed rank tests (Table 8.12) indicate that the difference is significant at the 0.05-level with p -value of less than 0.0001.

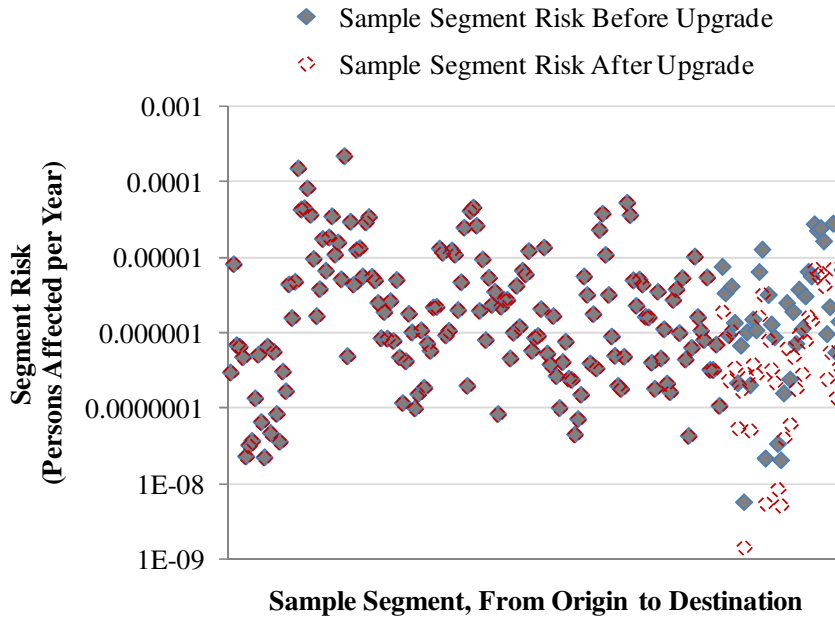


Figure 8.12: Effect of Track Infrastructure Improvement on Risk

Table 8.12. SAS output showing the results of sign and signed rank tests.

```

The SAS System          18:23 Monday, November 23, 2009

      The UNIVARIATE Procedure
Variable:  DiffSegmentRisk_

      Tests for Location: Mu0=0

Test          -Statistic-      -----p Value-----
Student's t   t   3.585726      Pr > |t|      0.0004
Sign         M       20      Pr >= |M|     <.0001

Signed Rank   S       410      Pr >= |S|     <.0001
    
```

Risk managers may wish to know a minimum level of investment in infrastructure upgrade that will result in a significantly reduction in route risk. A sensitivity analysis may be conducted using similar procedures to address this question.

There are a few issues involved with the tests presented in this section. First, the tests account for the signed ranks or the ranks of the differences in segment risk before and after improvement. The magnitudes of the differences determine those ranks but only small changes in magnitudes may not affect the rankings. Second, the segments that are not to be upgraded are excluded by the test procedure since they produce no differences. Therefore, it is likely that the tests may find no significant difference even though route lengths, track class considered for upgrade, or upgrade locations differ from the problem illustrated herein. In other words, if two routes are very similar and there are several zero differences as observations, these will contribute to the test of whether the two routes have difference segment medians, resulting in no significance difference. Thus, segment medians may not be the best parameter to test. A future study may consider other parameters for the tests.

8.5 Uncertainty of Estimates of Parameters Affecting Risk

In the realm of systems engineering, uncertainty is generally classified as epistemic or systematic and aleatory or statistical (Modarres, 2006). Estimates of track-segment-specific risk are subjected to both types of uncertainty with unquantified errors due to uncertainty in risk parameters: accident rates, the conditional probability of release, and persons potentially affected. It is important to note that this could result in apparent differences in risk being statistically non-significant in route risk comparison. In this section, I discuss possible sources of

error in the QRA of hazardous materials transportation by railroad. I also conduct a sensitivity analysis of uncertainty of estimates of parameters affecting risk to illustrate a potential whether such uncertainty would invalidate the result from statistical tests described earlier. Finally, I address some possible improvements to be considered for a more accurate estimation of segment-specific risk.

8.5.1 Possible Sources of Uncertainty in the Quantitative Risk Analysis

The following is a list of possible sources of error in an estimation of segment-specific risk that may contribute to uncertainty surrounding a route risk estimate.

- Measurement (observational or systematic) errors
 - Track class assignment based on speeds
 - Determination of CPR based on speeds
 - Estimation of number of persons potentially affected by a release
- Uncertainty (statistical) errors around point estimates of risk parameters
 - Track-class-specific accident rates
 - Release-source-specific CPR

From the past studies, one of the most obvious sources of observational errors in the QRA of hazardous material transportation is an assignment of track class, which is necessary for one to determine the corresponding accident rate. The problem is that many class-1 railroads do not maintain information regarding actual track class in their infrastructure database, and the U.S. DOT national transportation database (BTS, 2007) does not have such information for track-segment-specific risk analysis. To infer track class, previous studies considered proxy variables such as type of traffic control system in the U.S. DOT database (Kawprasert and Barkan, 2008) or timetable speeds (Kawprasert and Barkan, 2009a; 2010a). These could result in an error in track class estimates because railroads may maintain their tracks at standards higher than stipulated by track speeds. For example, a lower track class may be assigned to bridge, curves or track sections in highly populated areas because of restricted operating speeds, but these sections may have the same or higher maintenance standard as other sections. Thus, it would be helpful for a more accurate estimation of risk if actual track class information can be obtained.

In addition to track class assignment, track-class-specific accident rates themselves are subject to error and uncertainty such as variance in track quality within track classes and temporal variability over the period of data in which accident rates are developed (Anderson and Barkan, 2004). To provide numerical estimates of risk under these uncertainties, one may consider the confidence intervals of the accident rates developed by these authors to bound the point estimate of risk.

Using maximum track speeds to represent the worst case scenario in determining the tank car CPR is likely to result in an overestimation of risk (Kawprasert and Barkan, 2010a). A better estimate could be obtained by considering actual operating speed, or even better, accident speed, which could be much lower than maximum track speed. A development of track-class-specific average accident speed may contribute to a more accurate estimation of risk.

An error in consequence analysis may introduce a wider variety of uncertainty than the elements in frequency analysis mentioned above. In this dissertation, the consequence is expressed using a number of persons affected, which can be estimated per the U.S. DOT guidelines (PHMSA, 2008) using population data from the U.S. Census Bureau. Various kinds of error in population exposure estimation include uncertainty in population census tract densities, heterogeneity of population densities along track segments, time-of-day effect, and wind direction along which evacuation actually takes place.

The errors described above may exist as part of a route risk estimate and may affect the reliability of observed differences in route risk comparison. The statistical difference in risks associated with two routes may be caused by these uncertainty errors in risk estimation of one or both of the routes and not by the actual difference in route risk distributions. For example, Section 8.4.3 shows that the difference in risks becomes significant when one fourth of the route considered has been changed from track-class 3 to class 4. Likewise, error in track-class assignment between classes 3 and 4 for one fourth of the route would also cause a significant difference in risk and thus reduce the accuracy of the test result. In the next subsection, I provide quantified errors associated with two risk parameters: accident (derailment) rates and CPR.

8.5.2 Magnitude of Error of Risk Parameters and Sensitivity Analysis

It is quite difficult to accurately determine the magnitude of total error associated with route risk estimates because the error is likely to vary case by case, depending on the characteristics of the route and assumptions made. The only part of the total error that could be determined is statistical error associated with risk parameter estimates, e.g. errors around point estimate of accident rates and source-specific CPRs. Table 8.13 provides examples of potential errors for track-class-specific derailment rate (statistical error) and speed-dependent CPR (measurement error). Errors associated with these two parameters are easier to illustrate than that of the consequence analysis part. Note that apart from measurement error of the CPR, the source-specific loss CPR estimates themselves are also associated with statistical error (Treichel et al., 2006).

Table 8.13. Error bounds surrounding risk parameter estimates.

Track Class (Max. Speed for Freight Train)	Selected Error Types (% of Point Estimate)	
	95% Confidence Intervals Around Point Estimate of Derailment Rate ¹	Measurement Errors in Speed-dependent CPR ²
Class 2 (25 mph)	± 2.3%	± 35%
Class 3 (40 mph)	± 1.9%	± 18%
Class 4 (60 mph)	± 1.6%	± 14%
Class 5 (80 mph)	± 3.6%	± 9%

¹ The bounds were determined using 95% confidence intervals of cars derailed per billion freight car miles from Anderson and Barkan (2004)

² The bounds were determined by assuming trains travel at average track-class speed, defined as an average of maximum permissible speed on the corresponding track class and that on the preceding lower class. Use speed-dependent CPR for DOT 111A100W1 tank car (Kawprasert and Barkan, 2010a).

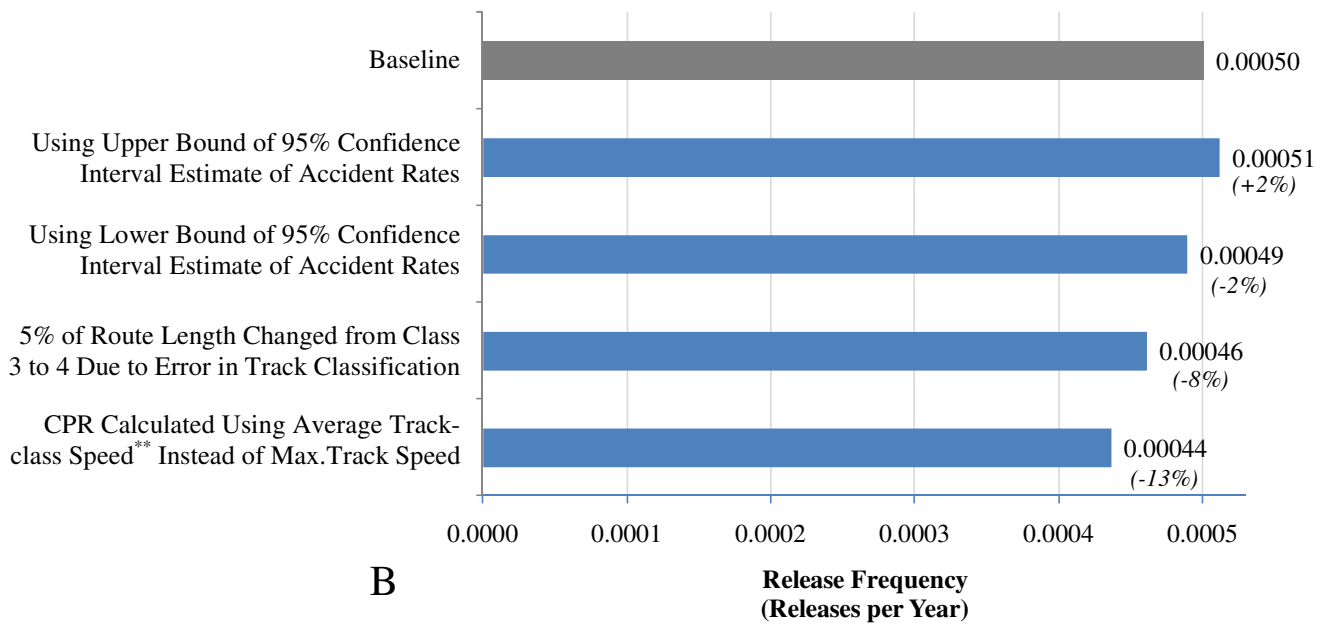
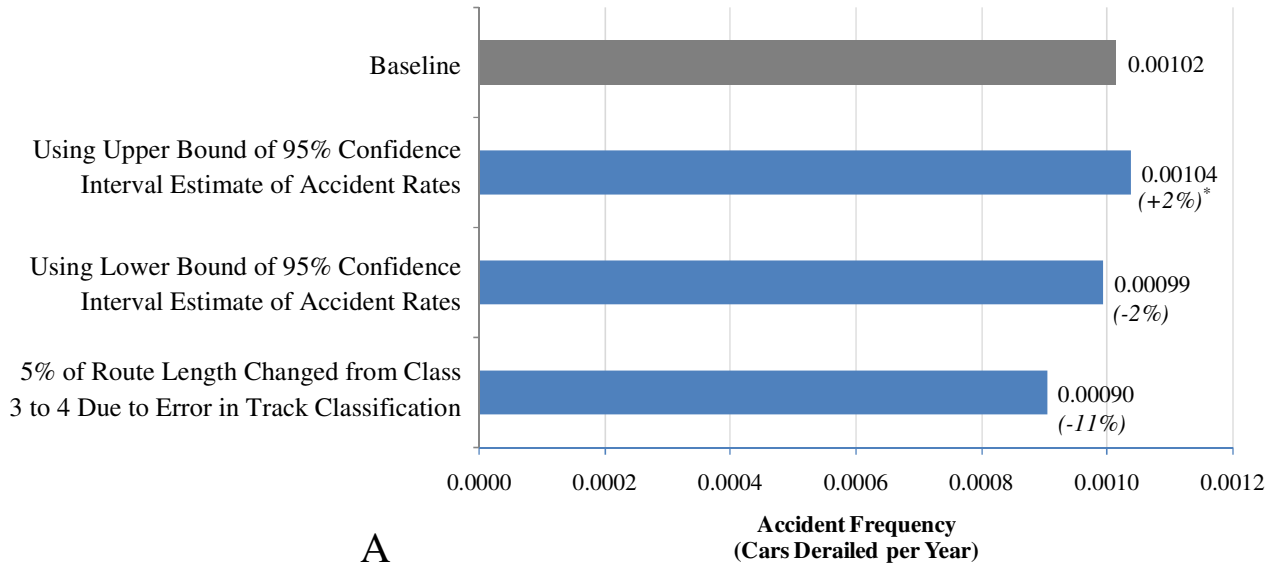
As shown by Kawprasert and Barkan (2009a; 2010a), typical hazardous material transportation routes comprise track classes 4 and 5 as a majority of the route length, and class-3 track is associated with the greatest proportion of the route risk. Since the difference in accident rates and also release rates between class-4 and class-5 track is the smallest compared to other track class pairs at one consecutive class, care should be taken in distinguishing among classes 2, 3 and 4. In particular, since class-2 track usually accounts for the smallest portion of the route

length (1% to 2% of the route on the class-1 freight rail network), one may focus even more when classifying class-3 over class-4 tracks. This is because there is a substantial difference in track-class-specific accident rates and release rates (taking effect of speed into account) for these two particular classes and a tendency that class-3 tracks may be located in populated places contributing majority of risk as shown in Chapter 4. Figure 8.13 shows a simple comparison of accident and release frequencies under various uncertainties in accident rates or track class assignment for a 100-shipment using DOT-111A100W1 car, assuming a route comprising 1%, 15%, 40% and 44% class-2, -3, -4 and -5 track, respectively, and a train operated at maximum track-class speed.

The results indicate that the effect of uncertainty in track-class-specific-accident rates (within 95% confidence interval) is smaller in this hypothetical scenario compared to other types of error such as track classification error or change in assumption for determining the speed-dependent conditional probability of release. Therefore, extra attention should be made to the latter two cases.

Similar analysis could be extended to evaluate potential error in risk estimate. I assume a route comprising 100 segments of 1 mile each and consider an affected area of 1 square mile and a uniform population density of 10 persons per square mile along the entire route with the same traffic as the previous analysis. Figure 8.14 indicates that a change in population density (due to error in estimation) has more effect on risk estimate for lower track classes, but the magnitude of error is small compared to the previous two cases: track classification and speed assumption errors. These remain a key issue that requires further improvements to reduce uncertainty errors in risk estimate.

The errors from the potential sources discussed above may possibly contribute a significant difference in route risk comparison, while the difference in risk may actually not be significant. Furthermore, the same types of error will constitute the risk of the routes in comparison if the routes are derived under similar approach, assumptions and transportation network data. This study, however, does not attempt to systematically quantify the magnitude of uncertainty surrounding route risk estimates. Future research could consider developing a method to determine an approximate range of total error of a point estimate of risk for a given route.



* numbers in parentheses indicate percentage changes in estimate from baseline

** defined as an average of maximum permissible speed on the corresponding track class and that on the preceding lower class

Figure 8.13: Sensitivity Analysis on Frequency Estimates Under Various Uncertainty Assumptions (A) Frequency of Accident and (B) Frequency of Release

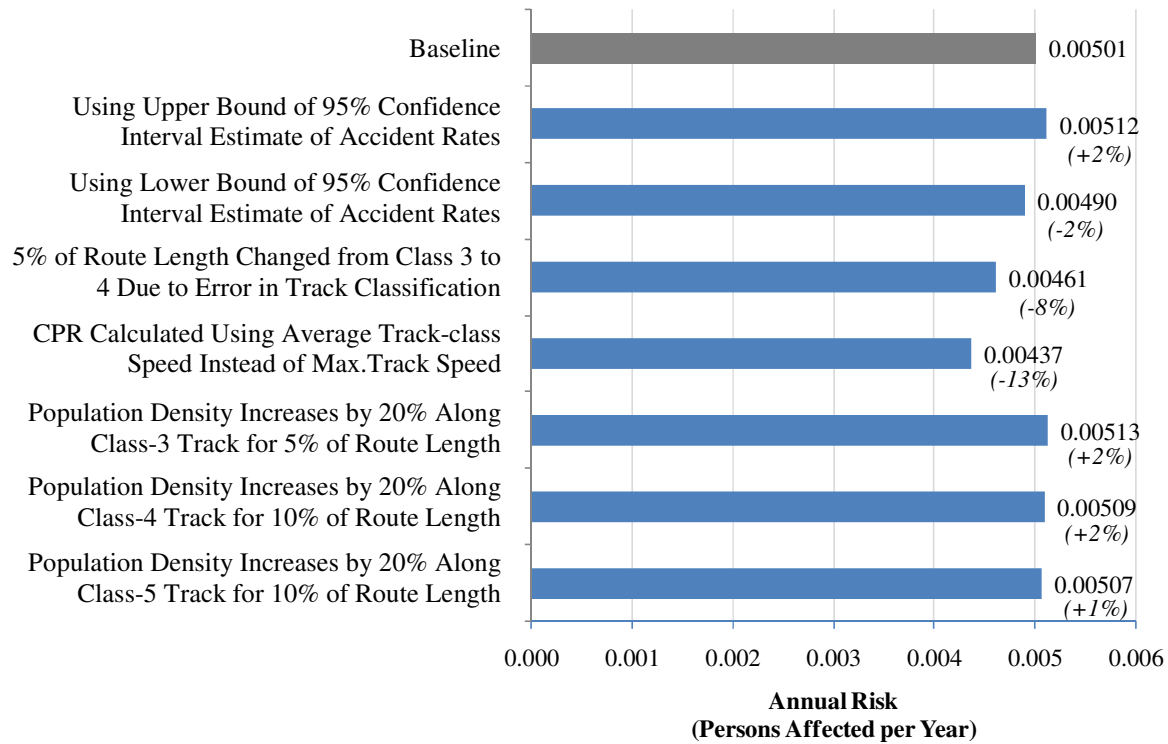


Figure 8.14: Sensitivity Analysis of Risk Estimate Under Various Uncertainties

8.5.3 Improvements in Route Segmentation to Reduce Uncertainty Errors

Another area that may be of interest for further improvement in risk estimation is route segmentation method. The transportation network considered may sometimes limit accuracy of segment-specific risk estimate. A long segment may include more heterogeneity in track characteristics and population density, especially in urban areas. On the other hand, a short segment may have less heterogeneity, but requires a significant level of resources in the overall route risk analysis. The development of optimal segment lengths to minimize uncertainty errors and heterogeneity of track-class-specific characteristics could be an interesting subject for future study.

8.6 Discussion

Conventional comparisons of route risks are usually made by observing single point estimates of risk and risk profiles. These provide information regarding the expected value of hazardous materials release consequence and the distribution of the frequency of release over various possible magnitudes of consequence, respectively. In this chapter, I introduce a new graphical

representation that combines both types of risk analysis result into a single graphic so that the information regarding such comparisons can be interpreted more easily. I discuss the common cases of route risk comparison and suggest which comparison method would be most suitable to facilitate decision-making in each case.

I also address the limitations of risk profiles under the special case in which both the point estimate of risk and the risk profiles would fail to indicate differences in route risk distributions. Other graphical techniques are proposed as alternatives, but these still do not necessarily provide confidence in routing decisions, especially when the difference in risks associated with two or more routes is marginal and difficult to observe.

To formally investigate whether the difference in risks associated with two or more routes are significant, a statistical approach for route risk comparison is considered. I describe and illustrate the use of several statistical techniques that may be applicable for comparison of the risks associated with the two routes. One of the benefits of using the statistical approach is that all the statistical tests considered are incorporated in modern statistical software so the computation and analysis are convenient. The statistical techniques can also be adapted to accommodate a variety of problems of interest, not only a comparison of route risks but also an assessment of the effectiveness of risk reduction options. To apply the statistical tests, it is important to understand the assumptions, the hypotheses and the limitations of the tests, as these may lead to different conclusions in some situations. A combination of several methods may be necessary to ensure the validity of the conclusions. Furthermore, it is applicable when analysis of the entire route is not possible.

Although the statistical approach provides more confidence in risk-based decision making, the numerical test results may not be sufficient because they do not portray the actual distribution of route risks. Instead, conventional, graphical and statistical approaches may be used in conjunction with each other. This will allow more complete information regarding how risks are distributed along the routes and whether or not the difference in the distributions is significant.

The statistical approach for route risks comparison is a rather new, challenging area to explore. There is little research or literature regarding application of the statistical methods for railroad hazardous materials transportation route risk comparison. This chapter provides a discussion of several potential methods, and illustrates their application using case studies. Nevertheless, a better understanding regarding the validity of these test methods for particular applications needs to be further explored. More research on this topic would help determine if the statistical approach is suitable to be incorporated as part of QRA and decision support systems for railroad hazardous materials transportation.

Despite potential applications of the statistical techniques, it is important to consider possible errors during the QRA process to develop numerical estimate of risk that could invalidate the statistical test results. Nevertheless, the two routes in which risk is developed under the similar approach using the same transportation network database may contain similar types of error. That is to say the data derived from the same databases or processes may share similar degrees of uncertainty. There is a need to formally quantify such errors relative to total route risk to better understand whether or not they have a significant effect on route-specific risk estimation and comparison.

8.7 Conclusions

This chapter discusses and illustrates several route risk comparison techniques. The risk profiles incorporating an expected consequence are proposed to help deliver information on both point estimates of route risk and the frequency distributions of risk outcomes in a single graphic. This conventional approach is often used to facilitate the risk-based decision-making on hazardous materials transportation route selection. Nevertheless, it does not deliver complete information regarding how risks are actually distributed along the route. Graphical representations that portray the distribution of route risks combined with appropriate statistical methods can help inform a risk manager of critical information thereby enhancing the quality of risk-based decision making by providing more confidence. However, the statistical approach for route risk comparison still requires further exploration for a better understanding of their general applicability and validity for railroad hazardous materials transportation route risks comparison.

CHAPTER 9

COMMUNICATION AND INTERPRETATION OF RESULTS OF ROUTE RISK ANALYSES

Adapted from Kawprasert, A and C.P.L. Barkan. Communication and Interpretation of Results of Route Risk Analyses of Hazardous Materials Transportation by Railroad. In *Transportation Research Record: Journal of the Transportation Research Board*, No. 2097, TRB, National Research Council, Washington, D.C., 2009a, pp. 125 – 135.

9.1 Introduction

Railroad hazardous materials transportation route risk analysis is receiving considerable new attention from industry and the government. Such analyses are necessary for effective public policy and the development of rational risk management strategies. However, route risk analysis is complex and generates results that can be difficult to properly interpret. The challenge for risk analysts is to effectively communicate with risk managers regarding objective information about how to effectively manage risk and the most effective options to reduce it.

In this chapter, I develop and illustrate several new techniques to more effectively present, interpret and communicate risk results, based on the results from a quantitative risk analysis of a particular hazardous material shipped by rail. The analysis accounted for the major factors affecting risk: infrastructure quality, traffic volume, population exposure along the shipment routes, tank car design, and product characteristics. I discuss different approaches for system-level and route-specific analyses, as well as the use of different risk metrics. These include absolute and normalized estimates of risk that may provide useful information under different contexts, depending on the questions of interest and the users, who may find different aspects of the information useful for their effective decision-making.

I develop various graphical techniques to enable risk metrics to be compared, either in a geographical context or independent of it, depending on which is most useful. I propose several techniques that help identify the locations that account for the highest concentration of risk and help provide a better understanding of risk-contributing factors. These also help clarify the mutual roles of carriers, shippers, and municipalities along a route regarding risk management, reduction, and mitigation options. The techniques presented in this chapter are also useful for

regulators and researchers who might be interested in a broader view of risk analysis at the network level. Moreover, the graphical representations of route risk can be easily incorporated into any decision support system for railroad hazardous materials transportation risk analysis.

9.2 Importance and Objectives of Hazardous Materials Transportation Risk Communication

Considerable attention has been given to the general subject of transportation risk analysis. The studies on the risk of railroad transportation of hazardous materials are an ongoing subject of interest. However, far less attention has been given to the development of how to effectively interpret and communicate the numerical estimates of risk. Currently, transportation risk communication has generally focused on policy from the perspective of industry or the government communicating with one another or the public (Glickman and Gough, 1990). Risk analysis, especially route-specific analyses, often requires sophisticated analytical techniques and large quantities of data and can produce a large amount of numerical results. In order for the results of route risk analyses to be understandable and useful to the concerned parties, more emphasis needs to be placed on technical interpretation and communication of these complex results.

The challenge for risk analysts is to interpret these large quantities of results, convert them into useful information, and effectively communicate them to risk managers and other interested parties (CCPS, 2007; Vrouwenvelder, 2008; Keeney and von Winterfeldt, 2008). In some instances, the information may also be used to help understand how to most efficiently choose among the options to reduce risk. If the results are too complex to understand or are presented in a manner that is prone to misinterpretation, these objectives will not be achieved, which could lead to inappropriate conclusions and decisions.

Therefore, the purpose of risk communication is to provide decision-makers and other concerned parties with critical information about how to effectively manage risk in forms that are easy to interpret and understand. To achieve this objective, I developed several new graphical methods to enhance the communication of risk results and to facilitate a more effective consideration of risk mitigation options. In this chapter, the graphical approach is presented for illustrative purposes. It does not imply any particular alternatives for risk reduction. The

techniques proposed are primarily designed to help risk managers evaluate and identify the most effective risk management options, i.e. the use of resources that will provide the most efficient means of improving safety. Identifying the critical locations on each shipment route and on the entire network that account for the highest concentration of risk and understanding the most important contributing factors will facilitate a more effective consideration of how to best manage the distribution of risk. It will also help clarify the mutual roles of carriers, shippers, and municipalities along a route regarding risk management, reduction, and mitigation options.

9.3 Case Study

The risk results used in this chapter are based on a case study of shipments of one hazardous material on the North American railroad network. The shipment structure consists of trains traveling along transportation routes from a single origin to eight different destinations. These eight routes involve trackage owned by several railroads, including three different Class-1 railroads and two non-Class-1 railroads (Table 9.1). The major factors affecting risk considered in this analysis are: segment-specific track infrastructure, traffic volume, and population exposure along the shipment routes. Tank car design and product characteristics represent constants in the analysis.

Table 9.1. Shipment routes data.

Origin – Destination	Annual Shipments (Carloads)	Estimated Mileage	Car-miles	Railroad Carriers	
				Class-1	Non Class-1
L-A	702	2,228	1,564,056	RR-1	RR-4
L-B	162	1,064	172,368	RR-1	-
L-C	75	1,403	105,225	RR-1	RR-4
L-D	42	1,966	82,572	RR-1, RR-2	-
L-E	33	2,048	67,584	RR-1, RR-2	RR-5
L-F	16	1,396	22,336	RR-1	RR-4
L-G	13	2,463	32,019	RR-1, RR-2	-
L-H	11	1,978	21,758	RR-1, RR-3	-

The risk estimates were developed for each individual route and for all routes combined using the quantitative risk analysis (QRA) methodology. More details of the QRA are provided by CCPS (1995) and Erkut et al. (2007). The risk model and the procedures to develop the numerical estimates of risk are provided in Appendix C.

Table 9.2 shows the characteristics of track infrastructure, the annual accident rate (number of hazardous materials cars derailed per year), the annual release rate (number of releases per year), the population exposure (total number of persons potentially affected), and the annual risk (expected number of persons affected per year). These absolute (non-normalized) estimates provide a basic comparison of each route while taking into account the route-specific characteristics, i.e. length, traffic volume, track infrastructure conditions, and population.

Table 9.2. Route characteristics and numerical estimates.

Route	Number of Route Segments	Average Segment Length (miles)	Percentage of Route Length by Track Class				Annual Accident Rate	Annual Release Rate	Total Population Exposure	Annual Risk
			2	3	4	5				
L-A	1,006	2.20	2	16	46	36	0.174	0.0236	337,268	5.17
L-B	463	2.30	1	12	30	57	0.015	0.0020	72,831	0.19
L-C	613	2.29	1	16	39	44	0.011	0.0015	237,563	0.41
L-D	819	2.40	4	18	45	32	0.011	0.0016	344,740	0.44
L-E	954	2.15	3	21	36	41	0.009	0.0012	818,035	0.68
L-F	598	2.34	1	16	39	44	0.002	0.0003	230,092	0.08
L-G	1,173	2.10	2	15	49	34	0.004	0.0005	1,772,312	0.65
L-H	790	2.50	2	15	39	45	0.002	0.0003	801,821	0.18
Combined	2,635	2.21	3	22	53	22	0.228	0.0309	3,127,268	7.80

9.4 Interpretation of Risk Results and Risk Communication Techniques

In hazardous materials transportation route risk analysis, there are many types of information for a variety of routes with unique geographical elements, and there are several different stakeholder groups, each with their own associated interests and perspectives. Information that is suitable in one context for a particular group may be of little value to others. In this section, I introduce several methods to help this process.

9.4.1 Routes Comparison

Absolute estimates of risk, such as those presented in Table 9.2, are typical deliverables from the QRA of hazardous materials transportation. Although they provide a high-level of understanding, more detail is needed to address many types of risk management questions. In part, this is because shipment routes are not compared on the same basis. For example, the number of shipments and the mileage for each route are not the same (Table 9.1) and, thus, contribute to the difference in route-specific risk estimates. Consequently, normalized estimates may be more helpful (Figure 9.1). There are different approaches to normalization when comparing routes; for example, population exposure versus risk (Figure 9.1a) and accident rate versus risk (Figure 9.1b) are two approaches developed using the risk results from Table 9.2 and the route information from Table 9.1.

The normalized estimates offer insight regarding the risk characteristics for each route with which different parties involved in the supply chain may be concerned. For example, route L-A has the highest overall risk because of its high traffic volume; however, when the risk per carload is considered, its rank is much lower. Conversely, route L-G appears to have low absolute risk, but, in fact, it has the highest risk per carload and the highest risk per car-mile due to the combined effects of distance and population distribution.

These differences suggest differing strategies for risk management appropriate to the various parties involved with these routes. Normalized estimates offer shippers insight regarding certain business decisions; shipments to different customers may have widely different levels of risk that could affect pricing. Another question that may arise involves selecting between routes with differing degrees of heterogeneity in risk along them. This may lead to potentially conflicting objectives among shippers, railroads, and local agencies. The shippers and/or railroads may prefer to minimize overall risk. Railroads may consider minimizing the number of incidents occurring, whereas local agencies may be more concerned with the consequences in their community or region. Each such case will have to be decided individually, but informed decision-making will benefit from all parties having a clear understanding of the trade-offs involved. Effective presentation of local versus system-level risk may help put such questions in perspective. Such comparisons may also help communities understand how local risk due to hazardous materials compares with other, more familiar risks.

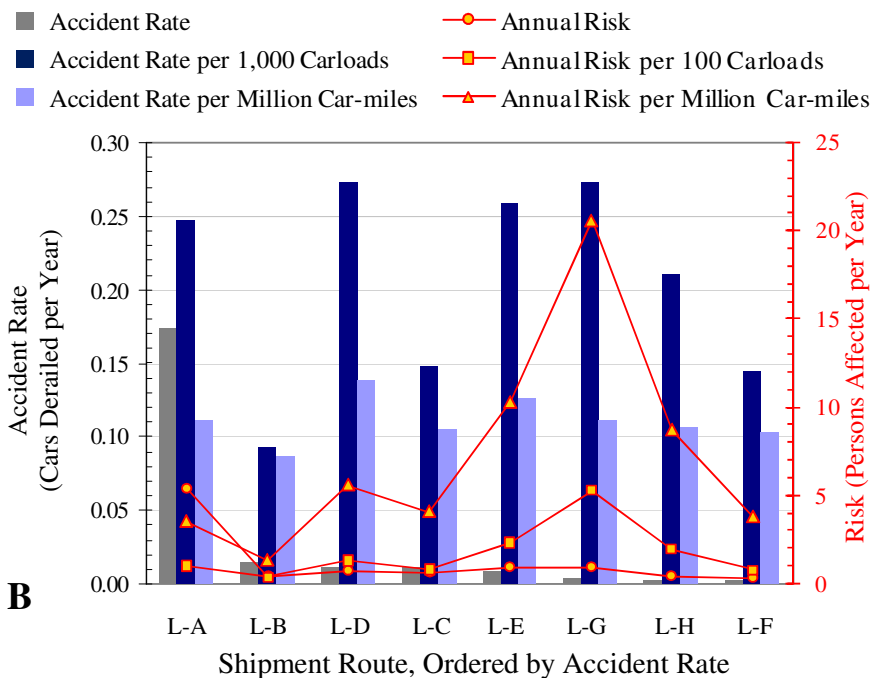
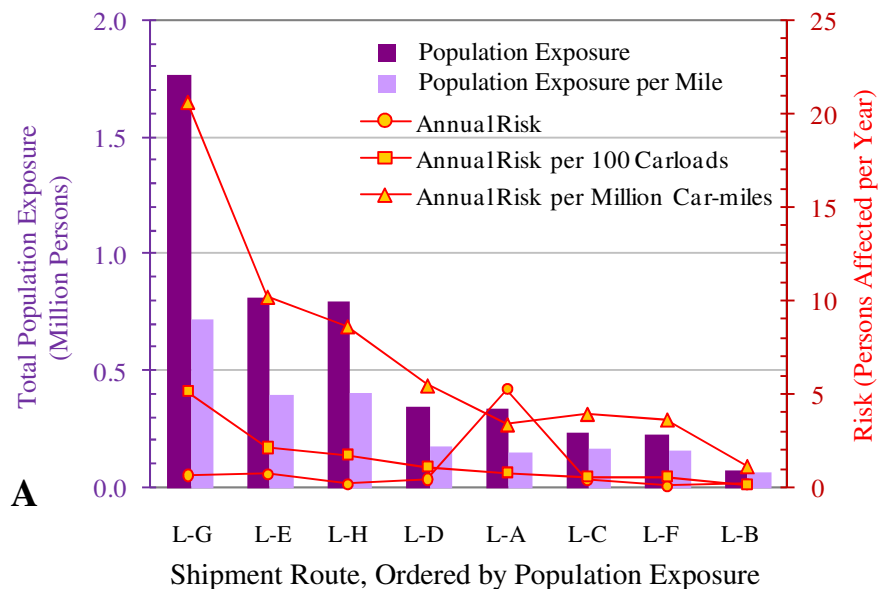


Figure 9.1: Route Comparison Using Different Normalization Metrics
(A) Population Exposure vs. Risk and (B) Accident Rate vs. Risk

9.4.2 Combined Shipment vs. Route-Level Analysis

The analysis of risk due to hazardous materials traffic on the rail transportation network can be performed at different levels depending on the objective of interest, e.g. combined shipment routes versus individual routes. The principal objective of combined shipment analysis is to identify the highest-risk locations over an entire distribution network. This information is particularly important for risk managers with responsibility for all traffic or an entire network. For shippers, it may facilitate the consideration of risk mitigation approaches such as enhanced packaging (Barkan, 2008; Saat, 2009) and alternative routing (Kawprasert and Barkan, 2008). Carriers may wish to compare all the segments over which they have traffic and identify which ones offer the best opportunity for infrastructure improvement or the deployment of technologies that could reduce accident likelihood (Ouyang et al., 2009). Comparison at this level may also be useful to regulators' decisions regarding the allocation of inspection resources. Conversely, these comparisons may not be as useful to local authorities along a route, except in helping them understand how their communities compare to others.

9.4.2.1 Individual Segment Comparison

Some aspects of effectively managing risk may require a more detailed understanding at either the system or route level. In the case study, a small number of track segments contributed a large portion of the risk. About 14% of the total number of segments (or 19% of the total length) accounted for 90% of the total risk (Figure 9.2a). A closer examination showed that the twenty segments with the highest risk contributed 35% of the total risk but less than 1% of the total length (Figure 9.2b). Actions that reduce risk on these segments will have a substantially greater impact on reducing risk than would similar improvements on other, lower-risk segments in the carrier's network. Information such as this can help guide certain risk management activities. If cost information is available, these results can be used to develop cost-effectiveness analyses that will further assist in prioritizing actions.

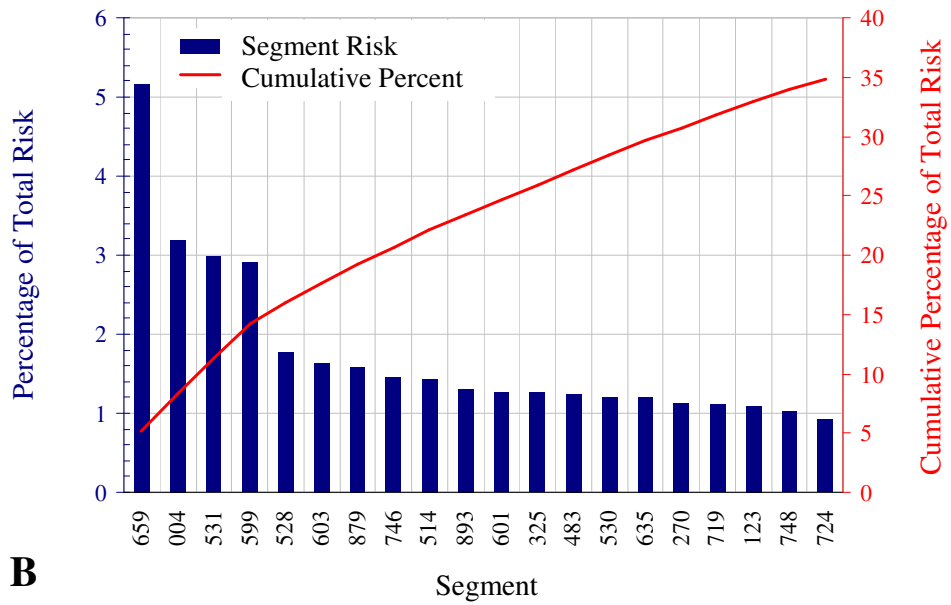
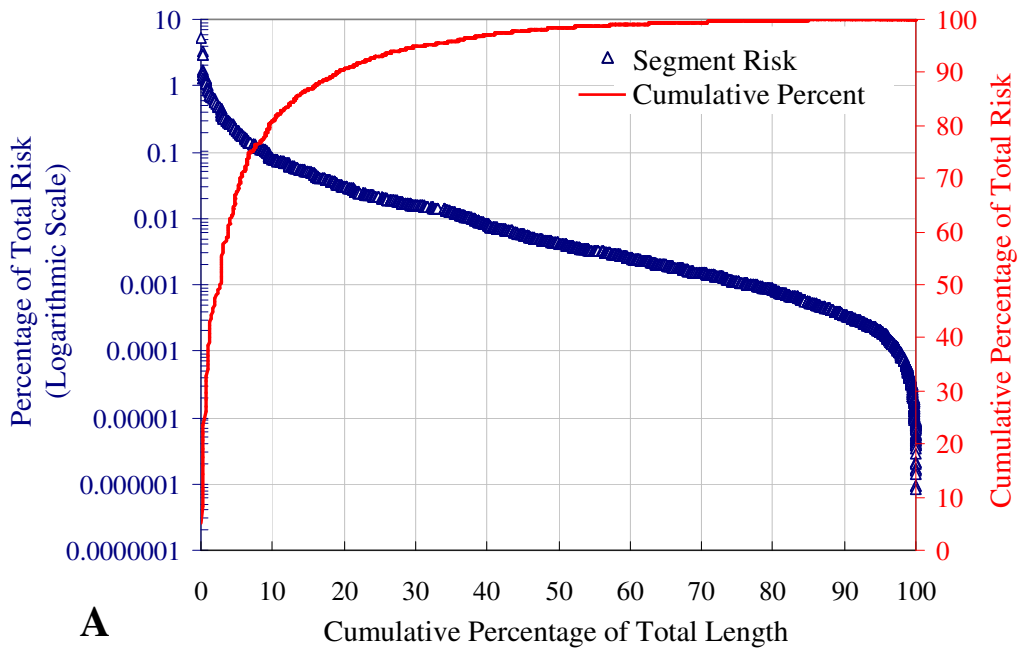


Figure 9.2: Graphical Representation of Combined Routes Risk Estimates
(A) All Segments and (B) Top 20 Segments with the Highest Risk

9.4.2.2 Geographic Comparisons

The preceding approaches help identify the highest relative risk segments; however, they do not provide information in a geographic context. Some types of questions may benefit from this type of consideration. As mentioned earlier, the use of GIS software facilitates the production of maps that can help managers visualize the risk associated with the different portions of the network being studied. Segment-specific risk that accounts for all of the traffic of a particular material can be portrayed. In this case, it is portrayed in terms of both absolute and normalized risk (Figures 9.3a and 9.3b, respectively). This graphical technique is applicable to both route-specific level and network-level analyses.

In Figure 9.3, the darker segments indicate those with higher risk. For absolute risk, shipment volume and segment length are accounted for in the risk calculation. Normalized risk is the absolute risk divided by the car-miles on the segment, and, thus, the distribution of risk on several critical segments differs from that of absolute risk. The merit of this is to provide appropriate and useful information for the parties who may need different information. For example, the graphic depicting the absolute risk estimate (Figure 9.3a) may be more useful for shippers interested in knowing where and how much their own current or anticipated shipments are contributing to risk. On the other hand, railroads responsible for infrastructure quality and operation may be interested in the track-segment condition and the risk distribution throughout their network, regardless of the shipment volume and/or the differential segment lengths. Therefore, they may find the normalized estimates (Figure 9.3b) more appropriate and helpful for infrastructure and operational improvement planning.

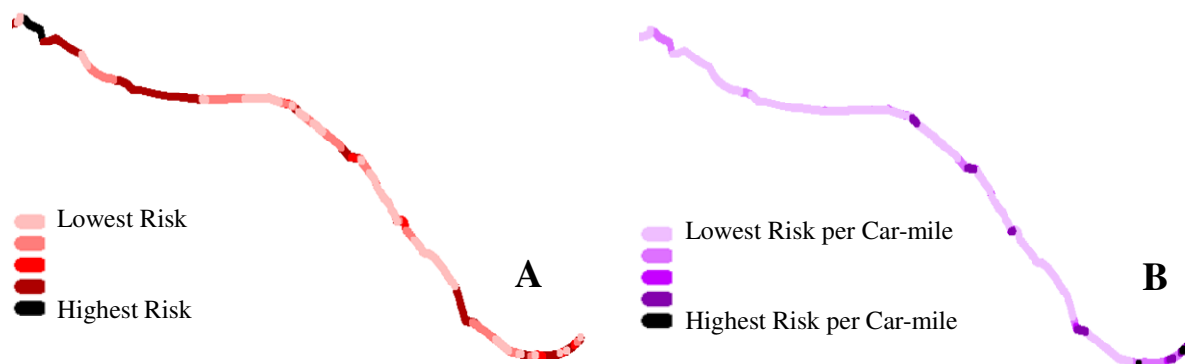


Figure 9.3: Map Showing Segment-specific Risk Based on (A) Absolute Risk Estimates and (B) Risk per Car-mile

Although these maps are useful for some types of information, they impose certain constraints on understanding the relative risk along a route. For example, it is difficult to present the numerical estimates of local risk on such maps (Figure 9.3). Other approaches that combine a geographic element with differences in risk magnitude can be useful in helping risk managers visualize quantitative, route-specific risk information. Figure 9.4a portrays track-segment risk data divided into two groups, with the high- and low-risk segments plotted on a log scale versus the mileage from the origin to the destination. In this example, the segment-risk-level threshold for the different symbols is 0.1% of the total risk; that is, individual segments contributing more than 0.1% were plotted using dark-colored triangles, and those with 0.1% or less, with light-colored circles. This technique clearly highlights the areas along the route that are contributing the majority of the risk. In this case, 77% of the route length accounted for only 4% of the risk, while 23% of the route accounted for 96% of the risk. The solid line indicates the cumulative percentage of the total risk of proceeding from origin to destination along the route. Locations with substantial changes in risk are indicated with abbreviations. The first two characters in the label (e.g. L-B-A) indicate the route L-B (Table 9.2), and the last character signifies specific points along the route.

Results such as these lead to questions about what is affecting the elevated risk at various locations along a route. In this example, the product and the tank car are constant throughout the route, so the two factors affecting the heterogeneity in risk are the accident probability (which implies infrastructure quality) and the population density. Either or both of these may be contributing to the elevated risk at particular locations. Figure 9.4b is intended to help risk managers visualize the degree to which each parameter is influencing localized risk. The letter “Z” on the chart indicates where the risk is mainly influenced by the accident rate, whereas “P” indicates locations where the population density is the major factor. For each track segment, these three parameters – accident rate, population density, and risk – are normalized by the average value of each, so that they can be plotted using the same normalized scale. Such information may suggest the most appropriate risk management strategy to consider for different locations; in particular, it may suggest where to consider infrastructure upgrades, operational changes, or emergency response training and planning.

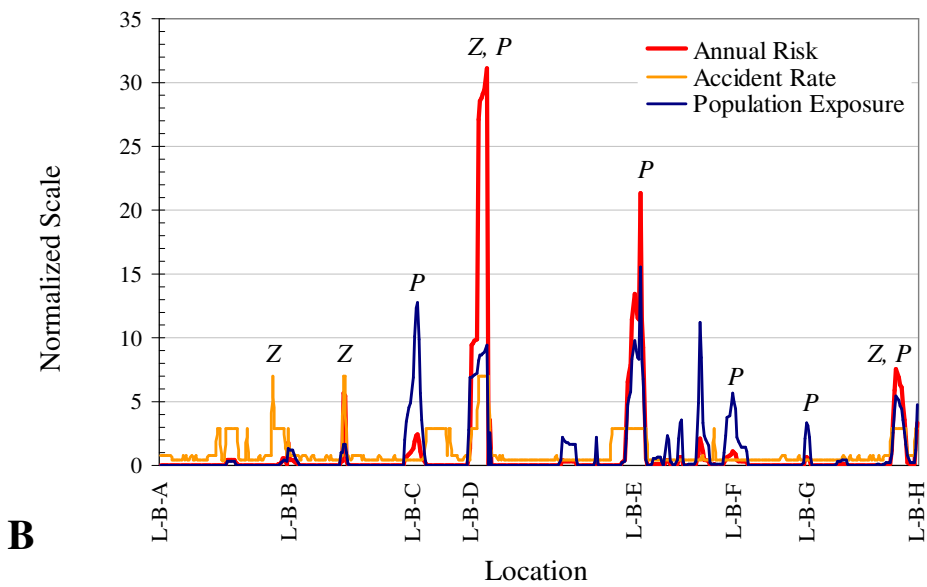
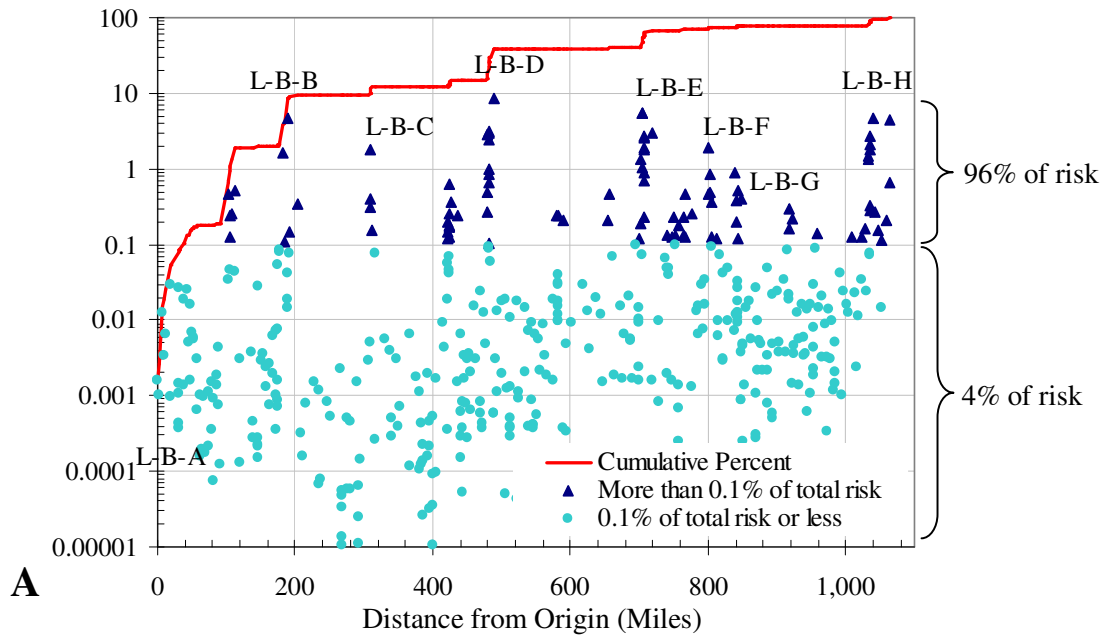


Figure 9.4: Graphical Representation of Route-specific Risk Estimates
(A) Route Segment Risk Grouped by Percentage of Total Risk
and (B) Effects of Risk Parameters

9.4.3 Other Graphical Techniques

9.4.3.1 Risk Profiles (F-N Curves)

Risk profiles or “F-N curves” show the annual rate or the frequency of release incidents for different levels of consequence (persons affected). This helps convey information regarding the frequency distribution of risk outcomes. A differential risk profile indicates the difference between two risk profiles. It can be expressed as either an absolute or a percentage difference versus the magnitude of the consequence. Differential risk profiles allow the comparison of two options and facilitate understanding the effects of changes or different options on risk at different magnitudes along the consequence scale. Figure 9.5a shows the risk profiles (solid lines) and the differential risk profile (dashed line) of two particular routes, route L-B and route L-E. The consequence below $N = 1$ is not shown in this plot.

The risk profiles show that, overall, route L-E has a lower annual frequency of release (F) than route L-B. However, at the consequence level of $N \geq 7$, route L-E has a higher likelihood of a release occurrence than route L-B at the same consequence level. Likewise, at the same frequency of release F the incidents on route L-E tend to affect a greater number of persons. Despite the lower annual frequency of release of route L-E, the highest possible level of consequence on this route is much greater than that of route L-B (5,850 persons vs. 2,873 persons).

The differential risk profile shows that the difference between the frequency of a release incident associated with route L-E and that of route L-B steadily decreases from 0.0008 toward zero at $N = 7$ and then fluctuates around 0.0002 between $N = 50$ and $N = 1,000$. The difference decreases to near zero between $N = 1,000$ and the maximum possible consequence of $N = 5,850$. The advantage of plotting the differential risk profile together with the conventional risk profiles is that it quickly portrays both the magnitude and the pattern of the difference in the frequency distribution of the two routes over various magnitudes of the consequence. In this particular case, the magnitude of the difference in the frequency distribution of these two routes is much greater for the lower range of consequence ($N < 7$) than for the higher range ($N > 7$). The differential risk profile is particularly useful for the comparison of the two routes, but it may produce results that are too complex for a comparison of three or more routes.

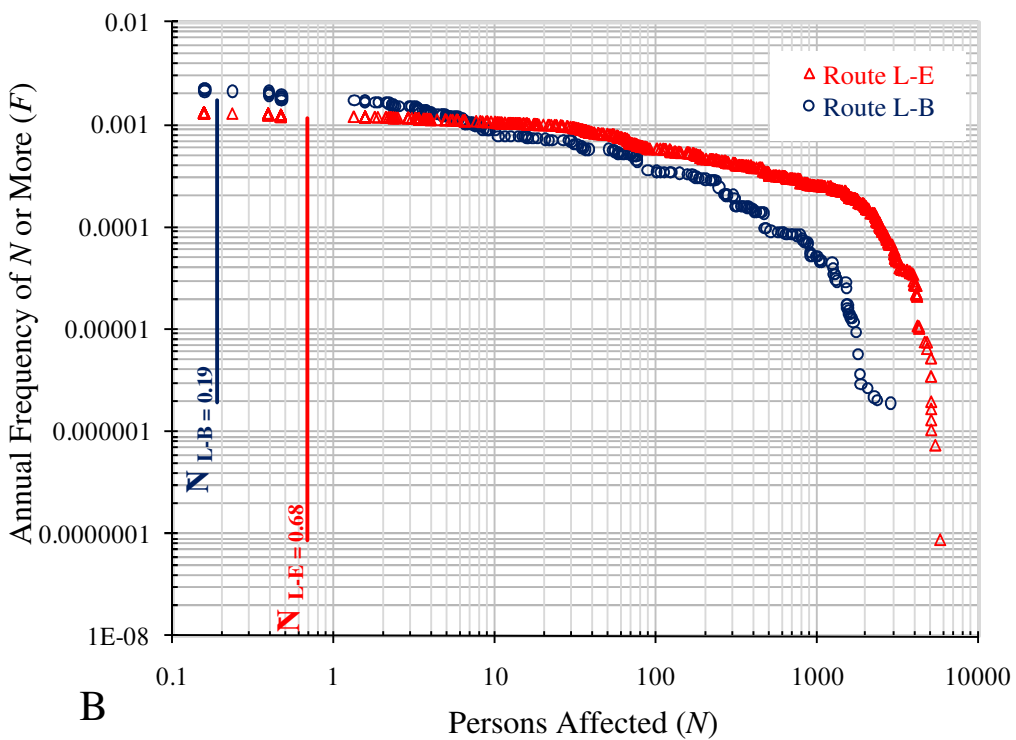
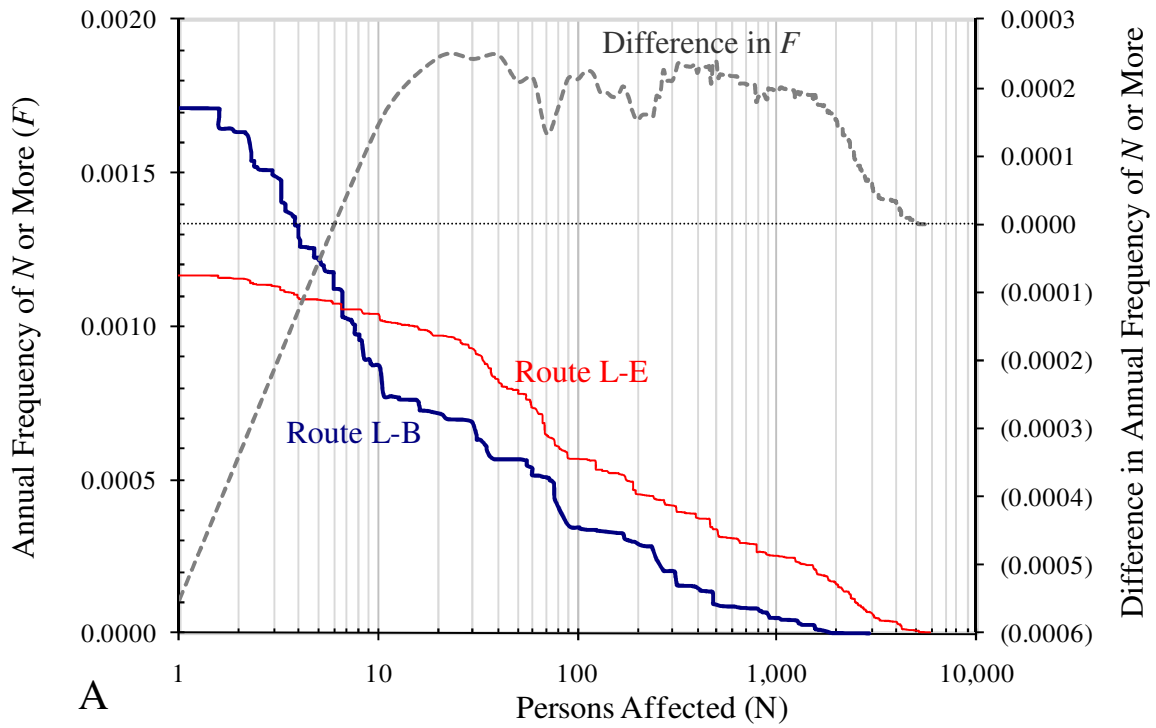


Figure 9.5: Risk Profiles (F-N Curves)

(A) Showing the Difference in Annual Frequency and

(B) Showing the Expected Consequence

The drawback of the risk profiles is that they usually do not explicitly provide the magnitude of the point estimate of route risk. In Figure 9.5b, the risk profiles are plotted together with the expected consequence (annual risk) of each route. The logarithmic scale is applied to both the horizontal and vertical axes of the chart so that the effect on high consequence is better portrayed. The expected consequence associated with each route is calculated by taking a summation of the product of the value of all F-N pairs corresponding to each segment. This equals 0.19 and 0.68 persons affected per year for route L-B and route L-E, respectively (Table 9.2).

Unlike the differential risk profiles, the point estimate of risk represents a single numerical index for the quantitative evaluation of route alternatives rather than the distribution of various consequences. It can be used to evaluate which route has a higher or lower potential consequence, in average, compared to the others. While the differential risk profile plot is more suitable for a two-route comparison, the risk profiles showing the point estimate of risk can handle multiple-route comparisons.

In this particular comparison, shown in Figure 9.5b, the annual frequency of release associated with route L-B is 1.7 times greater than that of route L-E. However, route L-B's expected consequence is only 0.3 times that of route L-E. This represents a classical dilemma regarding risk-based routing decisions (Barkan, 2006). That is, a difficulty may arise in the case where one needs to choose between these two routes: one with a higher overall frequency of incident and a lower expected consequence and another with a lower frequency but a higher expected consequence. This is often considered to be a high-level policy question and, therefore, is beyond the scope of this study. The purpose here is to provide the illustrations that help bring all significant aspects and information together to inform and facilitate the routing decisions accordingly.

9.4.3.2 Distribution of Segment Risk Showing the Effects of Risk Reduction Options

Previously, I discussed a sensitivity analysis of the options that could affect accident rate and subsequently risk (Chapter 4). Then, I considered track-segment upgrade for risk reduction (Chapter 5). To communicate the results of such changes and help risk managers understand the relative benefits of the risk reduction options in different contexts, graphical techniques can be used. In this section, I present a technique that helps portray the effects of track class upgrade on risk reduction along a particular route.

Route L-B is considered as an illustrative example. Rather than using multiple tank car types, only one car type with the highest CPR was assumed in this analysis. The corresponding route risk was estimated to be 0.208 persons affected per year.

According to Kawprasert and Barkan (2009a; 2010a), upgrading lower FRA track classes has a greater effect on risk reduction per mile of upgraded track. Furthermore, it also has a greater effect on risk as the population density increases compared to upgrading higher class trackage. Nevertheless, improving segments with the lowest track class does not have much effect on risk because they represent only a small proportion of total route length. As shown in Table 9.2, the percentage of class-2 track is only 1% of the total length of route L-B and 3% of the entire network. For class-3 track, despite its smaller proportion compared to classes 4 and 5, an improvement of this particular track class has the greatest effect on route risk reduction because of the reduction in the accident rate and the level of population density associated with this class.

The results of such analyses can help risk managers in understanding that the degree of risk reduction varies for different routes due to the difference in geographical characteristics, such as infrastructure characteristics and population distribution, along the route. Figure 9.6 below helps convey this critical information from the analyses of the effects of this route risk reduction option to risk managers accordingly.

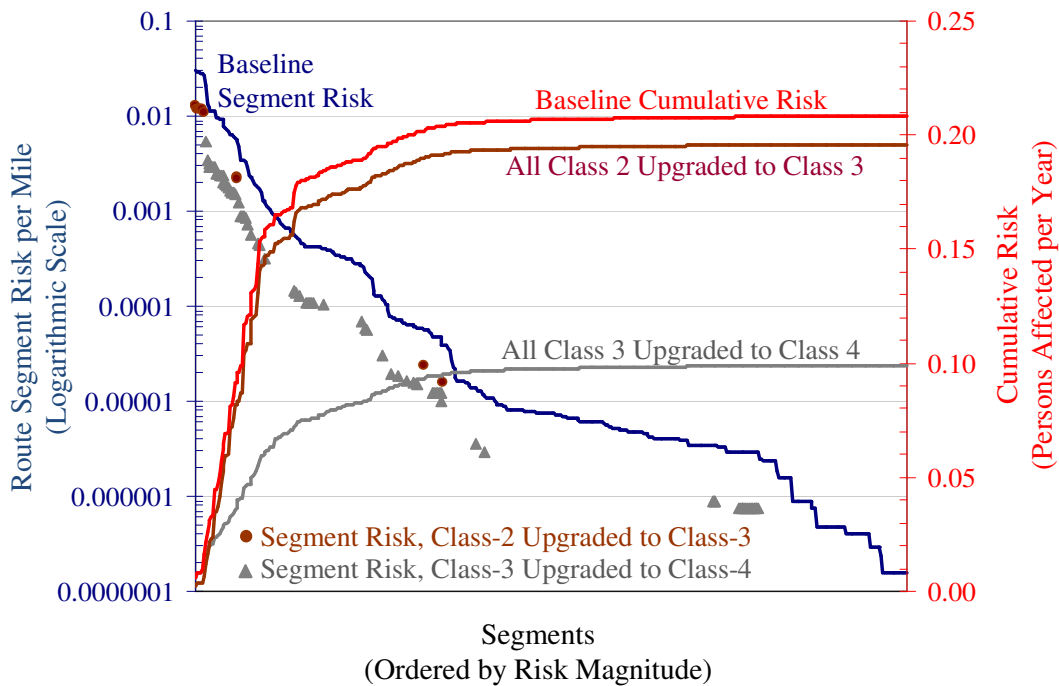


Figure 9.6: Segment Risk Plot Showing the Effects of Track Upgrade on Risk Reduction

9.5 Discussion

In this chapter, I provide examples of different types of information that can be generated to facilitate the effective management of hazardous materials transportation risk, which will generally benefit from mutual cooperation between the carriers, the shippers, and the municipalities along the route. Each of these parties plays different roles in rail transportation risk management and mitigation. Understanding their own and each others' roles will facilitate better individual and collective decision-making regarding the implementation of risk management practices.

Quantitative route risk analyses often generate a large amount of numerical results that can be difficult for one or all of these parties to interpret. Different portions of these data are important to different parties, and the value of various summaries and comparisons may vary as well. In particular, shippers may have shipment routes they wish to evaluate and compare using various absolute and normalized risk estimates (Figures 9.1a, 9.1b). Carriers may use the segment-specific risk estimates to focus maintenance planning and equipment-health monitoring technology for high-risk segments on corridors (Figures 9.2a, 9.3b). Similarly, in coordination with shippers and carriers, municipal authorities and regulators may allocate emergency response and inspection resources at locations based on priorities established using the types of information presented here (Figures 9.3a, 9.4b). Emphasizing and clarifying these roles for each party, using the techniques and options described, can help them better understand the critical information that is most relevant and useful to each. In addition to helping the different parties coordinate their activities, these approaches will also be helpful in assisting stakeholder groups to understand the rationale for other groups' risk management decisions.

Table 9.3 summarizes different graphical techniques for the interpretation and communication of hazardous materials transportation route risks to different parties, to aid in the visualization of the distribution of risk on the network or along each route.

Table 9.4 shows a subjective evaluation of how each party will potentially use the different types of information on hazardous materials transportation route risks according to their needs and interests.

Table 9.3. Summary of types of graphical illustrations of risk results.

<i>Name</i> (Figure Number)	Description
<i>Route Comparison Using Different Normalization Metrics</i> (Figures 9.1a, 9.1b)	The annual risk is plotted along with the factors affecting risk (accident rate and population exposure) to visualize the order of magnitude of risk and the factors simultaneously affecting risk for each shipment route in the network. Furthermore, normalization using different metrication is applied to both of these to illustrate how the metrics affect the order of magnitude of risk and the factors affecting risk for each route.
<i>Distribution of Risk by Segment</i> (Figures 9.2a, 9.2b)	This type of chart shows the route segment risk, ordered by risk magnitude, and the cumulative percentage of total risk. Normalization may be applied to show the risk estimates per unit of interest. These charts enable easy identification of the highest risk segments and facilitate understanding of the percentage of risk that is due to any particular number of segments, ordered from highest to lowest.
<i>Geographical Distribution of Risk on Network Map</i> (Figures 9.3a, 9.3b)	The network maps showing segment-specific risk estimates help indicate critical locations with relatively high accident rates / risk on part or all of the shipment network structure. This information may be useful for collaboration between chemical shippers, railroad carriers, and municipalities to develop appropriate, mutually satisfactory risk reduction strategies.
<i>Risk Increment with Travel Distance and Segment Risk Grouped by Percentage of Total Route Risk</i> (Figure 9.4a)	This chart shows the plot of cumulative annual risk versus the mileage along the shipment route. The locations where significant changes in risk occur are readily apparent. On the same chart, the route segment risk, expressed as a percentage of the total risk on that route, is plotted together with the cumulative risk along the distance scale. The segments are divided into groups according to the percent of their contribution to the total risk, so that risk managers can better understand the distribution of low- and high-risk segments.

Table 9.3. (cont'd)

<i>Name</i> (Figure Number)	Description
<i>Effects of Risk Parameters</i> (Figure 9.4b)	The normalized accident rate, population exposure, and annual risk are plotted on the same scale against the distance axis. The purpose of this chart is to show the effect of each parameter on risk and to help suggest the appropriate risk mitigation approach for critical locations along the shipment route.
<i>Risk Profiles Showing Differential Frequency Distribution</i> (Figure 9.5a)	<p>Risk profiles or “F-N curves” depict the likelihood of incidents versus various magnitudes of consequence. In the context of rail hazardous material transportation risk analysis, they show the annual rate or frequency of a release incident for different levels of the number of persons potentially affected by the releases. This helps convey the information on the probability distribution of risk outcomes.</p> <p>Differential risk profiles express the difference between two risk profiles as an absolute or a percentage graphed versus the magnitude of the consequences. These enable the comparison of two options and facilitate understanding the effects of changes or different options on risk at different magnitudes along the consequence scale.</p>
<i>Risk Profiles Showing Point Estimates of Risk</i> (Figure 9.5b)	The point estimate of risk represents the expected consequence associated with a particular route. It is the sum of the product of all frequency-consequence pairs with respect to each segment in the route. The point estimate of risk provides a single numerical index for the quantitative evaluation of routing alternatives.
<i>Distribution of Segment Risk Showing the Effects of Risk Reduction Option</i> (Figure 9.6)	Segment-specific risk, ordered by the magnitude from highest to lowest, is plotted along with the cumulative risk to represent the base case (before improvement). A similar plot is made on the same chart to portray the situation after improvement and, consequently, the changes in both segment-specific and cumulative risk that indicate the effectiveness of the risk reduction option considered.

Table 9.4. Potential usefulness of risk communication techniques.

Representations of Risk Results at Various Analysis Levels	Potential Users				
	Railroad Carriers	Chemical Shippers	Regulators	Local Authorities	Researchers / Academics
Regional / Network Level					
Characteristics and Numerical Estimates of Risk of Combined Routes (Table 9.2)	√	√	√		√
Geographical Distribution of Risk on Network Map (Figures 9.3a)	√	√	√	√	
Geographical Distribution of Risk per Car-mile on Network Map (Figures 9.3b)	√				√
Route Level					
Characteristics and Numerical Estimates of Risk of Individual Routes (Table 9.2)		√		√	√
Route Risk Comparison Based on Population Exposure (Figure 9.1a)		√		√	
Route Risk Comparison Based on Accident Rate (Figure 9.1b)	√	√			
Risk Increment with Travel Distance (Figure 9.4a)	√			√	√
Risk Profiles Showing Differential Frequency Distribution (Figure 9.5a)	√	√			√
Risk Profiles Showing Expected Consequence (Figure 9.5b)		√		√	√
Local / Segment Level					
Distribution of Risk by Segment (Figures 9.2a, 9.2b)	√			√	√
Segment Risk Grouped by Percentage of Total Route Risk (Figure 9.4a)		√		√	√
Effects of Risk Parameters (Figure 9.4b)	√	√		√	√
Distribution of Segment Risk Showing Effects of Risk Reduction Option (Figure 9.6)	√			√	√

9.6 Conclusions

This chapter presents results of a quantitative risk assessment of rail transportation of a hazardous material, along with several new graphical representations of these results that are intended to more effectively convey critical information from the numerical risk results to risk managers and parties concerned in the supply chain. In particular, various methods are presented to identify the shipment routes and segments that account for the greatest amount of risk within various contexts and groupings. Within routes, the segments with the highest accident and release rates, population densities, and risk are identified, along with various factors affecting risk. The techniques also apply on a network level to help the above parties focus their priority regarding risk mitigation on critical locations.

In summary, the techniques developed in this chapter will help risk managers focus priorities for risk management and mitigation regarding hazardous material shipments. They also facilitate comparison and communication of risks at both the local and network levels. I discuss different ways that route risk analysis results can be presented for the benefit of various stakeholders and enable them to work individually and cooperatively in applying safety resources in the most efficient and effective manner possible.

CHAPTER 10

FUTURE RESEARCH

10.1 Introduction

The principal objective of this dissertation is to provide information from quantitative analyses of the various options for reducing railroad hazardous materials transportation risk. Three alternatives for risk reduction were illustrated and discussed: route rationalization (Chapter 3), track infrastructure upgrade (Chapter 5), and train speed management (Chapter 6). The analysis frameworks and mathematical models were developed to facilitate the consideration of each of these risk reduction options and multiple options combined. Their applications were illustrated using the representative case studies with various scenarios.

This dissertation is also intended to provide techniques to improve the estimation and analysis of route risk and to enhance risk-based decision making. The speed-dependent conditional probability of release (Chapter 4) and the probabilistic model for risk estimation (Chapter 7) contribute advancements in risk estimation. Statistical methods for route risk comparison (Chapter 8) and options for communication and interpretation of route risk (Chapter 9) were developed to inform risk managers and decision makers of information that is a critical part of risk-based decision making.

The model frameworks to address the above require substantial information. While this information is unavailable or difficult to quantify, simplifying assumptions were made using the best information available at the time of this research to complete the work in each chapter. Furthermore, several topics in this dissertation are at the initial stage of exploration. The lack of supporting research, unquantified data, and limited information bring up several issues that could be investigated further to improve the assessment of the risk reduction options presented in this dissertation. Some particular techniques, especially the statistical techniques for route risk comparison, still require further investigation of their general applicability. There are remaining challenges for researchers who may be interested in the topics above. This chapter highlights the needs of future research in the areas pertinent to the topics presented in this dissertation.

10.2 Future Research

10.2.1 Route Rationalization

It is quite difficult to evaluate the effectiveness of route rationalization due to various, complicated constraints and information that is often unknown or difficult to quantify and incorporate into the model. In addition, it is difficult to implement route rationalization because of the conflict of interests that may arise. The following are issues that may be of interest for further investigation. These may help provide better understanding regarding how this option would perform in general.

The case study used in Chapter 3 was based on only one particular chemical, but the model allows for the consideration of multiple-product shipments. Similar analysis could be done for various chemicals with the potential for traffic rerouting. This is not only to estimate the extent of risk reduction by this option but also to better understand the patterns of change in the frequency distribution of release over various magnitudes of consequence for different route alternatives and objective functions.

Additional routing constraints may be considered depending on available information, such as traffic flow, track availability, scheduling, and acceptable risk levels.

Further refinements needed in risk estimation include the use of speed-dependent CPR and the consideration of the time-of-day effect on population density. Moreover, stationary facilities that are sensitive to hazardous materials release, as well as on-the-road population effects, may be incorporated into consequence analysis. These could be done using a GIS application provided that relevant data are available.

10.2.2 Speed-dependent Conditional Probability of Release

Chapter 4 provided a technique to adjust CPR for train speed using the recent tank car performance statistics. This enables an improvement in the local risk estimates and allows for a more appropriate evaluation of the risk reduction options that affect train operating speeds. The relationships proposed could be further updated using a more robust statistical method and more up-to-date tank-car-accident data. A logistic regression analysis may be considered to develop

new models that incorporate train speed and other possible factors affecting CPR. The results can be compared with the existing models such as those provided by CCPS (1995), Treichel et al. (2006), and Kawprasert and Barkan (2010a).

Another issue is to study other speed-dependent effects to enable more accurate estimate of risk. These include the probability distribution of spill sizes and the number of cars derailed, both of which may be dependent of train accident speeds.

Previous analyses often relied on information from railroad timetables to determine train speeds and infer track classes (Kawprasert and Barkan, 2009a; 2010a). This may not always represent the actual operating characteristics and/or maintenance practices and may contribute to inaccuracy in risk estimates. For example, a maximum operating speed corresponding to each track class was assumed when estimating the risk using speed-dependent CPR. This is likely to result in an overestimation of risk. Further study should develop a new approach for estimating track class and track-class-specific accident speed and/or consider obtaining track-specific information from railroads.

10.2.3 Track Infrastructure Improvement

In Chapter 5, I attempted to evaluate the potential benefits of an infrastructure upgrade on risk reduction by assuming track-upgrade and consequence costs in the model formulation. Further study may consider improving these estimates of track-class-specific upgrade and release consequence costs for use in the cost-effectiveness analysis of this option, as well as in other quantitative analyses that may require a more accurate estimate of such costs. New analyses may also consider dynamic investment strategies to determine the optimal multi-year upgrade plan. Improvement of route segmentation could be considered for a more efficient use of resources and a more accurate estimate of track-segment-specific risk. A new algorithm to determine an optimal track segment length could be developed to facilitate more effective use of an investment budget.

10.2.4 Train Speed Management

Although less frequently suggested as a means of reducing risk, there has been little research on the benefits train speed management may offer. Future research on this topic may focus on

developing a more accurate quantitative estimate of model elements, including release consequence and transportation delay costs. Efforts should be devoted to incorporating the system delay into the cost function. The consideration of shorter segment lengths allows for a better estimate of population exposure along the track but adds more difficulty to incorporating the system delay and may result in unrealistic speed changes. A new algorithm may be developed to consider an optimal segment length suitable for these that would allow a smoother or more practical transition in train speeds. Track geometry and train power may also be incorporated into the updated analysis framework.

Risk reduction achieved through lower train speed would result in increased travel time. However, there may be some compensatory benefits due to lower energy consumption. Longer time spent in transit implies that security threats might be higher. There still remain several areas for improvement and further study. These challenge one to consider whether train speed management is a viable option for hazardous materials transportation risk reduction.

10.2.5 Quantitative Framework for Selecting Multiple Risk-Reduction Options

This dissertation attempts to quantify the potential of the risk reduction options considered. A basic quantitative framework for choosing the most effective option for reducing risk was presented as part of Chapter 6. The framework accounts for track infrastructure improvement and speed reduction. Further study may consider a more comprehensive framework with the capability of handling more options, such as route selection, track upgrade, tank car type selection, and speed reduction, in one unified model.

10.2.6 Probabilistic Risk Modeling

Chapter 7 discussed the use of a probabilistic model based on a non-homogeneous spatial Poisson process to compute the probability of occurrence of a train accident along the route. Illustrations were made for a comparison of route risk results from the probabilistic approach and from the simplified approach. The results show that the difference in risk estimates from these two approaches is not very substantial within a 1,000-mile length. Further study may validate whether the risk model based on a Poisson process provides an accurate probability distribution. This could be done using past accident statistics and a statistical method to test whether the

Poisson distribution provides a satisfactory fit to the accident data. The probabilistic model assumes that a tank car derailment is an independent event. But, the fact is that hazardous material tank cars do not travel the route alone one by one and may be attached together as a multiple-car shipment in one train. An event of a particular tank car derailment may be dependent on a derailment of another car attached to it. Therefore, one may investigate the relationship between the number of tank cars derailed and the release quantities, the train speed, and the probability of derailment. Once these data are developed, a more accurate analysis can be performed using the validated, multiple-tank-car-derailments probability.

10.2.7 Options for Route Risk Comparison and Uncertainty Errors of Risk Parameter Estimates

Chapter 8 introduced techniques for risk comparison using modified risk profiles incorporating point estimates of risk. When resources are limited and analysis is not possible for the entire route, non-parametric statistical methods based on sample segments were introduced as alternatives. These include the Fisher sign test, the Wilcoxon signed rank test, the Wilcoxon rank sum test, and the Kruskal-Wallis test. These tests focus on detecting the difference in median risk. In addition, Chi-square and Kolmogorov-Smirnov tests focus on detecting general differences in distributions of route risk. Further study may investigate other techniques applicable for the entire route rather than for sample segments. Parameters other than median risk could be considered, e.g. risk distribution of the whole route and total route risk. A more complicated case, such as when risk profiles cross, could be included. There is not much research on the application of the statistical methods to risk-based decision-making for hazardous materials routing problems. These statistical methods still require further exploration regarding their validity for route risk comparison.

In the QRA process, estimates of parameters affecting risk are often associated with error that may affect the result of the statistical comparison of route risks. A large error may cause the difference in route risks to become non-significant. Future study may consider improving the route segmentation approach to reduce the uncertainty errors associated with parameter estimates.

REFERENCES

Abkowitz, M. *Transportation Risk Management: A New Paradigm*. Presented at 82th Annual Meeting of the Transportation Research Board, Washington, D.C., 2003.

Abkowitz, M. *All Hazards Risk Management Challenges & Opportunities*. Presented at 86th Annual Meeting of the Transportation Research Board, Washington, D.C. 2007.

Abkowitz, M., G. List, and A. E. Radwan. Critical Issues in Safe Transport of Hazardous Materials. *Journal of Transportation Engineering*, Vol. 115, No. 6, 1989, pp. 608 – 629.

Abkowitz, M., and P. D-M. Cheng. Developing a Risk/Cost Framework for Routing Truck Movements of Hazardous Materials. *Accident Analysis & Prevention*, Vol. 20, No. 1, pp. 39 – 51, 1988.

Abkowitz, M., P. D. Cheng, and M. Lepofsky. Use of Geographic Information Systems in Managing Hazardous Materials Shipments. In *Transportation Research Record: Journal of the Transportation Research Board, No. 1497*, TRB National Research Council, Washington D.C., 1990, pp. 35 – 43.

Alberini, A. What Is a Life Worth? Robustness of VSL Values from Contingent Valuation Surveys. *Risk Analysis*, Vol. 25, No. 4, 2005, pp. 783 – 800.

Aldrich, M. Regulating Transportation of Hazardous Substances: Railroads and Reform, 1883-1930. *Business History Review*, Vol. 76, No. 2, 2002, pp. 267 – 297.

ALK Technologies, Inc. (ALK). Princeton Transportation Network Model. ALK, Princeton, NJ, 1988.

ALK Technologies, Inc. (ALK). PC*HazRoute. ALK, Princeton, NJ, 1994.

ALK Technologies, Inc. (ALK). PC*MILER | Rail 13. ALK, Princeton, NJ, 2006.

Allen J., and Fronczak, R. *Comparing and Contrasting Highway and Rail Routing*. Presented at 86th Annual Meeting of the Transportation Research Board, Washington, D.C. 2007.

Alumur, S., and B. Y. Kara. A New Model for the Hazardous Waste Location-routing Problem. *Computers & Operations Research*, Vol. 34, 2007, pp. 1406 – 1423.

An, M., S. Huang, S., and C. J. Baker. *Railway Risk Assessment – The Fuzzy Reasoning Approach and Fuzzy Analytic Hierarchy Process Approaches: A Case Study of Shunting at Waterloo Depot*. Proceedings of the Institution of Mechanical Engineers, Vol. 221, Part F: Journal of Rail and Rapid Transit, 2007, pp. 365 – 383.

Anand, P. Cost-Effectiveness of Reducing Environmental Risk from Railroad Tank Car Transportation of Hazardous Materials. *PhD Dissertation*, Department of Civil and Environmental Engineering, University of Illinois at Urbana-Champaign, Urbana, IL, 2006.

Anderson, R. T., and C. P. L. Barkan. Railroad Accident Rates for Use in Transportation Risk Analysis. In *Transportation Research Record: Journal of the Transportation Research Board*, No. 1863, TRB, National Research Council, Washington, D.C., 2004, pp. 88 – 98.

Anderson, T. W., and D. A. Darling. Asymptotic Theory of Certain “Goodness of Fit” Criteria Based on Stochastic Processes. *Annals of Mathematical Statistics*, Vol. 23, No. 2, 1952, pp. 193 – 212.

Anderson, T. W., and D. A. Darling. A Test of Goodness of Fit. *Journal of the American Statistical Association*, Vol. 49, No. 268, 1954, pp. 765 – 769.

Arthur D. Little, Inc. (ADL). *Risk Assessment for the Transportation of Hazardous Materials by Rail, Supplementary Report: Railroad Accident Rate and Risk Reduction Option Effectiveness Analysis and Data (Second Revision)*. ADL, Cambridge, MA, 1996.

Assad, A. *Analytical Models in Rail Transportation: An Annotated Bibliography*. Working paper OR 066-77, Operations Research Center, Massachusetts Institute of Technology, Mass., 1977. <http://dspace.mit.edu/bitstream/1721.1/5149/1/OR-066-77.pdf> Accessed May 22, 2009.

Association of American Railroads (AAR). *Manual of Standards and Recommended Practices, Section C-III - Specifications for Tank Cars, M-1002*. Association of American Railroads, Washington, D.C., 2007.

Association of American Railroads (AAR). *Recommended Railroad Operating Practices for Transportation of Hazardous Materials*. AAR Circular OT-55, Washington, D.C., 1990.

Association of American Railroads (AAR). *Recommended Railroad Operating Practices for Transportation of Hazardous Materials*. Circular No. OT-55-J, Washington, D.C., 2009.

Babcock, M. W., and J. Sanderson. Should shortline railroads upgrade their systems to handle heavy axle load cars? *Transportation Research Part E*, Vol. 42, 2006, pp. 149 – 166.

Barkan, C.P.L. Improving the design of higher-capacity railway tank cars for hazardous materials transport: Optimizing the trade-off between weight and safety. *Journal of Hazardous Materials*, Vol. 160, 2008, pp. 122 – 134.

Barkan, C.P.L. *Risk Considerations for Rail Routing of Hazardous Materials*. Presented at 85th Annual Meeting of the Transportation Research Board, Washington, D.C., 2006.

Barkan, C.P.L., C.T. Dick, and R. Anderson. Analysis of Railroad Derailment Factors Affecting Hazardous Materials Transportation Risk. In *Transportation Research Record: Journal of the Transportation Research Board, No. 1825*, TRB, National Research Council, Washington, D.C., 2003, pp. 48 – 55.

Barkan, C.P.L., S. Ukkusuri, and S.T. Waller. Optimizing Railroad Tank Cars for Safety: The Tradeoff Between Damage Resistance and Probability of Accident Involvement, *Computers & Operations Research*, Vol. 34, 2007, pp. 1266 – 1286.

Barkan, C.P.L., T.S. Glickman, and A.E. Harvey. Benefit–Cost Evaluation of Using Different Specification Tank Cars to Reduce the Risk of Transporting Environmentally Sensitive Chemicals. In *Transportation Research Record, No. 1313*, TRB, National Research Council, Washington, D.C., 1991, pp. 33 – 43.

Bedford, T. Decision Making for Societal Risk Reduction using Multicriteria Analysis. *Research and Practice*, Management Science Working Paper No. 15, University of Strathclyde, Glasgow, United Kingdom, 2005.

Bendixen, L., R. A. Freeman, and D. Hendershot. Using the CCPS Guidelines for Chemical Transportation Risk Analysis. *Process Safety Progress*, Vol. 16, No.1, 1997, pp. 32 – 36.

Birk, M., J. Anderson, and J. Coppens. A Computer Simulation of a Derailment Accident: Part I – Model Basis. *Journal of Hazardous Materials*, Vol. 25, 1990a, pp. 121 – 147.

Birk, M., J. Anderson, and J. Coppens. A Computer Simulation of a Derailment Accident: Part II – Sample Simulation. *Journal of Hazardous Materials*, Vol. 25, 1990b, pp. 149 – 165.

Borener, S., G. Baker, J. Hitz, N. Meltzer, B. Talamini, M. Coltman, and M. Haines. *Comparative Safety of the Transport of High-Level Radioactive Materials on Dedicated, Key, and Regular Trains Technical Study*. DOT/FRA/ORD-05/03, U.S. Department of Transportation, 2006.

Borysiewicz, M. J. *Transportation Risk Assessment, A Supplement Document of Models and Techniques for Health and Environmental Hazards Assessment and Management*. Institute of Atomic Energy, Poland, 2006.

http://manhaz.cyf.gov.pl/manhaz/monography_2006_5/supplement/TRA_supplement_monografia_MANHAZ.pdf Accessed May 20, 2009.

Brown, D. F., A. J. Policastro, W. E. Dunn, R. A. Carhart, M. A. Lazaro, W. A. Freeman, and M. Krumpolc. *Development of the Table of Initial Isolation and Protective Action Distances for the 2000 Emergency Response Guidebook*. Publication ANL/DIS-00-1, Argonne National Laboratory, U.S. Department of Energy, 2000.

Brown, D. F., H.M. Hartmann, W.A. Freeman, and W.D. Haney. *Development of the Table of Initial Isolation and Protective Action Distances for the 2008 Emergency Response Guidebook*. Publication ANL/DIS-09-2, Argonne National Laboratory, U.S. Department of Energy, 2009.

Brown, D. F., W.A. Freeman, R.A. Carhart, and M. Krumpolc. *Development of the Table of Initial Isolation and Protective Action Distances for the 2004 Emergency Response Guidebook*. Publication ANL/DIS-05-2, Argonne National Laboratory, U.S. Department of Energy, 2005.

Brown, D. F., and W. E. Dunn. Application of a Quantitative Risk Assessment Method to Emergency Response Planning. *Computers & Operations Research*, Vol. 34, Issue 5, 2007, pp. 1243 – 1265.

Brown, D.F., W.E. Dunn, and A.J. Policastro. *A National Risk Assessment for Selected Hazardous Materials in Transportation*. Publication ANL-DIS-01-1, Argonne National Laboratory, U.S. Department of Energy, 2001.

Bubbico, R., S. D. Cave, and B. Mazzarotta. Risk Analysis for Road and Rail Transport of Hazardous Materials: A GIS Approach. *Journal of Loss Prevention in the Process Industries*, Vol. 17, 2004, pp. 483 – 488.

Bureau of Explosives (BOE). *Annual Report of Hazardous Materials Transported by Rail Calendar Year 2007*. BOE Report 07-1, Association of American Railroads, Transportation Technology Center, Inc., Pueblo, CO, 2009.

Bureau of Explosives (BOE). *Tariff No. BOE-6000-AA, Hazardous Materials Regulations of the Department of Transportation by Air, Rail, Highway, and Water Including Specifications for Shipping Containers*. BOE Publications, Annapolis, MD, 2007.

Bureau of Transportation Statistics (BTS), Research and Innovative Technology Administration, U.S. Department of Transportation. *National Transportation Atlas Database*.

http://www.bts.gov/publications/national_transportation_atlas_database Accessed May 1, 2007.

Bussieck, M. R., and A. Pruessner. Mixed-Integer Nonlinear Programming. *SIAG/OPT Views-and-News*, Vol. 14, No. 1, 2003, pp. 19 – 22.

California Department of Resources Recycling and Recovery. *Conducting a Diversion Study: A Guide for Local Jurisdictions*.

<http://www.calrecycle.ca.gov/LGCentral/Library/DSG/default.htm#table> Accessed June 23, 2010.

Casavant, K., and D. Tolliver. *Impact of Heavy Axle Loads on Light Density Lines in the State of Washington*. Report WA-RD 499.1, Washington State Transportation Center, Washington State University, Pullman, WA, 2001.

Carotenuto, P., S. Giordani, and S. Ricciardelli. Finding Minimum and Equitable Risk Routes for Hazmat Shipments. *Computers & Operations Research*, Vol. 34, 2007, pp. 1304 – 1327.

Center for Chemical Process Safety (CCPS), American Institute of Chemical Engineers. *Guidelines for Chemical Process Quantitative Risk Analysis*. New York, NY, 1989.

Center for Chemical Process Safety (CCPS), American Institute of Chemical Engineers. *Guidelines for Chemical Transportation Risk Analysis*. New York, NY, 1995.

Center for Chemical Process Safety (CCPS), American Institute of Chemical Engineers. *Guidelines for Risk Based Process Safety*. John Wiley & Sons, Inc., Hoboken, NJ, 2007.

Center for Chemical Process Safety (CCPS), American Institute of Chemical Engineers. *Guidelines for Chemical Transportation Safety, Security, and Risk Management*. Second Edition, Hoboken, NJ, 2008.

Centrone, G., R. Pesenti, and Ukovich, W. Hazardous Materials Transportation: A Literature Review and an Annotated Bibliography. In *Advanced Technologies and Methodologies for Risk Management in the Global Transport of Dangerous Goods*, C. Bersani (Ed.), IOS Press, 2008.

Chen, B., and P. T. Harker. Two Moments Estimation of the Delay on Single-Track Rail Lines with Scheduled Traffic. *Transportation Science*, Vol. 24, No. 4, November 1990, pp. 261 – 275
DOI: 10.1287/trsc.24.4.261

Chen, S.Y., and A. Kapoor. *The Resource Handbook on DOE Transportation Risk Assessment*. WM'03 Conference, February 23-27, 2003, Tucson, AZ, 2003.

Chen K., and Y. Xie. *Performances of Tests for Two Sample Location Problem*. December 10, 2007. http://www.stat.uiowa.edu/~kcowles/s166_2007/chenxieproject.pdf Accessed November 18, 2009.

- Chin, S-M., H-L. Hwang, and B. E. Peterson. *A Tool For Railroad Hazmat Routing Under Shipment Bans In Major Cities*. Presented at 85th Annual Meeting of the Transportation Research Board, Washington, D.C., 2006.
- Cochran, W.G. Some Methods for Strengthening the Common χ^2 Tests, *Biometrics*, Vol. 10, No. 4, 1954, pp. 417 – 451.
- Conover, W. J. *Practical Nonparametric Statistics*. John Wiley & Sons, Inc., New York, NY, 1971.
- Cordeau, J-F., P. Toth, P., and D. Vigo. A Survey of Optimization Models for Train Routing and Scheduling, *Transportation Science*, Vol. 32, No. 4, 1998, pp. 380 – 404.
- Covello, V.T., and M.W. Merkhofer. *Risk Assessment Methods*. Plenum Press, NY, 1993.
- Cox, L. A. Jr. Does Concern-Driven Risk Management Provide a Viable Alternative to QRA?, *Risk Analysis*, Vol. 27, No. 1, 2007, pp. 27 – 43.
- Cox, R.G. Routing of Hazardous Material. *PhD Dissertation*, School of Civil and Environmental Engineering, Cornell University, Ithaca, NY, 1984.
- Dadkar, Y., D. Jones, and L. Nozick. Identifying Geographically Diverse Routes for the Transportation of Hazardous Materials. *Transportation Research, Part E*, Vol. 44, 2008, pp. 333 – 349.
- Daniels, L. E. *Track Maintenance Costs on Rail Transit Properties*. TCRP Web-Only Document 43, Transit Cooperative Research Program, Transportation Research Board of the National Academies, September 2008.
- Day, K R. The Potential Impact of a Mid-America Earthquake on the Railroad Network. *Master of Science Thesis*, Department of Civil and Environmental Engineering, University of Illinois at Urbana-Champaign, Urbana, IL, 2002.
- Dennis, S. M. Estimating Risk Costs per Unit of Exposure for Hazardous Materials Transported by Rail. *Logistics and Transportation Review*, Vol. 32, No 4, 1996, pp. 351 – 375.
- Dennis, S. M. Changes in Railroad Track Accident Rates. *Journal of Transportation Research Forum*. In *Transportation Research Quarterly*, Vol. 56, No. 4, 2002, pp. 161 – 174.
- Dick, C. Tyler. Factors Affecting the Frequency and Location of Broken Railway Rails and Broken Rail Derailments. *Master of Science Thesis*, Department of Civil and Environmental Engineering, University of Illinois at Urbana-Champaign, Urbana, IL, 2001.

Dingler, M. H., Y-C Lai, and C. P. L. Barkan. Impact of Train Type Heterogeneity on Single-Track Railway Capacity. In *Transportation Research Record: Journal of the Transportation Research Board*, No. 2117, TRB, National Research Council, Washington, D.C., 2009, pp. 41 – 49.

Edwards, J.R., J.M. Hart, S. Todorovic, C.P.L. Barkan, N. Ahuja, Z. Chua, N. Kocher, and J. Zeman. *Development of Machine Vision Technology for Railcar Safety Appliance Inspection*. Proceedings of the International Heavy Haul Conference Specialist Technical Session - High Tech in Heavy Haul, Kiruna, Sweden, June 2007, pp. 745 – 752.

Erkut, E. Introduction to the Special Issue. *Computers & Operations Research*, Vol. 34, Issue 5, 2007, pp. 1241 – 1242.

Erkut, E., and A. Ingolfsson. Transport Risk Models for Hazardous Materials: Revisited. *Operations Research Letters*, Vol. 33, 2005, pp. 81 – 89.

Erkut, E, S. A. Tjandra, and V. Verter. Hazardous Materials Transportation. In *Handbooks in Operations Research and Management Science Volume 14 Transportation*, C. Barnhart and G. Laporte (Eds.), North-Holland, Amsterdam, The Netherlands, 2007.

Erkut, E., and T. Glickman. Minimax Population Exposure in Routing Highway Shipments of Hazardous Materials. In *Transportation Research Record: Journal of the Transportation Research Board*, No. 1602, TRB, National Research Council, Washington, D.C., 1994, pp. 93 – 100.

Erkut, E., and V. Verter. A Framework for Hazardous Materials Transport Risk Assessment. *Risk Analysis*, Vol. 15. No. 5, 1995, pp. 589 – 601.

Erkut, E., and V. Verter. Modeling of Transport Risk for Hazardous Materials, *Operations Research*, Vol. 46, No. 5, 1998, pp. 625 – 642.

ESRI. *Data & Maps*. Electronic Database (DVD-ROM), ESRI, 2005.

Fabiano, B., F. Currò, E. Palazzi, and R. Pastorino. A Framework for Risk Assessment and Decision-making Strategies in Dangerous Good Transportation. *Journal of Hazardous Materials*, Vol. 93, Issue 1, 2002, pp. 1 – 15.

Fedra, K. Integrated Risk Assessment and Management: Overview and State of the Art. *Journal of Hazardous Materials*, Vol. 61, 1998, pp. 5 – 22.

Federal Railroad Administration (FRA), U.S. Department of Transportation. *FRA Guide for Preparing Accident/Incident Reports*. DOT/FRA/RRS-22, 2003.

Federal Railroad Administration (FRA), U.S. Department of Transportation. *Track Safety Standards*. Code of Federal Regulations, Title 49, Vol. 4 (49 CFR 213.9), 2003.

Frank, W. C., J-C Thill, and R. Batta. Spatial Decision Support System for Hazardous Material Truck Routing. *Transportation Research Part C*, Vol. 8, 2000, pp. 337 – 359.

Freeman, R. A., and J. W. Kleffner. Risk Based Package Design. *Process Safety Progress*, Vol. 16, No.1, 1997.

Fronczak, R. E. *Policy and Operational Considerations for Rail Routing of Hazardous Materials*. Presented at 85th Annual Meeting of the Transportation Research Board, Washington, D.C., 2006.

General Algebraic Modeling System (GAMS). <http://www.gams.com> Accessed 2007.

Gheorghe, A. V., J. Birchmeier, D. Vamanu, I. Papazoglou, and W. Kröger. Comprehensive Risk Assessment for Rail Transportation of Dangerous Goods: A Validated Platform for Decision Support. *Reliability Engineering and System Safety*, Vol. 88, 2005, pp. 247 – 272.

Glickman, T. S. Rerouting Railroad Shipments of Hazardous Materials Transportation Risk Assessment. *Accident Analysis & Prevention*, Vol. 15, No. 5, 1983, pp. 329 – 335.

Glickman, T. S. *Estimated Costs and Benefits of Rerouting Trains with Hazardous Materials To Avoid the Highest-Threat Target Cities*. Testimony Before the Washington D.C. City Council's Committee on Public Works and the Environment, 2004.

<http://occ.dc.gov/occ/frames.asp?doc=/occ/lib/occ/information/hazmat/73515.pdf> Accessed May 29, 2009.

Glickman, T. S., and D. B. Rosenfield. Risks of Catastrophic Derailments Involving the Release of Hazardous Materials. *Management Science*, Vol. 30, No. 4, 1984, pp. 503 – 511.

Glickman, T.S., and D. Golding. For a Few Dollars More: Public Trust and the Case for Transporting Nuclear Waste in Dedicated Trains. *Policy Studies Review*, Vol.10, No.4, 1991.

Glickman, T. S., and E. Erkut. Assessment of Hazardous Material Risks for Rail Yard Safety. *Safety Science*, Vol. 45, 2007, pp. 813 – 822.

Glickman, T. S., E. Erkut, and M. S. Zschocke. The Cost and Risk Impacts of Rerouting Railroad Shipments of Hazardous Materials. *Accident Analysis & Prevention*, Vol. 39, 2007, pp. 1015 – 1025.

Glickman, T. S., and G. Evans. *A Comparison of Safety and Security Factors on Alternative Rail Routes*. Presented at INFORMS Annual Meeting, Washington, D.C., 2008.

- Glickman, T. S., and H. Khamooshi. Using Hazard Networks to Determine Risk Reduction Strategies. *Journal of the Operational Research Society*, Vol. 56, 2005, pp. 1265 – 1272.
- Goodchild, M. F. GIS and Transportation: Status and Challenges. *GeoInformatica*, Vol. 4, No. 2, 2000, pp. 127 – 139.
- Grimes, G. A., and C.P.L. Barkan. Cost-effectiveness of Railway Infrastructure Renewal Maintenance. *Journal of Transportation Engineering*, Vol. 132, No. 8, 2006, pp. 601 – 608.
- Haghani, A. E. Rail Freight Transportation: A Review of Recent Optimization Models for Train Routing and Empty Car Distribution. *Journal of Advanced Transportation*, Vol. 21, 1987, pp. 147 – 172.
- Haghani, A., S. Yang, and M. Hamedi. *Routing and Scheduling of Hazmat Fleet to Avoid Risk Accumulation*. TRB 85th Annual Meeting Compendium of Papers CD-ROM, Transportation Research Board of the National Academies, Washington, D.C., 2006.
- Hanna, S., S. Dharmavaram, J. Zhang, I. Sykes, H. Witlox, S. Khajehnajafi, and K. Koslang. Comparison of Six Widely-Used Dense Gas Dispersion Models for Three Recent Chlorine Railcar Accidents. *Process Safety Progress*, Vol.27, No. 3, 2008, pp. 248 – 259.
- Harker, P. T., and S. Hong. Two Moments Estimation of the Delay on a Partially Double Track Rail Line with Scheduled Traffic, *Journal of the Transportation Research Forum*, Vol. 31, 1990, pp. 38 – 49.
- Hartong, M., R. Goel, and D. Wijesekera. *A Risk Assessment Framework for TIH Train Routing*, Federal Railroad Administration, Howard University, George Mason University, 2007.
http://volgenau.gmu.edu/~klaskey/OR680/MSSEORProjectsSpring08/RR_Group_09MAY2008/CIP_TIH_Submitted.pdf Accessed May 25, 2009.
- Hauer, E. On the Estimation of the Expected Number of Accidents. *Accident Analysis & Prevention*, Vol. 18, No. 1, 1986, pp. 1 – 12.
- Hawthorne, K., R. B. Wiley, and T. Guins. *Wayside Monitoring with ATSI Aids Wagon Maintenance*, Railway Gazette International, 2005.
- Health and Safety Laboratory (HSL), and Health and Safety Executive (HSE). *Societal Risk: Initial briefing to Societal Risk Technical Advisory Group*, Research Report RR703, the Health and Safety Executive, 2009. <http://www.hse.gov.uk/research/rrpdf/rr703.pdf> Accessed September 24, 2009.
- Higgins, A., L. Ferreira, and E. Kozan. Modelling Delay Risks Associated with a Train Schedule. *Transportation Planning and Technology*, Vol. 19, No. 2, 1995, pp. 89 – 108.

Hillier, F. S., and G. J. Lieberman. *Introduction to Operations Research*, 8th Edition, McGraw-Hill, Dubuque, IA, 2005.

Hollander, M., and D. A. Wolfe. *Nonparametric Statistical Methods*. 2nd Edition, John Wiley & Sons, Inc., New York, NY, 1999.

Huang, B. and P. Fery. *Aiding Route Decision for Hazardous Material Transportation*. Presented at 84th Annual Meeting of the Transportation Research Board, Washington, D.C., 2005.

Huang, B., R. L. Cheu, and W. Liew. *Incorporating Security in Hazardous Materials Route Planning Using Geographic Information System and Analytic Hierarchy Process*. Presented at 83th Annual Meeting of the Transportation Research Board, Washington, D.C., 2004.

Jeong, D. Y., and D. Tyrell. *Improved Tank Car Safety Research*. Presented at 87th Annual Meeting of the Transportation Research Board, Washington, D.C., 2008.

Johnson, P. *Railroad Routing and Visualization Analysis (RRVA) User's Manual*. Oak Ridge National Laboratory. ORNL/NRTC-018, Rev. 0, Oak Ridge National Laboratory, Oak Ridge, TN, 2006.

Johnson, P. E. *Transportation Routing Analysis Geographic Information System—TRAGIS, A Multimodal Transportation Routing Tool*. Presented at Packaging and Transportation of Radioactive Materials PATRAM '95 Conference, Las Vegas, NV, December 3 – 8, 1995.

Johnson, P. E., and R. D. Michelhaugh. *Transportation Routing Analysis Geographic Information System (TRAGIS) User's Manual*. ORNL/NTRC-006 Rev. 0, Oak Ridge National Laboratory, Oak Ridge, TN, 2003.

Johnson, P. E., D. S. Joy, D. B. Clarke, and J. M. Jacobi. *INTERLINE 5.0 - An Expanded Railroad Routing Model: Program Description, Methodology, and Revised User's Manual*. ORNL/TM-12090, Oak Ridge National Laboratory, Oak Ridge, TN, 1993.

Kara, B.Y., E. Erkut, and V. Verter. Accurate Calculation of Hazardous Materials Transport Risks. *Operations Research Letters*, Vol. 31, 2003, pp. 285 – 292.

Kawprasert, A., and C.P.L. Barkan. Effects of Route Rationalization on Hazardous Materials Transportation Risk. In *Transportation Research Record: Journal of the Transportation Research Board*, No. 2043, TRB, National Research Council, Washington, D.C., 2008, pp. 65 – 72.

Kawprasert, A and C.P.L. Barkan. Communication and Interpretation of Results of Route Risk Analyses of Hazardous Materials Transportation by Railroad. In *Transportation Research Record: Journal of the Transportation Research Board*, No. 2097, TRB, National Research Council, Washington, D.C., 2009a, pp. 125 – 135.

Kawprasert, A and C.P.L. Barkan. *Managing Railroad Hazardous Materials Transportation Risk: The Trade-off Between Track Quality and Speed*. Presented at INFORMS Annual Meeting, San Diego, CA, October 11 – 14, 2009b.

Kawprasert, A., and C.P.L. Barkan. Effect of Train Speed on Risk Analysis of Transporting Hazardous Materials by Rail. In *Transportation Research Record: Journal of the Transportation Research Board*, No. 2159, TRB, National Research Council, Washington, D.C. 2010a, pp. 59 – 68.

Kawprasert, A., and C.P.L. Barkan. *Options for Rail Route Infrastructure Improvement to Reduce Hazardous Materials Transportation Risk*. Presented at ASME-IEEE-ASCE-AREMA-TRB Joint Rail Conference, University of Illinois at Urbana-Champaign, Urbana, IL, April, 27 – 29, 2010b.

Kawprasert, A., and C.P.L. Barkan. *Statistical Comparison of Railroad Hazardous Materials Transportation Route Risks*. Presented at ASME-IEEE-ASCE-AREMA-TRB Joint Rail Conference, University of Illinois at Urbana-Champaign, Urbana, IL, April, 27 – 29, 2010c.

Keeney, R. L., and D. von Winterfeldt. Improving Risk Communication. *Risk Analysis*, Vol. 6, Issue 4, 2008, pp. 417 – 424.

Kendall, M. A New Measure of Rank Correlation. *Biometrika*, Vol. 30, 1938, pp. 81 – 89.

Kendall, M. *Rank Correlation Methods*. Charles Griffin and Company Limited, London, UK, 1948.

Knuth, D. E. *The Art of Computer Programming*. Vol. 2, 3rd Edition, Addison Wesley Longman, 1998, pp. 66 – 69.

Kolmogorov, A. Sulla Determinazione Empirica di una Legge di Distribuzione. *Giornale dell' Istituto Italiano degli Attuari*, Vol. 4, 1933, pp. 1 – 11.

Kornhauser, A. L., and M. Bodden. Network Analysis of Highway and Intermodal Rail-Highway Freight Traffic. In *Transportation Research Record: Journal of Transportation Research Board*, No. 920, TRB, National Research Council, Washington, D.C., 1983, pp. 61 – 68.

Kruskal, W. H., and W. A. Wallis. Use of Ranks in One-criterion Variance Analysis. *Journal of the American Statistical Association*, Vol. 47, No. 260, 1952, pp. 583 – 621.

Lai, Y.-C., A. Kawprasert, C.-Y. Lin, C.-H. Liang, M. R. Saat, and C.P.L. Barkan. *Integrated Optimization Model to Manage the Risk of Transporting Hazardous Materials on Railroad Networks*. Submitted for publication in Transportation Research Record: Journal of Transportation Research Board, TRB, National Research Council, Washington, D.C., 2011, (under review).

Lai, Y.-C., M. H. Dingler, and S-Y Lin. *Optimization of the Railroad Network Track Class*. Proceedings of the 89th Annual Meeting of the Transportation Research Board. Compendium of Papers DVD. Transportation Research Board of the National Academies, Washington, D.C., 2010.

Larsson, D. A Study of the Track Degradation Process Related to Changes in Railway Traffic. *Licentiate Thesis*, Luleå University of Technology, Luleå, Sweden, 2004.

Law, A. M., and W. D. Kelton. *Simulation Modeling and Analysis*, 3rd Edition, McGraw-Hill, Boston, MA, 2000.

Lehmann, E. L. *Nonparametrics Statistical Methods Based on Ranks*. Revised 1st Edition, Springer Science+Business Media, LLC, Ney York, NY, 2006.

Lemeshko, B. Yu., E. V. Chimitova, and S. S. Kolesnikov. *Nonparametric Goodness-of-Fit Tests or Discrete, Grouped or Censored Data*. Proceedings of the 12th Applied Stochastic Models and Data Analysis (ASMDA) International Conference, C. H. Skiadas (Ed.), Chania, Crete, Greece, 2007.

Leonelli, P., S. Bonvicini, and G. Spadoni. Hazardous Materials Transportation: A Risk-analysis-based Routing Methodology. *Journal of Hazardous Materials*, Vol. 71, 2000, pp. 283 – 300.

Lewis, D., and Burke, C. J. The Use and Misuse of the Chi-square Test. *Psychological Bulletin*, Vol. 46, No. 6, 1949, pp. 433 – 489.

Liu, X., Saat, M. R., and C. P. L. Barkan. *Benefit-cost Analysis of Infrastructure Improvement for Derailment Prevention*. Proceedings of the ASME-IEEE-ASCE-AREMA-TRB Joint Rail Conference, University of Illinois at Urbana-Champaign, Urbana, IL, April, 27 – 29, 2010.

List, G. F., P. B. Mirchandani, M. A. Turnquist, and K.G. Zografos. Modeling and Analysis for Hazardous Materials Transportation: Risk Analysis, Routing/Scheduling and Facility Location. *Transportation Science*, Vol. 25, No. 2, 1991, pp. 100 – 114.

Lorig, J. 1988 *Princeton Transportation Network Model Tutorial and User's Guide*. Railroad Engineering Unit, Department of Civil and Environmental Engineering, University of Illinois at Urbana-Champaign, 2002.

- Lovett, A. A., J. P. Parfitt, and J. S. Brainard. Using GIS in Risk Analysis: A Case Study of Hazardous Waste Transport. *Risk Analysis*, Vol. 17, No. 5, 1997, pp. 625 – 633.
- Luczak, M. Following the Hazmat Trail. *Railway Age*, September, 2004, pp. 70 – 75.
- Madala, B.P.R. A Simulation Study for Hazardous Materials Transportation Risk Assessment. *Master of Applied Science Thesis*, Concordia University, Montréal, QC, 2000.
<http://www.collectionscanada.gc.ca/obj/s4/f2/dsk2/ftp03/MQ47837.pdf> Accessed May 20, 2009.
- Mann, H. B., and D. R. Whitney. On a Test of Whether one of Two Random Variables is Stochastically Larger than the Other. *The Annals of Mathematical Statistics*, Vol. 18, No. 1, 1947, pp. 50 – 60.
- Markowitz, H. M. *Mean – Variance Analysis in Portfolio Choice and Capital Markets*. Blackwell Science Ltd., Oxford, UK, 1987.
- Massey, F. J., Jr. The Kolmogorov-Smirnov Test for Goodness of Fit. *Journal of the American Statistical Association*, Vol. 46, No. 253, 1951, pp. 68 – 78.
- Matzzie, D. E., J. Caban, and B. Merlino. *Rerouting and Speed Reduction of Hazardous Material Train in Selected Conrail Corridors*. Publication DOT-TSC-1807. Transportation Systems Center, U.S. Department of Transportation, 1981.
<http://www.fra.dot.gov/downloads/research/TSC-1807.pdf> Accessed May 22, 2009.
- Miller-Hooks, E., and H. S. Mahmassani. Optimal Routing of Hazardous Materials in Stochastic, Time-Varying Transportation Networks. In *Transportation Research Record: Journal of the Transportation Research Board, No. 1645*, TRB, National Research Council, Washington, D.C., 1998., pp. 143 – 151.
- Minor IV, J., and M. D. Abkowitz. *An Integrated Risk Communication System for the Transportation of Hazardous Materials*. Presented at 83th Annual Meeting of the Transportation Research Board, Washington, D.C., 2004.
- Modarres, M. *Risk Analysis in Engineering: Probabilistic Techniques, Tools and Trends*, CRC Press (2006).
- Moore, D. S. Tests of Chi-Squared Type. In *Goodness-of-Fit Techniques*, R. B. D’Agostino and M. A. Stephens (Eds.), Marcel Dekker, Inc., New York, NY, 1986.
- Moses, L. N., and D. Lindstrom (Eds.) *Transportation of Hazardous Materials: Issues in Law, Social Science, and Engineering*. Kluwer Academic Publishers, Boston, MA, 1993.

Munshi, K., and E. C. Sullivan. *A Freight Network Model For Mode and Route Choice*. Working Paper No. 25, The University of California Transportation Center, The University of California, Berkeley, CA, 1989.

Murali, P., M. M. Dessouky, F. Ordóñez, and K. Palmer. A Delay Estimation Technique for Single and Double-track Railroads. *Transportation Research Part E*, 2009, doi:10.1016/j.tre.2009.04.016.

Murray, D. *Technical Advances in Hazmat Security*. Presented at 83th Annual Meeting of the Transportation Research Board, Washington, D.C., 2004.

Nardini, L., L. Aparicio, A. Bandoni, and S. M. Tonelli. Regional Risk Associated with the Transport of Hazardous Materials. *Latin American Applied Research*, Vol. 33, 2003, pp. 213 – 218.

National Capital Planning Commission (NCPC). Freight Railroad Realignment Feasibility Study Summary. NCPC, Washington D.C., 2007.
<http://www.ncpc.gov/initiatives/pg.asp?p=railroadrealignmentfeasibilitystudy> Accessed May, 22, 2009.

National Transportation Safety Board (NTSB). *Special Study: Risk Concepts in Dangerous Goods Transportation Regulations*. Report No: NSTB-ST-71-1, NSTB, Washington, D.C., January, 1971.

Nayak, P.R., D.B. Rosenfield, and J.H. Hagopian. *Event Probabilities and Impact Zones for Hazardous Materials Accidents on Railroads*. Report DOT/FRA/ORD-83/20. Federal Railroad Administration, U.S. Department of Transportation, Washington, D.C., November 1983.

Neuhauser, K. S., and F.L. Kanipe. RADTRAN 5 User Guide, SAND2000-1257, Transportation Safety and Security Analysis Department, Sandia National Laboratories, Albuquerque, NM, 2000.

Nicolet-Monnier, M., and A. V. Gheorghe. *Quantitative Risk Assessment of Hazardous Materials Transport Systems*. Kluwer Academic Publishers, 1996.

NIST/SEMATECH. *e-Handbook of Statistical Methods*. National Institute of Standards and Technology (NIST), 2003. <http://www.itl.nist.gov/div898/handbook/> Accessed September 24, 2009.

Office of Management and Budget (OMB). *Guidelines and Discount Rates for Benefit-Cost Analysis of Federal Programs*. Circular No. A-94 Revised (Transmittal Memo No. 64), 1992.
<http://www.whitehouse.gov/omb/rewrite/circulars/a094/a094.html> Accessed April 4, 2009.

Orr, M. F., W. E. Kaye, P. Zeitz, M. E. Powers, and L. Rosenthal. Public Health Risks of Railroad Hazardous Substance Emergency Events. *Journal of Occupational and Environmental Medicine*, Vol. 43, Issue 2, 2001, p. 94.

Ouyang, Y., X. Li, Y.C. Lai, C.P.L. Barkan, and A. Kawprasert. Optimal Locations of Railroad Wayside Defect Detection Installations. *Computer-Aided Civil and Infrastructure Engineering*, Vol. 24, 2009, pp. 1 – 11.

Paltrinieri, N., G. Landucci, M. Molag, S. Bonvicini, G. Spadoni, and V. Cozzani. Risk Reduction in Road and Rail LPG Transportation by Passive Fire Protection. *Journal of Hazardous Materials*, 2009, doi:10.1016/j.jhazmat.2008.12.122.

Peterson, S. K., and R. L. Church. *A Framework for Modeling Rail Transport Vulnerability*. SFTA Research Report # 24, Washington State University, Pullman, WA, 2007.
http://www.sfta.wsu.edu/research/reports/pdf/Report24_Rail_Vulnerability.pdf Accessed May 31, 2009.

Phanwar, S. T., R. Pitt, and M. D. Anderson. Development of a GIS-Based Hazardous Materials Transportation Management System A Demonstration Project. UTCA Report 99244, University Transportation Center for Alabama (UTCA), Tuscaloosa, AL.

Philipson, L. L., and H. S. Napadensky. The Methodologies of Hazardous Materials Transportation Risk Assessment. *Journal of Hazardous Materials*, Vol. 6, 1982, pp. 361 – 382.

Phillips, E. A., and H. Role. Analysis of Tank Cars Damaged in Accidents 1965 Through 1986. Report RA 02-6-55. RPI-AAR Railroad Tank Car Safety Research and Test Project, Association of American Railroads, Chicago, IL, 1989.

Pipeline and Hazardous Materials Safety Administration (PHMSA), U.S. Department of Transportation. *Emergency Response Guidebook*, 2004.
<http://hazmat.dot.gov/pubs/erg/erg2004.pdf> Accessed June 29, 2007.

Pipeline and Hazardous Materials Safety Administration (PHMSA), U.S. Department of Transportation. *Emergency Response Guidebook*, 2008.
http://hazmat.dot.gov/pubs/erg/erg2008_eng.pdf Accessed July, 2008.

Pipeline and Hazardous Materials Safety Administration (PHMSA), U.S. Department of Transportation. *PIH Tank Car NPRM - Regulatory Impact Analysis*, March 2008(b).

Pipeline and Hazardous Materials Safety Administration (PHMSA), U.S. Department of Transportation. *Ten Year Hazardous Materials Incident Data*.
<http://www.phmsa.dot.gov/staticfiles/PHMSA/DownloadableFiles/Files/tenyr.pdf> Accessed July 21, 2009.

Pipeline and Hazardous Materials Safety Administration (PHMSA), U.S. Department of Transportation. *Incident Reports Database*, <https://hazmatonline.phmsa.dot.gov/IncidentReportsSearch/> Accessed January, 2010.

Purdy, G. Risk Analysis of the Transportation Dangerous Goods by Road and Rail. *Journal of Hazardous Materials*, Vol. 33, 1993, pp. 229 – 259.

Resor, R. R., and A. M. Zarembski. *Factors Determining the Economics of Wayside Defect Detectors*. TRB 83th Annual Meeting Compendium of Papers CD-ROM, Transportation Research Board of the National Academies, Washington, D.C., 2004.

Resor, R. R., A. M. Zarembski, and P. K. Patel. Estimation of Investment in Track and Structures Needed to Handle 129 844-kg (286,000-lb) Railcars on Short-Line Railroads. In *Transportation Research Record: Journal of the Transportation Research Board*, No. 1742, TRB, National Research Council, Washington, D.C., 2001, pp. 54 – 60.

Resor, R. R., and P. K. Patel. Allocating Track Maintenance Costs on Shared Rail Facilities. In *Transportation Research Record: Journal of the Transportation Research Board*, No. 1785, TRB, National Research Council, Washington, D.C., 2002, pp. 25 – 32.

Rhyne, W. R. *Hazardous Materials Transportation Risk Analysis*. Van Nostrand-Reinhold, New York, 1994.

Robert, W., A. Aepli, and P. Little. *Post-audit of Wayside Detector Costs and Benefits*. For Transportation Technology Center, Inc. Cambridge Systemics, Inc., Cambridge, MA, 2009.

Ross, S. *A First Course in Probability*, 6th Edition, Prentice Hall, Inc., NJ, 2002.

Saat, M. R. Optimizing Railroad Tank Car Safety Design to Reduce Hazardous Materials Transportation Risk. *PhD Dissertation*, Department of Civil and Environmental Engineering, University of Illinois at Urbana-Champaign, Urbana, IL, 2009.

Saat, M.R., and C.P.L. Barkan. Release Risk and Optimization of Railroad Tank Car Safety Design. In *Transportation Research Record*, No. 1916, TRB, National Research Council, Washington, D.C., 2005, pp. 78 – 87.

Saat, M. R., and C. P. L. Barkan. *The Effect of Rerouting and Tank Car Safety Design on the Risk of Rail Transport of Hazardous Materials*. Proceedings of the 7th World Congress on Railway Research, Montreal, QC, 2006a.

Saat, M. R., and C. P. L. Barkan. *Tank Car Safety Design vs. Infrastructure Improvements in Reducing Hazardous Materials Transportation Risks*. Presented at INFORMS Annual Meeting, Pittsburgh, PA, 2006b.

Saccomanno, F.F., and A.Y. Chan. Economic Evaluation of Routing Strategies for Hazardous Road Shipments. In *Transportation Research Record: Journal of the Transportation Research Board, No. 1020*, TRB, National Research Council, Washington, D.C., 1985, pp. 12 – 18.

Saccomanno, F. F., and K. Cassidy (Eds.) *Transportation of Dangerous Goods: Assessing the Risks*. Institute for Risk Research, University of Waterloo, ON, Canada, 1993.

SAS Institute Inc. (SAS). SAS 9.1 Help and Documentation. SAS, Cary, NC, 2003.

Sawadisavi, S. V., J. R. Edwards, E. Resendiz, J. M. Hart, C.P.L. Barkan, and N. Ahuja. *Machine-Vision Inspection of Railroad Track*. Proceedings of the 88th Annual Meeting of the Transportation Research Board. Compendium of Papers DVD. Transportation Research Board of the National Academies, Washington, D.C., 2009.

Schaeffer, D. J., C. J. Werth, C. P. L. Barkan, H. Yoon, and N. Hridaya. *Hazardous Materials Transportation Environmental Consequence Model: Verification and Validation Document*. Railroad Engineering Program, University of Illinois at Urbana-Champaign, Urbana, IL, 2008.

Schafer II, D. H. Effect of Train Length on Railroad Accidents and A Quantitative Analysis of Factors Affecting Broken Rails. *M.Sc. Thesis*, Department of Civil and Environmental Engineering, University of Illinois at Urbana-Champaign, Urbana, IL, 2008.

Schafer, D. H., and C. P. L. Barkan. *A Prediction Model for Broken Rails and an Analysis of Their Economic Impact*. Proceedings of the American Railway Engineering and Maintenance of Way Association (AREMA) Annual Conference, Salt Lake City, UT, September 2008.

Schlake, B. W., J. R. Edwards, J. M. Hart, C.P.L. Barkan, S. Todorovic, and N. Ahuja. *Automated Inspection of Railcar Underbody Structural Components Using Machine Vision Technology*. Proceedings of the 88th Annual Meeting of the Transportation Research Board. Compendium of Papers DVD. Transportation Research Board of the National Academies, Washington, D.C., 2009.

Schoonover, W. S. *Federal Regulatory Update on Rail Routing of Hazardous Materials*. Presented at 85th Annual Meeting of the Transportation Research Board, Washington, D.C. 2006.

Smirnov, H. Sur les Écarts de la Courbe de Distribution Empirique. *Recueil Mathématique (Matematicheskii Sbornik)*, N. S. 6, 1939, pp. 3 – 26.

Snedecor, G. W., and W. G. Cochran. *Statistical Method*, 8th Edition, Iowa State University Press, Ames, IA, 1989.

- Spearman, C. The Proof and Measurement of Association Between Two Things. *American Journal of Psychology*, Vol. 15, 1904, pp. 72 – 101.
- STB Waybill. U.S. Surface Transportation Board (STB) Carload Waybill Sample. CD-ROM, 2007.
- Steele, M., and J. Chaseling. Powers of Discrete Goodness-of-Fit Test Statistics for a Uniform Null Against a Selection of Alternative Distributions. *Communications in Statistics-Simulation and Computation*, Vol. 35, 2006, pp. 1067 – 1075.
- Stehly, M. *Shipper/Carrier Cooperative Efforts in Risk Analysis*. Presented at 83th Annual Meeting of the Transportation Research Board, Washington, D.C. 2004.
- Stephens, M. A. Tests Based on EDF Statistics. In *Goodness-of-Fit Techniques*, D'Agostino, R. B. and M. A. Stephens (Eds.), Marcel Dekker, Inc., New York, NY, 1986.
- Tawarmalani, M., and N.V. Sahinidis. Convexification and Global Optimization in Continuous and Mixed-Integer Nonlinear Programming: Theory, Algorithms, Software, and Applications. In *Nonconvex Optimization and its Applications series*, Vol. 65, Kluwer Academic Publishers, Boston, MA, 2002.
- Tele Rail Automated Information Network (TRAIN II) Waybill. Association of American Railroads. CD-ROM, 2008.
- Toronto Area Rail Transportation of Dangerous Goods Task Force. *The Toronto Area Rail Transportation of Dangerous Goods Task Force: Final Report*. Transport Canada, Ottawa, ON, Canada, 1988.
- Tournay, H. M., and S. Cummings. *Monitoring the Performance of Railroad Cars By Means of Wayside Detectors in Support of Predictive Maintenance*. Proceedings of the 8th International Heavy Haul Conference, 14 – 16 June 2005, Rio De Janeiro, Brazil, pp. 501 – 510.
- Treichel, T. T., and C. P. L. Barkan. *Working Paper on Mainline Freight Train Accident Rates*. Research and Test Department, Association of American Railroads, 1993.
- Treichel, T. T., J. P. Hughes, C. P. L. Barkan, R. D. Sims, E. A. Phillips, and M. R. Saat. *Safety Performance of Tank Cars in Accidents: Probability of Lading Loss*. Report RA-05-02. RSI-AAR Railroad Tank Car Safety Research and Test Project, Association of American Railroads, Washington, D.C., 2006.
- U.S. Census Bureau, Geography Division. *Census 2000 Urban and Rural Classification*. 2002 http://www.census.gov/geo/www/ua/ua_2k.html Accessed November 16, 2009.

- U.S. Department of Transportation (U.S. DOT). *Hazardous Materials: Enhancing Rail Transportation Safety and Security for Hazardous Materials Shipments; Railroad Safety Enforcement Procedures; Enforcement, Appeal and Hearing Procedures for Rail Routing Decisions; Final Rules*. 49 CFR Parts 172, 174, and 209, Federal Register Vol. 73, No. 229, 2008.
- U.S. Department of Transportation (U.S. DOT). *Treatment of the Economic Value of a Statistical Life in Departmental Analyses*. Office of the Secretary of Transportation, U.S. DOT, 2008. <http://ostpxweb.dot.gov/policy/reports/080205.htm> Accessed May 18, 2009.
- U.S. Department of Transportation (U.S. DOT). Research and Innovative Technology Administration/Bureau of Transportation Statistics. *Commodity Flow Survey 2002*. CD-ROM, 2005.
- Verma, M. A Cost and Expected Consequence Approach to Planning and Managing Railroad Transportation of Hazardous Materials. *Transportation Research, Part D*, Vol. 14, 2009, pp. 300 – 308.
- Verma, M., and V. Verter. Railroad Transportation of Dangerous Goods: Population Exposure to Airborne Toxins. *Computers & Operations Research*, Vol. 34, Issue 5, 2007, pp. 1287 – 1303.
- Verter, V, and B. Y. Kara. A GIS-Based Framework for Hazardous Materials Transport Risk Assessment. *Risk Analysis*, Vol. 21, No. 6, 2001, pp. 1109 – 1120.
- Verter, V, and E. Erkut. Hazardous Materials Logistics: An Annotated Bibliography. In *Operations Research and Environmental Management*, A. Haurie and C. Carraro (Eds.), Dordrecht, Kluwer, 1995.
- Viscusi, W. K., and J. E. Aldy. The Value of a Statistical Life: A Critical Review of Market Estimates Throughout the World. *Journal of Risk and Uncertainty*, Vol. 27, No. 1, 2003, pp. 5 – 76.
- Vrouwenvelder, T., R. Lovegrove, M. Holicky, P. Tanner, and G. Canisius. *Risk Assessment and Risk Communication in Civil Engineering*. CIB Report, the Netherlands, 2001.
- Wald, A., and J. Wolfowitz. On A Test Whether Two Samples Are From the Same Population. *The Annals of Mathematical Statistics*, Vol. 11, 1940, pp. 147 – 162.
- Ward, H. *Practical Issues for Monitoring Hazmat Shipments*. Presented at 87th Annual Meeting of the Transportation Research Board, Washington, D.C. 2008.
- Ward, H. C., P. J. Student, and F. D. Lester. *Next-Generation Rail Car Project*. Presented at 87th Annual Meeting of the Transportation Research Board, Washington, D.C., 2008.

- Warner, J. E., A. A. Protopapas, D. L. Jasek, J. H. Overman, J. Huang, and C. A. Morgan. *Management of Hazardous Materials Transportation: Literature Summary*. Texas Transportation Institute, The Texas A&M University System, College Station, TX, 2008. <http://tti.tamu.edu/documents/0-5929-P2.pdf> Accessed May 21, 2009.
- Warner, J. E., and M. S. Terra. *Assessment of Texas Short Line Railroads*. Proceedings of the 85th Annual Meeting of the Transportation Research Board. Compendium of Papers CD-ROM. Transportation Research Board of the National Academies, Washington, D.C., 2006.
- Waters, N. Transportation GIS: GIS-T. In *Geographical Information Systems: Principles, Techniques, Applications and Management*, Chapter 59, 2nd Edition, P. Longley, M. Goodchild, D. Maguire, and D. Rhind (Eds.), John Wiley and Sons, 1999, pp. 827-844.
- Wijeratne, A. B., M. A. Turnquist, and P. B. Mirchandani. Multiobjective Routing of Hazardous Materials in Stochastic Networks. *European Journal of Operational Research*, Vol. 65, 1993, pp. 33 – 43.
- Wilcoxon, F. Individual Comparisons by Ranking Methods. *Biometrics Bulletin*, Vol. 1, No. 6, 1945, pp. 80 – 83.
- Wild, C. J., and George A. F. Seber. *Chance Encounters: A First Course in Data Analysis and Inference*. John Wiley and Sons, New York, NY, 1999.
- Williams, Jr., C. A. On the Choice of the Number and Width of Classes for the Chi-Square Test of Goodness of Fit. *Journal of the American Statistical Association*, Vol. 45, No. 249, 1950, pp. 77 – 86.
- Woodward, J. L. Does Separation of Hazmat Cars in a Railroad Train Improve Safety from Derailments? *Journal of Loss Prevention in the Process Industries*, Vol. 2, 1989, pp. 176 – 178.
- Yitzhaki, S. Stochastic Dominance, Mean Variance, and Gini's Mean Difference. *The American Economic Review*, Vol. 72, pp. 178 – 185, 1982.
- Yoon, H., C. J. Werth, C. P. L. Barkan, D. J. Schaeffer, and P. Anand. An Environmental Screening Model to Assess the Consequences to Soil and Groundwater from Railroad-tank-car Spills of Light Non-aqueous Phase Liquids. *Journal of Hazardous Materials*, Vol. 165, 2009, pp. 332 – 344.
- Yuan, Y.C., S.Y. Chen, D.J. LePoire, and R. Rothman. *RISKIND – A Computer Program for Calculating Radiological Consequences and Health Risks from Transportation of Spent Nuclear Fuel*, ANL/EAD-1, Argonne National Laboratory, Argonne, IL, 1995.

Zarembski, A.M. *Performance and Economics of New Generation Track Laying and Maintenance Equipment*. TRB 89th Annual Meeting Compendium of Papers DVD, Transportation Research Board of the National Academies, Washington, D.C., 2010.

Zarembski, A.M., and R.R. Resor. *Technical Monograph: Estimating Maintenance Costs for Mixed High Speed Passenger and Freight Rail Corridors*. U.S. Department of Transportation, Federal Railroad Administration, Office of Railroad Development, Washington, D.C., 2004 (unpublished).

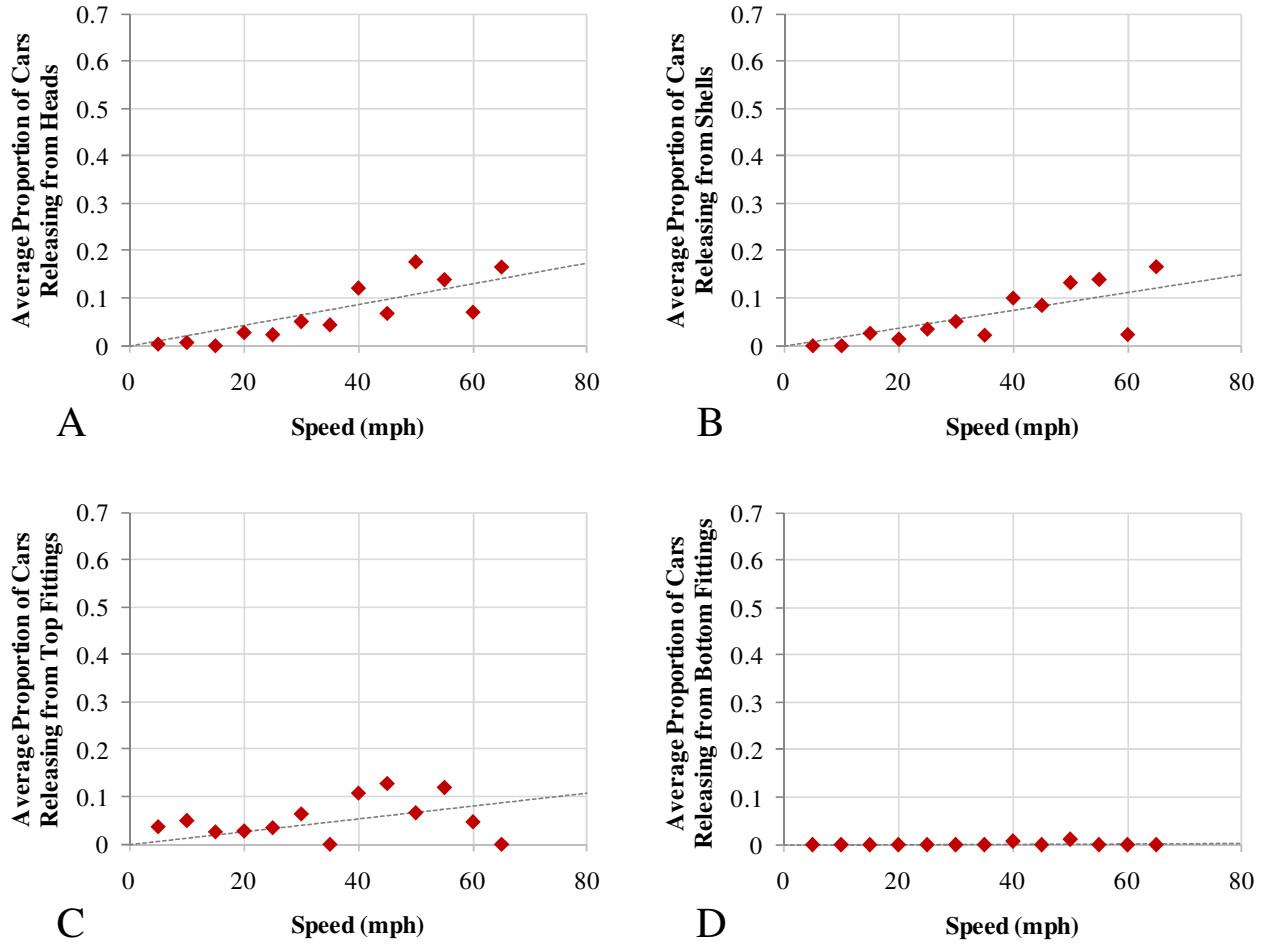
ZETA-TECH Associates, Inc. (ZETA-TECH) *An Estimation of the Investment In Track and Structures Needed to Handle 286,000 Ib. Rail Cars*. Prepared for the American Short Line and Regional Railroad Association, ZETA-TECH Associates, Inc., NJ, 2000.

Zhang, J., J. Hodgson, and E. Erkut. Using GIS to Assess the Risks of Hazardous Materials Transport in Networks. *European Journal of Operational Research*, Vol. 121, 2000, pp. 316 – 329.

Zografos, K. G., and K. N. Androutsopoulos. *A Decision Support System for Hazardous Materials Transportation and Emergency Response Management*. Presented at 84th Annual Meeting of the Transportation Research Board, Washington, D.C. 2005.

APPENDIX A

SPEED-DEPENDENT CONDITIONAL PROBABILITY OF RELEASE FOR PRESSURE TANK CARS



**Figure A.1: Proportion of Pressure Cars Releasing vs. Speed for Releases From
(A) Heads, (B) Shells, (C) Top Fittings, and (D) Bottom Fittings**

$$Y_h = 0.00215X \tag{A.1}$$

$$Y_s = 0.00187X \tag{A.2}$$

$$Y_t = 0.00133X \tag{A.3}$$

$$Y_b = 0.00004X \tag{A.4}$$

where Y_h = proportion of pressure cars releasing from heads, corresponding to train speed X

Y_s = proportion of pressure cars releasing from shells, corresponding to train speed X

Y_t = proportion of pressure cars releasing from top fittings, corresponding to train speed X

Y_b = proportion of pressure cars releasing from bottom fittings, corresponding to train speed X

X = train speed (mph)

Table A.1. Parameter estimates of the linear-speed CPR models.

Model	Estimate of Regression Coefficient, β	Standard Error	t-value	Pr > t	R^2
$Y_h = \beta_h X$	0.00215	0.00024811	8.66	<0.0001	0.8622
$Y_s = \beta_s X$	0.00187	0.00025911	7.23	<0.0001	0.8135
$Y_t = \beta_t X$	0.00133	0.00030915	4.32	0.0010	0.6084
$Y_b = \beta_b X$	0.00004	0.00002391	1.72	0.1106	0.1982

The speed-adjustment factors for pressure cars:

$$J_h = 0.02315X \quad (A.5)$$

$$J_s = 0.02306X \quad (A.6)$$

$$J_t = 0.02969X \quad (A.7)$$

$$J_b = 0.02222X \quad (A.8)$$

The speed-dependent conditional probability of release for pressure cars:

$$R' = 1 - [(1 - 0.02315R_h X)(1 - 0.02306R_s X)(1 - 0.02969R_t X)(1 - 0.02222R_b X)] \quad (A.9)$$

Example of the estimated speed-dependent conditional probability of release for an insulated 105A300W tank car without a head shield and without bottom fittings ($R_h = 0.0218$, $R_s = 0.0247$, $R_t = 0.0389$):

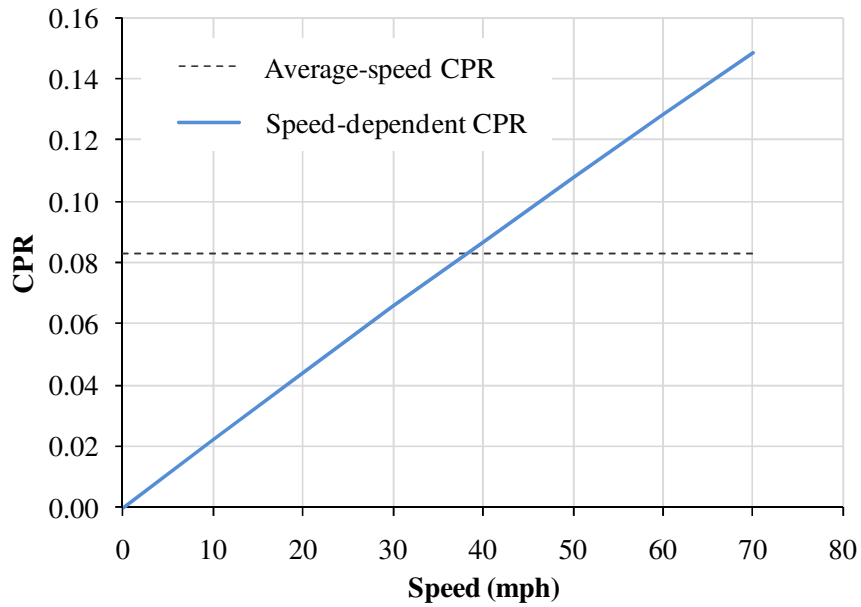


Figure A.2: Estimated Conditional Probability of Release Dependent on Speed for DOT-105A300W

APPENDIX B

ESTIMATED CONDITIONAL PROBABILITY OF RELEASE ADJUSTED FOR TRAIN SPEED

Table B.1. Estimated Conditional Probability of Release Adjusted for Train Speed for Non-pressure Cars.

DOTSPEC	Average-speed CPR	Conditional Probability of Release (CPR) Adjusted for Train Speed (mph) on Mainline														
		0	5	10	15	20	25	30	35	40	45	50	55	60	65	70
111A	0.3096	0.0000	0.0504	0.0992	0.1465	0.1923	0.2366	0.2794	0.3208	0.3608	0.3993	0.4365	0.4724	0.5069	0.5402	0.5721
No BO																
111A	0.1703	0.0000	0.0263	0.0523	0.0778	0.1029	0.1276	0.1518	0.1757	0.1992	0.2223	0.2450	0.2673	0.2892	0.3107	0.3319
No BO, Ins.																
111A	0.3527	0.0000	0.0587	0.1150	0.1690	0.2207	0.2701	0.3174	0.3626	0.4057	0.4469	0.4861	0.5234	0.5590	0.5927	0.6248
with BO																
111A	0.2072	0.0000	0.0324	0.0641	0.0951	0.1254	0.1549	0.1837	0.2119	0.2394	0.2662	0.2923	0.3178	0.3427	0.3669	0.3905
with BO, Ins.																
111A100W1	0.3527	0.0000	0.0587	0.1150	0.1690	0.2207	0.2701	0.3174	0.3626	0.4057	0.4469	0.4861	0.5234	0.5590	0.5927	0.6248
111A100W2	0.3527	0.0000	0.0587	0.1150	0.1690	0.2207	0.2701	0.3174	0.3626	0.4057	0.4469	0.4861	0.5234	0.5590	0.5927	0.6248
111A100W3	0.3527	0.0000	0.0587	0.1150	0.1690	0.2207	0.2701	0.3174	0.3626	0.4057	0.4469	0.4861	0.5234	0.5590	0.5927	0.6248
111A100W5	0.3527	0.0000	0.0587	0.1150	0.1690	0.2207	0.2701	0.3174	0.3626	0.4057	0.4469	0.4861	0.5234	0.5590	0.5927	0.6248
111A60W1	0.3527	0.0000	0.0587	0.1150	0.1690	0.2207	0.2701	0.3174	0.3626	0.4057	0.4469	0.4861	0.5234	0.5590	0.5927	0.6248
111A60W7	0.3527	0.0000	0.0587	0.1150	0.1690	0.2207	0.2701	0.3174	0.3626	0.4057	0.4469	0.4861	0.5234	0.5590	0.5927	0.6248
111J	0.1533	0.0000	0.0238	0.0474	0.0706	0.0935	0.1161	0.1384	0.1604	0.1821	0.2036	0.2247	0.2455	0.2661	0.2863	0.3062
No BO, Ins.																
1/2 HSTP																
111J	0.1910	0.0000	0.0299	0.0593	0.0881	0.1162	0.1438	0.1708	0.1973	0.2232	0.2485	0.2733	0.2975	0.3213	0.3445	0.3671
with BO, Ins.																
1/2 HSTP																
211A100W1	0.3527	0.0000	0.0587	0.1150	0.1690	0.2207	0.2701	0.3174	0.3626	0.4057	0.4469	0.4861	0.5234	0.5590	0.5927	0.6248
211J100W1	0.2072	0.0000	0.0324	0.0641	0.0951	0.1254	0.1549	0.1837	0.2119	0.2394	0.2662	0.2923	0.3178	0.3427	0.3669	0.3905
Non-pres.,	0.2072	0.0000	0.0324	0.0641	0.0951	0.1254	0.1549	0.1837	0.2119	0.2394	0.2662	0.2923	0.3178	0.3427	0.3669	0.3905
Ins.																
Non-pres.,	0.3527	0.0000	0.0587	0.1150	0.1690	0.2207	0.2701	0.3174	0.3626	0.4057	0.4469	0.4861	0.5234	0.5590	0.5927	0.6248
Non-Ins.																

Abbreviations: BO = Bottom Outlet, Ins. = Insulated, HSTP = Head Shield Thermal Protected, Pres. = Pressurized

Table B.2. Estimated Conditional Probability of Release Adjusted for Train Speed for Pressure Cars.

DOTSPEC	Average-speed CPR	Conditional Probability of Release (CPR) Adjusted for Train Speed (mph) on Mainline														
		0	5	10	15	20	25	30	35	40	45	50	55	60	65	70
105A100W	0.1028	0.0000	0.0135	0.0269	0.0402	0.0534	0.0664	0.0793	0.0921	0.1048	0.1174	0.1299	0.1422	0.1545	0.1666	0.1786
105A300W	0.0830	0.0000	0.0111	0.0221	0.0331	0.0439	0.0547	0.0655	0.0761	0.0867	0.0972	0.1076	0.1180	0.1282	0.1384	0.1486
105A500W	0.0622	0.0000	0.0079	0.0157	0.0235	0.0313	0.0390	0.0467	0.0543	0.0619	0.0695	0.0770	0.0845	0.0919	0.0993	0.1066
105A600W	0.0622	0.0000	0.0079	0.0157	0.0235	0.0313	0.0390	0.0467	0.0543	0.0619	0.0695	0.0770	0.0845	0.0919	0.0993	0.1066
105J100W	0.0855	0.0000	0.0114	0.0227	0.0339	0.0451	0.0561	0.0672	0.0781	0.0890	0.0997	0.1105	0.1211	0.1317	0.1422	0.1526
105J200W	0.0855	0.0000	0.0114	0.0227	0.0339	0.0451	0.0561	0.0672	0.0781	0.0890	0.0997	0.1105	0.1211	0.1317	0.1422	0.1526
105J300W	0.0691	0.0000	0.0094	0.0188	0.0281	0.0373	0.0465	0.0557	0.0648	0.0739	0.0829	0.0919	0.1009	0.1098	0.1186	0.1274
105J400W	0.0691	0.0000	0.0094	0.0188	0.0281	0.0373	0.0465	0.0557	0.0648	0.0739	0.0829	0.0919	0.1009	0.1098	0.1186	0.1274
105J500W	0.0480	0.0000	0.0062	0.0123	0.0185	0.0246	0.0307	0.0367	0.0428	0.0488	0.0548	0.0608	0.0667	0.0727	0.0786	0.0844
105J600W	0.0480	0.0000	0.0062	0.0123	0.0185	0.0246	0.0307	0.0367	0.0428	0.0488	0.0548	0.0608	0.0667	0.0727	0.0786	0.0844
105S100W	0.0855	0.0000	0.0114	0.0227	0.0339	0.0451	0.0561	0.0672	0.0781	0.0890	0.0997	0.1105	0.1211	0.1317	0.1422	0.1526
105S200W	0.0855	0.0000	0.0114	0.0227	0.0339	0.0451	0.0561	0.0672	0.0781	0.0890	0.0997	0.1105	0.1211	0.1317	0.1422	0.1526
105S300W	0.0691	0.0000	0.0094	0.0188	0.0281	0.0373	0.0465	0.0557	0.0648	0.0739	0.0829	0.0919	0.1009	0.1098	0.1186	0.1274
105S500W	0.0480	0.0000	0.0062	0.0123	0.0185	0.0246	0.0307	0.0367	0.0428	0.0488	0.0548	0.0608	0.0667	0.0727	0.0786	0.0844
105S600W	0.0480	0.0000	0.0062	0.0123	0.0185	0.0246	0.0307	0.0367	0.0428	0.0488	0.0548	0.0608	0.0667	0.0727	0.0786	0.0844
112A200W	0.2024	0.0000	0.0276	0.0547	0.0813	0.1075	0.1331	0.1582	0.1829	0.2071	0.2309	0.2541	0.2769	0.2993	0.3212	0.3427
112A340W	0.1687	0.0000	0.0232	0.0461	0.0686	0.0908	0.1127	0.1342	0.1555	0.1764	0.1970	0.2173	0.2372	0.2569	0.2763	0.2953
112A400W	0.1687	0.0000	0.0232	0.0461	0.0686	0.0908	0.1127	0.1342	0.1555	0.1764	0.1970	0.2173	0.2372	0.2569	0.2763	0.2953
112J200W	0.0855	0.0000	0.0114	0.0227	0.0339	0.0451	0.0561	0.0672	0.0781	0.0890	0.0997	0.1105	0.1211	0.1317	0.1422	0.1526
112J340W	0.0691	0.0000	0.0094	0.0188	0.0281	0.0373	0.0465	0.0557	0.0648	0.0739	0.0829	0.0919	0.1009	0.1098	0.1186	0.1274
112J400W	0.0691	0.0000	0.0094	0.0188	0.0281	0.0373	0.0465	0.0557	0.0648	0.0739	0.0829	0.0919	0.1009	0.1098	0.1186	0.1274

Table B.2. Estimated Conditional Probability of Release Adjusted for Train Speed for Pressure Cars. (cont'd)

DOTSPEC	Average- speed CPR	Conditional Probability of Release (CPR) Adjusted for Train Speed (mph) on Mainline														
		0	5	10	15	20	25	30	35	40	45	50	55	60	65	70
112S200W	0.1661	0.0000	0.0228	0.0453	0.0674	0.0893	0.1109	0.1322	0.1532	0.1739	0.1943	0.2144	0.2343	0.2538	0.2731	0.2920
112S340W	0.1386	0.0000	0.0193	0.0384	0.0573	0.0759	0.0945	0.1128	0.1309	0.1488	0.1666	0.1841	0.2015	0.2186	0.2356	0.2524
112S400W	0.1386	0.0000	0.0193	0.0384	0.0573	0.0759	0.0945	0.1128	0.1309	0.1488	0.1666	0.1841	0.2015	0.2186	0.2356	0.2524
112S500W	0.0971	0.0000	0.0128	0.0255	0.0380	0.0505	0.0629	0.0751	0.0873	0.0994	0.1114	0.1232	0.1350	0.1467	0.1583	0.1698
112T200W	0.1661	0.0000	0.0228	0.0453	0.0674	0.0893	0.1109	0.1322	0.1532	0.1739	0.1943	0.2144	0.2343	0.2538	0.2731	0.2920
112T340W	0.1386	0.0000	0.0193	0.0384	0.0573	0.0759	0.0945	0.1128	0.1309	0.1488	0.1666	0.1841	0.2015	0.2186	0.2356	0.2524
114A200W	0.2024	0.0000	0.0276	0.0547	0.0813	0.1075	0.1331	0.1582	0.1829	0.2071	0.2309	0.2541	0.2769	0.2993	0.3212	0.3427
114A340W	0.1687	0.0000	0.0232	0.0461	0.0686	0.0908	0.1127	0.1342	0.1555	0.1764	0.1970	0.2173	0.2372	0.2569	0.2763	0.2953
114A400W	0.1687	0.0000	0.0232	0.0461	0.0686	0.0908	0.1127	0.1342	0.1555	0.1764	0.1970	0.2173	0.2372	0.2569	0.2763	0.2953
114J200W	0.0855	0.0000	0.0114	0.0227	0.0339	0.0451	0.0561	0.0672	0.0781	0.0890	0.0997	0.1105	0.1211	0.1317	0.1422	0.1526
114J340W	0.0691	0.0000	0.0094	0.0188	0.0281	0.0373	0.0465	0.0557	0.0648	0.0739	0.0829	0.0919	0.1009	0.1098	0.1186	0.1274
114S200W	0.1661	0.0000	0.0228	0.0453	0.0674	0.0893	0.1109	0.1322	0.1532	0.1739	0.1943	0.2144	0.2343	0.2538	0.2731	0.2920
114S340W	0.1386	0.0000	0.0193	0.0384	0.0573	0.0759	0.0945	0.1128	0.1309	0.1488	0.1666	0.1841	0.2015	0.2186	0.2356	0.2524
114T200W	0.1661	0.0000	0.0228	0.0453	0.0674	0.0893	0.1109	0.1322	0.1532	0.1739	0.1943	0.2144	0.2343	0.2538	0.2731	0.2920
114T340W	0.1386	0.0000	0.0193	0.0384	0.0573	0.0759	0.0945	0.1128	0.1309	0.1488	0.1666	0.1841	0.2015	0.2186	0.2356	0.2524
120J200W	0.0855	0.0000	0.0114	0.0227	0.0339	0.0451	0.0561	0.0672	0.0781	0.0890	0.0997	0.1105	0.1211	0.1317	0.1422	0.1526
Pressurized Protected	0.1028	0.0000	0.0135	0.0269	0.0402	0.0534	0.0664	0.0793	0.0921	0.1048	0.1174	0.1299	0.1422	0.1545	0.1666	0.1786
Pressurized Un-Protected	0.2024	0.0000	0.0276	0.0547	0.0813	0.1075	0.1331	0.1582	0.1829	0.2071	0.2309	0.2541	0.2769	0.2993	0.3212	0.3427

APPENDIX C

QUANTITATIVE RISK ANALYSIS METHODOLOGY AND RISK MODEL

C.1 Risk Analysis Methodology

In this dissertation, I used the quantitative risk analysis (QRA) methodology (CCPS, 1995) to develop numerical estimates of the risk associated with the shipments considered. The QRA includes three principal stages: route analysis, determination of risk parameters, and risk calculation.

For the first stage, the preliminary shipment routes were determined using rail routing software, PC*Miler/Rail 13 based on the specified origin-destination (O-D). Geographic Information Systems (GIS) data layers were then obtained from BTS (2007) and ESRI (2005) and prepared using ArcGIS Desktop 9.2. These data layers include the 2007 U.S. and Canadian railroad network data and population census data. After the preliminary routes had been determined, the final shipment routes were created using ArcGIS.

The second stage involved the estimation of risk parameters. This consisted of two parts: the estimation of the annual frequency of accident-caused releases and the estimation of the consequences of the release. The former deals with the estimation of track-segment-specific tank car derailment and release rates. The latter involves the estimation of the consequence in terms of the number of people potentially affected by hazardous material releases.

The third stage was to determine the annual risk associated with hazardous materials shipments for each route and for all routes combined. The final risk output comprises the quantitative estimate of the various risk metrics.

C.2 Risk Model and Parameters

A formal definition of risk is the multiplication of the frequency of an event times the consequence of that event, i.e.

$$S = M R C \tag{C.1}$$

where

- S = annual risk of transporting product (persons affected per year)
- M = annual rate of tank car involvement in Federal Railroad Administration (FRA) reportable derailments on main-line track
- R = conditional probability of release given that a tank car derails
- C = consequence level, defined as the number of persons affected by releases

FRA track-class-specific accident rates (Anderson and Barkan, 2004) were used to determine the derailment rates. It was assumed that the likelihood of a hazardous materials car derailment is independent of the material being transported (Anand, 2006). Track speed reflects FRA track class, which has been shown to be correlated with railroad accident rates (Nayak et al., 1983). For the Class-1 railroads involved, their timetable speeds were used to infer the FRA track class and other operating restrictions for all segments of the routes considered. For the limited mileage of non-Class 1 railroads involved, the industry average derailment rate for this class of railroads was used (Anderson and Barkan, 2004).

Tank car design has a major effect on the conditional probability of release (CPR) given that a car is derailed in an accident, and the probabilities developed by Treichel et al. (2006) were used to determine the CPR of the tank cars considered. Release probability is also affected by train accident speed (Nayak et al., 1983; CCPS, 1995; Barkan et al., 2003; Kawprasert and Barkan, 2010a). Unless otherwise mentioned, the average-speed implicit in the statistics of Treichel et al. (2006) was assumed when calculating tank car performance.

In the case that multiple car types with different design features are involved, the aggregated CPR can be determined using the weighted mean of the different car types' conditional probabilities (Kawprasert and Barkan, 2008).

The consequence is the impact of the release and is generally affected by the characteristics of the product (e.g., its toxicity and reactivity), the atmospheric conditions, and the proximity of people to the spill. In this dissertation, the consequence is generally expressed as the number of persons who might be evacuated or sheltered in place as a result of a release, based on the recommendations in the U.S. Department of Transportation (DOT) Emergency Response Guidebook (ERG) (PHMSA, 2008; Brown and Dunn, 2007; Brown et al., 2009;). The

consequence here equals the affected area, which is defined as the minimum area in which the U.S. DOT recommends that people be evacuated or sheltered in place in a hazardous materials release incident, multiplied by the average population density in the affected area. For some materials, consideration of multiple-release scenarios may be necessary (Chapter 3). For the product studied in other chapters, only a single-release scenario was appropriate according to the industry expert opinion. In this dissertation, time-of-day effects on population were not considered for simplicity.

C.3 Risk Model Incorporating Segment-specific Parameters

Different levels of analysis can be considered depending on the degree of precision required. That is, accident rate and population density may be accounted for at the route level or the track segment level. This dissertation requires an analysis at the segment-specific level, and, thus, track-segment-specific parameters need to be incorporated in the risk model.

Track segments here correspond to the rail links in the railroad network data layer in the GIS database (BTS, 2007). Each link (segment) has a unique link ID assigned by the FRA in the rail network. For the shipment route comprising n segments, Eq. C.1 can be rewritten as:

$$S = V R' A \sum_{i=1}^n Z_i L_i D_i \quad (C.2)$$

where

- V = annual shipments (carloads)
- R' = aggregated conditional probability of release given that a tank car derails
- A = affected area per the U.S. DOT ERG recommendation
- Z_i = accident rate associated with track segment i
- L_i = length of track segment i
- D_i = average population density along track segment i
- n = total number of segments in the shipment route

C.4 Overlay Analysis Using GIS

The merit of using GIS to facilitate route analysis is that it enables the creation of maps to convey geographic information and results related to risk, in addition to its analytical power for handling the data needed for route risk analysis (Fedra, 1998). In this dissertation, I used ArcGIS

9.2 with the Network Analyst feature to create the shipment routes over the national railroad network (BTS, 2007) and population census tract layers (ESRI, 2005). A buffer was created representing the exposure area – the area within the radius from the track center equal to the U.S. DOT ERG maximum evacuation distance corresponding to the material and release scenario considered. Then, the average population density of the affected area corresponding to each track segment was determined (Figure C.1) using the following equations:

$$A = \pi E^2 \quad (C.3)$$

where

A = affected area per the U.S. DOT ERG Guidebook recommendation

$\pi \approx 3.14159$

E = the U.S. DOT ERG recommended evacuation distance for the worst-case release scenario

$$U_i = B L_i \quad (C.4)$$

where

U_i = exposure area, corresponding to track segment i

B = buffer width = $2E$

L_i = length of track segment i

$$P_i = \sum_t (\alpha_{ti} \delta_{ti}) \quad (C.5)$$

where

P_i = potential population exposure, corresponding to track segment i

α_{ti} = area of census tract t , coincident with the exposure area for track segment i

δ_{ti} = population density of census tract t , coincident with the exposure area for track segment i

$$D_i = \sum_t (\beta_{ti} \delta_{ti}) \quad (C.6)$$

where

D_i = Average population density, corresponding to track segment i

β_{ti} = proportion of the area of census tract t , coincident with the exposure area for track segment i

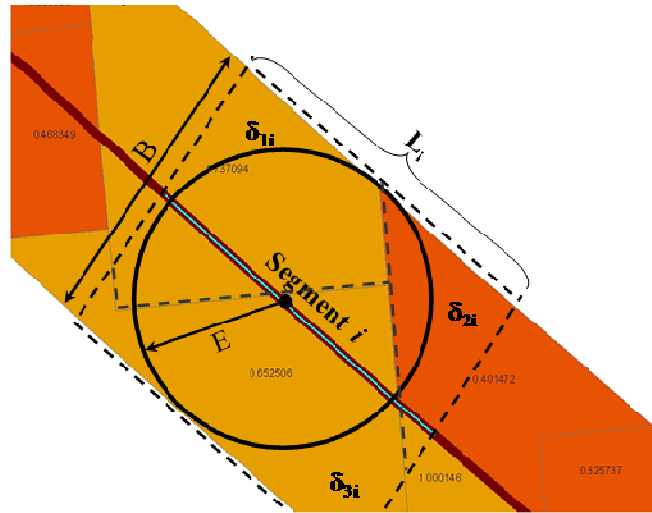


Figure C.1: Estimation of Consequence Using Overlay Analysis in GIS

AUTHOR'S BIOGRAPHY

Athaphon (Kwan) Kawprasert received a Bachelor of Engineering degree in Civil Engineering from Sirindhorn International Institute of Technology, Bangkok, in 1998, and a Master of Engineering degree in Civil Engineering from Asian Institute of Technology, Bangkok, in 2000. He came to the University of Illinois at Urbana-Champaign in August 2005 to pursue a graduate study towards a Ph.D. degree in Civil Engineering.

His research interests include hazardous materials transportation route risk analyses using a quantitative method, applications of operations research techniques to various options for hazardous materials transportation risk reduction, statistical analysis of hazardous material incidents, risk communication, and applications of Geographic Information System (GIS) to hazardous materials transportation problems. During his study, he engaged in hazardous materials transportation risk analysis projects supported by the Association of American Railroads, Monsanto, ICL Performance Products, and Visual Risk Technologies. He has published three articles in a peer-reviewed journal. He also presented his research at various national and international conferences, including the Transportation Research Board Annual Meetings, the International Heavy Haul Association Conference, the Institute for Operations Research and Management Sciences Meetings, and the American Society of Mechanical Engineers Joint Rail Conference.

Prior to joining the University of Illinois Railroad Research Program, he worked for one year as a civil engineer at ION Joint Venture for Bangkok Underground Blue Line Construction Project. Subsequently, he was employed at the State Railway of Thailand in the position of Engineer In-charge Permanent Way Design Section. During his four-year work at the State Railway of Thailand, he had participated in several design and construction projects, including Suvarnabhumi airport rail link feasibility study and detailed design, Bangkok commuter train – northern section detailed design, the new motorway to southern Thailand feasibility study and the railroad crosstie renewal projects. Considering that further study will be useful for his contribution to the development of rail system in Thailand, he then requested a study leave from the State Railway of Thailand in 2005.