Analytical Approaches to
Railroad and Rail-Truck Intermodal Transportation
of
Hazardous Materials

by

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TABLE OF CONTENTS

LIST OF FIGURES

Abstract

Hazardous Materials are potentially harmful to people and environment due to their toxic ingredients. Although a significant portion of dangerous goods transportation is via railroads, prevailing studies on dangerous goods transport focus on highway shipments. We present an analytical framework that incorporates the differentiating features of trains in the assessment of risk. Each railcar is a potential source of release, and hence risk assessment of trains requires representation of multiple release sources in the model. We report on the use of the proposed approach for the risk assessment of the Ultra-train that passes through the city of Montreal everyday. The risk assessment methodology is then used to model the operations of freight trains in a network, wherein freight involves both hazardous and regular cargo. We present an optimization model distinct from the conventional ones, a *Memetic Algorithm* based solution technique, and a number of scenarios intended to gain numerical and managerial insights into the problem. In an effort to combine the economies of trains and efficiencies of trucks, we deal with rail-truck intermodalism for hazardous and non-hazardous cargo. Two special cases and a general case of rail-truck intermodal transportation models, driven by the element of ***'time',*** are presented.

Résumé

Les matériaux dangereux sont potentiellement nuisants pour les gens ainsi que l'environnement en raison de leurs ingrédients toxiques. Bien qu'une portion significative du transport de marchandises dangereux soit effectuée via les chemins de fer, les études existantes sur le transport de matériaux dangereux se concentrent principalement sur les autoroutes. Nous présentons un cadre analytique d'évaluation de risque qui incorpore les caractéristiques uniques des trains. Etant donné que chaque wagon est une source potentielle de diffusion de produits toxiques, une approche d'évaluation du risque avec sources multiples est plus appropriée. Nous appliquons cette approche a un "Ultra-train" traversant quotidiennement la ville de Montréal. Nous proposons un modèle pour les opérations du train impliquant le transport des matériaux dangereux ainsi que réguliers. Nous présentons aussi un modèle unique, une solution technique basée sur un algorithme, et un certain nombre de scénarios permettant une meilleure compréhension du modèle. Dans un effort du combiner les économies associées à l'utilisation des trains ainsi que l'efficience des camions, nous proposons trois modèles de transport bi-modes par un "rail-truck" conditionnés par le facteur temps.

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EXPLANATION OF CONTRIBUTIONS

1. I am the sole author of Chapter 2-*Literature Review*.
2. Chapter 3 was written jointly with Professor Vedat Verter, and a paper based on this chapter is forthcoming in *Computers & Operations Research*.
3. Chapter 4 was written jointly with Professor Vedat Verter and Professor Michel Gendreau, but I am the first author with regards to the level of contributions to this work.
4. I am the sole author of Chapter 5-*Rail-Truck Intermodalism*.

CHAPTER 1

Introduction

Hazardous Materials (hazmats), an indispensable part of any industrialized society, are harmful to both the environment and human health since exposure to their toxic chemical ingredients may lead to injury or death. The *United Nations* recognizes the severity of the problem and expends efforts for minimizing risks associated with hazmats. The *Basel* Convention, adopted in 1989 by 105 countries, states the international consensus to minimize the generation of hazardous wastes. It also regulates the transboundary movement of hazardous wastes to secure their disposal under environmentally sound conditions. Vast amounts of hazmats are shipped from their points of origin, such as refineries and chemical plants, to their points of consumption such as manufacturing facilities, gas stations and homes. For example, the daily number of dangerous goods shipments in the United States amounts to well over 800,000, the number stands at 74,000 for Canada. Roughly 94% of the shipments in the United States and 92% in Canada are moved by trucks and freight trains.

Public and environmental mitigation (or elimination) of risk associated with these shipments has become a popular concern. Over the past two decades highway transportation of hazmat has received a lot of academic attention, as a result of which, a whole gamut of work has been done in this domain. Prevailing literature review show that an overwhelming majority of research on hazmat transportation focuses on road shipments (Erkut et al. (2005)), (Erkut and Verter (1995)), (List et al. (1991)). Although trucking companies do carry a larger share of dangerous goods shipments in many countries, railroad shipments can easily reach comparable levels. In Canada, for example in 2000, 48 million tons of hazardous freight was carried via rail while 64 million tons was shipped via trucks.

Railroad transportation, despite the comparable volume in Canada, saw very few academic works. Most of these works were in the area of accident rate analysis, which in turn facilitated better collision-impact forecasting and safer tank car design. Although the proprietary nature of the railroad industry precludes a definitive statement about intra industry research endeavors, but given the formation of an intra-industry task force it would be reasonable to presume that hazmat related projects were undertaken.

The potential for spectacular accidents, public sensitivity, and presence of multiple stakeholders driven primarily by the perception of risk, make hazmat decisions extremely difficult. The risk averseness of individuals and inadequate information about actual risk invariably results in a higher perceived risk quotient than what would be (objectively) assessed by experts. Inequity in the distribution of risk associated with hazardous facilities and hazmat movements also contribute to public sensitivity.

My *Doctoral Thesis* addresses sources and mitigation of hazmat Risk. Two major inland uni-modes, trucks and railroads, and their intermodal combination are considered as sources of transportation risk. While Chapter 2 reviews the work relevant to hazmat logistics, each individual chapter reviews pertinent works **not** reviewed in chapter 2. The chapters in the thesis are organized as follows:

Chapter 2 presents a comprehensive literature review of every aspect of hazardous materials logistics. This review enabled us to get an understanding of what has been done, and what else could be done in order to mitigate hazmat risk. The environmental and societal impact of hazmats necessitates an appropriate understanding of the types and source of risk, and the steps involved in the risk assessment process. Fixed facilities and inland transportation modes are the two sources of risk discussed in detail. The former is generally relevant due to the nature of hazardous processing units; for us its relevance stems from the handling of containers (loading units) with hazardous cargo at transfer / connection points such as marshalling yards, multimodal facilities, etc. Inland transportation, via trucks and railroads, is the other source of risk. As alluded to earlier, these two modes together are responsible for moving the bulk of hazmat shipments in both Canada (92%) and the United States (94%).

Numerous research possibilities in hazmat transportation were brought to light as a result of the literature review. Some noteworthy conclusions are: relative dearth of research in the area of railroad compared to trucks; absence of a robust and a priori risk assessment methodology for trains; no consensus on the safety of truck and railroad as hazmat transportation mode; no concrete relationship between hazmat volume and resulting consequence; and, impact of atmospheric stability categories on non-uniform consequence zones. In addition, there was not a single work addressing the intermodal transportation of hazardous materials. This is a rapidly growing area of railroad revenue, and one that deserves increased academic research attention. The next three chapters are motivated by the desire to fill the aforementioned gaps in hazmat transportation literature.

The **first** research question is: *"Develop a risk assessment methodology for train transportation of hazardous materials, one that can capture the distinct features of railroad operations."*

Chapter 3 reviews the relevant works and develops a risk assessment methodology for train transportation of Hazmat, and answers the first question. This methodology is not a straightforward adaptation of the approach developed for highway transportation, since it captures the differentiating features of railroads viz. higher volume, potential of multiple sources of release, etc. and the effect of atmospheric stability categories. *Gaussian Dispersion Model* is used to estimate the concentration of airborne hazmats at different points in the network. Instead of the traditional measure of transport risk, a more aggregate measure, viz., *population exposure* is proposed in this chapter. The proposed model estimates the exposure zone around the railroad as a function of volume (and type) of hazmats on the train, and hence extends the fixed bandwidth approach to risk. A railcar referencing mechanism is presented to effectively capture the nature of the train accidents, viz., multiple sources of release. Several numerical analyses were conducted to validate our insights into the nature of railroad transportation risk. An approximation method, that is computationally efficient and robust to both train design and atmospheric stability categories, is presented to ease the computational complexity. An immediately dangerous to life and health *(IDLH)* approach to demarcate non-uniform consequence areas in the exposure zone is proposed. *GIS ArcView* environment was used to report on an application of our methodology to a real life case in Montreal.

The **second** research question is: *"Given the risk assessment methodology developed earlier and a realistic railroad operation, conceptualize and develop an optimization model and a solution methodology to enable railroad transportation of both hazardous and non-hazardous materials."*

In *Chapter 4*, the risk assessment methodology (developed in chapter 3) is used to model the operations of freight trains in a network, wherein freight involves both hazardous and regular cargo. A literature review of relevant work not discussed in the earlier chapters is provided. A bi-objective tactical planning model with *risk* and *cost* objectives is developed, wherein risk calculation is inspired by our earlier work and cost coefficients reflect a distinct characteristic of railroad industry, notably *economies of scale.* This optimization model decides the traffic-routings of individual railcars from their origin to destination yards, and the number of freight trains of different types required in the network. The structure of the model, quite distinct from the conventional models, necessitated the development of a heuristic solution technique. A *Memetic Algorithm* based solution methodology was developed to solve a realistic-size railroad industry problem. We report on the algorithmic efficiency of the model, and make use of seventeen scenarios to present results and managerial analysis aimed at gaining numerical insights. A *Quasi-Pareto* frontier on which each point contains a set of traffic-routings, blocking/transfer activities at different yards, and train frequency for different services, is presented.

The contributions of this chapter are four-fold: ***first***, it is the only work that makes use of population exposure as a measure of risk in context of railroad transportation of mixed freight; ***second***, it is the first work that proposes a risk-cost optimization model to determine the railcar routing, marshalling activities at different yards; and, frequency of different trains; ***third***, it is the only work that builds a *Quasi-Pareto* frontier, for railroad operations, using *Memetic*

Algorithm based solution methodology; and ***finally***, the only work that compares the "cost-risk" effect accruing from railroad transportation of propane and chlorine as the hazardous cargo in a mixed freight.

Although studies comparing the safety of railroads and trucks for transporting hazardous materials do not arrive at a conclusive result, one can conceive of combining the advantages of these two modes. Intermodalism, movement of freight on more than one mode, accounts for 17% of rail revenues in both Canada and the United States. This is a nascent but promising area of research that has sustained an impressive growth over the past twenty-five years.

The **third** research question is: *"Is it possible to combine the advantages of more than one mode to move dangerous goods shipments?"*

Chapter 5 endeavors to answer this question. This chapter combines the efficiency advantage of trucks with the economies advantage of trains, in order to yield an intermodal transport chain that is better than the two uni-modes. The chapter describes an intermodal transportation system, and underlines its importance in the current global market. A medium size illustrative example is used to explain the workings of rail-truck intermodalism, and to demonstrate the usage of intelligent enumeration to solve mixed freight supply-demand problem. A risk-cost tradeoff analysis based on the dimension of time-elapsed is presented, where the element of ***time*** drives the evaluation. Three distinct cases of rail-truck intermodal transportation system are presented, and corresponding mathematical models developed. We contrast the general case model with the tactical planning model developed in the previous chapter, and propose the development of a different solution technique.

The contributions of this chapter are four-fold: ***first***, it studies an unstudied problem in intermodal literature; ***second***, builds a rail-truck intermodal realistic-size case example for evaluation and analysis; ***third***, presents the risk-cost tradeoff driven by the element of 'time'; and ***fourth***, presents a mathematical model to capture the time-based rail-truck intermodal movement of hazardous and non-hazardous intermodal units (IMUs).

In *chapter 6*, we conclude the thesis and outline the possible directions for future research.

Appendices contain *Appendix-A* for Chapter 4 and *Appendix-B* for Chapter 5. These two appendices contain the auxiliary details to support the explanation and analysis provided in the body of the two chapters.

CHAPTER 2
Literature Review–Hazardous Materials

2.1 Introduction

Hazardous Materials (hazmats) by nature and composition pose risk, and hence any risk mitigation effort has to be preceded by a proper understanding of the specific-context and dimensions involved. Hazmats impact both the environment and the society, which necessitates an appropriate understanding of the types and sources of risk, and the steps involved in the risk assessment process. We review works relevant to hazardous materials logistics in this chapter, and it has been organized as follows. Section *two* postulates a few popular definitions of risk and delineates the various steps involved in the risk assessment process, and a literature review on risk. The next three sections present the literature review of the two sources of risk, viz., *fixed facility* and *transportation*. Section *three* contains the fixed facility location literature review, since handling of hazmat containers at transfer facilities at transfer points (e.g. railroad marshalling yards, intermodal terminals, etc.) pose risk to the surrounding population, and hence is a source of risk. Sections *four* and *five* present the literature review on *inland* transportation as the source of risk. In North America, trucks and trains account for 94% of hazardous materials shipments. A detailed literature review discerns an abundance of research in the truck transportation, a relative dearth in railroad shipments of hazardous materials, and nothing in the arena of rail-truck intermodalism. The latter two presented us with an opportunity to contribute towards the evolution of the discipline. The conclusion in section *six* provides a natural transition to the subsequent chapters.

2.2 Risk

Risk could be defined as a characteristic of a situation or action wherein two or more outcomes are possible, the particular outcome that will occur is unknown and at least one of the possibilities is undesirable. Hence risk is at minimum a two-dimensional concept involving: the possibility of an adverse outcome, and uncertainty over the occurrence, timing, or magnitude of that adverse outcome. Risk is said to be present when there is a source of risk, an exposure process and a causal process.

Defining risk as the product of probability of a release event and consequence magnitude of that event is slightly more common than defining risk as just a probability or magnitude of consequence. This definition is appropriate only if a single release event is possible, such as single shipment of hazmats between an origin and a destination pair. In the case of multiple shipments, or the operation of a hazardous facility, the expected total consequence of all possible incidents needs to be computed. A non-traditional definition of risk, propositioned by the *Nuclear Regulatory Commission*, is by envisioning a model that is assumed to behave similarly to the system under study and computing the frequency with which the model predicts various outcomes. The term risk is used to describe the model results, and the term uncertainty is used to characterize the degree of confidence in the results based on the confidence in the model.

In the realm of hazardous materials logistics, risk is a measure of the possible undesirable consequences of a release of hazmats during their use, storage, transport or disposal. The release event can be caused by an accident-*accident risk,* or due to leakage from a hazmat container (or toxic emissions from a hazardous waste incinerator)-*exposure risk.*

2.2.1 Risk Assessment - Concepts

Covello and Merkhofer (1993) define risk assessment as a systematic process for describing and quantifying risks associated with hazardous substances, processes, action or event. According to Moore (2000) risk assessment consists of risk analysis, risk communication and risk management. According to Alp (1995) risk assessment involves estimating three elements: probabilities or expected frequencies of undesirable events, consequences to people of these undesirable events, and the associated risk in quantitative terms. According to Erkut and Verter (1995) the major components of risk assessment are: incident probabilities, the consequence of each incident and the volume of activity.

According to Van Steen (1987a) risk analysis usually involve description of the system under consideration, identification of undesirable events, calculation of the effects of the release of hazardous materials, translation of the effects into fatalities and injuries and into damage to buildings and installations (damage calculations), and quantification of the probabilities with which the damages calculated can occur.

Broadly Risk-Assessment can be broken down into five inter-related but conceptually distinct steps: *hazard / receptor identification, release assessment, exposure assessment, consequence assessment and risk estimation*. Each step is briefly described below (For a detailed description of all these methods see: Verma (2002a)).

2.2.1.1: Hazard / Receptor Identification

The first step in public safety risk assessments is the identification of hazards that are of relevance, and the critical receptors who might be exposed to these hazards. Hazard identification refers to identifying the potential sources of release of contaminants into the environment, the types and quantities of compounds that are emitted or released, and the potential health and safety effects associated with each substance.

2.2.1.2: Release Assessment

Release assessment consists of describing and quantifying the potential of a risk source (which could exist in different forms) to release. Some common release methods are *monitoring*, *performance testing & accident investigation*, *statistical methods*, *fault/event tree analysis*, *component-failure and initiating-event model,* etc.

2.2.1.3: Exposure Assessment

Exposure Assessment is the process of measuring or estimating the intensity, frequency and duration of human or other population exposures to risk agents. Some of the noteworthy models for exposure assessment are: *atmospheric models*, *surface-water models*, *groundwater models*, *watershed runoff models*, etc.

2.2.1.4: Consequence Assessment

It consists of describing and quantifying the relationship between specified exposures to a risk agent and the health and environmental consequences of those exposures. A few important models used for assessing consequence are: *monitoring/screening methods for assessing health consequences, controlled human exposure studies, animal research for assessing health consequences*, etc.

2.2.1.5: Risk Estimation

Individual risk is estimated by multiplying the effect probability with the associated frequency of occurrence of that hazard. It is expressed in units of chances of an exposed individual to be affected due to the hazard in question during the period of exposure. For linear risk sources like transportation corridors (as opposed to point risk sources such as fixed transportation facilities, such as loading/unloading terminals or rail-marshalling yards), the individual risk must be calculated using a receptor-based integration along the length of the corridor separately for each hazard.

Societal risk is calculated for each segment of uniform accident environment and uniform population density, and the segment societal risks are summed to arrive at the total network societal risk. *Composite Risk Models* estimate the outcomes of a risk and associated probabilities. *Classical* and *Bayesian Methods*, use objective and subjective probabilities respectively, to estimate risk.

2.2.2 Literature Review

Abkowitz and Cheng (1989) identified statistical inference as the most commonly used procedure for estimating risk. This technique presumes that sufficient historical data exist to determine the frequency and consequences of the release incidents, and that past observations can be used to infer future expectations.

Glickman (1991) points out that the major risk of transporting hazardous materials by truck, or by any other mode of transportation, for that matter, arises from the consequences of releases that can occur either on route segments or during loading /unloading. Traffic accidents and container failures are the two major contributors to the expected consequence of a release on a route segment, which in turn impact society (surrounding community) and hence raise the issue of societal risk. He suggests that the *risk-estimation* process could be expedited by basing assessment on existing experience and observations like the *Batelle* Report.

Erkut and Verter (1995) suggest aggregating individual risk to determine societal risk. The societal risk determined can in turn be used as input for analytical models in hazmat logistics decisions. In this work, societal risk is expressed as a product of the individual risk and the population size, given that each individual in a population center incurs the same risk. Individual risk is a conditional probability function of accident, release, incident and fatality.

Another approach to model risk is by just concentrating on minimizing accident probability in designing hazmat management systems. Yet another approach could be to use the threshold-distance model to find origin-destination routes for hazmat shipments, doing so minimizes the number of people exposed to transport risks. Proponents of the latter approach claim that, with its emphasis on population instead of accident probabilities, this measure is suitable for modeling the exposure risk as perceived by the people living near potentially hazardous activities. Exposure minimization may in turn result in the minimization of public opposition.

In spite of its widespread use, the traditional expected consequence representation of risk is deemed inappropriate for hazmat logistics since it implies a risk-neutral public. Most human beings are averse to risk. Hence a complete and realistic representation of risk would require the use of a *risk profile*, which is a cumulative distribution function of the random consequences of a potentially hazardous activity.

The *risk-disutility* model can be used to address the issue of risk aversion. A high value of the risk-aversion parameter will force the model to select road-segments with low population densities, thereby reducing undesirable consequence in the case of an accident. However, increasing the aversion parameter does not necessarily result in a reduction in the total number of people placed at risk during the transport. Abkowitz et al. (1992) suggested modeling (the perceived) risk by using a risk-preference parameter.

The traditional representation of risk is also inappropriate for the case involving multiple hazmat shipments between an origin and a destination. The fact that subsequent shipments, are likely to be suspended to allow for a re-evaluation of the routing policy when a catastrophic accident occurs during the transportation of an extremely hazardous substance, is not captured in the traditional representation of risk. Jin (1993) studied alternate risk measures such as the expected total consequence, given that shipments will continue until a threshold number of accidents occur or a fixed number of shipments are completed. She viewed each shipment as a probabilistic experiment and observed that the number of accidents in a finite number of shipments is binomially distributed. Traditional risk model ignores the safety measures, taken by the communities around a potentially hazardous activity, to mitigate the undesirable consequences of release accidents.

According to Kaplan and Garrick (1981), the notion of risk involves both uncertainty and some kind of loss or damage that might be received, and is subjective to the observer. They propose a triplet function: *scenario identification*, *probability of occurrence* and *the related damage*, to define an *individual risk-curve*. They did not define risk as the product of probability and consequence. They correctly observed that doing so equates low probability–high consequence scenario with high probability–low consequence scenario, which is clearly not the same thing.

Slovic et al. (1984) focus on societal impacts, i.e., the relative weighting of multiple-fatality accidents. In their view social response to multiple-fatality accidents does not reflect risk aversion. They contend that because people view these risks (e.g. nuclear reactor accidents) as unknown and possibly immense, they react strongly to actual and potential accidents. Moreover, the ability to draw conclusions from these results is limited by catastrophic potential and imprecision of the events.

In the last few years another line of risk-research has come to light. This is based on the dispersion of toxic gases from a potential spill or release. The convention is to use air dispersion models to compute air-concentration levels of the released substance. Air dispersion models, its application for hazardous materials, and relevant literature are reviewed in chapter 3.

2.3 Location (Siting)

Although the potentially hazardous facilities are undesirable from a public and environmental safety viewpoint, their services e.g. production of gasoline, or safe disposal of the nuclear and other hazardous wastes, are imperative for our contemporary lifestyle. The first step in designing such a facility is the identification of the geographical region it will serve, which is followed by the estimation of the types and volumes of the hazmats to be dealt with. Given the service area and the type of service to be provided, facility planning involves decisions regarding number, location, size of the facilities, technology to be used at each facility, as well as the service areas for each facility. The designed system must have sufficient capacity to serve the region, and the service should be provided with minimum possible adverse impacts and cost.

Minimization of total *cost and risk*, and maximization of *equity* are the primary objectives of the design problem. Planning could make use of multi-objective mathematical programming models or multi-criteria decision analysis techniques. Thanks to public sensitivity over locating obnoxious facilities, siting decisions of hazardous facilities has received much more attention in the academic literature than other configurational decisions. Location of a facility and toxicity of the materials used in the facility, are significant determinants of facility risk.

Boffey and Karkazis (1993) attribute *asymmetry* (hazmat does not hold any benefits as does other materials); *complexity* (a typical hazardous materials situation will involve aspects of cost, risk and a variety of stakeholders); and, *recency* (is still a nascent area) to be some of the reasons to explain the erstwhile dearth of attention on hazmat research.

Location literature dealing with obnoxious facilities is relevant to hazardous materials. Obnoxious facility location decisions aim to minimize the negative impacts of these facilities on the surrounding population and environment; and can be viewed as a two-step process. The *first* involves screening of potential sites and terminates with the identification of the set of candidate locations, while the *second* carries out a comparative evaluation of the candidate locations and terminates with the selection of the location(s) to be used.

Obnoxious Facility Location literature can be broadly divided into single criterion and multi-criteria models. *Single-criterion models* seek to optimize some function of the distance between the facility location(s) and the surrounding problem. *Multi-criteria models* incorporate conflicting criteria into the obnoxious facility location decision-making process. Two distinct categories of such models exist. *Multiattribute decision analysis* models are used when the evaluation process for the selection of the best site is based on a small number of alternative sites e.g. nuclear power plants / waste disposal sites, energy facilities etc. *Multiobjective* models are used when the number of feasible alternative locations is large.

Single-Criterion Models

Erkut and Neuman (1989) suggest that a planner should optimize an aggregate measure containing the weights of the population centers and their respective distances from the obnoxious facility. On the other hand the users may want to maximize the distance from the facility and would be content with anything, which is fair or equitable to other individuals. Erkut and Neuman (1991) compared single-criterion models for locating undesirable facilities. Here the facilities are located relative to each other and not based on the demand points. Four different, but related, objective functions were examined in order to determine the difference between their solutions. List et al. (1991) suggest that given a set of potential locations for siting facilities, a network that provides routes to these sites, and an underlying set of zones; select that site(s), which provide sufficient capacity to perform all the processing required and minimize the adverse impacts that result.

Multi-Criteria Models

Cohon et al. (1980) included a non-cost objective in the multiobjective linear programming model, formulated to select sites, types and sizes of power plants. The population impact objective minimizes the sum of all populations within a specified distance of a selected nuclear power plant location. The size of the problem and an enormous number of efficient solutions, force the authors to generate only a very coarse approximation of the efficient set. Erkut and Neuman (1992) proposed a three-objective mixed-integer programming formulation to address the problem involving a region, which must build one or more undesirable facilities. Two of the 3-objectives, viz. minimizing total opposition and maximizing equity, were based on the notion of disutility.

In a qualitative paper Morell (1984) points out that perceptions of injustice and unfairness drive public opposition to undesirable facility siting proposals. He suggests simultaneous siting of multiple facilities to address the equity issue. Rahman and Kuby (1995) adopted the attitudinal approach to model public opposition. Here probability of opposition was inversely related to distance using a logit function. However they could not discern the effect of public opposition on facilities size and could not work on the concept of location-equity. Ratick and White (1988) used a three-objective model to capture public opposition as a function of the scale of the undesirable facility. They concluded that building several smaller facilities would invoke less opposition than building a few very large ones.

Voluntary-Siting seems to be the most effective approach in mitigating the public opposition to hazardous facilities. This approach makes use of compensation packages to make the obnoxious facility attractive rather than undesirable for the host community. One way to protect people from adverse impacts is to ensure that facilities are no closer than a threshold distance. A more common approach is to maximize some function of the distance between the facilities and the population centers. Church and Garfinkel (1978) determine a point on the network, which maximizes the weighted sum of distances along the network links to all points of interest. Dasarathy and White (1980) maximize the minimum Euclidean distance from the point selected to all other points of interest. Erkut and Verter (1995) incorporated public opposition function, in terms of system risk and equity in the objective function, to decide on the siting decision of a hazardous facility.

ReVelle et al. (1991) used a two objective formulation to decide the siting and routing of hazardous waste. A tradeoff curve is generated between ton-miles and tons-past-people and any point on this frontier represents a compromise between two objective values. Jennings and Sholar (1984) present a model that uses risk penalty functions for the external impacts due to shipment, treatment and disposal. Helander and Melachrinoudis (1997) propose an integrated model for siting and routing, since it is difficult to separate one from the other.

An analytical detail of the *single-facility* and *multi-facilities* (Karkazis and Papadimitriou 1992) models is available in Erkut and Neuman (1989). The studies of Dasarathy and White (1980), Drezner and Wesolowsky (1980) and Melachrinoudis and Cullinane (1985) fall under single-facility category. Church and Garfinkel (1978), Minieka (1983), Hansen et al. (1981) and Drezner and Wesolowsky (1988) studied the multi-facilities category.

A couple of works indirectly related to location are reviewed hereafter. Mirchandani and Rebello (1995) suggest a formulation to decide on the optimal location of inspection stations along the links of the network with the objective of intercepting as many trucks (violating hazmat regulations) as possible. Non-linearity in the problem structure necessitated solving it using a greedy heuristic. Toland et al. (1998) detail few remedial measures for Department of Energy (DoE) once hazmat reaches the processing facility.

A brief evaluation of the work done on obnoxious facility location points out the little attention paid to the *quantification of equity*. Most researchers have accepted that the center and covering models are adequate for the modeling of equity. Although these models deal with minimizing the maximum distance, or assuring that no distance exceeds a set standard, but are not directly concerned with the relative distribution of the distances. In addition not much work has been done to establish the inequality measures for obnoxious facilities.

2.4 Truck Transportation

Highway transportation involves trucks. Trucks could be for-hire or privately owned. Trucks, not constrained by waterways, rail tracks, or airport locations, have potential access to almost every origin and destination. The accessibility advantage of motor carriers is evident in the pick-up or delivery of freight in an urban area. Another service advantage of the trucks is speed. When compared to the rail car and barge, the smaller cargo capacity of the truck enables the shipper to use the truckload rate, or volume discount, with a lower volume. The smaller shipping size of the trucks provides the buyer and seller with the benefits of lower inventory levels and inventory carrying costs. The small size of most carriers has enabled them to respond to customer equipment and service needs. These are some of the factors, which make trucks the major haulers of hazardous (or regular) traffic, and in turn explain the research focus on highway shipments.

Erkut et al. (2005) provide a comprehensive account of the work done in hazardous materials transportation to date, and is a very valuable reference material. Erkut and Verter (1995) presented a bi-objective model, which minimizes transport cost and risk. They also listed the different risk-models viz. traditional, population exposure, incident-probability, perceived and conditional risk. Kara and Verter (2001) proposed a bi-level formulation to focus on the nature of the relationship between the government and the carriers. The problem involves selecting the road segments that should be closed to hazardous traffic (minimize risk), and then let the carrier choose the best path on the remaining network (minimize cost).

Batta and Chiu (1988) analyzed a local routing problem (minimum exposure, consequence and weighted-length) where the population is continuously distributed both along the transport links and at the nodes. Saccomanno and Chan (1985) pointing out the relevance of multiple objectives in hazmat transportation, used a shortest path algorithm to identify the best route under three strategies minimizing truck operating cost, accident likelihood and risk exposure. A multi-objective study done by Robbins (1985) found a weak relationship between route length and population exposure. Zografos and Davis (1989) used the goal programming technique to solve the local route-planning problem, with *population risk*, *special population-risk*, *property damages* and *travel time* as objectives. Although goal programming offers considerable flexibility to the decision-maker by changing the goal attainment levels and the associated priority, it can lead to the acceptance of inferior solution if the attainment levels are dominated. Klein (1991) suggested using fuzzy sets for the incorporation of imprecise information (tiding over reliable estimates issue) in the logistics model.

A recent trend in hazmat routing is the integration of analytical approaches with the databases containing population, road and toxic substances data, and geographical information system (*GIS*). This significantly enhances the data input and solution output stages in the decision process. Abkowitz et al. (1992) developed HazTrans (software) that incorporates shipping distance, travel time, accident probability, population exposure and expected consequence, in facilitating the local routing decisions. Glickman (1994) presented PC-HazRoute, a decision support system, to solve the local routing problem, which incorporates shortest path, population exposure, accident probability, societal risk and user-defined risk path as different criteria. Boffey and Karkazis (1995) described two models for hazardous routing. A condition is derived which if satisfied ensures that the linear model and the non-linear model generate the same solution path and if not satisfied, provides a strategy for obtaining the optimal solution to the non-linear problem.

McCord and Leu (1995) solved the multi-attribute utility of a single shipment cost-exposure, hazmat optimal routing problem, by using shortest path algorithm (minimum dis-utility). Further research is warranted if one wishes to extend the suggested methodology for multiple shipments, and attributes other than cost & exposure. Current et al. (1988) proposed a bi-objective (population cover & shortest path) formulation that yields a trade-off curve connecting predetermined origin-destination pair.

Abkowitz and Cheng (1988) present a formulation which models cost and risk. They estimated risk using direct and indirect measures, whereby the former occurs at the accident site and the latter in the surrounding vicinity. Relative weights were used to combine fatalities, injuries and property damage into a single overall measure of risk, which was then traded off against transportation cost to identify *Pareto* optimal routes for individual origin-destination pairs. Cox (1984) was probably one the first few to apply, multiobjective shortest path algorithm using a node-labeling method to solve a hazmat routing and scheduling problem.

All the models reviewed until this point, assume un-capacitated network links. This assumption leaves open the possibility that a small number of network links will carry a large fraction of all hazardous materials shipments. An immediate result of such a routing procedure is the assignment of risk to the population residing along the links. Thus these models fail to capture equity in the distribution of risk. The work of Zografos and Davis (1989) incorporates the aspect of equity by imposing capacity constraints on the network links in the multi-criteria formulation. Gopalan et al. (1990) tackled equity by a formulation which finds a minimum total risk set of specified-routes such that the maximum difference in risk between any pair of zones is below a specified bound. Lindner-Dutton et al. (1991) opine that when several routes are being used it is equitable to spread risk fairly over time and space.

Sivakumar et al. (1995) proposed a conditional risk model, which determines a path that minimizes risk given that an accident occurs. Routing shipment on this path continues until the occurrence of the first accident, at which time re-evaluation of the routing policy takes place. Sherali et al. (1997) attempt to reduce the risk of low probability-high consequence accidents, by minimizing the conditional expectation of a catastrophic outcome. They concluded that route selection should minimize the risk of multiple-fatality accidents by avoiding situations where the most lethal combination of risk factors is present. Nembhard and White III (1997) determine a path(s) that maximizes a multi-attribute, non-order preserving value function. It is a preferred path based on transportation cost and risk to population.

List and Mirchandani (1991) assume that the impact to a point of concern from a vehicle incidence is proportional to the volume and inversely related to the square of distance. Computational ease was achieved by aggregation, which may compromise estimation when done at second and third order moments. Jin and Batta (1997) derive 6 objectives for routing hazardous material by viewing shipments as a sequence of independent Bernoulli trials. The purpose of this work was to present a probabilistic perspective to hazmat routing and illustrate some meaningful objectives derived from such modeling.

Boffey and Karkazis (1993) proposed a formulation for routing hazmat vehicles and observed that minimization of risk, by restricting the arcs that can be used should be the principal objective. An implicit assumption here is the uniform accident probability along the arc, which was argued against by Batta and Chiu (1988). However, the problem can be tackled by splitting the arc into subsections for which uniform probability assumption will be reasonable. Cox and Turnquist (1986) considered routing & scheduling of hazardous materials shipments in the presence of curfews. Helander and Melachrinoudis (1997) used path reliability measure to derive the expected number of accidents over a given planning horizon, where reliability refers to the probability of completing a journey without accident.

Most models that find the least-risk route for obnoxious vehicles are non-linear and are linearized through approximations. These approximations are applicable when the risk is low say 0.0001%, but not when risk is much higher where the model remains non-linear. Marinov and ReVelle (1998), making use of probability of survival on each arc of the route, propositioned a linear, non-approximated model for routing obnoxious vehicles. The goal here is to protect the vehicle from the environment, from some specific danger, which may depend on the route taken by it. Wijeratne et al. (1993) developed a stochastic multiobjective shortest path algorithm to find a set of non-dominated paths from an origin to a destination in a network where links have several attributes, some or all of which are stochastic. Turnquist (1987) used a simulation approach to investigate the effect of stochastic link attributes on routing.

In conclusion, there is no dearth of research done in the area of highway transportation of hazardous materials. It has consumed the interest of researchers from a number of fields over the last two decades. In spite of this much activity in this arena, a concerted effort is required in addressing the issue of '*risk-equity*' and '*risk-quantification*'. Although these two issues have been dealt with, the results and analysis are tenuous to number of shipments or dollar figures. A more concerted and unified approach on the part of academics would be required to address the aforementioned issues.

2.5 Railroad Transportation

For nearly a century railroads have commanded a dominant position in the U.S. transport system, though it lost some market share to the alternate transport modes (motor carriers, pipelines and maritime) in the late 70's / early 80's. In an attempt to regain traffic lost to these modes, railroads have been placing an increasing emphasis on equipment and technology. Most recent figures show a consistent increase in the rail intermodal traffic. Furthermore they have invested a significant amount of money recently in improving right-of-way and structures to help improve service by preventing delays. The evolution of tank-car design resulted in more durable and robust tank cars. Railroads own very few tank cars, almost 99% are owned by leasing companies or shippers. The U.S. Department of Transportation (DOT) establishes regulations for the specifications of tank cars intended for the movement of hazardous materials.

On an average 10% of railroad freight consists of hazardous materials, and 99% of them reach their destination without incident. Rail is by far the safest way to transport hazardous materials. The *AAR* (Association of American Railroads) in the U.S. and the *RAC* (Railway Association of Canada) is involved in cooperative efforts to further improve the rail industry's safety record. An *inter-industry rail safety task force* comprising of the chief executives of major railroads, chemical manufacturers and tank builders has been set up to ensure the safe transportation of hazardous materials.

Prevailing literature review show that an overwhelming majority of the research on hazmat transportation focuses on road shipments (List et al. (1991)), (Erkut and Verter (1995)). Although trucking companies do carry a larger share of dangerous goods shipments in many countries, railroad shipments can easily reach comparable levels. In Canada, for example, 48 million tons of hazardous freight was carried via rail while 64 million tons was shipped via trucks in 2000 (Transport Canada (2002-03)). There are a number of factors that differentiate rail transport from truck shipments. A train usually carries non-hazardous and hazardous cargo together, whereas these two types of cargo are almost never mixed in a truck shipment. A rail tank-car has roughly three times the capacity of a truck-tanker (80 tons and 25-30 tons respectively) and the number of hazmat railcars varies significantly among different trains.

Empirical evidence suggests that trains have lower accident rates than trucks (Saccomanno et al. (1990)). Train accidents, however, can have much worse consequences due to the higher amounts of hazmats involved and the interaction between railcars. A well-known example is the 1979 accident in Mississauga, Ontario, when a train carrying toxic chemicals derailed and chlorine leakage from damaged tank cars forced the evacuation of 200,000 people (Swoveland (1987)).

Although a large number of researchers have studied railroad transportation system, the literature on the use of trains for dangerous goods shipments is rather sparse. Early work on railroad shipments focused on the impact of spills within one mile around the accident site.

Analyzing past data on train derailments, Glickman and Rosenfield (1984) derived and evaluated three forms of risk. These are probability of the *number of fatalities* in a single accident, probability of the *total number of fatalities* from all the accidents in a year, and *frequency of accidents* which result in any given number of fatalities. Glickman (1983) showed that rerouting of trains with (or without) track upgrades can reduce risk. The trade-off between the societal and individual risks of hazmat shipments is addressed in Saccomanno and Shortreed (1993). Davies and Lees (1991) contended that two types of freight train accident data, *collisions* and *derailments*, are required for the hazard assessment of the transport of hazardous materials by rail. Both pieces of data are not easy to obtain, and the ones authors got hold of did not form a meaningful sample-size to facilitate scientific conclusions.

Dennis (1996) presents a calculation of risk costs per unit of exposure for major hazardous materials releases involving railroad transportation. Risk costs are the incremental costs incurred by railroads as a result of the presence of hazardous materials. The study, using 10 years of risk cost and related data, indicated a variance in the risk costs per unit of exposure among commodity groups. The risk costs per unit of exposure for the most hazardous commodities can represent more than 13 percent of the cost of a typical movement.

More recent work focused on the comparison of rail and road shipments in terms of transport risk. Glickman (1988) concluded that the accident rate for significant spills (when release quantities exceed 5 gallons or 40 pounds) is higher for for-hire truck tankers compared to rail tank cars, whereas rail tank cars are more prone to small spills. Saccomanno et al. (1990) pointed out that differing volumes complicate comparison between the two transport modes, and showed that the safer mode varies with the hazmat being shipped. Purdy (1993) presents the results of the study, conducted in Great Britain, to compare *societal-risk* of transportation of dangerous goods by road and rail. The case study for chlorine concluded that road was safer for moving large hazard ranges while rail was safer for smaller hazard range. This conclusion is skewed due to a common factor in British transport systems: most the rail system was built over 100 years ago and was intended to go from town to town while the major roads have been built over the past quarter century and have been specifically routed to take traffic away from population centers. It is not surprising that latter results in lower societal-risk compared to the former. It would be possible to construct a route, which would be more favorable to rail.

Purdy et al. (1988) describe the models developed to analyze the level of *Societal Risk* arising out of the transport by rail of chlorine and LPG. These models were designed to take account of human behavior in the event of an incident. The results from these models, based on four representative hazardous substances, were to be used by *Health and Safety Commission* in Great Britain to make necessary routing decisions and advise on the need for additional voluntary or mandatory controls.

Woodward (1989) suggested separating hazmat cars in a train consist, as a way of reducing the probability of involving hazmat cars in a derailment accident. He proposed an expression that could be used to indicate the range of conditions, such as train speed and train length, over which separation of hazmat cars is advantageous. He concluded that separating hazmat cars in a consist decreases the probability of multiple hazmat cars being derailed for small accidents involving relatively few cars derailed. However, it increases the probability of multiple hazmat cars being derailed in large accidents, such as those involving more than eight or nine cars in a 70 car train that has seven hazmat cars.

Barkan et al. (2000) studied the non-accidental release (NAR) of hazardous materials from railroad tank cars. The field service results and impact testing showed that surge pressure reduction devices (SPRD) are an effective means of preventing NARs due to burst frangible disks. They go on to contend that SPRD requirement on the new tank cars has contributed to the decline in safety-vent NARs observed in recent years.

With regard to hazard / risk assessment of explosives transport, Davies (1994) tried to identify and quantify stimuli which can cause explosives to initiate. Although accidental initiation is, in principle, possible from a number of stimuli, only *impact* and *fire* are most likely to cause initiation. He went on to add that explosives sensitivity cannot be quantified in exact units of measure. This conclusion is not a huge disappointment since it is rate of delivery and not how much of energy released that causes initiation of explosives.

Almost all of the works reviewed above approach risk assessment from accident rate perspective. Infrequent accidents and the safety initiatives of railroad operators and affiliated agencies have made it extremely difficult to conduct a reliable analysis based only on accident rates. In an effort to tide over this limitation we will, alike some other researchers, work with *population exposure* as a measure of risk. Population Exposure is the number of people exposed due to the handling/transportation of hazardous materials. A novel way to estimate risk from multiple sources, as would be the case for a train with multiple railcars carrying hazardous cargo, will be proposed. To the best of our knowledge, ours is the only work that conducts a priori risk assessment of railroad transportation of hazardous materials. An approach to establish a relationship between hazmat volume and consequence (hazard area) was conceptualized and then used.

2.6 Conclusion

In this chapter, the definitions, types and sources of risk were presented. Keeping in line with the spirit of the doctoral work the focus was on hazmat risk, both at a fixed location and along a transportation corridor (highway and rail tracks). We contend that obnoxious facility mimics the risk posed by the handling of hazmat shipments at stationary locations. Due to urban accessibility, speed and volume flexibility benefits, truck transportation of hazmats has been a very busy area of academic research over the past two decades, and consequently is richer than rail transportation of hazmats. The relatively sparse literature on railroad transportation of hazmats is compounded by the fact that models for truck transportation cannot be extended to railroads due to the distinct features of the two modes. Almost all of the risk assessment work done in context of railroads is based on accident rate analysis; there is no work that establishes any relationship between volume of hazmat released and resulting consequence.

The above observations provided the starting point for my doctoral thesis. The dearth of academic work in the railroad transportation of hazmat domain motivated me to contribute in this area, hopefully to further mitigate or eliminate societal/environmental risk. The next three chapters are going to address this potential void.

In Chapter 3, we use *'population exposure'* as the measure of risk. This enabled us to tide over the limitations associated with accident rate analysis, and also facilitated conservative risk assessment which is very important for planning emergency response systems. An assessment measure is developed for estimating hazmat release from multiple sources such as a train, wherein the estimated concentration level is a function of volume. This assessment method is based on air-dispersion modeling, and is greatly inspired by their widespread usage at the hands of regulatory agencies and carriers to decide evacuation and response planning. This chapter also reviews the relevant literature and sets up the precepts for our risk assessment model for train shipments of hazmats.

In Chapter 4, the risk assessment methodology developed in chapter 3, is applied to a realistic size railroad operation for moving mixed (hazardous and regular) freight. A mathematical model that captures the intricacies of railroad freight operation, solution methodology, computational experiments, and numerical insights are presented.

The absence of any consensual work related to the comparative safety of trucks and trains provided the motivation to explore combining the best features of the two modes which lead to *Intermodalism*. In Chapter 5 this relatively nascent area of intermodal transportation system is introduced, an intelligent enumeration technique to solve 100 supply-demand pair problem is presented; and, a ***"time"*** driven bi-objective mathematical model with *risk* and *cost* objectives is developed.

CHAPTER 3

Risk Assessment for Train Shipments

3.1 Introduction

In the wake of the recent catastrophic accidents in Iran and North Korea, risk assessment of railroad transportation of dangerous goods has become a popular concern. United Nations Environment Programme reports 328 fatalities and 460 injuries in Iran, and 161 fatalities and 1300 injuries in North Korea due to explosions (UNEP). Despite the potentially catastrophic nature of train accidents, an overwhelming majority of the research on hazardous material (hazmat) transportation focuses on road shipments (List et al. (1991)), (Erkut and Verter (1995)). Although trucks carry a larger share of dangerous goods shipments in many countries, railroad shipments can easily reach comparable levels. In Canada, for example, 48 million tons of hazardous freight was carried via rail while 64 million tons was shipped via trucks in 2000 (Transport Canada (2002-03)).

There is a need for the development of risk assessment methodologies that incorporate the specific nature of railroad shipments, which we address in this chapter thereby answering the **first** research question: *"Develop a risk assessment methodology for train transportation of hazardous materials, one that can capture the distinct features of railroad operations."*

There are a number of factors that differentiate rail transport from truck shipments. A train usually carries non-hazardous and hazardous cargo together, whereas these two types of cargo are almost never mixed in a truck shipment. Furthermore, a rail tank-car has roughly three times the capacity of a truck-tanker (80 tons and 25-30 tons respectively) and the number of hazmat railcars varies significantly among different trains. The resulting variability in the total amount of hazardous cargo needs to be taken into account in assessing the transport risk associated with trains. Also, railroads typically offer much less routing flexibility compared to highway networks.

Another important characteristic of trains, from a risk assessment perspective, is the possibility of incidents that involve multiple railcars. In the United States, there were eleven train derailments during the 1990-2003 period in which more than six railcars were ruptured and released their toxic cargo (see Table 3.1 for details). Note that this amounts to an average of about one major railroad accident per year. Canada had its share of multiple railcar accidents as well. In December 1999, CN's Ultratrain (which constitutes our case study in Section 3.5) released 2.7 million liters of petroleum products due to the derailment of 35 tank cars just outside Montreal. 30 cars were seriously punctured and had to be demolished at the accident site (Railway Investigation Report (2002)). Another well-known accident took place near Toronto in 1979, where chlorine leaking from damaged tank cars forced the evacuation of 200,000 people (Swoveland (1987)). Thus, train accidents can have more severe consequences than those involving trucks, mainly due to the higher volumes of hazmats being shipped and the interaction between railcars. Fortunately, empirical evidence suggests that trains have lower accident rates than trucks (Saccomanno et al. (1990)).

Incident Year	**Number of Derailed Cars**	**Number of Derailed Cars Carrying Dangerous Goods**	**Number of Cars released hazardous cargo**
1990	61	19	12
1990	14	13	10
1990	14	14	11
1991	14	14	13
1993	30	23	9
1995	24	17	13
1996	34	16	16
2000	32	18	18
2002	17	17	7
2002	39	15	11
2003	50	19	7

Table 3.1: Release incidents involving more than 6 railcars (FRA)

Traditionally, hazmat transport risk is defined as the *expected* undesirable consequence of the shipment i.e., the probability of a release incident multiplied by its consequence. This risk measure is also called the "technical risk" since it requires a detailed assessment of the accident probabilities across the shipment route as well as the number of fatalities, injuries and evacuations that would be caused by an incident. Such a detailed analysis can become prohibitive for railroad shipments, since not only the likelihood of the entire train involved in an accident, but also the number and precise locations of the damaged railcars – and their interaction- are relevant. Based on the difficulties in deriving detailed accident probability estimates for railroad shipments, we resort to a more aggregate risk measure in this chapter: *population exposure*. We represent transport risk as the total number of people exposed to the possibility of an undesirable consequence due to the shipment. For example, according to the North American Emergency Response Handbook (2000), 800 meters around a fire that involves a chlorine tank, railcar or tank-truck must be isolated and evacuated. Therefore, the people within the predefined threshold distance from the railroad are exposed to the risk of evacuation. This fixed bandwidth approach has originally been suggested and used by Batta and Chiu (1988), and ReVelle et al. (1991). It is important that, in contrast with the traditional "average" risk measure, population exposure constitutes a "worst-case" approach to transport risk. Therefore, it is particularly suitable for assessing risk as perceived by the public as well as for estimating the required emergency response capability.

We focus on railroad transportation of hazmats that become airborne in the event of an accidental release, such as chlorine, propane and ammonia. Airborne toxins can travel long distances due to wind and expose large areas to health and environmental risks. We use the Gaussian plume model in estimating spatial distribution of the toxic concentration level. Concentration increases with release rate of hazmat, whereas it decreases with distance from the accident site and wind speed. At a given distance from a release source, the maximum concentration is observed at the downwind location. We use the Immediately Dangerous to Life and Health (*IDLH*) concentrate levels of the hazmat being shipped in determining the threshold distances for fatality and injuries (NIOSH). In estimating the population exposure, we adopt the worst-case approach by assuming least favorable weather conditions and focusing on maximum concentrate levels. Also, our population exposure estimates are based on the derailment and rupture of all railcars with hazardous cargo, which constitute a real possibility (see the 1996 and 2000 incidents in Table 3.1). Less conservative exposure scenarios can be easily incorporated in the parameter settings of the risk assessment methodology as presented in Section 3.3.

The originality of our model is in its ability to estimate the exposure zone around the railroad as a function of volume (and type) of hazmats on the train. Thus, the model extends the fixed bandwidth approach to population exposure, which is more suitable for truck shipments. We show that the multiple release-source nature of train accidents can be effectively captured by using a railcar referencing mechanism. We also present a risk approximation procedure that is robust to train make-up, i.e., length of the train as well as the type and positioning of its hazardous cargo. The remainder of this chapter is organized as follows: Section 2 presents an overview of the relevant literature. Section 3 describes the use of a Gaussian plume model for the assessment of railroad transport risk. Section 4 delineates the mathematical calculation of population exposure. Section 5 reports on an application of the proposed methodology in the province of Quebec, Canada. Finally, Section 6 provides some concluding comments and directions for future research, and leads into the next chapter.

3.2 Literature Review

Although railroad transportation has been a popular area of research (see Cordeau et al. (1998) for a comprehensive survey), the literature on the use of trains for hazmat shipments is rather sparse. In this section, we present an overview of the most relevant threads of research. Early academic studies focused on the impact of spills in the vicinity of the accident site. Analyzing past data on train derailments, Glickman and Rosenfield (1984) derived and evaluated three forms of risk: the probability distribution of the number of fatalities in a single accident, the probability distribution of total number of fatalities from all the accidents in a year, and the frequency of accidents that result in any given number of fatalities. Glickman (1983) showed that rerouting of trains with (or without) track upgrades can reduce risk. The trade-off between the societal and individual risks of hazmat shipments is addressed in Saccomanno and Shortreed (1983). Recently, Barkan et al. (2003) undertook a study to identify proxy variables that can be used to predict circumstances most likely to lead to a hazmat release accident. They concluded that the speed of derailment and the number of derailed cars are highly correlated with hazmat release.

Over the past three decades, railroad industry has spent considerable effort in reducing the frequency of tank car accidents as well as the likelihood of releases in the event of an accident. To this end, the Association of American Railroads, Chemical Manufacturers Association, and Railway Progress Institute formed an inter-industry task force in the early 1970's (Conlon (1999)). Unfortunately, the activities of this voluntary task force largely ceased in about 1994, and most of their internal reports were never publicized and considered proprietary to the sponsoring organizations (Barkan (2004), Conlon (2004)). More recent industry initiatives have focused on improving the tank car safety at the design stage. By studying the risks associated with non-pressurized materials, Raj and Pritchard (2000) report that the DOT-105 tank car design constitutes a safer option than DOT-111. Barkan et al. (2000) showed that tank cars equipped with surge pressure reduction devices experienced lower release rates than those without this technology.

A number of studies focused on the comparison of rail and road as alternative modes for hazmat transport, and no consensus has been reached with respect to the safer option. Glickman (1988) concluded that the accident rate for significant spills (when release quantities exceed 5 gallons or 40 pounds) is higher for for-hire truck tankers compared to rail tank cars, whereas rail tank cars are more prone to small spills. Saccomanno et al. (1990) pointed out that differing volumes complicate comparison between the two transport modes, and showed that the safer mode varies with the hazmat being shipped. Leeming and Saccomanno (1994) report on a case study in England, which involves the handling of chlorine by a major industrial facility with two options for delivery (i.e., rail and road). They found out that the two options do not differ significantly in terms of total risk, although rail shipments pose more risk to the residents around the facility. Kornhauser et al. (1994) present a case study of DuPont's Mississippi facility, wherein they conclude that railroad is a safer option than highway to ship anhydrous ammonia. The difference in shipment volumes between the two transport modes, however, was handled through a linear adjustment factor.

A variety of air dispersion models have been proposed for transport risk assessment. The most comprehensive study thus far is carried out by Hwang et al. (2001), who used a Lagrangian-integral dispersion model to estimate impact zones for six toxic-by-inhalation materials. In analyzing the chlorine-handling facility mentioned above, Leeming and Saccomanno (1994) made use of Dense-gas dispersion model to estimate the impact areas stemming from each possible release scenario. The Gaussian plume model (GPM), however, is by far the most popular dispersion model used by micro-meteorologists, air pollution analysts, and regulatory agencies (Gifford (1975)), (US EPA-Computer Aided). In his 1999 book, Arya states that GPM based models have received "official blessing" from state and federal regulatory agencies in the U.S. and their use has been recommended in official regulatory guidelines (Arya (1999)). For example, the 1996 Guidelines on Air Quality Models by the U.S. Environmental Protection Agency (*EPA*) recommends the use of nine standard air quality models for specific regulatory applications, which are mostly based on Gaussian formulations with empirical dispersion parameterization schemes (US EPA-Technology Transfer).

Patel and Horowitz (1990) were the first to use the GPM, coupled with a geographical information system (*GIS*), for risk assessment of road shipments. In an effort to develop closed-form expressions, they assumed that dispersion parameters are equal to one. They devised a numerical method to determine the minimum risk path under four scenarios: specific wind direction, uniform average wind direction, maximum concentration wind direction and wind-rose averaged wind directions and speeds. Patel and Horowitz (1990) focused on the technical risk by assessing the total expected contaminant concentration due to a potential spill. Recently, Zhang et al. (2000) modeled the probability of an undesirable consequence as a function of the concentration level and, again, used the expected consequence representation of transport risk. They adopted a raster GIS framework that approximates the plane with a set of discrete points (i.e., pixels). This enabled the authors to compute the concentrate levels without having to make the linearity assumption as in Patel and Horowitz (1990) that essentially ignores atmospheric stability conditions. The method proposed by Zhang et al. (2000), however, assumes a pre-specified wind direction and speed.

In summary, the prevailing studies on railroad transportation of dangerous goods overwhelmingly focus on accident risk, whereas exposure risk has not been well-studied in this context. Furthermore, GPM based dispersion models – that constitute a potentially effective means of estimating the exposure zone due to a rail shipment- have only been developed for highway shipments. In the next section, we develop a risk assessment methodology to fill this gap in the literature.

3.3 Risk Assessment & Air-Dispersion Modeling Framework

Ang and Briscoe (1989) and Pijawka et al. (1985) have suggested frameworks for risk assessment in hazardous materials transportation. Broadly risk assessment can be decomposed into three stages: determining the probability of an accident (incident); estimating the level of potential exposure as a result of hazmat volume; and estimating the magnitude of consequences given the level of exposure. The first stage is usually ascertained or estimated using the historical data. We develop an approach to address the remaining two stages of the risk assessment process.

3.3.1. Single Source

Gaussian plume model is used by micro-meterologists, air pollution analysts, and regulatory agencies dealing with hazardous materials (EPA (2003)). It is the most widely used model for air pollution dispersion. It is simple enough that one can visualize diffusion effects and also flexible enough to incorporate a host of special phenomena.

Perhaps the importance, of Gaussian Plume Model (*GPM*), has been best summed up by Gifford (1975): *"The important point is that the Gaussian formula, properly used, is peerless as a practical diffusion modeling tool. It is mathematically simple and flexible, it is in accord with much though not all of working diffusion theory, and it provides a reliable framework for the correlation of field diffusion trials as well as the results of both mathematical and physical diffusion modeling studies."*

The standard Gaussian Plume Dispersion Model is:

$$C(x,y,z,h_e) = \frac{Q}{2\pi u \sigma_y \sigma_z} \exp(-\frac{1}{2}(\frac{y}{\sigma_y})^2)[\exp(-\frac{1}{2}(\frac{z-h_e}{\sigma_z})^2) + \exp(-\frac{1}{2}(\frac{z+h_e}{\sigma_z})^2)] \quad (3.1)$$

where,

$C(x,y,z,h_e)$:	concentrate level (ppm) at point defined by (x,y,z,h_e) in *steady state*[1];
x:	downwind distance from the source of release (meters);
y:	crosswind (perpendicular) distance from the source (meters);
z:	elevation of the destination (meters);
h_e:	elevation of the source (meters);
Q:	release rate of the pollutant (mg/sec);
u:	average wind speed (meters/sec);
σ_y:	horizontal dispersion coefficient (meters), $\sigma_y = a\, x^b$;
σ_z:	vertical dispersion coefficient (meters), $\sigma_z = c\, x^d$;

In estimating the steady state concentration level at point *(x, y)*, the model assumes that the release rate and atmospheric conditions remain constant over the period of dispersion. Although the steady state conditions are rarely

[1] Pasquill and Smith (1983) contend steady state to be between 10 and 60 minutes from the time release starts.

reached, this is a common assumption – particularly reasonable during the first hour of release (ESS), (EPM). We use ALOHA (US EPA-Computer Aided), a popular software among North American regulatory agencies including EPA, U.S. Department of Transportation and Transport Canada, to calculate the release rate. Although ALOHA can also be used for estimating the concentration level, *C(x,y),* its results are only reliable within 1 hour of the release event, and 10 kilometers from the release source. In order to assess the population exposure under worst case conditions, the highest release rate is incorporated in the model by assuming a 24 inch rupture at the bottom of the railcar (The impact of non-worst case conditions is discussed later in this section through an analysis of smaller rupture sizes). Dispersion coefficients σ_y and σ_z are determined by atmospheric stability category and the downwind distance, x, to the release source. Pasquill and Smith (1983) and more recently Arya (1999) provide the values of dispersion parameters *a, b, c* and *d* based on atmospheric stability category. Each atmospheric category is determined by a combination of factors such as solar radiation, cloud-cover, and humidity; and it is compatible with a range of wind-speeds. Minimum wind speed, under any atmospheric category, results in the maximum concentration at all points in a plane. Thus, we focus on the minimum possible wind speed under the neutral atmospheric conditions i.e., 2.5 meters/sec. There are six atmospheric stability categories: A (very unstable), B (moderately unstable), C (slightly unstable), D (neutral), E (slightly stable) and F (very stable).

In hazardous materials transportation accidents, one can assume the source to be near the ground and one usually considers the concentration level on the ground i.e. the elevation of the source and destination is zero ($h_e=0$, $z=0$). In this instance, (3.1) reduces to (3.2).

$$C(x,y) = \frac{Q}{\pi\, u \sigma_y \sigma_z} \exp(-\frac{1}{2}(\frac{y}{\sigma_y})^2) \qquad (3.2)$$

It is rather evident from (3.2) that at a given (Euclidean) distance from the release source, the maximum concentration level is observed at the downwind point i.e. when crosswind distance $y=0$.

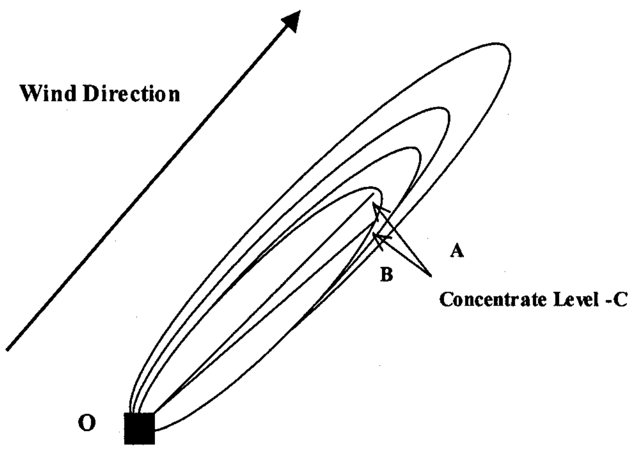


Figure 3.1: Gaussian Dispersion Plume

In figure 3.1 points *A* and *B* are not equidistant from the point of release ***O***, *B* is closer to the point of release. Despite that they have the same concentration level. Given the direction of wind in figure 3.1, *A* is in the downwind direction while *B* is crosswind from the source of release at ***O***. Although *A* is further away from the point of release compared to *B*, it has the same concentration level. From (3.2) and figure 3.1 one could surmise that points downwind receive more concentrates than points at the same distance but not downwind from the release source. Thus, the maximum concentration level at (downwind) distance *x*, from the source of release is given by (3.3):

$$C(x) = \frac{Q}{\pi u \sigma_y \sigma_z} \tag{3.3}$$

The Gaussian Dispersion Plume in figure 3.1 corresponds to a specific wind-direction (north-east) and a defined wind-speed. We do not know the wind direction (or wind speed) before hand but wish to conduct anticipatory risk-estimation, and hence what we need is a series of contiguous Gaussian Dispersion Plumes for all possible wind-directions (at all possible wind speeds) at the source of release ***'O'***. One way to address the uncertainty in wind direction is by rotating the plume-footprint around the release source, which will construct two concentric circles as in figure 3.2. An alternate way is incorporation of the variance of risk as suggested by Sivakumar and Batta (1994).

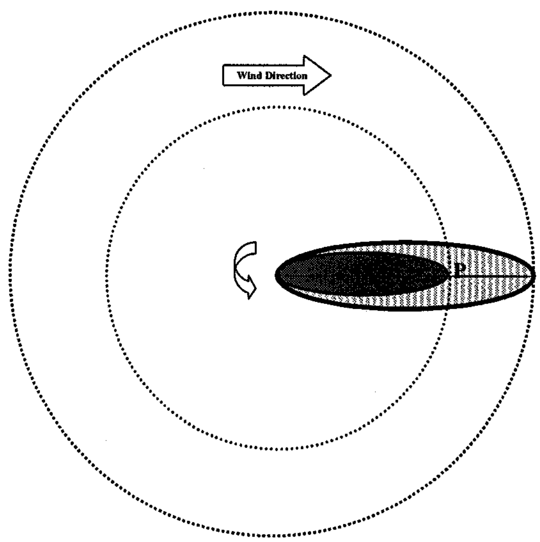


Figure 3.2: Two Zones of Gaussian Plume and the associated Danger Circles

Figure 3.2 depicts the Gaussian Plume with two footprints from a single release source when the wind is blowing east. Each footprint represents the area where toxicity is higher than a pre-specified concentration level i.e. the IDLH (NTIS 1994) level associated with a certain undesirable consequence. The inner footprint has higher exposure to hazmat transport risk. The furthest point from the release source in the downwind direction, where the threshold concentration level (*IDLH*) is attained will determine the radius of the circle (e.g. point *P* in Figure 3.2). This is consistent with our desire to simulate worst-case condition, since concentrate level at any point on the circle cannot be higher under any plausible wind direction. The two concentric circles in fig. 3.2 represent, for example, *severe* and *non-severe* impact areas under wind direction uncertainty. Conceivably, there may be prevailing winds along some segments of the train's route. If, for example, winds only blow within the east and north directions along a track segment, then only the upper-right quarters of the danger circles need to be used for estimating population exposure. It is important to note that, in contrast with the fixed bandwidth approach, the radius of each impact area in figure 3.2 varies with the release rate, and hence the volume of hazmat released.

3.3.2 Multiple Hazmat Sources

The Gaussian plume model introduced in the previous sub-section is standard for a single source viz. a truck or a railcar. Now, we extend the basic model to incorporate multiple release-sources.

3.3.2.1: Model Development

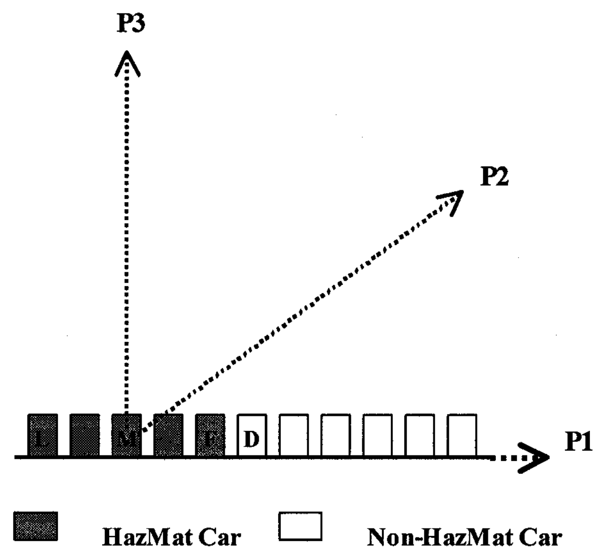


Figure 3.3: Schematic Representation of an 11-railcars train

In figure 3.3, assuming that the 11-railcar train is traveling east, *F* and *L* denote the first and last railcars with hazardous cargo, respectively. *M* is the point with equal amount of hazmats on both sides, which we call *hazmat-median*[2] of the train. Note that *M* and *D*, the middle of the train, do not necessarily refer to the same point. *P1*, *P2* and *P3* are equidistant from *M*. In fig. 3.3, the five hazmat railcars are *blocked*[3] at the back of the train.

Pasquill and Smith (1983) suggested that pollution from an array of sources, with an arbitrary distribution of position and strength of emission, can be modeled by superimposing the patterns of pollution from these sources, and hence aggregating the resulting contamination at each impact point. In figure 3.3, when the wind is blowing east, *P1* constitutes a downwind location where

[2] If there is an even number of hazmat railcars, then *M* is the midpoint of the two hazmat railcars at the center of hazardous cargo.

[3] They are back-to-back. *Block*, a railroad term, refers to a group of cars traveling together (as a block) to the same next intermediate yard.

crosswind distance $y=0$ for all railcars. In the event of a major incident (although very rare) that ruptures all five railcars with hazardous cargo, the total concentrate level at *P1* would be sum of the concentrate levels associated with each railcar, which can be estimated using (3.3). In an effort to simulate the worst case, we assume the same release rate for each railcar.

The three curves in figure 3.4 depict total concentration at *P1* as a function of distance to *F*, *M* and *L* respectively. Consider a fixed reference point at $x=0$. As the train travels east, *F*, *M* and then *L* pass by the reference point. Thus, figure 4 also shows the upward shift in concentrate level as a result of the train's movement. Note that contaminant toxicity increases much faster at impact points closer to the train. It is due to the accumulation effect (caused by non-linearity) closer to the source, while the reverse is true for points away from the source.

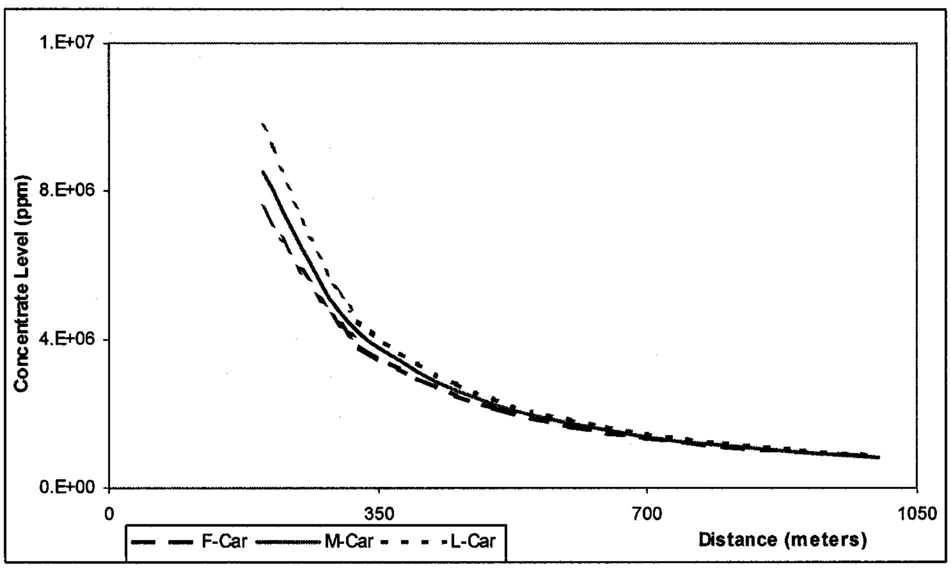


Figure 3.4: Impact of a 5 tank-car propane block

When the wind is blowing northeast in fig. 3.3, *P2* is downwind from *M* and it has positive crosswind distances (i.e. $y > 0$) to the other four railcars. Therefore, the maximum concentration at *P2* cannot exceed that at *P1*, when the latter is downwind as explained earlier. Similarly, the maximum concentration at *P3*, which is attained when the wind is blowing north, is less than when *P1* is downwind to all the five railcars. Thus, *P1* is the *maximum concentration point* among all the locations equidistant from *M*. When the distance from hazmat-median of an 11-car propane block is 1500 meters, for example, the concentrate levels at *P2* and *P3* are 95.8% and 95.5%, of the maximum level, respectively. This difference decreases with distance and increases with the number of hazmat railcars.

In accordance with the worst-case approach to transport risk, we focus on the maximum concentration level that can be reached at a given distance irrespective of the wind direction. Analogous to the single release-source case, it is possible to construct a danger circle around the train by rotating the maximum concentration point, *P1*, around the hazmat-median, *M*. Therefore, we use the hazmat-median as the *reference point* for the train. This assures consistency among the maximum concentrate levels under opposite wind directions, when hazmat railcars are blocked. If another point were used as reference, the concentrate levels at the opposite downwind locations from the hazmat railcar block would be different. Take, for example, *F* as an alternative reference point. Since all the railcars are behind F, the total concentrate level at a certain downwind distance will be higher when the train is moving upwind. Because the amount of hazardous cargo on both sides of *M* (hazmat-median) is the same, it constitutes the best option for a reference point.

Thus, the maximum concentrate level at distance x from the hazmat-median of an *n-railcar* hazmat block is:

$$\begin{aligned} C_n(x) = & \frac{Q}{\pi\, u\, a\, c\, x^b\, x^d} + \frac{Q}{\pi\, u\, a\, c\,(x-l)^b\,(x-l)^d} \\ & + \frac{Q}{\pi\, u\, a\, c\,(x+l)^b\,(x+l)^d} + \ldots\ldots\ldots\ldots \\ & + \frac{Q}{\pi\, u\, a\, c\,(x-nl/2)^b\,(x-nl/2)^d} + \frac{Q}{\pi\, u\, a\, c\,(x+nl/2)^b\,(x+nl/2)^d} \end{aligned} \tag{3.4}$$

where, l denotes the length of each railcar. In the next sub-section we will present a number of insights obtained via the above model.

3.3.2.2: Nature of Railroad Transport Risk

Evidently, the definition of the worst case scenario is at the core of population exposure estimates, and hence it is a possible source of contention among various stakeholders in hazmat transport risk. For example, it is plausible that a 24 inch rupture on all damaged hazmat railcars, which we use in the analyses above, could be deemed extremely unlikely. Nonetheless, widespread acceptance of the population exposure estimates can be achieved by establishing their robustness to reasonable changes in the worst case parameter settings. To illustrate this, we provide a parametric analysis of the impact of rupture size on exposure levels.

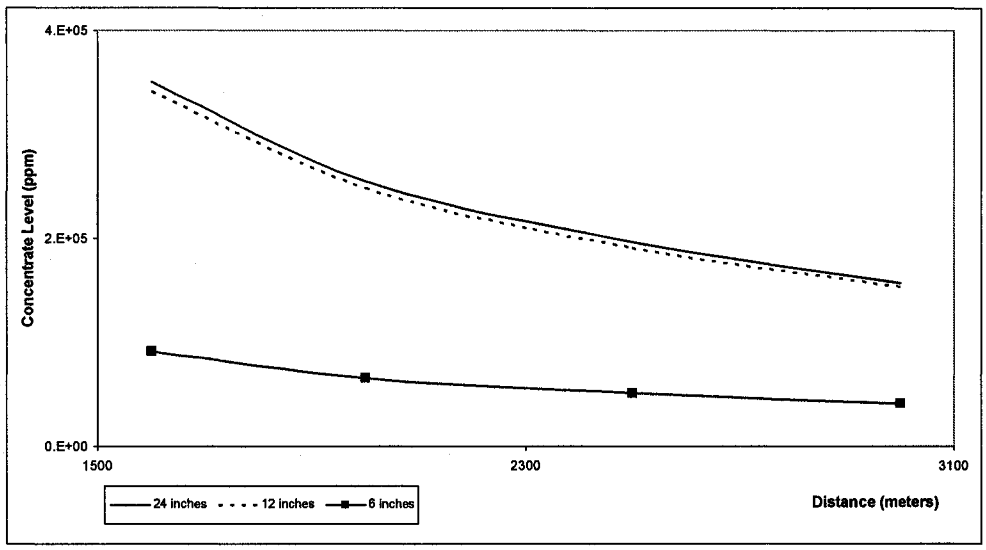


Figure 3.5: Effect of varying rupture diameters

Focusing on the instances with equal damage to all hazmat railcars, figure 3.5 depicts the total concentrate levels induced by 6, 12, and 24 inch ruptures in a 5-railcar propane block. It is important that the concentrate curve associated with 12 inch ruptures is very close to the curve due to 24 inch ruptures. This can be explained by the small difference between the release rates from an 80-ton railcar for these two rupture sizes: 2600 and 2670 pounds/sec, respectively. Our analysis also showed that all concentrate curves representing the scenarios with either 12 or 24 inch ruptures on each of the five railcars fall within the top two curves in figure 3.5. The concentrate curve is below the 12 inch curve only when there is a 6 inch rupture on one or more of the railcars. This is due to the significant decline in the release rate for small ruptures i.e., 693 pounds/sec for a 6 inch rupture. Consequently, as long as all the stakeholders can be convinced that none of the hazmat railcars would have a small rupture in the worst case, 24 inch constitutes a robust parameter setting in the model.

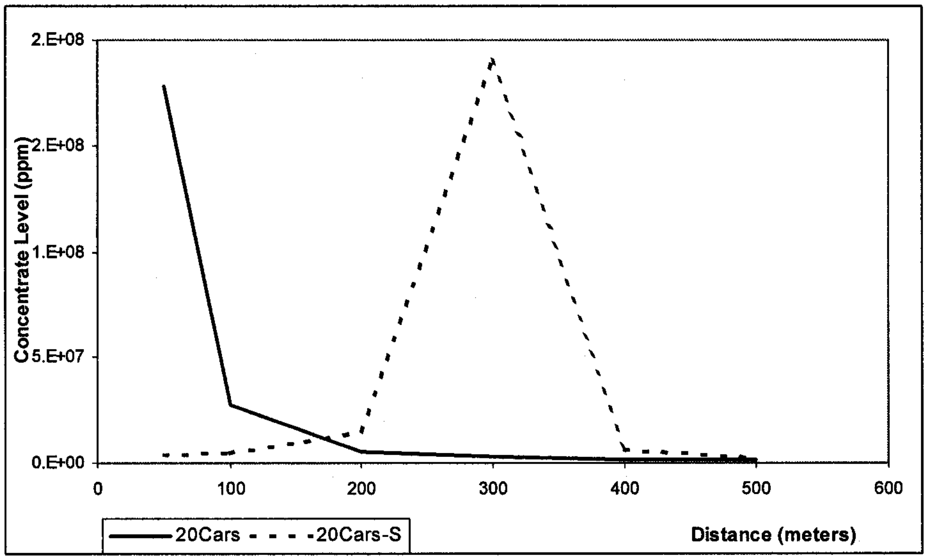


Figure 3.6: Impact of the positioning of hazmat railcars in the train

Using (3.4), we analyze the independence between train make-up and threshold distance. We first address the question "How does the impact area vary with the positioning of a given number of hazmat railcars in the train?" The following comparison between two alternative configurations of a 68-railcar train that includes 20 tank-cars of propane provides some insight. In figure 3.6, "20 Cars" represents the concentration curve associated with a block of 20 propane tank-cars at the center of the train. "20 Cars-S" is obtained by placing a 10 tank-car block at each end of the train.

"20 Cars-S" causes less contamination only at downwind distances (along the direction of the train) of less than 180 meters. This is because people who are "too close" to the hazmat-median of "20 Cars-S" are exposed more to the 10 tank-car block at the back of the train than the block in the front. Given that the train is 612 meters long, the peak concentrate level at 306 meters from M (along the length of the train in the downwind distance) is clearly more due to the 10 tank-car block at the front of the train. As may be evident, the area within 180 meters of M is extremely vulnerable to changes in wind direction. Figure 3.6

also shows that blocking hazmat railcars, as in "20 Cars", imposes less transport risk as one moves away from the train.

Threshold Distance	Number of hazmat railcars		
	30	68	120
Severe Zone	*1238*	*2041*	*3015*
Non-Severe Zone	*4466*	*7788*	*11518*

Table 3.2: Threshold distance (in meters) as a function of *n*

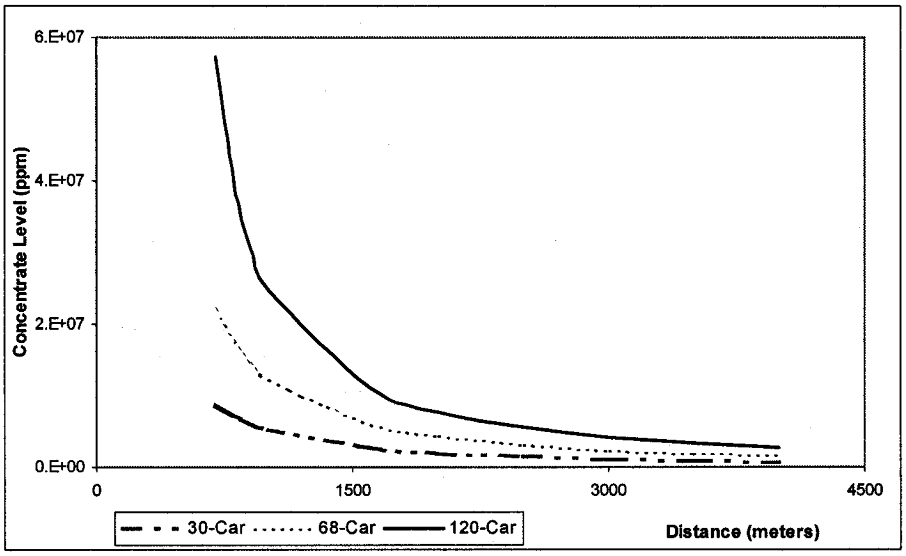


Figure 3.7: Impact of Increasing the number of propane tank-cars

Perhaps a more important question is "How does the impact area vary with the number of railcars?" To address this, we assume the hazmat railcars are blocked. Figure 3.7 depicts the maximum concentrate levels as a function of distance for 30-railcar, 68-railcar and 120-railcar hazmat blocks.

As expected, concentration curve shifts upward as the number of hazmat railcars increases. Consequently, the curve associated with 68 railcars lies within the area defined by the 30-railcar and 120-railcar shipments. At points closer to the train, contaminants accumulates at a higher pace than the increase in the number of hazmat railcars. At 1,000 meters, for example, the concentrate level due to 120 railcars is 4.7 times that of 30 railcars.

The IDLH levels for propane exposure are 4,200,000 ppm for fatality and 600,000 ppm for injuries (NIOSH). Since concentrate curves monotonically decrease with distance (see figure 3.7), toxic concentration remains higher than a specified IDLH level until a threshold distance. The people within this threshold face the possibility of suffering the associated undesirable consequence. In table 3.2, we provide the severe and non-severe threshold distances for the three hazmat blocks under consideration. For each configuration, these two thresholds define three concentric regions around the train i.e., the fatality zone, the injury zone and the non-exposure zone (where the concentration is less than 600,000 ppm). Consequently, the exposure level is a *step function* of distance despite the continuous nature of concentration. An individual would be indifferent to changes in the number of hazardous railcars in a train as long as the resulting adverse consequence remains unaltered. For instance, an individual residing at 1,500 meters from the train would be indifferent between 68 and 120 railcars because of being exposed to the fatality risk in both cases (Table 3.2 shows that the severe zone for a 68-railcar block is up to 2,041 meters). This individual, however, would certainly prefer a 30-railcar block (as opposed to the 68 or 120 railcar train) since the exposure reduces to the non-severe level as a result of the reduction in the number of hazardous railcars. In general, an individual will be indifferent between two trains of different lengths as long as there is no change in unfavorable consequence. But the same individual will prefer a single exposure from a longer train (say 120 hazmat railcars) to multiple exposures from shorter trains (two trains with 60 hazmat railcars), as long as the adverse consequence stemming from the two train lengths is identical.

Table 3.2 (and Figure 3.7) show that threshold distance increases with the number of hazardous railcars in the train, which we denote by n. We also observe that the rate of increase in the threshold distance is consistently less than that of n. For example, the fatality threshold for $n=30$ is 1,238 meters, whereas it is 3,015 meters for $n=120$. This translates into a 143% increase in the threshold distance for the severe zone when the number of hazmat railcars is quadrupled. Focusing on a 120 railcar shipment for illustration; the choice among $n=30$ and $n=120$ blocks involves a trade-off between exposing the people within 1,238 meters to fatality risk four times and exposing those within the 3,015 meters only once. The total population exposure associated with each alternative depends on the spatial distribution of population density around the tracks. Clearly, the number of people within the larger zone is 143% higher, when population density within 3,015 meters is constant.

The above observations relate to the concept of equity in the spatial distribution of transport risk. Gopalan et al. (1990) pointed out that equity can be improved by the use of alternate routes for a shipment. Although this is plausible for highway shipments, the sparse railroad network in North America does not present many routing options. This leaves train make-up as a primary determinant of risk equity. Given a certain demand to be shipped, the use of fewer trains would lead to an increase in the exposure zone while reducing the number of times people close to the tracks are exposed. When the railroad passes through a large region with uniform population density, this would spread exposure over a larger populace that improves equity according to the established measures e.g., the Gini Coefficient (Erkut (1993)), (Verter and Kara (2001)).

3.3.2.3: Approximating the Maximum Concentration Level

The typical cross-length of a Gaussian plume is 2-3 km, while the separation distance of consecutive railcars is around 10 meters. This implies a substantial overlap of Gaussian plume footprints emanating from hazmat railcars positioned anywhere in the train. Therefore, (3.4) lends itself to the following approximation that can be used as a practical means to estimate the exposure levels:

$$\overline{C}_n(x) = n \times \frac{Q}{\pi\, u\, a\, c\, x^b\, x^d} \qquad (3.5)$$

where, n is the number of identical release sources with rate Q. This amounts to assuming that all the hazardous cargo is located at the hazmat-median of the train. In the remainder of this section, we show that (3.5) is not only reliable for estimating the threshold distances, but also robust in terms of the train make-up.

Threshold Distance	**Number of hazmat railcars**		
	30	**68**	**120**
Severe Zone	*0.81%*	*1.17%*	*1.26%*
Non-Severe Zone	*0.04%*	*0.06%*	*0.10%*

Table 3.3: TD (in meters) as a function of n

Table 3.3 depicts the percent error in the threshold distances for 30-railcar, 68-railcar and 120-railcar propane blocks computed via (3.5). The error is defined as the percent deviation from the corresponding values in Table 3.2. Note that the approximate model estimates all the threshold distances within an error margin of 1.26%. The approximate concentrate level shifts upward proportionately to the number of hazmat railcars. However, as mentioned in the previous section, the percent increase in the actual concentrate level is more than the percent increase in n at points close to the train. Consequently, accuracy of (3.5) increases with distance and decreases with the number of hazmat railcars. At 1,000 meters, for example, the approximation errors associated with the severe zone for 30 and 68 propane cars are 1.14% and 7.11%, respectively. These errors reduce to 0.45% and 3.64% at 1,600 meters from hazmat-median of the train. Nevertheless, the approximation errors near the train are inconsequential since the concentrate levels are very high, making a severe consequence almost certain.

In order to analyze robustness of the approximate model with respect to positioning of the hazmat railcars in a train, we considered three cases: 5, 11, and 21 propane tank-cars in a train with 68 railcars. Transport Canada regulations stipulate that the first and last five railcars in a non-unit train cannot carry hazardous cargo (Swoveland (1987)). Thus, 100 train make-ups were generated for each case by randomly positioning the hazardous cargo among the 6th and 63rd railcars. Table 3.4 shows the (statistics associated with) non-severe threshold distances as well as the approximations. Given n, (3.5) estimates the same distance for all random train make-ups, since all hazmat is aggregated at the hazmat-median. The accurate calculation of total concentrate level, however, needs to incorporate the actual distance to each hazmat railcar. To illustrate this, consider a train make-up with hazardous cargo in the 6th, 11th, 15th, 37th and 63rd railcars. The hazmat-median, in this example, is the 15th railcar. Note that the hazmat- median will remain the same if the hazardous cargo in the 63rd railcar was moved to the 38th railcar, whereas the actual toxicity level at downwind distances from the train will change as a result.

Thus, the average threshold distances of 100 random train make-ups for each of the three cases are depicted in Table 3.4.

Threshold Distance	5 Hazmat Railcars	11 Hazmat Railcars	21 Hazmat Railcars
Approximate	*1341*	*2204*	*3417*
Average	*1366*	*2213*	*3422*
Std. Dev.	*60*	*41*	*33*

Table 3.4: TD (in meters) under random positioning of hazmat railcars

The approximation error is within 2% for all three cases. This enables us to surmise that the approximate model remains effective under uncertainty regarding the positioning of hazmat railcars in the train. Also, the approximate model performs better as the number of hazmat railcars increases. This can be explained by the reduction in variance of the threshold distance as hazardous content of the train increases. The distances in Table 3.4 are calculated at downwind locations assuming that the train is traveling east, as in Figure 3.3. If the train is traveling in the opposite direction, the average threshold distances will be slightly different, whereas the approximate distance will remain the same.

3.4 Population Exposure

Population Exposure assessment can be done either mathematically or more efficiently in GIS ArcView environment. This section develops the mathematical expression necessary for population exposure determination.

Figure 3.8 depicts three things: population center, unit rail-link and exposure zones. The exposure zone around rail-link *'s'*, on the underlying population centers, is generated due to the shipment of hazardous materials on *'s'*. As mentioned earlier we intend to capture the non-uniform consequence distribution. Hence there are two exposure zones separated by the severity of concentration levels. The extent of the *severe* and *non-severe* zones is a function of the volume and type of hazmat released. It is possible to mathematically replicate the *GIS ArcView* generated Figure 3.8.

To achieve that we introduce the relevant notations and their definitions.

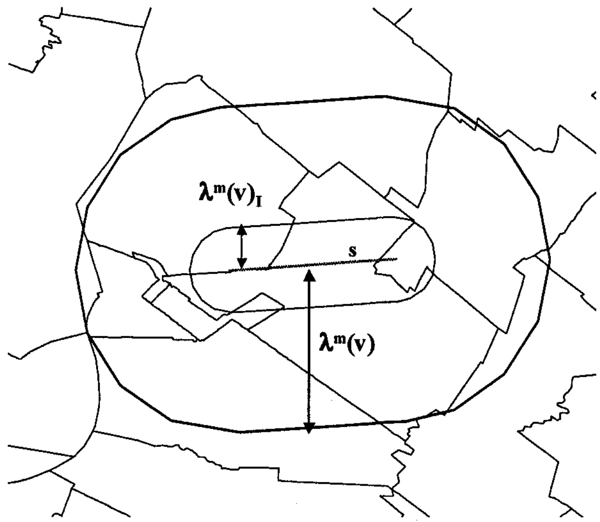


Figure 3.8: Exposure Zone around service leg *'s'*

Population Exposure Calculation:

Define:

$d^m_{i,s}$ = population density of sub-division i exposed to movement of hazmat m on link s.

$C^m_s(v)$ = number of people exposed around link s due to hazmat m of volume v.

$\overline{C}^m_s(v)_I$ = number of people exposed in the severe-zone, due to hazmat m of volume v on link s.

$\overline{C}^m_s(v)_N$ = number of people exposed in the non-severe-zone, due to hazmat m of volume v on link s.

l_s = length of link s.

$\lambda^m(v)$ = threshold distance (impact radius) due to hazmat m of volume v.

$\lambda^m(v)_I$ = threshold distance of the severe-zone due to hazmat m of volume v.

$EZ^m_s(v)$ = exposure zone around link s due to hazmat m of volume v.

$EZ^m_s(v)_I$ = severe exposure zone around link s due to hazmat m of volume v.

$A(i)$ = area of sub-division i.

If *rail-link 's'* is a straight line, then:

$$EZ_s^m(v) = \pi\,[\lambda^m(v)]^2 + 2\,l_s\,\lambda^m(v)$$
$$EZ_s^m(v)_I = \pi\,[\lambda^m(v)_I]^2 + 2\,l_s\,\lambda^m(v)_I \tag{3.6}$$

It is in essence the area of the square plus the area of one-unit circle formed by two semi-circles at either ends of the straight line. Note that the difference between these two exposure zones is the non-severe zone.

Now,

$$\overline{C}_s^m(v) = \text{population density of the exposed sub-divisions} \times \text{intersectional area}$$
$$= \sum_i d_{i,s}^m \left(EZ_s^m(v) \cap A(i)\right) \tag{3.7}$$

The number of people exposed around link -*'s'* due to hazmat *'m'* of volume *'v'* can be determined using (3.7). This can be done efficiently using GIS. For route $R = \{1,2,..,r\}$, number of people exposed due to hazmat *'m'* of volume *'v'* is:

$$\sum_{s=1}^{r} \overline{C}_s^m(v) = C_R^m(v) \tag{3.8}$$

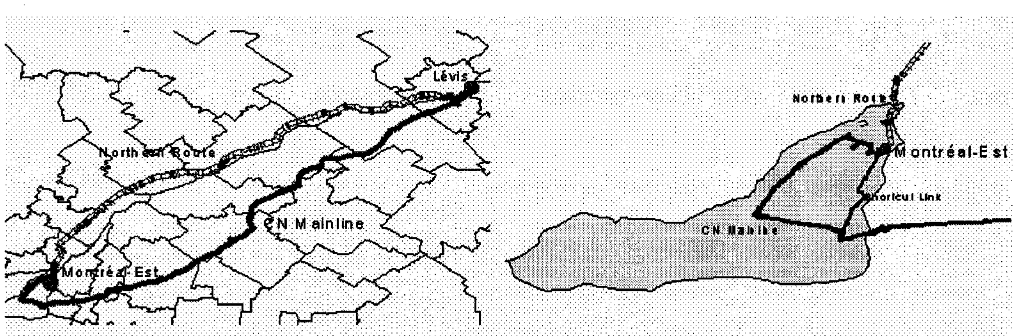
Finally the population exposure of route 'R' formed of rail-links 's' can be computed using (3.8). The aforementioned methodology and the correction suggested by Kara et al. (2003) can be used to determine population exposure. Volume and Hazmat dependent population exposure for any route can also be calculated extremely efficiently, and is illustrated in the next section with the help of a real example.

3.5 Assessment of the *'Ultra-train'* Shipments

In this Section, we present a case study that makes use of the proposed methodology in the province of Quebec, Canada. Every day, CN (Canadian National) runs a train from Ultramar's refinery near Quebec City to its terminal in Montreal. This 68 tank-car train, which CN calls the "Ultra-train", is devoted to finished petroleum products such as, gasoline, diesel, jet fuel and propane. Ultra-train uses the CN main-line, which is the southern route in Figure 3.9a.

The public is sensitized to the Ultra-train shipments due to a 1999 accident near Mont-Saint-Hilaire that killed two CN employees. A popular newspaper (Dougherty (2000)) pointed out that if the derailment occurred in a residential area, rather than an industrial zone, its impact could have been much worse. Consequently, there is considerable concern with the circuitous nature of the current route in the city of Montreal, which is depicted in Figure 3.9b.

According to a report commissioned by the EPA (CAPCOA (1997)), bulk evaporation is typically quite high for refined petroleum products e.g., 90 to 100 percent for gasoline. The report also suggests that these products can be modeled as neutrally buoyant gases, although their vapors are heavier than air. The content of Ultra-train varies daily, and the information regarding its cargo is not publicly available. Propane is shipped as a liquefied gas, which becomes airborne immediately after an accidental release. Gasoline, on the other hand, is initially released as a liquid, which results in a spill (puddle formation), and then evaporates gradually. In the absence of more detailed information, we modeled the entire cargo as a propane shipment that enabled us to derive conservative estimates of population exposure. The other model parameters are set as described in Section 3.3.



a: Through Quebec b: Through Montreal

Figure 3.9: Ultra-train

The ppm level of concern for propane is 2,100 ppm. A 5-minute exposure to propane at this level can cause minor injury while a 35-minute exposure can cause major injury or fatality. These numbers hold for closed environment and not open air. We are estimating critical ppm levels in open air conditions, hence we had to convert 'ppm-time' into instantaneous values that can cause the same effect. The two corresponding values are 600,000 ppm for non-severe consequence and 4,200,000 ppm for severe-consequence (NTIS, 1994).

Currently, CN is using a single threshold distance of 800 meters in their risk assessment as per the suggestion in ERG (2000). Our model, however, indicates that the fatality threshold distance for the Ultra-train is 2 kilometers, whereas people within 7.7 kilometers of the railroad are exposed to injury risk. Brown et al. (2000) provides the technical documentation for the values of initial isolation and protective action distances in the 2000 Emergency Response Guidebook (2000). These values are calculated using a number of hypothetical scenarios, and corresponding safe distances with chemical concentration below hazard level are determined. *Spill size* and the presence of *multiple sources of release* are the two reasons (plus the different atmospheric parameters) to account for the difference in the threshold distance as computed here and the one specified in the ERG (2000). Large spill size in ERG (2000) means anything more than 55 gallons, whereas in our computation 80 tons (per rail tank car) of hazmat is released and hence modeled for exposure level calculations (perfect worst-case scenario). Secondly, for propane, ERG (2000) presents values based on spill-size (and day/night variants) without considering multiple sources of release as in the event of a hazmat-unit train. In contrast we have used specific number of release sources to calculate aggregate concentration levels and threshold distances. Our results and analysis imply that the method used by CN grossly underestimates the population exposure risk and hence the danger posed by the Ultra-train.

We use ArcView, a popular Geographical Information System, and *Avenue Programming* Language to generate the corresponding exposure zones around the CN main-line. Then, we overlay these zones on the population centers (i.e., the polygons in Figure 3.9a, Figure 3.10) and identify the intersection areas. The total number of people in the severe zone is 492,195, whereas the population within the non-severe zone is 986,206. In total, Ultra-train exposes about 1.5 million people to varying degrees of transport risk.

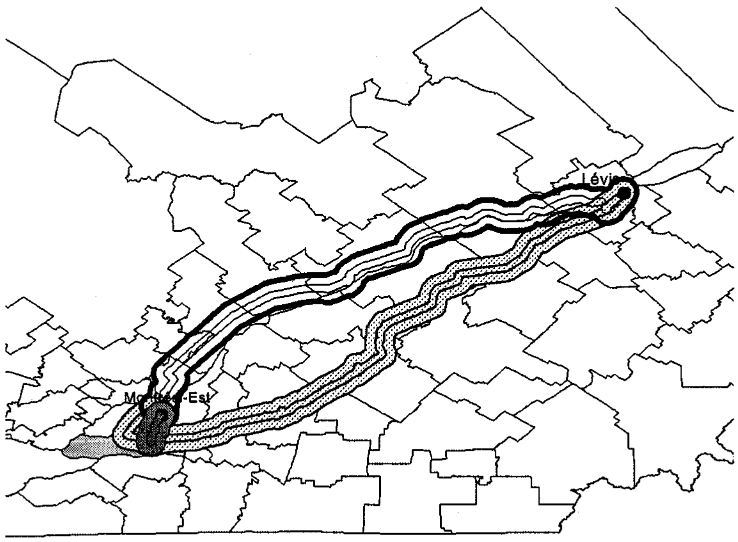


Figure 3.10: Exposure Zones on Mainline, Northern Route, and Shortcut Link

During our analysis of the existing railroad network, we identified two alternative routes for Ultra-Train. The "shortcut link" allows for a detour from the CN main-line via a north turn upon entering the island of Montreal (see Figure 3.9b, Figure 3.10), which results in a 16 kilometer reduction in inner-city travel. The "northern route", however, avoids the island of Montreal almost entirely by entering from northeast (see Figure 3.9a). Using our model, we also assessed the transport risk associated with these two routes. If the shortcut link is used, the number of people in the severe zone will reduce 36% and there will be a 24% reduction in the exposure to non-severe consequences. The use of northern route, however, will result in a 57 % reduction in both fatality and injury exposures. The northern route is only 3.4% longer than the current route, whereas the shortcut link provides a 5.6% reduction in travel distance. The primary reason for CN to continue using its main-line, which has much higher population exposure, is track quality. The company is deterred from using either of the two alternate routes by the significant capital outlay required for track upgrades and installation of monitoring equipment.

The large amount of refined petroleum products shipped through the city of Montreal on a daily basis is a significant concern for the emergency response planners in Quebec. The analysis in Section 3.3 shows that a reduction in the volume of hazmats will not pay off in terms of the resulting decrease in the threshold distance. If the number of tank-cars in Ultra-train is halved, for example, the threshold distance of the current severe zone will decrease only 9%. In this case, CN will have to run two 34 tank-car trains daily in order to satisfy Ultramar's demand. Each shipment exposes 437,176 people to fatality risk, and hence total exposure in the severe zone will increase 78% due to the use of 34 tank-car trains. Due to the non-linearity of concentrate curve, the impact is less drastic within the non-severe zone: threshold distance for injuries decreases 38%, which puts 619,099 people at injury risk and results in a 26% increase in exposure to non-severe consequences. These numbers are based on the assumption that these two trains reach their destination, without an accident, using the mainline route.

The net effect of a hazmat release is a function of both the severity of the accident and the follow up efforts of the emergency response team. It is interesting to note that emergency response planners are more concerned with the number of people within the exposure zone than the total exposure. Clearly, this amounts to ignoring the number of times an individual is exposed to a certain risk. A common response to hazmat incidents is evacuation of the impact area around the site of accidental release. Reducing the impact area of an accident, through decreasing the volume of hazmat involved, certainly makes emergency response planning easier. Therefore, emergency response planners in Quebec prefer any reduction in the length of Ultra-train despite the associated increase in population exposure.

3.6 Conclusion

In this chapter a risk assessment methodology for railroad transportation of hazardous materials was presented. Focusing on hazmats that are airborne on release, exposure zone was represented as a function of volume of hazmat shipped and the make-up of the train. The definition of exposure in terms of concentrate levels enabled modeling the reduction in transport risk with distance from the railroads. In addressing the multiple release-source nature of train accidents, the use of hazmat-median as the reference point of the train is proposed, which also provides a solid basis for approximating threshold distances for different consequences. In setting parameters of the model, a worst-case approach within the operating stability condition is adopted. This allowed incorporation of the uncertainty in wind direction by focusing on maximum concentration levels. An approximation method which is robust to the design of train and atmospheric stability categories was presented.

The proposed methodology provides valuable insights with regards to the nature of railroad transport risk. Most notably, a conflict of interest among the people living nearby railroad tracks and those who are not in the immediate vicinity was pointed out. Given a certain amount of hazmat to be shipped, increasing the amount of hazardous cargo on each train would favor the former group. It was also established that, in general, blocking hazmat railcars would reduce (global) population exposure. Although neutral atmospheric stability category was assumed, additional computational experiments shows that the overall results and hence the analysis do not change under other stability conditions. Application of the methodology, and the GIS environment, for the assessment of Ultra-train's transport risk enabled us to validate our insights.

Some important noteworthy points related to this chapter are indicated or summarized hereafter.

First, although rupture scenario analyses wherein the effect of different release rates was simulated has been provided in this chapter, but given the absence of any work on hazmat interaction it is rather impossible to capture the latter effect between different hazmat mixes. *Second*, evidently there are different risk methodologies present but the one we have used was motivated by the desire to capture the effect of volume and multiple sources of hazmat release as is characteristic of any railroad operation.

Third, wind-rose is a graphical representation, which takes into consideration the variations in wind direction and speed, of the percent frequency with which winds from a certain direction occur. Adopting a wind-rose approach, together with Lagrangean dispersion model for dense gas dispersion, will enrich population exposure estimations although the data requirements will go up substantially but this is definitely an avenue we wish to explore in future research.

Fourth it is true that *FN-curve* due to a specific hazard captures the societal risk in the form of the frequency of exceedance curve of the number of deaths, if the specified level of harm can be narrowed down to the loss of life. But this approach has its limitations: in here the notion of risk has to be reduced to the total number of casualties, although other forms of damage can be captured by more complicated expressions; and, there is no agreement on whether societal risk should be judged with a risk-averse or risk-neutral attitude. In spite of the inherent shortcomings, if we can procure all the relevant data, it would be extremely interesting to incorporate FN-curve into the *Quantitative Risk Assessment* (QRA) analysis.

*Fifth, a*s detailed in this chapter the efficiency of GIS takes care of the overlaps generated due to the moving railcars. The exposure band is generated for a complete path and not a section of the track, and hence the exposed populace is counted only once. The use of GIS eliminates the concern for multiple counting due to overlaps, although Kara et al. (2003) have proposed a correction algorithm even if the exposures are calculated mathematically as outlined in Section 3.4.

Sixth, fortunately there aren't enough train accidents which also means there aren't enough data points to conduct meaningful analyses. Moreover past accident rate data are representative of the past, and in no way preclude the occurrence of something more severe in the future. However if such detailed probability numbers were available were for each and every track segment of a rail network, for each and every railcar position, and for a range of hazmat volume (and type), then the risk assessment would be much simpler. One could have use these numbers for (robust and meaningful) risk assessment, and not develop a new risk assessment methodology that can capture the effect of volume and one that is not susceptible to absence of accident rate data.

In this chapter, yard-to-yard unit train operation was evaluated. In most instances individual railcars move from the origin yard to their destination yard via a series of yards and a number of different trains, wherein they go through typical yard and line operations. In Chapter 4, by incorporating the risk assessment methodology developed in this chapter, a mathematical model for railroad transportation of hazardous and non-hazardous materials will be presented. This model will capture the intricacies of railway freight operations namely classification, blocking, transfer, etc. Memetic Algorithm based solution methodology together with a range of computational experiments and numerical analyses will also be presented.

CHAPTER 4
A Bi-Objective Mathematical Model for Railroad Transportation of Mixed Freight

4.1 Introduction

In Chapter 2, we presented a comprehensive review of the work done in the hazardous materials domain. A close evaluation led us to conclude that railroad transportation of hazardous materials did not receive as much attention from academic researchers as truck transportation of hazardous materials did. Moreover most of the published work deals with past accident data, whose analysis can improve the safety statistics by upgrading tracks or coming up with better tank designs. This is good, but there is no work relating volume of hazardous materials to consequence with railroad as the transportation mode. Motivated by that, we developed a risk assessment methodology for trains as described in the previous chapter. We used our methodology to get an insight into the workings of railroads and applied to a specific case in Montreal. In this chapter we will use the risk assessment methodology to model the operation of freight trains with both hazardous and non-hazardous cargo. More specifically we will present an optimization model, which will decide the traffic-routings and the frequency of train services, while incorporating the risk assessment methodology developed in the previous chapter and the intricacies of railroad operations.

In this chapter we answer the **second** research question: *"Given the risk assessment methodology developed earlier and a realistic railroad operation, conceptualize and develop an optimization model and a solution methodology to enable railroad transportation of both hazardous and non-hazardous materials."*

The chapter has been organized as follows: Section *two* describes a railroad transportation system. Section *three* contains the much deserved review of relevant railroad literature. Section *four* provides a detailed description of railroad operations, thereby introducing all the concepts pertinent to railroad industry. Section *five* details problem definition and assumptions, develops a mathematical model and then explains parameter estimation. This bi-objective model will decide how to route railcars from their origin yards to their destination yards, and the number of different freight train types needed in the system. Section *six* presents a detailed *Memetic Algorithm* based solution methodology for solving the bi-objective model. Section *seven* applies the model to a realistic-size illustrative example from the railroad industry. Section *eight* delineates the algorithmic efficiency of the model and makes use of seventeen scenarios to present the results and managerial analysis aimed at gaining numerical insights. The supporting details for this section are provided in ***Appendix-A***. Conclusion and possible directions of future work is presented in section *nine*.

The contributions of this chapter are fourfold. *First*, to the best of our knowledge, this is the only work that makes use of *population exposure* as a measure of risk in context of railroad transportation of mixed freight (hazardous and non-hazardous cargo). *Second*, this is the first bi-objective mathematical model that determines the routes of railcars, distinguished by the nature of cargo, from their origin yard to their destination yards; and the number of trains of different types required in the system. *Third*, the only work of its kind, where *Memetic Algorithm* based solution methodology facilitated the development of a *Quasi-Pareto* frontier. Each point on this frontier translates into a set of railcar routes, number of different trains, and blocking/classification/transfer at various yards in the network. *Fourth*, the only work that compares the "*cost-risk*" effect accruing from the railroad transportation of *propane* and *chlorine*, as the hazardous cargo in a mixed freight.

4.2 Railroad Transportation Systems

The most common approach to represent the railroad transportation system is via a network, whose nodes represent *yards* (or stations) and whose arcs represent *lines* of tracks on which trains carry freight (passengers). Rail transportation problems can be classified into *three* categories according to the planning horizon. *Strategic Decisions* involve resource acquisition over long time horizons and typically require major capital investments. *Tactical Decisions* have medium-term planning horizon and focus on effective allocation of existing resources. Train selection and traffic routing, train make-up, yard classification policy and train lengths, are some examples of tactical decisions. Finally, *Operational Decisions* deal with day-to-day activities in a fairly dedicated and dynamic environment. As would be evident in the sections to follow, our work aims at the efficient utilization of the available resources and hence is tactical in nature.

Freight demand (in railroad industry) is usually expressed in terms of tonnage or number of railcars of certain commodities to be moved from an origin to a destination. Given these demands, the railroad must establish a set of *operating policies* that will govern the routing of trains and freight. For every origin-destination pair of (traffic) demand, the corresponding freight may be shipped either directly or indirectly. When demand is important enough, delivery delays are obviously minimized by using direct trains as opposed to sending the traffic on indirect trains and hence subjecting them to a number of intermediate handling. However, when demand does not warrant dispatching direct trains, delays are inevitable. Either traffic is consolidated and routed through intermediate nodes, or freight cars have to wait at the origin node until sufficient tonnage has accumulated.

Broadly speaking, one may view rail-operating policies as a sequence of decisions striving to meet demand by a suitable allocation of resources and facilities available to the railroad. On the *demand side* traffic volume to be moved between an origin and destination is known data, while on the *supply side* the set of available resources viz. feasible train routes, train itineraries, crew and motive power availabilities and yard facilities are given. The *operating policies* determine assignment of the available resources to move traffic, and consist of *line policies* and *yard policies*.

Line policies determine the routing of each demand (railcars) on the physical rail network as well as the assignment of demand to trains. They affect the movement of trains on the tracks. As such, they interact with the overall routing decisions that determine the flow of traffic on the rail network. *Scheduling*, *Timetabling* and *Track Priority Rule* are some examples of line policy.

Yard policies specify the operations performed on different classes of traffic in the yards they visit. At each yard the incoming traffic is regrouped according to final destination. The classification of cars into these destination-oriented blocks is called the *grouping or blocking policy*. The blocks of traffic are next placed on classification or departure tracks where they wait for outbound trains. Each outbound train has a *take-list* specifying the blocks of traffic it will pick-up at a given yard. The decision as to which blocks of traffic a given train may carry is called the *make-up policy*. Also, when a train passes through an intermediate classification yard, it may leave or pick-up blocks of cars. A block left by an inbound train is either transferred to a different train (*block-swap*) or it is broken up and its cars reclassified. Hence, the origin and destination of a block may or may not be the same as that of a train and the railcars forming that block.

Section 4.4 will make use of examples to illustrate the intricacies of a railroad operation.

4.3 Literature Review

Rail transportation industry is very rich in terms of the problems that can be modeled and solved using optimization and in some instances heuristic techniques. However, the related literature has experienced a sluggish growth and, until recently, most work failed to capture the intricate nature of rail transportation industry. Surveys by Assad (1980a, 1980b) and Haghani (1987) suggest that optimization models for rail transportation were not widely used in practice and that railroad companies often resorted to simulation. However, in the last decade, the strong competition facing rail carriers, the privatization of many national railroads, deregulation, and the ever increasing speed of computers motivated the use of optimization models at various levels in the organization. Cordeau et al. (1998) provide a survey of the various optimization models for routing and scheduling of train.

Beckmann et al. (1956) were perhaps the first to give a detailed account of rail operations and freight transportation. Almost all of the subsequent studies drew inspiration from their classical work. Broadly rail transportation problem can be broken down into *routing problems* and *scheduling problems*[4]. *Routing Problems* incorporate everything from the activities at the marshalling yards to train make-up, freight car management and train route. *Scheduling Problems* on the other hand is concerned with train dispatching, locomotive assignment etc. In line with the objective of the *Thesis*, we will review just the routing problem literature, but interested readers can consult Cordeau et al. (1998) for relevant work on the scheduling problems.

Perhaps Crane et al. (1955) was the first team to conclude that a freight car spends approximately two-thirds of its' time stationary. Martland (1982) conducted an analysis to determine the average intermediate yard times for a railcar, and arrived at a range of 15 to 27 hours with one daily outbound connection. Keaton (1989) pointed out that most of the time required, to move rail-freight, from its origin to destination, is spent in the terminals or marshalling yards waiting to be operated upon. Mansfield and Wein (1958) had proposed a simple model to determine the best location for installing automated classification yards. Petersen (1977a and 1977b) used queuing theory to conduct an elaborate analysis of rail yard operations, and the proposed model was being used by CN (Canadian National) for its' yard operations. Yagar et al. (1983) proposed a screening technique and a dynamic programming approach to optimize the classification and related yard operations.

The *blocking problem* (explained in section 4.4) concerns the repetitive regrouping of traffic on a rail network in its movement from the origin yard to the destination yard. It is an operation within individual marshalling yards. It starts with the disassembling (sorting) of railcars brought by an inbound train. Bodin et al. (1980) developed a non-linear, mixed integer programming model for the railroad blocking problem. The speed and power of the computers then forced them to resort to some heuristic and limit the size of the formulation in

[4] This is in line with Cordeau et al. (1998).

order to solve the problem. Assad (1983) uses 'cuts' (contiguous string of incoming cars belonging to the same group) in order to analyze and measure the classification work done in the yards. Daganzo (1986) suggested a 2-stage sorting of the incoming traffic using a train, which he calls static blocking. Van Dyke (1986 and 1988) described a cost based heuristic blocking approach, driven by the shortest path algorithm. Newton et al. (1998) modeled the blocking problem as a network design problem. The model structure and some clever adaptations enabled the authors to use column generation, and hence save themselves the hassle of complete enumeration without compromising on the quality of the results. Barnhart et al. (2000) formulated the railroad blocking problem as a network design problem. The complicated mixed-integer programming problem, which is NP-hard, is first subjected to Lagrangean Relaxation and then decomposed into two simple subproblems. Subgradient optimization is used to solve the Lagrangean dual.

The blocks (groups of railcars) have to be moved to the next yard using available trains. As can be expected, there is a strong interaction between yard and line operations. Haghani (1989) outlined a rather intense interaction between routing, makeup, frequency and freight car distributions. Thomet (1971) proposed a cancellation procedure, which cancels direct shipments in favor of a series of connections, towards a train formation plan. Assad (1980a) proposed a multicommodity network flow model for train routing and makeup that tried to capture the yard activities – line activities interaction and the economies associated with consolidating blocks of traffic into a single train. Keaton (1989) proposed a Lagrangean relaxation heuristic for the combined problem of car blocking, train routing and train makeup. He used the same model to quantify the costs (1991) of providing a range of transit times for general carload traffic for several representative U.S. rail systems. Petersen and Fullerton (1975) developed a rail network model for over-the-road and yard activities. The objective was to route freight on the rail network to meet demand at minimal total delay.

Crainic et al. (1984) proposed a nonlinear mixed integer programming model, which deals with the interactions between blocking, makeup, and train & traffic routing decisions. A heuristic technique was used to solve this model. Haghani (1989) proposed a combined model for solving train routing, makeup and empty car distribution. He had used a decomposition algorithm to solve the problem. Martinelli and Teng (1996) used neural networks to solve train formation problems. Marin and Salmeron (1996a and 1996b) proposed and analyzed the expected performance of local search heuristics for the tactical planning of rail freight networks.

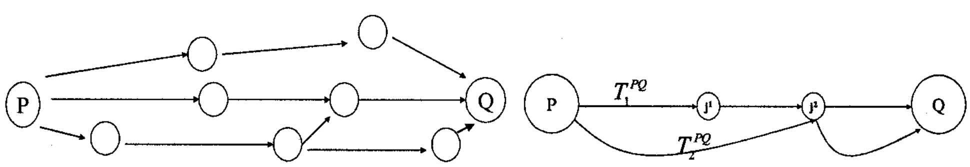
Huntley et al. (1995) developed a demand-driven approach to routing and scheduling. Gorman (1998a) used tabu-enhanced genetic algorithm to address the weekly routing and scheduling problem. Kwon et al. (1998) describe a dynamic freight car routing and scheduling model that can produce more achievable and market-sensitive car schedule.

To conclude, literature pertinent to yard operations, blocking and routing have been reviewed. Railroad transportation literature reviewed in the previous two chapters has not been repeated here. As we concluded in the previous chapter there is no work that conducts a priori risk assessment of railroad transportation of hazardous and non-hazardous materials. We developed a risk assessment methodology to that effect, and make use of that methodology and the intricacies of railroad freight operations to develop an optimization model in section 4.5

4.4 Railroad Operations

As referred to earlier, the hazardous materials transportation literature is favorably skewed towards highway shipments, and hence truck as the primary mode of transportation. The comprehensive literature review in chapter 2, pertinent reviews in chapter 3 and fundamental review in section 4.2 underline the need for increased attention in the domain of railroad transportation of hazardous materials. We recognized the dearth of work done in this domain, and hence developed a framework for the railroad transportation of hazardous materials, which was presented in Chapter 3 and constitutes the first step in that direction. In this chapter we will put to use the earlier development, but with all the characteristic nuts and bolts of a railroad freight operation. The rest of this section is devoted to describing railroad operations and its' intricacies, thereby preparing the ground for the introduction of the mathematical model in the next section.

What follows is a simple representation of rail-freight network to aid the introduction of concepts relevant to railroad industry and to our work. Figure 4.1a represents a *physical network*[5] by a directed graph $G_{ph} = (N, A_{ph})$ where N is the set of nodes (yards and junction points) and A_{ph} is the set of links representing the track sections between yards.



a: Physical Network b: Service Network

Figure 4.1: Railroad Network

Based on the physical network G_{ph}, the *service network* $G = (N, A)$ specifies the set of feasible routes on which train services may be operated. In Figure 4.1b, the service network of two train-services T_1^{PQ} and T_2^{PQ} is graphed. The *service* of a train is characterized by *an origin yard*, *a destination yard*, a *path of arcs* (rail-links) from the origin to destination yard, and a set of *intermediate stops*. The track section between two consecutive stops of a train service is called a *service leg*, the train travels non-stop on this section of tracks. Although the two trains have the same origin and destination, the set of intermediate stops and service legs for the two are different thereby distinguishing one from the other. While T_1^{PQ} passes through both j^1 and j^2 picking up (and/or dropping off) traffic at these intermediate yards, T_2^{PQ} has just j^2 as the intermediate stop. Train service T_1^{PQ} has 3 service-legs P-j^1, j^1-j^2 and j^2-Q, while T_2^{PQ} has two P-j^2 and j^2-Q.

Conventionally, demand is characterized by the origin-destination-commodity triplets in multicommodity network models. In here we characterize *demand* or equivalently *traffic-class*, by unique origin and destination yards. For example

5 Some terms and representations have been inspired by the work of Crainic et al. (1984).

in Figure 4.1b, $P\text{-}j^2$ would constitute a demand or traffic class, since it has a unique origin (P) and destination yard (j^2). This demand can be met using either of the two train services on the available network.

In railroad literature, a feasible journey from the origin yard to the destination yard, of a traffic-class, including the train *service legs* and the yard operations performed on a traffic-class is called its *itinerary*. The train service legs are composed of track-sections between two consecutive stops, while yard operations can be either classification & blocking and/or just transfer of railcars. For our simple case, traffic-class ($P\text{-}j^2$) has two itineraries. One on train service T_1^{PQ} via intermediate yard j^1, where traffic-class ($P\text{-}j^2$) is not touched since the train just performs the drop-off and pick-up operation at j^1. The other itinerary is using T_2^{PQ} a direct non-stop service. This is a simple illustration, of railcar movement, one without any classification or transfers at intermediate yards. A more realistic representation will involve classification and/or transfer of railcars and a number of train services to move railcars from their origin to their destination.

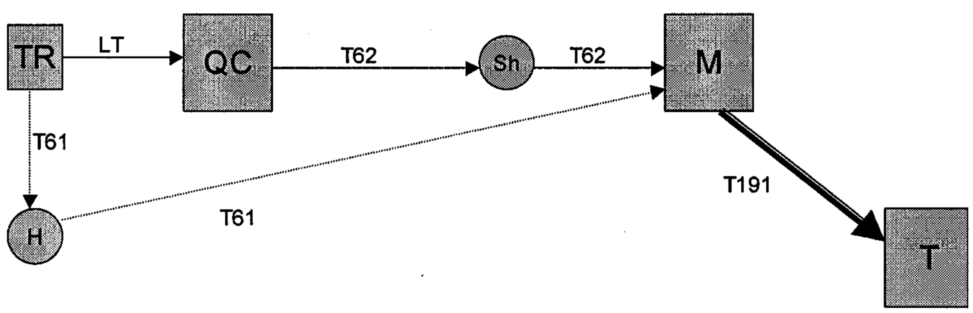


Figure 4.2: Service Network, Itinerary and Blocking

Figure 4.2 will be used to illustrate pertinent concepts and intricacies of railroad industry. Here we wish to track the *traffic-class* or *demand* (*TR*→*T*), where *'TR'* is the origin yard and *'T'* is the destination yard, on the available network. There are four train services: *'LT'* is a local train between *TR* to *QC*; *'T61'* is formed at *TR* and terminates at *M*; *'T62'* originates at *QC*, passing through *Sh*, terminates at *M*; and finally, *'T191'* between *M* and *T*. Square nodes indicate fully equipped yards i.e. they possess both classification and transfer capabilities, while circular nodes have only the *transfer* facility i.e.

drop-off and pick-up of railcars by two different trains, what is called *block-swap.*

The illustration of railroad industry is incomplete without describing the determinant that enables railroads to enjoy economies of scale viz. *classification* and *blocking*. Let us assume that local train *LT* brings traffic-class, *TR→T,* to *QC.* At *QC* some operation would be performed on this incoming traffic to get it ready for onward journey. We want to get an understanding of this yard operation at *QC.* Consider traffic-class, *TR→T,* has been delivered at the receiving tracks of yard *QC* in Figure 4.3.

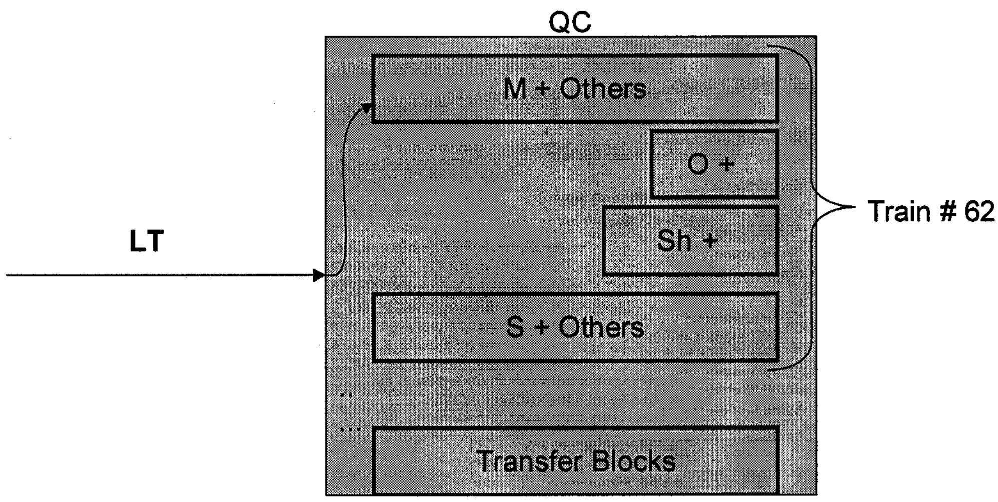


Figure 4.3: Activities within a YARD

One of two activities will be performed on traffic-class, *TR→T,* at yard *QC.* If the number of railcars in traffic-class, *TR→T,* is sufficient to form a block (group of railcars with common handling point), then this incoming traffic will not be classified with other railcars at yard *QC* for onward journey. The whole block of cars will be placed on the departure track or the *transfer* track at yard *QC*, waiting to be connected to the outbound train *'T62'*. This is a simple transfer or block-swap instance. But if the number of railcars is not enough to be deemed a block (typical case), then more yard-intensive activities would have to be carried out. *First,* the incoming cars will be classified (sorted) according to the final (intermediate) destination and then the railcars destined for *T* will be blocked (grouped). Yard *QC* may have dedicated tracks for building blocks for different destinations (figure 4.3). Typically incoming railcars would be classified and blocked, on these tracks, with other traffic with same designated handling points, and wait for their onward journey. Let us suppose there is a dedicated track "*M+Others*" for traffic to *M* and connections through *M*. All the railcars belonging to traffic class, *TR*→*T*, will be placed on this track and blocked with other railcars bound for *M*. In other words the destination for the block formed on this track is *M*. This is how classification, block formation and transfer operations will be performed at yard *QC*.

'T62' leaves *QC* with the blocks on its' *take-list*. It stops at *Sh*. *Sh*, being a service yard will just provide block-swap or receive traffic destined for it. *'T62'* terminates at *M*, where *"M+Others"* would be classified to separate the traffic bound for *T* (e.g., *TR*→*T*) from others. The yard operation(s) to be performed on the incoming traffic at *M* will depend on the operations performed on them at the preceding yards (for our case it is *QC* and *TR*).

Blocking of railcars is done to prevent handling of each railcar at every intermediate yard on its journey. A group of railcars with common handling points are grouped together at the start of its journey, and this group will not be disbanded until it reaches the specified handling yard, which is the destination for that block. On reaching the destination for that specific block, further classification and blocking operations may have to be performed on individual railcars depending on their destinations. This process continues till a railcar reaches its' destination yard. Newton et al. (1998) and Barnhart et al. (2000) introduced the term *'blocking path'*. It is the sequence of blocks, to which one shipment (railcar) is assigned along its route from the origin to the destination. It is worth noting that, for a given shipment, the blocking path may be different from its physical route. For example, consider the physical route O-A-B-C-D for a shipment from location O to location D, passing through locations A, B and C. Blocks might be built only from O to B and from B to D. Once the block built at O reaches B, it is reclassified and grouped with the other traffic for D. Then, the blocking path for the traffic-class is O-B-D, which is a subsequence of its physical route. This is the blocking path because of the classification and blocking activities being performed at O and B, and just sorting at destination D.

From figure 4.2, we notice that traffic-class (*TR→T*) has two physical routes: *TR-'T61'-M-'T191'-T* and *TR-'LT'-QC-'T62'-M-'T191'-T*. We also know from the two references in the previous paragraph, that the blocking path may be different than the physical route. In addition, we know the capabilities of yards (square and circle) in figure 4.2. Given the aforementioned, we can enumerate all the *blocking paths* on each of the two *physical routes*.

- Route : *TR-'T61'-M-'T191'-T.*
  - *2 Blocking Paths*: TR-T and TR-M-T.
- Route : *TR-'LT'-QC-'T62'-M-'T191'-T.*
  - *4 Blocking Paths*: TR-QC-M-T; TR-QC-T; TR-M-T and TR-T.

It is worth noting, that even for this simple case, for one traffic-class and sparse rail network, we end up with 6 possible blocking paths on 2 physical paths. Having delineated the characteristic features and intricacies of railroad operation, we are ready to introduce some definitions and assumptions made in context of our tactical planning model.

For us an *itinerary* will convey something more than the conventional railroad industry definition (as introduced before). An ***itinerary*** for our model will a <u>feasible journey</u> from origin to destination yard, including the <u>train service paths</u> followed AND the *blocking-path* (*BP*). So in the above illustration, each combination of physical route with an embedded blocking path will constitute an ***itinerary*** for us.

- Route : *TR-'T61'-M-'T191'.*
  - If *BP* is TR-T, then itinerary is: *TR–'T61'–transfer@M-'T191'–T.*
  - If *BP* is TR-M-T, then itinerary is: *TR–'T61'–classification@M-'T191'–T.*
- Route : *TR-'LT'-QC-'T62'-M-'T191'.*
  - If *BP* is TR-QC-M-T, then itinerary is:
    TR–'LT'–classification@QC-'T62'– classification@M-'T191'–T.
  - If *BP* is TR-QC-T, then itinerary is :

TR–'LT'–classification@QC-'T62'–transfer@M-'T191'–T.

- If *BP* is TR-M-T, then itinerary is :

  TR–'LT'–transfer@QC-'T62'–classification@M-'T191'–T.

- If *BP* is TR-T, then itinerary is:

  TR–'LT'– transfer@QC-'T62'–transfer@M-'T191'–T.

Again even for a single traffic-class, we end up with six itineraries corresponding to six blocking paths illustrated before. As is typical in most network problems, the problem size increases exponentially. But given the sparse railroad network, we probably will not be bogged down too much due to size increments. But if we are, we can always resort to what Barnhart et al. (2000) did. We will limit the number of possibilities by some rule of thumb. We will enumerate only the direct itineraries, which involves no circular connections or too many intermediate handlings. Enumerating only the direct itineraries makes sense, since indirect itineraries besides being costly are also risky as frequent handling increases the chances of hazmat release. But we will still enumerate itineraries within 200% of shortest path between an origin-destination pair, besides including all the direct itineraries using the available train services.

We use *population exposure* as the measure of risk. As explained in Chapter 3, we consider a populace exposed if the aggregate concentrate level exceeds the *IDLH* level specified for the hazardous material in question. Figure 4.4, an extension of figure 4.2, illustrates another concept relevant to hazmat transportation and hence us. We want to propose a methodology (inspired by our work in chapter 3) which can enable us to capture the *population exposure economies* whenever more than one railcar moves together, while incorporating the nature of freight operations as described above.

We will make use of figure 4.4 (below) to illustrate some other concepts pertinent to the development of our model, which is distinct from the purely *cost-based* railroad models. Suppose we wish to track two traffic classes: *TR→T* as before, and *N→T*. Both traffic classes have alternate ways to get from their respective origin yard to their destination yard. One possible route for both the traffic classes will contain yards *QC* and *M* with the train service *'T62'*, i.e. *QC-'T62'-M*.

Figure 4.2's illustration was based on traffic-class; here, we would like to go one step further and divide the traffic class into railcars containing hazardous materials and regular freight. For example, traffic class *TR→T* contains three hazmat railcars and two regular freight railcars, and traffic class *N→T* contains just two hazmat railcars.

To recollect, train *'T62'* is formed at *QC* and terminates at *M* with a stop at *Sh*. As before, the track-section between *QC-Sh* and *Sh-M* are the *service-legs* of train *'T62'*. Let us focus on the first service-leg, *QC-Sh*. These two traffic classes present four possible combinations to the service-leg *QC-Sh*.

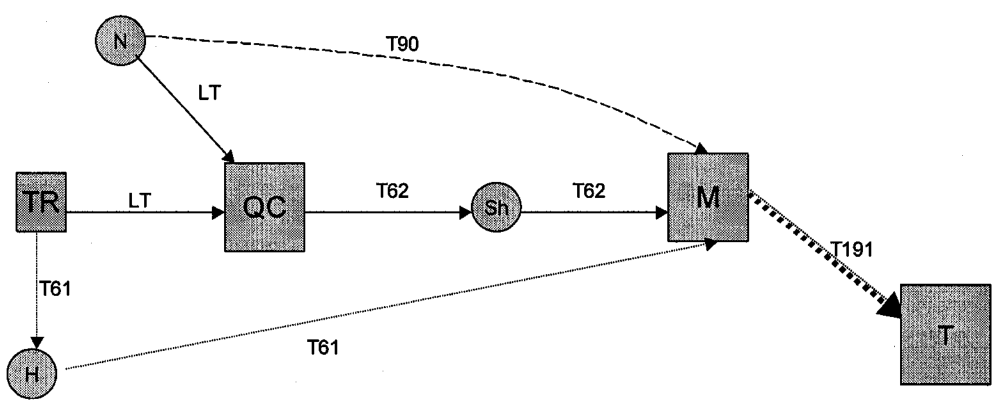


Figure 4. 4: Illustration of *Economies of Risk*

First, both *TR→T* and *N→T* will be connected to train *'T62'* and take the said service leg. *Second*, only *TR→T* will take this service leg. *Third*, only *N→T* will take this service leg. *Finally*, neither will take this service leg. For service leg *QC-Sh*, let '**Ω**' be a set containing possible combinations of the two traffic classes as its elements. Hence **Ω** = {(*TR→T*, *N→T*), (*TR→T*), (*N→T*), ( )} corresponding to the four combinations, and μ_i would indicate the elements of this set. Since *population exposure* stems from the number of railcars with hazardous cargo, the four elements of **Ω** will result in four different (in this case) population exposure numbers for the service leg in question. Hence we would end up with four population exposure figures corresponding to the four elements of the set **Ω**.

Since we know the number of hazmat railcars for each element of the set **Ω**, it is possible to calculate the corresponding population exposure for each. For example, the population exposure as a result of the first combination (element), involving both traffic classes, would be calculated as follows. The total number of hazmat railcars, in this instance when both traffic classes use service leg *QC-Sh*, is five. We recall (3.5) from chapter 3, and hence the aggregate concentrate level at downwind distance 'x' due to five hazmat railcars will be given by:

$$\overline{C}_5(x) = \frac{Q}{\pi\, u\, a\, c\, x^b\, x^d} \times 5 \tag{4.1}$$

We make use of our reference about the *IDLH* levels and replace the left hand side of (4.1) with the *IDLH* level ($\overline{C}$) appropriate for the hazmat in question. Now we end up with,

$$x^b x^d = \frac{5 \times Q}{\pi\, u\, a\, c\, \overline{C}};\ \overline{C} \text{ is the IDLH level.} \tag{4.2}$$

This threshold distance becomes the radius of the danger circle centered at the *hazmat-median*[6] of the train. For *QC-Sh*, this danger circle will move along the length of the service leg thereby carving out a band around the service leg, and the number of people within this band is the corresponding *population exposure*. Mathematically, the band is the area enclosed by the length of the service-leg *QC-Sh* and the threshold distance (radius) on either side of the service-leg. Specifically, we will end up with

$$x = \sqrt[b+d]{\frac{n \times Q}{\pi\, u\, a\, c\, \overline{C}}} \tag{4.3}$$

and,

Population Exposure for this service leg

= *(x)** *(length* of the service leg)*(population density within *x).*

It is rather intuitive that x and population centers exposed depend on the number of hazardous materials railcars. The relationship between 'n' and 'x' is distinct in (4.3). The value of 'x' determines the exposure zones and thereby the impacted population centers. The aforementioned also implies an indirect

[6] It is center of the hazmat block, which will be the third car for the five hazmat car instance.

relationship between impacted population centers and the number of hazmat railcars.

We can use (4.3) to calculate population exposure for all the four elements of set '**Ω**'. It should be noted that the population exposure at *M* (or *QC*) due to the five hazmat cars is simply the product of the area of circle with *x* as the radius, centered at *M* (or *QC*) and the population density of the exposed centers.

We used figure 4.4 and the above discussion to describe (traffic combination dependent) the calculation of population exposure parameters for different service legs and yards. It is to be noted that each element in set **Ω** is uniquely defined by the triplet *{train type, service leg* and *traffic combination}*. For the simple representation, it is trivial to enumerate all possible combinations. But any realistic size railroad applications would entail a huge number of possible combinations for any service-leg. For example, if a service-leg is one of the possible routes for 10 traffic-classes, there would be 1024 combinations possible (elements) for that service-leg. Generating all the possible combinations for hundreds of different traffic-classes is both inefficient and extremely cumbersome. We will elaborate on this in the sections to follow, but for now we just wanted to allude to the complexity of the problem.

Train *'T62'* has a capacity on the number of railcars it can carry. We note that this capacity typically varies from one service leg to the other, owing to the different track / road-bed quality or the capacity of the receiving tracks at the intermediate yards. We will assume a constant capacity (a conservative 120 railcars) for a given train service as *'T62'*, without breaking it down into service leg capacities. It is rather intuitive that the number of cars to be moved from one yard to the other will determine the number of train services of any particular type. More specifically the service leg with the maximum number of railcars to be moved by a particular train service determines the number of trains of that type needed in the system. In essence, it is a reverse bottleneck, as the frequency of a train type is determined by the maximum number of railcars to be hauled over a service leg.

As illustrated in Figure 4.2, yard '*QC*' has a classification facility. There is a capacity constraint on the number of railcars that could be classified at this yard.

Similarly yards with transfer facility will have an upper limit on the number of railcars that can be transferred at that yard.

4.5 Mathematical Model

We intend to address the interests of two stakeholders: regulatory agencies & railroad companies. A bi-objective model will be developed to realize the aforementioned objective. Among other things, our model development will draw upon the *risk assessment* framework developed in Chapter 3, and the workings of the railroad industry as discussed in the previous sections of this chapter. We will make use of the *approximation method* and the *economies of risk* to conduct risk assessment, while the cost components will accrue from the intricacies of railroad operations. The best weighted *'cost-risk'* solution will enable us to determine the best possible traffic routing, blocking path and number of trains of different types required to meet demand in the network.

Problem Definition

Decide on the best **itineraries** for various traffic-classes and the number of train services of different types, in order to minimize global *population exposure & dollar cost*, while meeting demand. This should be done using the existing train services and yard-operations network, and adhering to the capacity limitations of different resources.

Motivation

The methodology developed in the previous chapter and the subsequent application unraveled *economies of risk* in the railroad industry, while the crux of railroad operation is *economies of cost*. In hazardous materials literature *'cost-risk'* modeling has been done in the highway context (truck shipments), but to the best of our knowledge has not been extended to railroads. We intend to develop a Decision Support System (*DSS*) for the railroads to plan, monitor and manage hazardous materials shipments. As we saw in the previous chapter, most of the work deals with the statistical analysis of past accident and release data. Moreover all the work in the context of railroads does not distinguish between hazmat and non-hazmat traffic, and hence a generic model is applied irrespective of the characteristics of the traffic.

Without undermining the importance of dollars and cents, we wish to emphasize the relevance of *risk-minimization* for carriers dealing with hazardous materials. It is in the broader interest of the society (including railroad operators) that '*risk*' find the same or equivalent currency as '*dollars*'. We intend to contribute towards closing the gap between the two aforementioned objectives, and hence propose a *bi-objective mathematical model*. The solutions stemming from this bi-objective model will form different points of a trade-off curve, with weights on the *number of people* and *dollars* as the two axes. The stakeholders in question can choose points on the curve mutually acceptable and synergistic for the system. Of course each point on this *risk-cost* curve, associated with a *population exposure–dollar* pair, will correspond to a complete solution to the problem, i.e., traffic-routing, blocking paths and numbers of train of different types moving in the network. This is being done while maintaining the global constraints and ensuring effective utilization of the available resources.

Assumptions

We will make three assumptions. *First*, demand is weekly and expressed in terms of number of railcars (both hazmat and non-hazmat). All the demand numbers have been generated to represent a seven-day horizon, and doing so justifies the tactical nature of the problem. *Second*, the number of railcars to be moved is available at one time on a weekly basis and hence, we are not concerned about the traffic accumulation/delay. More specifically we are treating a railcar waiting for 5 days for connection to be the same as the one waiting 1 day for connection. Doing so enables us to do two things: not be bogged down at an operational level of details; and not attempt to capture (quantified) waiting costs in different yards at different points in a railcars journey. *Finally*, the hazmats being shipped possess identical chemical properties, and hence have no interaction. This assumption although conservative is essential since there is no credible study demonstrating the interaction among (between) hazardous materials transported in North America.

Model

We are ready to formulate the mathematical model, and define the indices, sets, parameters and decision variables, next.

Sets and Indices:

L: Set of train services, indexed by l.

S_l : Set of service legs for train service l, indexed by s.

M : Set of demand (traffic - class), indexed by m.

I^m : Set of itinerary for demand m, indexed by i.

J_{sl} :Set of itinerary that uses s_l, indexed by j.

C: Set of classification yards, indexed by c.

T: Set of transfer yards, indexed by t.

J_y :Set of itinerary using yard c, $y \in C \cup T$.

Decision Variables:

$$X_i^m = \begin{cases} 1 \text{ if demand } m \text{ is met using itinerary } i \\ 0, \text{otherwise} \end{cases}$$

N_l = Number of train service of type l

$Y_{l,s}$ = Number of hazmat railcars using service leg s of train l

Y_y = Number of hazmat railcars using yard y

Parameters:

$CE(Y_{l,s})$ = cumulative exposure of variable $Y_{l,s}$.

$CE(Y_y)$ = cumulative exposure of variable Y_y.

C_i^m = operating cost per railcar of demand m on itinerary i.

C_l = operating cost of train service l.

W^m = weekly demand of traffic - class m.

h^m = number of hazmat cars in m.

nh^m = number of non - hazmat cars in m.

U_l = maximum number of railcars on train service l.

χ_c = number of railcars that can be classified per week at yard c.

χ_t = number of railcars that can be transfered per week at yard t.

(P)

$$Min \sum_{l \in L} \sum_{s \in S_l} CE(Y_{l,s}) + \sum_{y \in C \cup T} CE(Y_y) \quad (4.4)$$

$$\sum_{i \in I^m} \sum_{m \in M} C_i^m X_i^m + \sum_{l \in L} C_l N_l$$

$s.t.$:

$$\sum_{i \in I^m} X_i^m (h^m + nh^m) = W^m \quad \forall\, m \in M \quad (4.5)$$

$$\sum_{m \in M} \sum_{i \in I^m \cap Js_l} X_i^m (h^m + nh^m) \le U_l N_l \quad \forall s \in S_l\ \forall l \in L \quad (4.6)$$

$$\sum_{m \in M} \sum_{i \in I^m} X_i^m (h^m + nh^m) \le \chi_c \quad \forall c \in C \quad (4.7)$$

$$\sum_{m \in M} \sum_{i \in I^m} X_i^m (h^m + nh^m) \le \chi_t \quad \forall t \in T \quad (4.8)$$

$$\sum_{m \in M} \sum_{i \in J_{S_l}} X_i^m h^m \le Y_{l,s} \quad \forall s \in S_l, \forall l \in L \quad (4.9)$$

$$\sum_{m \in M} \sum_{i \in J_y} X_i^m h^m \le Y_y \quad \forall y \in C \cup T \quad (4.10)$$

$$X_i^m \in \{0,1\}; \quad (4.11)$$

$$Y_{l,s} \ge 0\ INT; Y_y \ge 0\ INT; \quad (4.12)$$

$$N_l \ge 0 \quad INT \quad (4.13)$$

Model Description & Parameter Calculation:

Objective Functions: (P) has population exposure and dollar cost as objectives.

Population Exposure

First objective in (4.4) contains population exposures on *lines* and at *yards* in the rail network. The exposure parameters are derived from only the hazmat railcars. Just to reiterate, the concentration level will be determined using (3.5) and we intend to capture the economies of risk whenever more than one railcar with hazmat cargo is moving together.

Line: It is the *service leg* measure. It says that population exposure for a particular service-leg of a specific train-type is a function of the number of hazardous materials railcars, belonging to different traffic-classes and itineraries, using that service-leg of the train. Hence, population exposure is not only a function of the population density of the centers exposed and non-linear, but also without a closed-form expression for the risk objective. The last observation stems from the fact that one needs to know the traffic-combination (elements of the set), a priori, in order to have a closed form expression. The only way to do that is complete enumeration, which is both inefficient and extremely cumbersome. In fact the original expression for the risk-objective for a service-leg is:

$$\sum_{l \in L} \sum_{s \in S_l} CE\left(\sum_{m \in M} \sum_{i \in J_{s_l}} X_i^m h^m\right) \tag{4.14}$$

The expression within the parentheses represents the number of hazardous materials railcars, belonging to different traffic-classes and coming from various itineraries on this service leg. Most importantly it enables us to capture *economies of risk* and also to calculate the exposure parameters.

$CE(Y_{l,s})$ = (threshold distance *(x))* **(length* of service-leg*)* *

(population density *(ρ_i's)* of the centers exposed*)*

From (3.5), we know how to calculate the aggregate concentration and the threshold distance (on either side of the service leg) for the corresponding volume of any hazardous material. Hence,

$$\overline{C} = Y_{l,s} \times \frac{Q}{\pi\, u\, a\, c\, x^b\, x^d} \Rightarrow Y_{l,s} = \frac{\overline{C}\pi\, u\, a\, c}{Q} x^b\, x^d = Kx^b\, x^d \Rightarrow x = \sqrt[b+d]{\frac{Y_{l,s}}{K}}$$

(4.15)

(4.15) returns the threshold distance for any value of $Y_{l,s}$,the number of railcars with hazardous cargo, for an IDLH specified concentration level, $\overline{C}$. As we noted earlier, threshold distance is a function of the number of hazardous materials railcars on a service-leg. This threshold distance in turn enables us to identify and capture the exposed population centers. Clearly the exposed centers will have different densities of population. Hence, cumulative population exposure for a service-leg will have to be determined by:

$$CE(Y_{l,s}) = x(Y_{l,s}) \times length\, of\ s \times \rho(x(Y_{l,s})) \qquad (4.16)$$

It is easy to see from (4.16) that cumulative population exposure is non-linear with a rather complicated form, and without a closed form expression.

<u>Yard:</u> The number of hazmat railcars, belonging to different traffic-classes, subject to a yard activity will also cause population-exposure. This population exposure will, alike for service legs, stem from only the hazmat railcars using that yard. As before, we will make use of (3.5) to calculate the aggregate concentrate level and the corresponding threshold distance at an IDLH specified level for the hazmat in question. The original expression is:

$$\sum_{y \in C \cup T} CE(\sum_{m \in M} \sum_{i \in J_y} X_i^m h^m) \qquad (4.17)$$

It pertains to the yard activities (classification or transfer) performed at a single or group of railcars with hazardous cargo. The cumulative *population exposure* at a yard will be the total population within the danger circle centered at this yard.

$$CE(Y_y) = (\pi)^*(x^2)^*\textit{(population density of the centers exposed)}$$

where, x is the threshold distance for the hazmat in question.

The threshold distance and population density will be calculated using (4.15). So the cumulative *population exposure* for a yard is:

$$CE(Y_y) = \pi(x^2(Y_y)) \times \rho(x(Y_y)) \quad (4.18)$$

As in (4.16), we again notice non-linearity and a complex function without any closed form expression in (4.18).

Dollar Cost:

The cost of moving traffic and using available resources forms the other objective in **(P)**.

Railcar routing cost: will be incurred for both hazardous and non-hazardous railcars. It comprises 3 elements: travel cost; transfer cost and classification & blocking cost. *Travel cost* is calculated on a per car basis for the journey from the origin to the destination yard for a specific railcar. *Transfer cost* is the cost incurred due to the handling at intermediate yards. It will be linear or non-linear depending on the handling points of the railcars in a group. If the common handling point for railcars is not the same, the resulting cost will be linear to the number being transferred. But if some or the entire group of railcars have a common intermediate or final destination, transfer cost will be non-linear and lead to economies of scale. Classification cost is incurred at the marshalling yards depending on the number of cuts required and number of blocks assigned to, in order to arrive at railcars' destination. Just like the transfer cost it could be subject to linearity or non-linearity, depending on the (final/intermediate) destination of the railcars in an incoming block. The cost coefficients take care of non-linearity in cost, and hence, they do not in any way enter variables or constraints of **(P)**.

Train Service Cost: is the cost for providing the required frequency of different train services. It depends on the *motive power cost* and *crew cost.* Motive power means the engines required to haul the load, while crew cost accounts for the wages of the driver, engineer, etc. accompanying the train.

Constraints:

- (4.5) says that the weekly demand for each traffic-class (W^m), consisting of hazmat and non-hazmat railcars, will be met using one of the available itineraries (I^m) for each traffic class.
- (4.6) pertains to the capacity of service-legs. The number of railcars belonging to various traffic-classes on a particular service-leg, such that it is a part of their itinerary, of a train service should not exceed the trains' capacity on that service-leg. In addition the maximum number of railcars to be moved between two service legs of a particular train type determines the number of trains of that type required in the network.
- (4.7) models the capacity of the yard for classifying railcars. The total number of railcars, belonging to different traffic-classes and coming from various itineraries, classified at a certain yard y cannot exceed the capacity of the yard. Yard y belongs to the set of designated classification yard for traffic-class m on itinerary i.
- (4.8) models the transfer capacity of the designated transfer yards. Like in (4.7), only the traffic-classes with this yard on their itinerary use it.
- (4.9) says that the number of hazmat cars, of different traffic-classes, given that they are using the service leg will determine the cumulative population exposure in the objective function. As alluded to earlier, this representation allows us to capture '*economies of risk*' on different service legs of any train service.
- (4.10) follows much of the argument and justification of (4.9), except that everything is within the context of a yard.
- (4.11) restricts the choice of the variables to binary.
- (4.12) defines the number of hazardous railcars on any service leg or yard.
- (4.13) indicates the number of train services of different types needed to satisfy the demand over the tactical planning horizon.

4.6 Solution Methodology

(P) does not have a closed form expression for the risk objective, which in turn rules out the possibility of calling a standard optimization package to solve it. One possible way to solve **(P)** is to decompose it into two parts. The first part will deal with just cost and the second with just exposure (risk). After decomposition, **(P)** will have two components, ***Cost Sub-Problem*** **(P1)** and ***Exposure Sub-Problem*** **(P2)**, and they are as follows:

Cost Sub-Problem (P1):

$$Min \sum_{i \in I^m} \sum_{m \in M} C_i^m X_i^m + \sum_{l \in L} C_l N_l$$

s.t.:

$$\sum_{i \in I^m} X_i^m (h^m + nh^m) = W^m \qquad \forall\, m \in M$$

$$\sum_{m \in M} \sum_{i \in I^m \cap Js_l} X_i^m (h^m + nh^m) \le U_l N_l \qquad \forall s \in S_l \ \forall l \in L$$

$$\sum_{m \in M} \sum_{i \in I^m} X_i^m (h^m + nh^m) \le \chi_c \qquad \forall c \in C$$

$$\sum_{m \in M} \sum_{i \in I^m} X_i^m (h^m + nh^m) \le \chi_t \qquad \forall t \in T$$

$$X_i^m \in \{0,1\};$$

$$N_l \ge 0 \quad INT$$

Exposure Sub-Problem (P2):

$$Min \sum_{l \in L} \sum_{s \in S_l} CE(Y_{l,s}) + \sum_{y \in C \cup T} CE(Y_y)$$

s.t.:

$$\sum_{m \in M} \sum_{i \in J_{s_l}} X_i^m h^m \le Y_{l,s} \qquad \forall s \in S_l, \forall l \in L$$

$$\sum_{m \in M} \sum_{i \in J_y} X_i^m h^m \le Y_y \qquad \forall y \in C \cup T$$

$X_i^m \in \{0,1\}$;

$Y_{l,s} \geq 0\, INT; Y_y \geq 0\, INT$;

(P1) can be solved using any optimization package to return the minimum cost solution. But how to solve **(P2)**? The complex form of **(P)** and the absence of a closed form expression for risk tell us that it is a classic candidate for metaheuristic solution, but there is a whole range of metaheuristic solution approaches. Which one should be used? We noticed that **(P)**, typically, will contain a huge number of variables but few constraints. Against this observational backdrop, **(P)** appeared to be a very good candidate for *Genetic Algorithm* (GA). GA is appropriate for problems with large number of variables, few constraints, and complicated objective functions. Each of the three conditions was encountered in **(P)**.

GA, being a population search heuristic, is adequate to address the aspect of *diversification* and global search of the solution space. But it has rather limited efficiency in the realm of local or neighborhood search (*intensification*) namely the mutation rate. To overcome this limitation, we will supplement global search of GA with a *neighborhood search.* This neighborhood search replaces the mutation step of conventional GA. So our methodology, for **(P)**, involves combining global and local searches, and can appropriately be designated as a *Hybrid* or *Memetic Algorithm*, rather than a pure GA.

MEMETIC ALGORITHM

Steps

1. Solve **(P1)** using any optimization package.
2. Encode and Initialize **(P2)** on the solution from **(P1)**.
   Randomly generate other feasible solutions
   - **MASK** (uniform 0-1 bit string) to fix certain itineraries to demands.
     - Re-Solve **(P1)**, with MASK induced assignments as additional constraints.
     - Attach the corresponding **(P2)** components.
3. Evaluate each feasible solution in Step-2.
   - Penalize capacity violations by adding to the weighted objective value.
4. **Rank** the solutions, on the basis of weighted objective value, in the starting pool.
5. **Rank** based **Roulette-wheel selection**: to generate children.
   - Generate a pair of random numbers to choose Parents to mate.
   - Execute Uniform crossover (MASK) to generate children.

- Conduct *neighborhood* search(s) on children.
  - Uniform binary string.
  - One-bit exchange.
- Create a new generation.

6. Preserve the best solution in each generation.
7. Repeat steps 4, 5 & 6 until:
   - No improvement in weighted objective value.
   - No Diversity
   - Significant convergence.
8. STOP. Decode the Solution.

Table 4.1: Summary of *Memetic Algorithm*

Details on the STEPS of '*Memetic Algorithm*'

Step-1:

This step is rather straightforward as for any other mathematical model with similar characteristics.

Step-2:

Encoding: We tested both binary and non-binary encoding schemes, and decided to use non-binary coding. Although binary coding has its' advantages, our problem structure favors a non-binary scheme. The latter enables us to exploit the versatility it provides for representational purposes. An illustration of non-binary coding for our problem structure follows:

$\mathbf{m_1}$	$\mathbf{m_2}$	$\mathbf{m_3}$	.....	$\mathbf{m_n}$
2	3		1	4

The numbers in the second row indicate that i^{th} itinerary of the corresponding traffic-class is being used to meet that demand. For example, the *2nd* itinerary of $\mathbf{m_1}$ is being used to meet that demand, and so on.

Initializing:

- The minimum cost solution returned by **(P1)** will constitute one solution once the weighted population exposure part is attached to it.
- Other feasible solutions in the starting pool:
  - Generate a string of 0-1 values (a 0-1 random MASK). The number of elements in the string should correspond to the number of traffic-classes or demand ($\mathbf{m_n}$).

Demand	m_1	m_2	m_3	...	m_n
MASK	*1*	*1*	*0*		*1*
Itinerary	*2*	*3*	*1*	*1*	*4*

For example, the second row in the above table is a representation of 0-1 binary string. It tells us that traffic-class (demand) with bit value *1* will be assigned to one of the available itineraries to meet that demand. But we also know that some traffic-classes have more than one way to move from their origins to their destinations. So another random number, whose range corresponds to the number of possible itineraries, is generated to decide which itinerary will be assigned to move traffic. For example, bit-value *1* below $\mathbf{m_1}$ implies that demand $\mathbf{m_1}$ will be pre-assigned to one of the possible itineraries. Let us assume that $\mathbf{m_1}$ has four itineraries, hence another random number is generated between one and four, each corresponding to one itinerary. Suppose the resulting random number is two, then *2nd* itinerary of demand $\mathbf{m_1}$ will be used to meet this demand.

These demand-itinerary assignments are based on the generation of a string of binary random numbers and then another random number depending on the number of itineraries for the corresponding traffic-class. These assignments (demand to certain itinerary) are introduced as additional constraints in **(P1),** which is re-solved every time to generate a feasible solution for the gene pool after **(P2)** component has been added.

This approach ensures diversity and richness in the gene pool, since the starting solutions in the pool will be from all over the solution space. This will ensure good results and prevent premature convergence.

Step-3:

Evaluation: Each feasible solution in the gene pool is evaluated to determine its weighted objective value. The two components of the objective function are weighed according to the preferences of the parties involved. Furthermore, depending on the resource (train or yard capacity) requirement and violations, a penalty amount is added to the weighted objective value. For example, train service capacity can be addressed by adding an extra train to move additional railcars.

Step-4:

Ranking: Each feasible solution in the gene pool has been evaluated in ***Step-3***. Based on their evaluated values they are ranked, the one with minimum weighted objective value occupy the first rank and the one with maximum weighted objective value the last, with others in between. We execute *roulette-wheel* selection (explained next) mechanism to choose parents for mating. Our ranking ensures that fitter parents, viz. ones occupying top ranks in the pool have a higher probability of being selected for mating than ones at the bottom of the pool. That is exactly what we want since procreation by fitter parents will produce better children and ensure passing of good genes.

Step-5:

Roulette-Wheel Selection: After the feasible solutions have been ranked in the gene pool, their selection probabilities are determined. Sub-steps are as follows:

i. Selection range, based on selection probability, is calculated for each feasible solution. $\mathbf{P(S)_i}$

ii. Generate a pair of random numbers between 0 and 1.

iii. Select the solution (parent, hereafter) whose selection range values contain the random number.

- A parent (chromosome) with high **rank** will have a greater selection range, and hence a higher probability of being selected for mating. This ensures more frequent selection of fitter parents and propagation of good solution features to the next generation.

iv. Uniform crossover is executed.

- A random binary MASK (as in *Step 2*) is generated to determine the crossover points between the two parents. Such a string enables us to not be limited to one point or multi-point crossovers.

v. Offspring are produced.

- Neighborhood search is conducted on the offspring.
    - o If the local search yields a better offspring, then this will enter the next generation. Or else the one originally generated enters the next generation.

- Type of local searches can vary. We will present two types of local searches (uniform binary string & bit-exchange) in the realistic size case example in the next section.

Step-6:

The best solution of each generation is preserved and used as a stopping condition.

Step-7:

The algorithm continues until no improvement is observed in the weighted objective value. The stopping condition depends on the problem at hand. We will present two stopping conditions in the sections to follow.

Step-8:

Decode the solution after the algorithm has stopped. This is the best known weighted solution for the problem in question.

4.7 Illustrative Example

We intend to use this section to demonstrate the application of **(P)** and the associated solution methodology on a realistic size railroad example. Figure 4.5 (below) represents the (available) physical railroad network in the provinces of Ontario and Quebec.

The problem statement and other details are as follows:

- The network has 10 nodes on it, each representing both supply and demand point for the other nine. Hence there are 90 supply-demand pairs, which need to be accounted for.
- There are six types of train services on this network, with three traveling east and the other three traveling west. The number of trains (frequency) of each type is a variable to be determined. Each train service is defined by, an origin-destination yard, a set of service-legs (track sections) and intermediate yards to pick/drop traffic. Moreover the train capacity on each service leg is defined as a constant, i.e. 120 railcars.

- Out of the 10 nodes (yards for railroad purposes), some are *fully-equipped* while others are just *service yards*. In addition the classification and transfer capacity of yards are predefined.

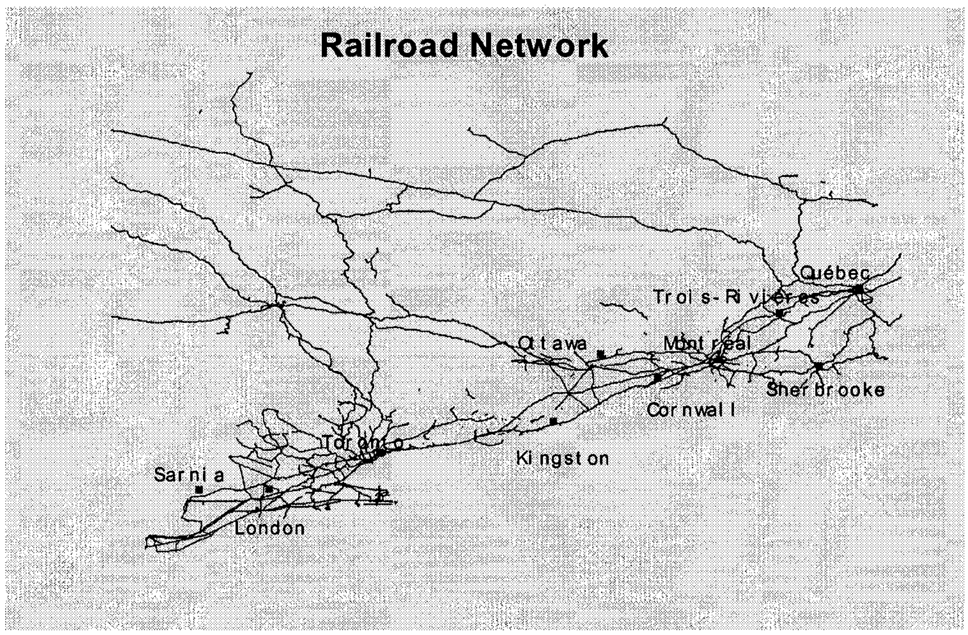


Figure 4.5: Realistic Size Railroad Network in Ontario and Quebec

"Determine the freight routing (both hazmat and non-hazmat) for the 90 traffic-classes and the train frequency of different train-services to meet the respective demands, while adhering to the capacity limitations of the resources being utilized in the network."

Figure 4.5 presents the railroad network in the provinces of Ontario and Quebec. On this network, the service networks of the six train types are illustrated in figure 4.6 (below).

Total Demand Matrix										
From/To	*S*	*L*	*T*	*K*	*O*	*C*	*M*	*TR*	*Sh*	*QC*
Sarnia		15	18	17	17	15	18	17	15	19
London	19		18	20	18	17	16	16	17	17
Toronto	15	20		16	18	15	18	19	20	20
Kingston	15	15	16		20	18	20	17	17	19
Ottawa	20	17	18	16		19	17	20	17	18
Cornwall	16	20	16	15	19		20	15	18	15
Montreal	15	16	19	15	16	16		18	16	16
Trois-Rivieres	20	18	17	18	18	17	16		19	15
Sherbrooke	17	17	19	18	15	16	19	15		15
Quebec City	16	18	19	17	16	17	18	19	17	

HAZMAT Demand Matrix										
From/To	S	L	T	K	O	C	M	TR	Sh	QC
Sarnia		9	8	8	5	5	8	10	6	10
London	8		10	9	10	8	10	7	10	8
Toronto	6	10		10	5	10	10	6	10	10
Kingston	8	9	10		10	7	5	5	7	10
Ottawa	6	5	8	9		6	10	9	6	6
Cornwall	10	5	6	6	5		5	8	9	7
Montreal	10	10	5	5	10	8		6	9	8
Trois-Rivieres	9	6	7	5	9	9	8		9	9
Sherbrooke	8	7	9	9	6	5	9	10		7
Quebec City	5	6	10	10	9	10	5	10	8	

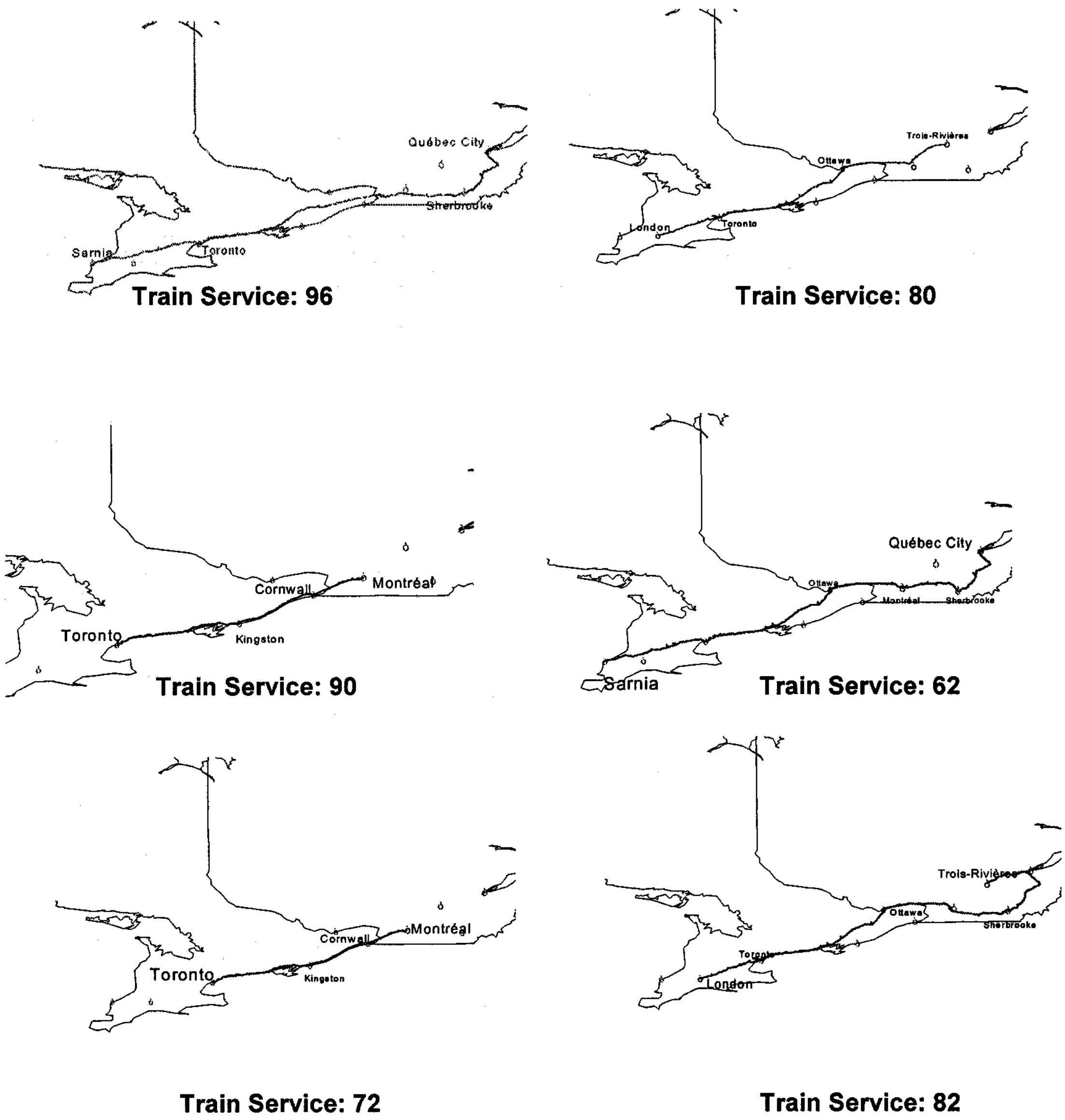


Figure 4.6: Routes of the six Train Services

Using the given information, we formulated the problem as **(P)** which was then decomposed into the cost sub-problem **(P1)** and exposure sub-problem **(P2)**, as described in Section 4.4.

Cost Sub-Problem (P1)

- **(P1)** consists of railcar routing and has the fixed cost of providing train services as objective function. The cost numbers were generated using the publicly available information on railroad cost, classification and transfer data.
- Only the 170 itineraries out of a possible 700 were enumerated. The ones included are the direct itineraries, the remaining are indirect and at times circular, which will never be taken for routing purposes. As alluded to earlier, these indirect itineraries are not only more expensive but also more risky. It should be noted that our **itinerary** definition encompasses both movement on track sections as well as classification and/or transfer at yards.
- There are 126 constraints, out of which 90 are demand constraints and 36 related to train-services and yard operations capacities. The demand constraints correspond to 90 complete supply-demand points in the network. 20 capacity constraints pertain to the allowable train lengths on different service-legs for that train type, which was capped at 120 railcars for any train. 6 capacity constraints capture the classification ability of the yards in the network, which are Sarnia, London, Toronto, Montreal, Trois-Rivieres and Quebec City.

The classification constraint was 500 railcars/week for each of the 6 yards. The remaining 10 addresses the transfer ability of each of the 10 yards, whereby the capacity was 500 railcars/week. Given the tactical nature of our model, the two capacity numbers are not very relevant. They are significant on an operational level, when one is concerned about congestion and accumulation effect. For the purpose of our work here, we are not aiming to capture either of the two and hence the daily handling capacity is not pertinent.

➢ After inputting all of the above data, we called CPLEX and it returned the *minimum cost solution.*

Exposure Sub-Problem (P2)

- To recap, the objective function is without a closed form expression and is highly non-linear with a rather complicated form. Moreover **(P)** contains a huge number of variables, fewer constraints and has a highly complicated form, which makes it an ideal candidate for a population based heuristic solution.
- GA requires some initial starting points to begin iteration. It is advisable to populate the initial gene pool (Parents) with good and diverse starting points in the solution space, since the two together would ensure rich and appropriate convergence. We will elaborate on the size of the gene pool in the section on *Computational Experiments*. For now, what follows is how we get the first member in the initial gene pool.
- For the 90-itineraries, returned by CPLEX for **(P1)**, corresponding *population exposure* is calculated. How?
- Gaussian Dispersion Plume, IDLH level for the hazmat in question and spreadsheet (to determine threshold distance), are used as described in Chapter 3, and the previous two sections of this chapter.
- Geographical Information System (GIS ArcView): The threshold distance calculated in the previous stage is used to generate exposure bands around the train-service legs and at the yards.
  a) GIS ArcView provides us with the population centers.
  b) We overlay the NTSB railroad network on top of the population centers.
  c) Bands or Exposure zones, for different number of railcars with hazardous cargo, were created around the service-legs and yards in question.
  d) *Avenue Programming* was used to determine the intersectional area between the bands and population centers. Then the population residing within the intersectional area was *extracted* to yield population exposure figures.

It should be noted that c) and d) have to be done individually for every possible number of railcars with hazardous cargo on every service-leg and at every yard of concern. For the problem in question there are 20 service legs for the six train types, and 10 yards. Since we do not know the number of railcars with hazardous cargo at either the yards or at different service legs before hand, we need to provide (compute) the population exposure values for every possible combination. The train lengths are capped at 120 railcars, hence 2400 (120*20 service legs) population exposure calculations had to be done for the 20 service legs. Six of the ten yards possess classification ability for a weekly capability up to 500 railcars, hence 3000 (500*6) population exposure calculations had to be done for the classification part. Similarly, 5000 (500*10) population exposure bands had to be generated for the ten yards to account for the transfer function. In total, 10,400 exposure bands had to be (avenue) programmed and generated in GIS ArcView, so as to be able to start the ***Memetic Algorithm***.

➢ After completing all these steps, one feasible solution (parent) is ready to enter the initial gene pool. But we need to populate the gene pool further.

Initial Gene Pool: Other Parents

The minimum cost solution gives us the first parent for the initial gene pool, but we need others. As mentioned earlier, the intent is to populate the gene pool with as diverse and rich parents as possible.

- Generate a binary *MASK* (or 0-1 string) or random numbers with 90 elements, one corresponding to each of the 90 demands (traffic-classes) as illustrated below in table 4.2.

Demand	m=1	m=2	m=3			m=85	m=86	m=87	m=88	m=89	m=90
MASK	1	1	0			1	1	0	0	0	1
Itinerary	**2**	**4**				**5**	**1**				**3**

Table 4.2: Encoding and MASK Generation Scheme

The first row in Table 4.2 represents the number of demand (traffic-classes) for our problem. 90 bits is the length of each parent string (chromosome). This length lets us worry only about the 36 capacity constraints during *MA* iterations, and not be bogged down by demand violation issues. As long as each chromosome has 90 elements inside it, which will always be the case here, the demand is automatically met, and hence there is no need to check for violations of demand.

The string of binary random numbers (*MASK*) in row 2 of the table enables us to populate the initial gene pool. The bit-position with a value '*1*' implies that the corresponding demand has to be (pre) assigned to one of the available itineraries. The choice of which itinerary, to be assigned to, is based on another random number corresponding to the number of itineraries available to that traffic-class (demand). For example, demand **m=2**, has to be assigned to an available itinerary. Let us assume that this traffic-class has four available itineraries. The third row in the table gives the itinerary to which a particular demand should be assigned to. This is again generated randomly. So for, demand **m=2**, itinerary number *4* will be used to move shipments from their origin to destination yards. This double randomness prevents any voluntary or involuntary bias. Moreover, it ensures solutions of all types and from all over the solution space.

Once the pre-assignments for the appropriate traffic-classes have been done, they are introduced as additional constraints in the cost sub-problem **(P1)**. These *MASK* and random number induced constraints would force **(P1)** solutions away from minimum cost, and return a variety of solutions from all over the search space.

To recap, after generating a *MASK* and a random number, certain demands are assigned to one of the available itineraries, which in turn become hard (additional) constraints in **(P1)**. Now CPLEX is called to solve **(P1)** with these additional constraints. The solution returned goes through the different steps of exposure sub-problem (as described above) for consequent '*risk*' addition to result in a weighted objective value. Once this has been done, the solution (parent) is introduced in the initial gene pool.

The aforementioned steps are repeated, depending on the number of parents in the starting solution. We tried, gene-pool sizes of 30, 50 and 100 chromosomes, the details on which is presented in the section on computational experiments. Ideally to facilitate good convergence, one should aim at having equal number of all the relevant attributes in the gene pool.

Memetic Algorithm:

Ranking

The starting solutions in the gene pool are ranked according to their weighted objective value (table 4.3). Since we are interested in minimizing the values of cost and risk, the string with lowest evaluated value occupies the first rank and so on. Based on the rank, there is a selection probability and hence a selection-range for each string (chromosome) in the gene pool. We execute a *rank-based roulette wheel selection* method for choosing parents.

D/C	m=1	m=2	m=3	... ...	m=87	m=88	m=89	m=90	W.V. (0.5,0.5)	RANK	P(Select)	P(Range)
Y1	1	1	2	... ...	1	1	1	1	69259	1	0.0645	0.0645
Y2	1	1	2	... ...	1	2	1	1	70009	2	0.0624	0.1269
Y3	1	1	2	... ...	1	1	2	2	70759	3	0.0602	0.1871
Y4	1	1	1	... ...	1	2	2	1	71173	4	0.0580	0.2451
Y5	1	1	2	... ...	1	2	2	1	71807	5	0.0560	0.3011
Y6	1	1	2	... ...	1	2	2	2	72437	6	0.0538	0.3549
Y7	1	1	2	... ...	1	2	2	2	72750	7	0.0516	0.4065
...	...	...	...	... ...		...	...	...	...	...	...	..
...	...	...	...	... ...		...	...	...	...	...	...	..
Y24	1	1	3	... ...	1	1	2	2	77214	24	0.0150	0.9441
Y25	1	1	2	... ...	1	1	1	1	77401	25	0.0129	0.9591
Y26	1	1	3	... ...	2	2	2	2	77401	26	0.0108	0.9720
Y27	1	1	1	... ...	1	2	1	2	77659	27	0.0086	0.9828
Y28	1	1	1	... ...	1	2	1	2	77844	28	0.0065	0.9914
Y29	1	1	3	... ...	3	1	1	1	78830	29	0.0043	0.9979
Y30	1	1	1	... ...	1	2	1	2	79389	30	0.0021	1.0000

Table 4.3: Ranked Chromosomes, Selection Probability and Range

$$p^i = \frac{2(P+1-i)}{P(P+1)}$$

where,

p^i=selection probability of the ith ranked chromosome.

i =solution ranked in the ith position of the sorted list.

P= number of parent chromosomes in the gene-pool.

For a population pool size of 30, the chromosome occupying the first rank slot has a probability of selection of 0.0645, which should be the *P(Select)* for the best chromosome. Hence *Y1* (best chromosome in table 4.3) has a *P(Select)* of 0.0645, and so on for the others.

Selection and Mating

A pair of random numbers, between 0 and 1, is generated simultaneously. In table 4.4, the two random numbers (0.84654 and 0.07971) belong to the selection-ranges of the 3rd and 24th chromosome in the gene pool. Hence, these two chromosomes are chosen for mating. Such a selection based mechanism accords greater probability for choosing higher ranked chromosomes, thereby propagating the good structures of the strings onto the subsequent generations.

Generate Random Numbers Between 0 and 1.												
0.84654	0.07971											
Y3	1	1	2	...	...	2	2	1	1	2	2	*70759*
Y24	1	1	3	...	...	3	1	1	1	2	2	*77214*

Table 4.4: Selected Chromosomes

Generate Uniform Crossover String.												
MASK	0	0	1	..	..	1	1	0	0	0	1	
D/C	*m=1*	*m=2*	*m=3*	...	...	*m=85*	*m=86*	*m=87*	*m=88*	*m=89*	*m=90*	W.V.
O/S -1	1	1	3	..	..	3	1	1	1	2	2	*74367*
O/S -2	1	1	2	..	..	2	2	1	1	2	2	*76253*

Table 4.5: Crossover Technique

Now that the two parents have been chosen for mating, the exchange of chromosome bits or crossover between the two has to be decided. One could resort to single-point or multi-point crossover. We did not want to restrict ourselves to either of the two, and hence used a string of binary random numbers (*MASK*) to decide the crossover points.

Table 4.5 illustrates the crossover technique employed. Whenever the bit-position value is ***1***, the corresponding bits of the two parents need to be swapped. For example, the third bit-position has a value of ***1*** hence the third bit of chromosomes *Y3* and *Y24* are exchanged. This is happening at **m=1, m=85** and **m=86**. But when the bit-value is ***0*** no exchange happens. Also, when bit-value is ***1*** and the corresponding bits contain the same elements, exchange is meaningless, as for **m=90**.

After the exchange two offspring *O/S-1* and *O/S-2* are produced. But before inserting them into the next generation pool a neighborhood search is conducted on each offspring. We are conducting two different types of independent local searches on each offspring and the impact of each on the solution will be detailed in the section on computational experiments.

The *first* type is based on our **uniform binary string** technique (*MASK*), whereby bit value of '1' indicates replacing the existing itinerary with an alternate itinerary for that demand class. This technique is similar to the explanation for table 4.2 for generating other starting solutions, earlier in this section. We call the *second* type a **one-bit exchange** technique. In here, only one bit is replaced by an alternate itinerary for that demand-class, while the remaining 89 retain the bit-values from crossover. Generally speaking one would expect the second type to be more local, since it will make only one step jump around the chromosome generated from crossover. In contrast the first type is subject to bigger jumps, since more than one bit-values can be replaced at a time.

Once the local search has been conducted, the evaluated value of the offspring before and after the local search is compared. The offspring with lower weighed objective value, either pre- or post-local search, enters the next generation. This local search is conducted on every offspring. Following the same steps, other offspring are produced thereby creating a completely new generation. This generation replaces the parent (initial gene pool) generation and now becomes the new parents, who would be chosen and mated for producing subsequent generations and so on.

Best Solution

The best solution of each generation was captured separately, and used as a stopping condition.

Stop & Decode

The aforementioned steps of *Memetic Algorithm* are repeated until some stopping condition is satisfied. We have experimented with two stopping conditions, the results of which will be presented in the following section.

First, when the best observed solution does not change for a certain number of generations. *Second*, when a maximum of two solutions are left in the gene pool and the difference between the two is insignificant. It is here that we stop the algorithm and decode the solution. The results from different scenario analysis and numerical experiments are presented in the following section.

4.8 Computational Experiments

We ran a number of scenarios to ascertain algorithmic efficiency and to get numerical insights, which also forms the basis for demarcating the following two subsections. Subsection 4.8.1 addresses the issue of algorithmic efficiency, while 4.8.2 provides a number of scenarios aimed at getting numerical insights. The supporting details on these scenarios are presented in **Appendix-A**, listed under referenced sections.

4.8.1 Algorithmic Efficiency

This subsection deals with the impact of gene pool size, local search, and types of stopping conditions on the *solution quality* and *CPU* time.

	Size of the Gene Pool													
	30 Pops				50 Pops					100 Pops				
Mask Local Search														
CPU Time:	24	36	38	48	30	36	48	60		42	48	60	72	
Best Solution:	1056276	1054228	1053198	1053198	1055209	1053198	1053198	1053198		1055651	1053198	1053198	1053198	
Generation #:	4	9	14	16	4	9	14	19		4	9	14	19	
One-bit Local Search														
CPU Time:	24	36	42	72	24	36	48	60	65		48	60	72	80
Best Solution:	1055717	1053198	1053198	1053198	1055162	1053198	1053198	1054475	1053198		1053823	1054475	1053198	1054475
Generation #:	4	9	14	19	4	9	14	19	24		9	14	19	24

Table 4.6: Pop. Size and Local Search on CPU Time & Solution Quality

Table 4.6 provides a summarized snapshot of some important results. Before explaining the results, it is pertinent to outline the software, programming language and background used to generate results.

The *Memetic Algorithm* was coded in ***Visual Basic 6.0***, and ran with different combinations of local searches and stopping conditions. Each scenario consisting of a number of iterations (generations) and one of the two types of local searches, will be referred to as a ***single run***. The question as to how much iteration was enough depended on the quality of the solution. If the solution quality demonstrated improvement, further generations (of children) were created. When no improvement in the best solution was observed for a certain number of generations (usually>5), no further iteration was conducted. But then the second stopping condition (maximum of two solutions left in the gene pool) was checked, even if the solution did not improve. This was done with the objective of ensuring that no better solutions go unnoticed.

Each scenario was run 50 times. Given the presence of random numbers it made sense to run the same scenario setting multiple times. Doing so enabled us to cite the best solutions from these 50 runs for each scenario in question. In table 4.6, the objective value of 1,056,276 ($+people) is the best value out of the 50 runs conducted for this specific scenario (viz. creation of 4 new generation and Mask-based local search). Similarly all the other objective values are the best possible, out of the 50 runs, for that specific scenario. For the 30 Pops case, the 8 best solution values reported are the 8 best values out of 200, although some values are returned on multiple occasions and in different scenario settings.

Table 4.6 also presents the CPU Times, Best Solution & corresponding Generation, and the type of Local Search for 3 different gene pool (population) sizes.

- ***CPU Time (in seconds):*** It is the average of 50 runs for a specific scenario setup. For example, on average it takes 24 seconds to run a scenario with 4-generations and mask-based local search.
- ***Best Solution (in $ + People):*** This is the best solution among the 50 returned from 50 distinct runs for the scenario setup in question.
- ***Generation (iteration):*** It is the number of children generations created since the Memetic Algorithm started running. For the 30 pops case, the CPU time and Best Solution reported are for the 4^{th} generation (does not include the initial generation). Hence, the gene pool has been completely replaced four times (plus the starting gene pool) since the algorithm started.
- ***Local Search (Mask):*** The above three are in context of the first type of local search, as described in the previous section. The corresponding

results for the second type of local search are reported in the bottom half of the table.

POPULATION SIZE

Although a population-pool with 30 starting solutions is a satisfactory start, we decided to vary the pool size and gauge the impact on solution quality. In general if the starting solutions are diverse but rich, good generations can be ensured irrespective of the pool size. It is also true that if the pool size is larger, it will take longer to run any scenario. The choice of 30 was following convention. Size of 100 was motivated by the idea that each attribute should be represented in roughly the same number of starting solutions. The size of 50 was intentioned as an intermediate point to enable us to comment on the three pool-sizes.

In general, everything else being the same, larger pool-sizes requires more CPU time to complete runs. For example in the mask local search category, on an average it takes 24, 30 and 42 seconds respectively, for 30 pops, 50 pops and 100 pops to complete the runs in one specific scenario. It is important to qualify this observation. It should be noted that two independent sets of uniform random number strings, and corresponding to the second random number string a set of random number, are being generated every time, before two offspring are ready to be introduced into a new gene-pool. This *triple randomization* will have a bearing on the two chosen chromosomes (parents) thereby on the generation of offspring, and consequently on the CPU times for each run.

30 Pops

The 30 population-pool size was run for a number of other intermediate scenarios, 8 pertinent ones have been presented in table 4.6.

Mask local search: The CPU times, best solution and generation number have been reported under this type of local search.

The 50 runs done for the 4th generation scenarios, took an average of 24 seconds and the best solution had an objective value of 1,056,276 ($+People). Since there was improvement in the objective value, further generations were created. There was good improvement in the 9th generation, hence higher iteration was introduced. Further improvements were registered until the 14th generation, where 5 out of the 50 runs had a value of 1,053,198 ($ +People), the new *best yet* solution. There were no improvements in the 15th and 16th generations, although 50% of the runs had the same solution in latter generation. Starting from the 19th generation the solution starts deteriorating, although the frequency of the occurrence of the '*best yet*' solution had started going down from the 17th generation. After noting, no improvement in the '*best yet*' solution, its' reduced occurrence and eventual deterioration in the best solution value, there was no point of further iteration. It is important to point out here, that the other stopping condition was evident in the outputs of the 19th generation. Only two types of chromosomes were returned, and both were worse-off than the '*best yet*' result returned earlier.

<u>One-Bit Local Search:</u> differs from Mask-based local search as described in the previous section.

The 50 runs for the 4th generation, on average took about the same time as the mask-based option, although the objective value returned was 1,055,717 ($+People). This objective value was returned 10% of the time, and since there was improvement further iteration was introduced. At 9th generation, the '*best yet*' objective value (from above) was returned in 10 out of the 50 instances or 20% of the time. The 14th generation, on average took 42 seconds to run, registered no improvement in solution but contained the '*best yet*' solution 20% of the time. Moreover there were instances when only two terminating solutions were present in some of the runs (indicator of the second stopping condition).

Although no further improvement was noted in the '*best yet*' solution, there was remarkable convergence in the 20th generation. In here some runs ended up containing only one type of chromosome in the pool, indicating that all the others have been eliminated from the pool. But unfortunately none of the solutions beat the '*best yet*' solution.

30 Pops section in table 4.6 is reporting results from 400 runs, 50 in each of the 8 scenarios. The '*best yet*' solution was returned in 55 runs. Given the randomness involved, it is perhaps premature and risky to compare the effectiveness of the two types of local searches. But for the 30 Pops instance, the *one-bit* local search returns the *'best yet'* solution much earlier than by *mask-based* local search. As alluded to earlier, given its execution-structure, *one-bit* local search is more thorough in combing the immediate neighborhood of any solution. It is because of the one step jump at a time for only *one-bit* while all the other bits retain the values generated at the crossover. The *mask-based* local search on the other hand is subject to multiple-step jumps, since more than one bit values can change simultaneously.

50 Pops

The population pool of 30 was replaced with a population pool of 50 randomly generated starting solutions. Table 4.6 depicts the results for 450 runs, constituting 9 scenarios, between the two types of local searches.

Mask local search: As for 30 Pops, the CPU times, best solution at each generation and corresponding generation numbers have been reported.

4th generation exhibits improvement from the starting solution. The best solution's objective value is 1,055,209 ($+People), based on 50 runs for this scenario, and occupies 5 out of 50 values returned. Improvement in solution necessitated further iteration. At the 9th generation, the '*best yet*' solution from 30 Pops case was returned as the best solution. It took an average of 36 seconds for each run for this scenario. The intent to find a solution better than the '*best yet*' encouraged further iteration. The 14th generation returned the *'best yet'* solution with a 40% frequency, hence 20 out of 50 were '*best yet*'. Although no improvement was observed in objective value, terminating solutions in some instances appeared to be losing diversity. The solution has not improved for 5 generations, and hence according to the first stopping condition there is no need to continue.

The 19th generation, which on average took a minute of CPU time, did contain some *'best yet'* solution but the frequency dropped to 12%. The terminating solutions were almost the same in all the 50 slots, implying absence of diversity and algorithm termination. This was the second stopping condition.

One-Bit Local Search: Just like for mask-based local search, the '*best yet*' did not occur in the 4^{th} generation, although the best for that generation was returned in 10% of the runs. An objective value of 1,055,162 ($+People), was returned in this generation, wherein each run took an average of 24 seconds to be executed. Since there was improvement, further generations were introduced and the program was re-run. The 9^{th} generation saw the occurrence of the '*best yet*' in 5 instances, while taking an average of 36 seconds for a single-run. Additional iterations returned the '*best yet*' solution in the 14^{th} generation, and again in 10% of the instances. The frequency of occurrence of the '*best yet*' solution is far below the 40% recorded with the mask-based local search for the 14^{th} generation, and the solution starts deteriorating in subsequent generations.

It is interesting to note that when implementing the second stopping condition, we encountered the re-occurrence of the *'best yet'* solution in the 24^{th} and higher generations. In here the frequency of occurrence of the '*best yet*' was a very impressive 40% of the time.

Generally, it appears that the one-bit local search is more effective in returning the '*best yet*' results in later generations as opposed to mask-based local search. But again, such assertions may be premature as the yields are contingent on *triple-randomization*.

For the 50 Pops case, the '*best yet*' solution was returned in 65 instances out of 450 runs. Comparing the number of *'best yet'* solution returned by the 30 Pops and the 50 Pops, it can be said that the 50 Pops has a higher percentage but then the number of runs was higher as well. With a 12.5% increment in the number of runs with 50 Pops, 18.2% more '*best yet*' solution instances were returned.

100 Pops

Now the 50 population-pool was replaced with a 100 solution-pool, generated randomly as described in the previous section. Table 4.6 contains the snapshot report of 8 scenarios with 50 runs each, for a total of 400 runs, 200 runs under each of the two local search types.

Mask local search: Now, on average, it takes longer to create four generations. The 4th generation runs are achieved at an average time of 42 seconds, while the best solution in this generation was 1,055,651 ($ + People). In here the string with minimum weighted objective value occurred 20% of the time. Further iteration was introduced. 9th generation saw the '*best yet*' solution (from 30 Pops and 50 Pops) being returned in 5 instances, at an average run time of 48 seconds. Further iteration was introduced, in the hope of improving the '*best yet*' solution. The 14th generation registered a very impressive 60% of '*best yet*' solution instances. Some instances exhibited convergence to two terminating solutions. Given that there was no improvement, one could have stopped here, but noting that the best solution from the 14th generation was not worse-off than the '*best yet*', additional iteration was introduced.

The 19th generation still contained the '*best yet*' as the best solution, again in 60% of the instances. On average it took about 72 seconds to complete one single run. But now the terminating solutions were identical in 40% of the instances, and a two solution convergence in the remaining 60%. The '*best yet*' solution was not beaten for 10 generations and substantial two solution convergence in later generation, meant that both stopping conditions have been satisfied, and hence the algorithm was terminated.

One-Bit Local Search: The solutions returned in the 4th generation were insignificant. The best solution returned in the 9th generation took an average time of 48 seconds. This solution (1,053,823 $+People) appeared in 10% of the runs. It was better than the starting solutions and hence necessitated further iteration. Amazingly in the 14th generation, 80% of the time one of the starting solutions was returned. This clearly indicated deterioration of results, while taking an average time of 60 seconds. Going by first stopping rule, one could have stopped iteration here.

Observation, from the 50 Pops case, that one-bit local search becomes more effective in later generations, motivated the introduction of further iteration. As expected the '*best yet*' solution started being returned, although infrequently, from the 17^{th} generation. In the 19^{th} generation, it occurred in 20% of the runs. The frequency of occurrence started going down in the 20^{th} generation, whereby convergence to one or two solutions became more frequent. In the 24^{th} generation, the best solution cycled back to the one of the starting solutions, implying termination.

Once again it was noticed that the '*one-bit*' local search tends to be more effective in later generations than the '*mask-based*' local search. The mask-based local search returns the '*best yet*' solution more frequently in earlier generations than the other local search. But once again, such observation needs caution and appreciation of the *triple-randomization* process inherent to our ***Memetic Algorithm***.

Comparing the solutions returned by the 3 population sizes, 100 Pops resulted in 75 instances of *'best yet'* solution. In other words, 18.75% of the 400 instances resulted in *'best yet'* solution. It compares rather favorably to 13.75% and 14.44%, respectively for 30 Pops and 50 Pops. Although the '*best yet*' solution may be returned in different proportions by each of the three population sizes, it should be evident that it has been returned in 170 out of the 1250 runs. It is an indicator of our algorithm's efficiency and effectiveness. Given that 1250 runs were made for the original problem, there is very little chance that all the possible solutions and much less the <u>best possible</u> solution have not been captured.

Although the run-times for the 3 population sizes are not vastly different, it should be ensured that each and every attribute has roughly the same representation in the pool. It is true that generating 100 starting solutions is unnecessary when the same results could be arrived at with 30 or 50, as may appear to be case for our problem. But one could take satisfaction from the fact that 100 Pops returned the highest proportion of <u>best possible</u> solutions.

Moreover it is important to represent each and every attribute in roughly a similar number of starting solutions in the gene-pool, since this will ensure diversity and richness. All the analysis hereafter is conducted with 100 Pops, but comparisons to 30 Pops and 50 Pops will be presented when necessary and relevant.

Best Solution: Decoding

To recollect there were six fully equipped yards and four service yards, the former possessing both classification and transfer facility while the latter just transfer. The best solution of problem **(P)** as returned in 175 of the 1250 runs is presented in table 4.7, below.

BASE CASE OF (P)											
Weighted Objective Value: 1053198											
SL1	=	1	TTR1	=	1	CK1	=	1	SHS1	=	1
ST1	=	1	TSH1	=	1	CO4	=	1	SHL1	=	1
SK1	=	1	TQC1	=	1	CM1	=	1	SHT1	=	1
SO1	=	1	KS1	=	1	CTR2	=	1	SHK1	=	1
SC1	=	1	KL2	=	1	CSH2	=	1	SHO2	=	1
SM1	=	1	KT1	=	1	CQC2	=	1	SHC1	=	1
STR1	=	1	KO2	=	1	MS2	=	1	SHM1	=	1
SSH1	=	1	KC1	=	1	ML4	=	1	SHTR1	=	1
SQC1	=	1	KM1	=	1	MT1	=	1	SHQC1	=	1
LS1	=	1	KTR4	=	1	MK1	=	1	QCS1	=	1
LT1	=	1	KSH2	=	1	MO1	=	1	QCL1	=	1
LK1	=	1	KQC2	=	1	MC1	=	1	QCT1	=	1
LO1	=	1	OS1	=	1	MTR2	=	1	QCK1	=	1
LC1	=	1	OL1	=	1	MSH1	=	1	QCO1	=	1
LM1	=	1	OT1	=	1	MQC1	=	1	QCC1	=	1
LTR1	=	1	OK2	=	1	TRS2	=	1	QCM1	=	1
LSH1	=	1	OC2	=	1	TRL1	=	1	QCTR1	=	1
LQC1	=	1	OM2	=	1	TRT1	=	1	QCSH1	=	1
TS1	=	1	OTR1	=	1	TRK1	=	1	N(96)	=	3
TL1	=	1	OSH2	=	1	TRO1	=	1	N(80)	=	2
TK1	=	1	OQC2	=	1	TRC1	=	1	N(90)	=	2
TO1	=	1	CS1	=	1	TRM1	=	1	N(72)	=	2
TC1	=	1	CL2	=	1	TRSH1	=	1	N(82)	=	3
TM1	=	1	CT1	=	1	TRQC1	=	1	N(62)	=	2

Table 4.7: Best Solution for (P)

Table 4.7 is a sample of the solution returned by memetic algorithm coded in ***Visual Basic 6.0***. It is the best solution for problem **(P)**, which is hereafter referred to as the **base case**. It contains the 90 itineraries (corresponding to 90 demands) in the best-solution and the number of trains of different types needed to meet the demand on a weekly basis. The itinerary variables were represented in view of the origin and destination yards for these itineraries. For example, '*SL1*' would mean the first itinerary from Sarnia (S) to London (L). The abbreviation used for other yards are as follows: Sarnia (S), London (L), Toronto (T), Kingston (K), Ottawa (O), Cornwall (C), Montreal (M), Trois-Rivieres (TR), Sherbrooke (SH), and Quebec City (QC). There were six train types running in the network, and they are referenced by the train number. On a weekly basis, the total number of trains needed in the **base case** is 14.

Table 4.7 provides the snapshot on routing and yard activities and ***Appendix-A*** contains the details for the **base case**. Briefly here is what is happening in different parts of the railroad network in the provinces of Ontario and Quebec.

<u>Sarnia</u>: Train N(96) is the only outbound train, and it carries all the outbound railcars. These railcars had to be classified (and blocked with other traffic) at Sarnia before being connected to N(96). A total of 134 railcars, including 69 hazmat railcars, had to be classified here. Sarnia in turn has demands from the other nine yards. A total of 153 railcars were demanded, including 70 hazmat ones, and were delivered by the only inbound train N(62).

<u>London</u>: like Sarnia has only one outbound train N(80), which will be used to move all the outbound railcars. Before that these railcars have to be classified and blocked. A total of 158 railcars, including 80 railcars with hazardous cargo, were classified (blocked) and formed the *take-list* of N(80). London has just one inbound train. This train, N(82), will bring in the railcars demanded by London and supplied by the other nine yards. A total of 156 railcars, of which 67 contained hazmat, were moved to London by train N(82).

<u>Trois-Rivieres</u>: Train N(82) will carry all the outbound traffic. Since this train is formed at Trois-Rivieres, all the blocks made here and the ones for connection will constitute the *take-list* of N(82). A total of 158 railcars, including 71 with hazmat cargo, were classified (blocked) to form train type N(82). This yard demanded 156 railcars from other yards, of which 71 contain hazardous cargo. Train N(80) delivers the inbound railcars.

<u>Quebec City</u>: Train N(62) carries the outbound traffic from Quebec City, while N(96) delivers the inbound traffic. A total of 157 railcars, including 73 railcars with hazardous cargo, were classified / blocked, train N(62) was

formed. On the other hand 154 railcars, including 75 with hazardous cargo, were demanded at this yard. The inbound railcars were delivered by N(96).

The next four yards have only service facility, and hence can only receive traffic from and connect traffic to inbound and outbound trains, respectively.

Cornwall: yard demanded a total of 150 railcars including 68 with hazardous cargo. It connected 99 railcars to train N(72) and 51 railcars to train N(90). Of these 150 railcars, 61 contained hazardous cargo.

Kingston: A total of 152 railcars, including 71 with hazardous cargo, were demanded at this yard. 87 railcars were connected to train N(72) and 70 to train N(90) for onward journey, 69 of these railcars had hazardous cargo.

Ottawa: A total of 157 railcars were dropped at this yard. 69 of the railcars dropped contained hazardous cargo. Three trains picked-up the traffic with origin at this yard. Train N(62) carried 20 railcars, train N(80) carried another 20, while train N(82) picked-up 122 railcars. 65 of the railcars contained hazardous cargo. Another phenomenon is noticeable in the Ottawa yard. Some of the traffic, for which it is the handling point, will be transferred (connected) to other trains for onward journey. A total of 54 railcars, including 23 with hazmat cargo, was connected to train N(62). The total was 54 for train N(82) of which 21 carried hazmat.

Sherbrooke: The demand at this yard constituted a total of 156 railcars, including 74 carrying hazmat. Three train types picked up the traffic with Sherbrooke origin. Train N(96) picked-up 15 railcars, while N(62) picked-up 85 railcars and N(82) picked-up 51 railcars. Of the total picked-up by the three trains, 70 contained hazardous cargo. There was some transfer traffic. 33 railcars, including 17 with hazmat content, were connected to train N(62). On the other hand 37 railcars, including 16 with hazardous cargo, were connected to N(82).

Toronto and Montreal are two of the busiest yards, and within each a range of yard operations are being performed.

Toronto: Four different train services connect Toronto with other nodes of the network. One of these trains is formed at the Toronto yard, while the other three pass through it. A total of 160 railcars were demanded from the other nine yards, of which 73 were with hazardous cargo. The transfer function being performed here was for all the four trains. A total of 100 railcars, including 53 with hazardous cargo, were connected to N(80). Another 66, including 33 hazmat cars, to train N(82). Train N(90) moved 157 railcars, including 68 with hazardous cargo. Train N(96), moved 185 railcars including 99 with hazmat.

This yard also has the option of just connecting the outbound railcars, without classification, to the other three trains via the *pick-up* feature. A total of 37 railcars, including 11 with hazmat, was picked-up by N(80). Furthermore 20 railcars (10 hazmat) and 40 railcars (20 hazmat) were connected to trains N(82) and N(96), respectively.

Most importantly classification (blocking) function is being performed here. A total of 15 railcars (6 hazmat) were classified for Sarnia and connected to N(80). Three different blocks were on the take-list of N(90), a train-service with origin in Toronto. A block destined for Montreal, with 18 railcars including 10 with hazardous cargo. A second one destined for Cornwall with 15 railcars, including 10 with hazardous cargo. A third one, of 16 railcars, to be dropped in Kingston including, 10 with hazmat cargo. There was another classification (blocking) operation done for the Quebec City traffic. This operation contained 31 railcars, including 17 with hazmat content, and was connected to train N(96).

<u>*Montreal*</u>: Just like Toronto, Montreal is busier than the other eight yards in the network. Montreal is connected to the other yards via three different train services. One of the three trains is formed in Montreal, while the other two pass through it. A total of 162 railcars, including 70 with hazardous cargo, are demanded from the other nine yards. Montreal performs the transfer function for some traffic, with it as an intermediate yard, and connects these to trains for onward journey. A total of 36 railcars (10 hazmat) were connected to train N(62), while 85 railcars (43 hazmat) were connected to train N(72).

Some of the railcars, demanded from Montreal, were picked-up by passing train without any specific block formation. A total of 65 railcars, including 36 with hazardous cargo, were picked-up by train N(62) from the Montreal yard. 31 railcars destined for Sarnia were classified and blocked in Montreal. This block was connected to train N(62). More intensive block formation occurred before the formation of train N(72). Six blocks were formed, one each for London, Toronto, Kingston, Cornwall, Sherbrooke and Quebec City. The number of railcars moved in each block was 16, 19, 15, 16, 16 and 16, respectively. These six blocks comprised the *take-list* of N(72), and determined its *make-up*.

Table 4.7 also tells us the number of trains of different types required to move these railcars, to meet demand. As will be evident in the subsequent section, this is not the *minimum cost solution*. This solution should be viewed as the **best possible weighted solution,** and the instance as the **base case**. The best solutions obtained in the subsequent section and subsections will be compared to the one obtained in the **base case** above. Although decoded solutions are similar to those in the **base case**, only deviations from base case instances will be explained.

4.8.2 Numerical Insights

In this subsection we will present a number of scenarios intended to get insights into the problem. As mentioned earlier, only deviations will be discussed in the chapter, while the details of computational experiments and numerical insights will be presented in **Appendix-A**. Encouraged by the effectiveness of 100 Pops in the previous subsection and the rationale for doing so, we have conducted all the runs with 100 Pops. Seventeen sets of scenarios will be presented and their results analyzed. The first four scenarios broadly fall under the *demand increment* class. The fifth is a weight based analysis and runs with *normalized* data. 12 different scenarios are clubbed under the fifth section entitled "***Cost-Risk Analysis***". The last scenario aims at evaluating the effect when the hazardous material being shipped is *chlorine*, and not propane. Formally these seventeen scenarios are organized under six categories:

1. Only hazardous materials demand (and consequent supply) increases by 25% at each node.
2. Only non-hazardous demand increases by 25% at each node.

3. Both hazardous materials and non-hazardous materials demand increase by 25% at each node.
4. Both hazardous materials and non-hazardous materials demand (and supply from) increase only at Toronto and Montreal.
5. Cost-Risk Analysis
   5.1. Quasi-Pareto Frontier
   5.2. Different Weight Coefficients for Risk and Cost objectives.
   5.2. Normalized Numbers.
6. Hazardous Material of different type i.e. Chlorine.

4.8.2.1: Only Hazmat Increase at All Nodes

Under this instance just the hazmat demand has increased by 25% at each of the 10 nodes. **Appendix-A,** referenced to as ***Scenario#1,*** contain the details on computational experiments and numerical insights.

In general the CPU times have gone up from the base case. Now the 19th generation takes 84 seconds, on average, for the *mask-based* local search and 108 seconds for the *one-bit* local search. The similar numbers were 72 seconds for the **base case.**

Under the *Mask-based* local search, the *'best yet'* solution was reached in the 9th generation with a 10% frequency, and stayed there till the 14th generation wherein the frequency went up to 20% but instances of solution ***convergence*** were noticed. The second stopping condition also did not improve the solution till the 19th generation.

Under the *One-Bit* local search, there was no occurrence of *'best yet'* solution until the 14th generation, wherein the frequency of occurrence was a healthy 40%. The 19th generation exhibited substantial convergence of terminating solution without any improvement.

It should be noted that the 300 runs produced 95 instances of the best possible solution (*1,168,746 people+$*), which is a rather healthy rate and underlines the efficiency and effectiveness of our algorithm. There is absolutely no interpretational difference between this scenario and the base case, except that the cost and risk numbers have increased to adjust for the increased demand. It should be noted that due to *non-linearity* and *economies of risk*, the increment in population exposure is not 25%.

4.8.2.2: Only Non-Hazmat Increase at All Nodes

Under this instance only the non-hazmat demand (regular freight) has increased at each of the 10 nodes by 25%. **Appendix-A,** referenced to as ***Scenario#2,*** contain the details on computational experiments and numerical insights.

The best solution reported for this scenario is different that the one for either the base case or scenario#1. Since only the demand for regular freight went up, the algorithm did not have to embark on extra search to readjust risk and return a weighted risk-cost solution, and hence the CPU times are not that different from the base case.

Under the *Mask-based* local search, the *'best yet'* solution as returned in the 9th generation in 20% instances and had a value of 1,174,669(People+$). There was no improvement in the solution until the 19th generation, wherein both the stopping conditions were met and hence the algorithm was stopped.

Under the *One-Bit* local search, the *'best yet'* solution was returned, in thirty of the fifty runs, in the 14th generation. The 19th and 20th generation exhibited significant convergence to two and three solutions, without any improvement in solution, and hence the algorithm was terminated. Once again it was noted that the second type of local search becomes more effective in later generations than the first type.

There were 105 instances of *'best yet'* solutions in the 300 runs, which underlines the efficiency of our memetic algorithm.

The 'best yet' solution for this scenario is different than that for the earlier two. Two itineraries *'MO2'* and *'SHO1'* have respectively replaced *'MO1'* and *'SHO2'*. As a result of the replacement *Montreal* and *Sherbrooke* yards, and train services *N(62)* and *N(82)* would be affected.

The traffic bound for *Ottawa* from *Sherbrooke* will now be carried by train *N(82)* and not *N(62)*. In addition, the population exposure at *Montreal* yard has increased as now both classification and blocking has to be performed at the yard before connecting the *Ottawa* bound traffic to train *N(62)*.

4.8.2.3: Increase at All Nodes (Hazmat and Non-Hazmat)

Under this scenario both the hazmat and non-hazmat demand increases by 25% at each of the 10 nodes. **Appendix-A,** referenced to as ***Scenario#3,*** contain the details on computational experiments and numerical insights.

The CPU times have gone up and are different for the two types of local searches. In general the one-bit local search takes longer to execute the runs.

Under the *Mask-based* local search, the *'best yet'* solution was reached in the 14^{th} generation in 60% instances and had a value of 1,295,345(People+$). The solution quality started deteriorating and the algorithm was terminated in the 20^{th} generation. This was also the first instance when the 'best yet' solution was not returned before the 14^{th} generation.

Under the *One-Bit* local search, more CPU time was expended for each run, and the *'best yet'* solution was returned in the 14^{th} generation in 60% instances. The 19^{th} generation had 80% instances of best solution, which started deteriorating in the 20^{th} and 21^{st} generation when the algorithm was terminated. Once again this local search becomes more effective in later generations, while the mask-based is more effective in the earlier generations.

There were 100 instances of the *'best yet'* out of a total of 300 runs for an encouraging return of 33.33%. This set-up seems to favor the one-bit local search as 70% of the *'best yet'* instances came from it. There is no interpretational difference of the *'best yet'* solution for this scenario and that of the **base case**, except that one extra train of type *N(82)* is needed to haul the increased traffic, and the risk-cost numbers have increased as a result of higher demand. It should be noted that due to *non-linearity* and *economies of risk*, the increment in population exposure is not 25%.

4.8.2.4: Increase at Toronto & Montreal (Hazmat and Non-Hazmat)

Under this scenario both the hazmat and non-hazmat demand increases at the two busiest yards, viz. Toronto and Montreal, and each by 25%. **Appendix-A,** referenced to as ***Scenario#4,*** contain the details on computational experiments and numerical insights.

Under the *Mask-based* local search, the *'best yet'* solution was returned in the 14^{th} generation in 20% instances and had a value of 1,137,923(People+$). This solution was not surpassed in later generations, which required much more CPU times, and in turn underlined our assertion that this search is more efficient and effective in earlier generations than in later generations.

Under the *One-Bit* local search, the *'best yet'* solution was reached in the 8^{th} generation and with regularity in the 9^{th}. The best solution was retained until the 19^{th} generation, after which deterioration crept in. Once again this search is effective over a wider range of generations than the mask-based local search, perhaps due to confinement of the search process around only the attributes of Toronto and Montreal yards.

Out of a total 300 runs, 55 instances of best solution were returned. Although it is not as healthy as for the earlier scenarios, it is still a satisfactory 18%. The itineraries contained in the best solution were different than that in the base case. *'ML3'* replaces *'ML4'*, as a result of which the classification and blocking activity at Toronto yard increases. The Toronto yard classifies and prepares a block of 16 railcars, 10 with hazardous cargo, for London.

4.8.2.5: Cost-Risk Analysis

This subsection will deal with three things. First subsection generates a quasi-pareto frontier using a number of un-dominated solutions. The second part conducts a detailed weight based ***cost-risk*** analysis, while the third uses ***normalized*** data for the runs. Weight based section will present the results from and analysis of 11 different weight combinations. The third subsection uses normalized risk data, in an effort to discern the influence (dominance) of cost or risk in the bi-objective model **(P)**.

4.8.2.5.1: Quasi-Pareto Frontier

Figure 4.7 (below) has been generated using a number of un-dominated solutions. Point ***A*** on the frontier is the minimum risk solution while Point ***B*** is the minimum cost solution. The other seven points are the un-dominated solutions. This frontier can be used by the two stakeholders, viz. the regulatory agencies and the railroad companies to decide on the mutually acceptable points from both risk and cost perspectives. If we could quantify risk exactly, then in an ideal world an economic environment could be created to ensure that there is only one point that is suitable to both stakeholders.

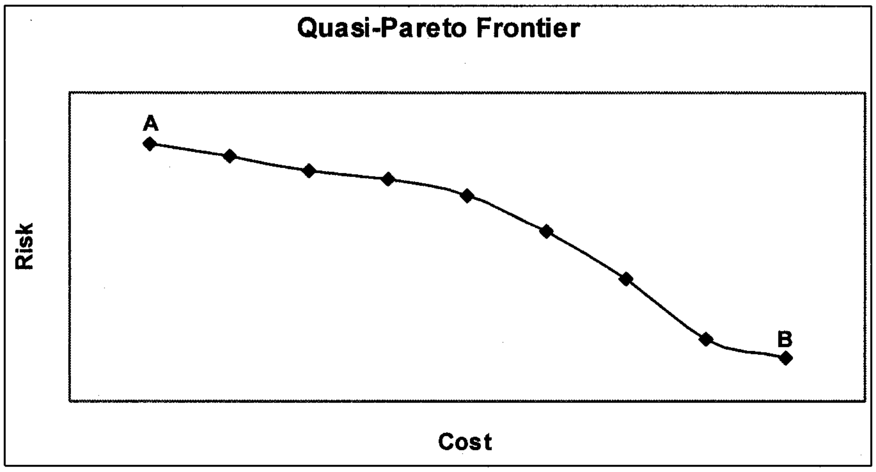


Figure 4.7: Quasi-Pareto Frontier

4.8.2.5.2: Different Weight Coefficients

The bi-objective nature of **(P)** leads to a natural question. How does the '*best yet*' solution vary with different weights for the two objectives? The following eleven scenarios are devoted to answering this question.

	Mask Local Search			One-bit Local Search		
	CPU Time	Best Solution	Generation Number	CPU Time	Best Solution	Generation Number
A			983703			
B	72	892443	9	60	892443	9
C	50	801170	9	48	801170	9
D	60	709904	9	54	709904	9
E	60	618521	14	54	618521	9
F	54	526639	9	54	526639	9
G	60	434677	14	60	434677	14
H	72	342754	9	90	342754	14
I	60	250816	14	54	250816	14
J	58	158877	14	42	158877	9
K		66985			66992	

Table 4.8: Best-solutions for various Cost-Risk coefficients

Each '*cost-risk*' weight combination was run under the two local search types and the two stopping conditions, as described in the previous section and subsections. Table 4.8 reports the best-solution, under each local search type and from 300 runs for each weight combination. As in the previous scenarios, 100 chromosomes were used to evaluate the results. The interpretation of CPU times, best solution and generation # is the same as in the previous four scenarios and in the base case.

Table 4.8 capture the weight based analysis for problem **(P)**. There are eleven weight combinations presented in the table and the figure. Point A represents the best solution when unit weight is attached to cost and zero to risk. Point B, when cost has a 0.9 and risk a 0.1 weight. Points C through J have been represented using the same decrement and increment in weight for cost and risk objectives, respectively. Of course K has a unit value against risk objective, and zero weight attached to the cost objective.

Each point represents a set of *itineraries* for the railcars to move from their origin yard to their destinations yards, the corresponding *number* of trains of different types needed to move these railcars and the *blocking/classification/transfer* operations at the yards. As alluded to in earlier sections, each itinerary for a particular demand (traffic-class) is uniquely identified by origin-destination yards, trains to be connected to and yards activities (classification & blocking or just transfer) to be performed. ***First***, we will analyze table 4.8 corresponding to various *cost-risk* combinations. ***Second***, the best solutions will be presented for each point, and the ones with the same itineraries in the best solution will be presented collectively. It should be noted that this collective presentation only implies that same itineraries, but not same objective values, are observed in the *best solution*. **Appendix-A,** referenced to as ***Cost-Risk Analysis,*** contain the details on computational experiments and numerical insights.

'A': The minimum cost solution

With a weight of 1 against the cost objective, it is not surprising to have the minimum cost solution being returned as the best solution. It is indeed the minimum solution, and has been verified independently using CPLEX.

'B', 'C', and 'D':

The best solutions returned for each of the three points contained exactly the same itineraries, but different weighted objective value, as that for the minimum cost instance. It is rather expected since the lowest weight attached to the *cost* component is 0.7 while the highest weight attached to *risk* is 0.3, and hence the minimum cost solution framework dominates the search process.

The best solution for these four points is different from that for the base case. Itinerary *'KO4'* replaces *'KO2'*, and that has an impact on the network. The pickup load for train *N(72)* will decrease at the *Kingston* yard, and increase proportionately for train *N(90)*. In *Montreal*, the total number of railcars transferred to train *N(62)* will increase by 20 railcars, which in turn will increase the exposure at the yard. The yard operation at the *Toronto* yard will go down since the previous traffic to be connected to *N(80)* is not coming in anymore, which in turn reduces the population exposure risk.

'E', 'F', 'G', 'H', and 'I':

These five points contain the same itineraries in their best solutions, of course with different weighed objective values, but different itineraries than those in the minimum cost instance. '*E*' is the first indication that the effect of cost coefficients have been reduced enough to affect a set of itineraries different than the minimum cost solution.

Although this illustrates the diminishing effect of cost and increasing influence of risk, more importantly it tells us that the itineraries in the best solution in the *base case* is **not** the minimum cost solution itineraries. There is absolutely no interpretational difference between the best solution for the above five points and that for the **base case**.

'J':

The increased weight on the risk objective has affected further change in the best solution. With a higher weight on the risk coefficient, the itineraries appear to be moving towards the minimum risk solution. *'SHO1'* replaces *'SHO2'* and distinguishes this solution from the **base case** solution.

This replacement affects the *Sherbrooke* yard, and train services *N(62)* and *N(82)*. The number of railcars to be picked up *N(62)* goes down by 15, and that is the incremental pick-up for *N(82)*.

'K': The Minimum Risk Solution:

This solution is distinct from both the **base case** and the minimum cost solution, which validates the results of the base case. It tells us that base case results are indeed a balance between the *minimum cost* and *minimum risk* solutions, and hence weighted between these two extremes.

Three itineraries are different than in the best **base case** solution. In this solution *'KO4'*, *'CS3'* and *'SHO1'* replaces *'KO2'*, *'CS1'* and *'SHO2'* respectively in the **base case**.

The traffic-load for train *N(72)* reduces and train *N(90)* increases by 20 railcars due to *'KO4'* being in the solution. Moreover in *Montreal*, train *N(62)* increases by 20 railcars thereby increasing the yard exposure there. But at the *Toronto* yard lesser traffic is going to come in, and hence there will be a reduction in yard population exposure.

'CS3' will affect the yard operations in both *Montreal* and *Toronto*. The classification load for *Montreal* will be eliminated, with a corresponding reduction in the traffic-load for train *N(62)*. Population exposure at the *Toronto* yard will go up, since more railcars will have to be classified (blocked) before being connected to train *N(80)*, thereby increasing its traffic-load.

4.8.2.5.3: Normalized Numbers

We know from the second subsection that the best possible solution for the base case is **not** the same as either the minimum cost or the minimum risk solution. To get an idea about the dominance of either cost or risk, memetic algorithm was run with normalized data. **Appendix-A,** referenced to as ***Normalized Data Analysis,*** contain the details on computational experiments and numerical insights.

Given the number of hazmat railcars to be moved in the base case, the maximum risk on a service-leg was 6600 people while the maximum cost for a block of railcars from its origin to destination yard was $27,943. The ratio between the two is 4.2, and hence each risk (population exposure) value was multiplied by 4.2. Now, the data our *Memetic Algorithm* will consult when evaluating different strings of chromosomes will have new values for population exposure.

Under the *Mask-based* local search, the *'best yet'* solution was returned in the 14^{th} generation in 10% instances and had a value of 1,267,493 (People+$). The solution did not improve for the next seven generations, when the algorithm was terminated after observing two solution convergences.

Under the *One-bit* local search, the *'best yet'* solution was returned in the 14th generation in 20% instances. The solution quality did not improve for the next seven generations after which the algorithm was terminated.

There were 55 instances of *'best yet'* solutions in the 450 runs. Most importantly the normalized data do not change the itineraries in the best solution, which are the same as those in the best **base case** solution. It underlines the robustness of our results, and implies that results obtained with un-normalized data were not skewed towards either risk or cost.

There is no interpretational difference between this solution and the best solution of the **base case**, although the risk and cost numbers have been adjusted appropriately. Since we end up with the same set of itineraries in both the base case and the normalized case, we can conclude that this set is indeed the **best solution** for problem **(P)**.

4.8.2.6: Evaluation with Chlorine

All of the computational experiments conducted and presented until now were based on the assumption that there is no interaction between the hazardous materials being transported. This assumption had to be made since there is no published study that details the interaction amongst the hazardous materials transported in North America. In an effort to be conservative and aid the planning of emergency response system, we worked with the numbers for propane.

To ascertain the sensitiveness of our approach to the hazmat in concern, we replaced propane with chlorine. Two factors namely instantaneous escape on release and 95% chlorine shipments in Canada moving on railroad motivated us to run similar experiments with chlorine. **Appendix-A,** referenced to as ***Evaluation with Chlorine,*** contain the details on computational experiments and numerical insights.

	Size of the Gene Pool													
	30POPS				50POPS					100POPS				
Mask Local Search														
CPU Time:	36	42	48	54	38	42	48	72	81	36	48	54	96	108
Best Solution:	1081918	1080938	1080219	1080922	1083881	1080828	1080219	1080219	1080219	1083992	1080826	1080219	1080219	1080219
Generation #:	4	9	14	19	4	9	14	19	24	4	9	14	19	24
One-bit Local Search														
CPU Time:	36	42	45	48	36	42	48	60	72	42	48	72	96	98
Best Solution:	1082561	1081136	1080509	1080219	1081454	1080219	1080219	1080219	1081344	1084058	1080895	1080219	1080219	1080219
Generation #:	4	9	14	19	4	9	14	19	24	4	9	14	19	24

Table 4.9: Pop. Size and Local Search on CPU Time & Solution Quality

Each scenario was run 50 times and the best solutions are presented in table 4.9. Out of a total of 1400 runs, 320 instances of 'best yet' solution were returned. 100 Pops had a 30% return rate, followed by 50Pops at 25%, and 30Pops at 11.25%. Appendix-A contains the other details.

There is not interpretational difference between the best solution of the two instances, viz. propane and chlorine as the hazmat. They contain the same itineraries, identical number of trains of different types, and similar operations for the different yards.

Given the sparse rail network in North America and the consideration of mostly direct itineraries in the best solutions in the two instances, the result is both expected and welcome. But most importantly, the presence of same itineraries in the best solutions for the two hazmats (propane and chlorine), in a way, underlines the efficiency and effectiveness of our memetic algorithm. The only difference is in the risk numbers since with chlorine exposure numbers increase at similar volumes, due to the persistence of IDLH levels at lower ppm levels compared to propane. This lower IDLH level implies a large hazard area, since toxic levels of concern are present until a longer distance thereby increasing the threshold distances.

4.9 Conclusion

To conclude, this chapter incorporated the risk assessment methodology for multiple sources (developed in chapter 3) and the intricacies of railroad operation to develop a bi-objective tactical planning model for railroad transportation of hazardous and regular freight. The relevant literature on railroad transportation was reviewed and is distinct from the reviews in the previous chapters.

Chapters 3 and 4 are further motivated by the qualifiers associated with accident rates. Although train accident rates are public information they are not particularly useful for our purposes because of two reasons: *first*, the accident-details are specific to a particular rail-link; and *second*, there are not enough accident data points for all the rail-link in a network to conduct a meaningful analysis as is possible for highways.

An illustrated detail of railroad freight operation is presented to enable visualization, and also to aid the development of a mathematical model with *cost* and *risk* objectives. Our model is distinct, from the classical ones, in that its form was motivated by the desire to capture *economies of risk* whenever more than one railcar with hazmat cargo travels together. The lack of any closed form expression for the risk objective, non-linearity in the model, and complicated expression for the objective function, ruled out commercial package based solutions and necessitated a problem specific solution technique.

A metaheuristic is an algorithmic approach to approximate optimal solutions for problems in combinatorial optimization. Simply put it is a template of solution methodology where the individual steps are fine-tuned depending on the problem structure. The choice of *Genetic Algorithm* was largely influenced by the observation that a typical problem such as **(P)** in this chapter will contain a large number of variables but few constraints. A *Memetic Algorithm*-based solution technique was developed for the mathematical model, which decides the routing of individual railcars and the number of different train types required in the system. A realistic-size railroad example is solved using the model and the solution technique. A complete section has been devoted to discussion on algorithmic efficiency and numerical insights. A total of seventeen different scenarios were used to gain additional insight into the problem.

Although the illustrative example presented in this chapter is smaller than the continental network of CN, the formulation and solution methodology can tackle larger problem instances. In fact the number of trains employed in the illustrative example, in this chapter, is more than the number of weekly train being operated between the two provinces. We do not foresee any problem in being able to solve 200 origin-destination pair problems. Given the same stopping conditions but with twice the current network size, the new CPU times will be under 180 seconds as compared to around 100 seconds for moderately deep search currently, i.e., creating around 20 generations.

In closing, we note that a hazmat railcar is subject to the conventional destination-based blocking phenomenon just like any other railcar, and that does not decrease the risk of release since each of these railcars are brought down a hump and grouped with other railcars for the same destination. We realize that the current blocking-practice may not be optimal, but it is an irreplaceable component of the railroad industry, and one that drives the economies of railroad operations. Although our managerial insights into the unit-train operations made us believe that hazmats should be shipped without resorting to any blocking, but given its' benefits it is extremely unlikely that anything can be done to move away from destination-based blocking.

This chapter has a *four-fold* **contribution** to the existing hazmat domain.

This is the *first* work that uses population exposure as a measure of risk for railroad transportation of mixed freight. This is extremely valuable since it enables us to conduct a hazmat volume and related consequence based evaluation of different parts in a railroad network, which in turn can be an effective tool for planning emergency response systems.

Second, the tactical planning model with cost and risk objectives is the first of its type in the realm of railroad transportation of mixed freight. It determines the routes of individual railcars and the number of trains of various types required to meet the network demand.

Third it develops a *Quasi Pareto* frontier, using the *Memetic Algorithm* based solution methodology. Since each point on this frontier contains railcar routes and the number of different trains, measured against risk + cost, it could serve as a negotiating tool between the two stakeholders viz. regulatory agencies and railroad operator. The two parties can decide the points mutually agreeable to them.

Fourth, this chapter compares the effect of *propane* and *chlorine*, when one of the two represents the hazardous part of a mixed freight. Since chlorine is more lethal at a relatively lower ppm levels, the population exposure risk stemming from it is higher than that for propane given that all other factors are constant.

There are a number of future research directions coming out of this chapter. *First*, extend the bi-criteria model to a tri-criteria model, wherein the accident rate probabilities could be the third criterion. *Second*, the assumption of the entire shipment being propane can be relaxed, and the actual interaction effect between hazmats transported could be modeled. Given the absence of any interaction work to date, this extension may be difficult. *Third*, exploring further ways to mitigate or eliminate hazmat transportation risk. One possible way to reduce hazmat transportation risk is by combining the benefits of two or more modes (***intermodalism***). We intend to combine the economies of railroads with the efficiencies of trucks, and hence focus on rail-truck intermodalism in the next chapter.

CHAPTER 5
Intermodal Transportation Systems: A *Cost* Analysis - *Risk* Assessment Perspective to Mixed Freight Shipments

5.1. Introduction

Studies comparing the safety of railroads and trucks for transporting hazardous materials do not arrive at a conclusive result. A range of factors like volume, distance, shipment-frequency, accident rates, etc. goes to determine which of the two is safer for a specific situation. Generally speaking one can conceive of combining the advantages of more than one mode for moving shipments, for example, efficiency of trucks and economies of rail (ships). This movement of freight on more than one mode is referred to as ***multimodalism*** or (by a more inclusive term) ***intermodalism***.

Multimodal is the movement of freight on more than one mode, and the freight (or the flow unit) is transferred from one mode to the other. In other words, the flow unit is removed from the container or mode carrying it, to be transferred to the next mode for onward journey. An express package delivery is an example of multimodal movement, as it combines jets, propeller aircraft and ground vehicles to move a package from its origin to its destination. On the other hand, *intermodal* freight transport is the movement of goods in one and the same loading unit or vehicle which uses successive, various modes of transport (road, rail, water) without any handling of the goods themselves during transfers between modes. The latter terminology, by being inclusive, encompasses every aspect of multimodalism and is a more popular term to describe '*movement of cargo using more than one mode of transportation*'.

In both Canada and USA, intermodal traffic stands to overtake coal shipments as railroads largest source of revenue (Logistics Management (2004)). It has grown from 3.1 million intermodal units (IMUs) in 1980 to 8.8 million IMUs in 1998, and accounts for 17% of rail revenues. Despite this impressive sustained growth over the last twenty-five years, intermodal transportation systems have not received the attention of academic researchers, but promises tremendous research potential (Bontekoning et al. (2004)). It is interesting to note that in Europe, intermodal transport has been a policy objective for years, while it is still new as a policy objective in USA and Canada. The European Commission and industry partners formed the LOGIQ Consortium to identify actors in the decision-making process and to provide information on underlying criteria and constraints in the use of intermodal transport (LOGIQ (2005)). While a number of research projects were undertaken by the Consortium to address different aspects of intermodal transportation systems, only the findings relevant to dangerous goods transportation are pertinent to the thesis.

In Europe, a high percentage of chemical industry products are carried by intermodal transport. Just like for rail and trucks, dangerous goods regulation is developed by United Nations, which is then implemented at the national level. The U.N. approach, being mode oriented, develops regulation for each mode, which has to be complied within that link of the intermodal chain. This approach works fine, except when maritime and overland modes are linked. These two use different symbols for and classifications of dangerous goods, and hence causes transfer delay thereby leading to inefficiency. The *rail-truck* intermodality focus of the thesis eliminates any incompatibility issues between overland and maritime movements, and endorses a mode oriented approach towards rail-truck transportation of hazardous materials. Macharis and Bontekoning (2003) and Bontekoning et al. (2004) provide a good review of work related to other types of intermodality.

In this chapter we answer the **third** research question: *"Is it possible to combine the advantages of more than one mode to move dangerous goods shipments?"*

This chapter is motivated by the desire to contribute in the realm of rail-truck intermodal transportation of hazardous materials. This work while combining the advantages of uni-modes like rail and truck, also intends to compare and comment on the safety of rail-truck intermodality vis-à-vis railroads and trucks, for transporting hazardous materials. The chapter has been organized as follows: Section 5.2, while reviewing the relevant works, describes an intermodal transportation system and delineates its growth and importance in the current global market. Section 5.3 provides the literature review of papers relevant to rail-truck intermodalism, thereby setting up the stage for introducing our work. Section 5.4 makes use of a medium-size example both to explain the workings of a rail-truck intermodal transportation system and to demonstrate how intelligent enumeration can be used to solve freight routing problems. A risk-cost tradeoff analysis on '*time-dimension*' is presented, where the element of "***time***" drives the evaluation. Section 5.5 develops three cases of rail-truck intermodal transportation system for mixed freight. Two special cases and a general case model are developed. Extensive analysis of the first special case is presented. The supporting details on the two special cases are presented in **Appendix-B** under referenced sections. Section 5.6 contains the conclusion and outlines the direction of future work.

The contributions of this chapter are ***fourfold***: studies an unstudied problem in intermodal literature; builds a rail-truck intermodal realistic case example for evaluation and analysis; presents the '*risk-cost*' tradeoff driven by the element "***time***" (or service-level); and, presents a mathematical model intended to capture the time based rail-truck intermodal movement of shipments, and two special instances of the general case.

5.2. Concepts:

Globally transportation sector consumes more than 60% of the world's total oil products, with motorized transport accounting for over 80% of all the oil used, aviation accounting for about 15%, rail and shipping for the remainder. This heavy reliance upon oil leads to a tremendous amount of pollution, and hence there is a great need to develop solutions that utilize each mode's commercial and technical advantages so as to create an intermodal system that minimizes negative impacts and enhances the productivity of local, regional, national, and international transportation systems. In addition, as the freight transportation industry becomes more competitive, creative cost-cutting solutions are needed to ensure the continuing viability of carriers. One way of achieving lower costs, especially for intra-continental long haul freight movements, is by using rail-truck intermodal system for freight movements.

According to the ***Eno Transportation Foundation***, the meaning of intermodalism can vary depending on the definer's perspective. Jennings and Holcomb (1996) proposed an inclusive definition of *intermodalism*, one that does **not** limit research and the potential to create an integrated transportation system.

Intermodal transportation began in the United States and Europe with the use of containers that could be transferred between ships and railcars, thereby minimizing cargo loading and unloading time, linking water and land routes, and speeding the delivery of raw materials, intermediate and finished goods. The tremendous growth in intermodal traffic over the past two decades has made it one of the largest sources of revenues for North American railroaders (Logistics Management (2004)). According to ***Association of American Railroads*** (AAR), railroads moved more than 12 million containers in 2003, up from 11.3 million in 2002. Most consumer goods that move by rail move by intermodal, and that had an impact on growth this past year. Over the past 20 years intermodal volumes have annually risen by an average of 4.5 percent, and had an expected growth of 6.8% in 2004.

According to Szyliowicz (2003), the need to maintain global supply chain to remain competitive, social awareness and non-traditional non-economic perspective of transportation, and how transportation impacts environmental and ecological systems as well as the society has led to the growth of intermodal transportation. According to Stone (1997), ocean carriers started to drive innovation, demanding new service patterns. Stone (1999) attributes the strong intermodal transport growth, to the expansion of globalization among companies in North America. Rondinelli and Berry (2000) listed economic globalization, speed-to-market product delivery; agile manufacturing and business practices; and, integrated supply chain management, as the four reasons driving demand for intermodal transportation. Muller (1998) contended that moving goods through the intermodal freight transportation network is cost effective only if it is coordinated, continuous, flexible, and reliable. According to Yehuda (1994) greater efficiency and savings have been achieved by capitalizing on the relative advantages of various transport modes on every segment of the journey, and through improved coordination of the various transport segments.

According to Priemus et al. (1999), the wide use of containers implies largely mechanized and automated loading/unloading of seagoing vessels, and is the driver of the faster growth of freight transport in Europe. As opposed to Europe, the three countries in North America have different experiences of intermodal transportation. In the US experience, partnerships between modes of transportation were limited, until recently, to those that were absolutely necessary. The Canadian experience, however, has been significantly different. At the turn of the 20th century, the Canadian Pacific Railway Company ran an intermodal empire, with ownership and operation of railroad, ocean steamship, lake-steamship, local freight delivery and pickup services, and later adding intercity trucks and an airline. Arguably, the absence of antitrust legislation and a regulatory climate that did not segregate modal ownership and operation were responsible for this path of development. The development of transportation services in Mexico provides another pattern. Foreign shipping companies dominated early transportation until national maritime and railroad companies were created in the last century (Intermodal Transportation Institute (1997)).

Apogee Research International has done considerable cost analysis of the environmental impacts by mode and has priced these impacts. Many of the costs are borne by society, as the costs are not currently reflected in the market prices being charged to shippers. For instance, Apogee has calculated that the external costs of pollution for goods moved by truck to be some 2 times the external costs of pollution for goods moved by rail. Subsection 5.2.1 outlines the differences between a conventional freight train and an intermodal train. Subsection 5.2.2 provides a detailed description of rail-truck intermodal operation.

5.2.1. Rail Operations: Intermodal V/s Conventional.

While in years past intermodal traffic (truck trailers or containers on flatcars) was carried in regular freight trains and passed through classification yards with other traffic, it is now carried almost exclusively on separate intermodal trains. These trains operate between intermodal terminals and bypass classification yards entirely. The intermodal network on major U.S. railroads is essentially distinct from that for other rail freight traffic, with the exception of sharing the main line tracks and other infrastructure. The rail portion of intermodal transportation also begins and ends at the intermodal terminals where containers or trailers are loaded onto, and unloaded from, special rail flatcars. The movements before the rail journey from the shipper's location (origin) and after the rail journey to the consignee's location (final destination) occur over the road. This is in contrast to most other rail movements in which the railcar is typically loaded by the shipper at a private rail siding, and then moved in a local freight train to the origin classification yard for placement on a through freight train. This process is reversed at the destination, and hence the entire move is by rail.

Once a decision regarding the IM routes has been made, that trailer is loaded on a railcar, and the car is placed on a train. This train might then take it directly to the destination terminal, as some intermodal trains operate essentially non-stop to the final terminal, or the intermodal train may stop at intermediate terminals to drop off and pick up cars, and sometimes these are transferred to other trains to complete the trailer's journey. Intermodal trains, unlike traditional freight trains, operate on a ***fixed-schedule***, and are usually quite ***punctual***.

It is evident from the above that intermodal rail operations are different than conventional rail operations in several important aspects. *First*, because of the high cost of container handling equipment, intermodal terminals have relatively few, widely spaced terminals. With such a structure, economies of scale can be realized not only in container handling, but also in train movements from terminal to terminal. Transport from the customer to the nearest intermodal terminal is handled by truck or by regional or feeder railroads. *Second*, because of the distances between intermodal terminals, a typical container makes few stops and is transferred between trains only a few times on its journey. This eliminates the need to consider blocks i.e. groups of railcars that travel as a unit for one or more segments of their journey (to reduce train reassembly time at rail yards) which are essential in conventional rail scheduling and routing decisions (as discussed in Chapter 4). *Finally*, shorter delivery leadtimes are promised for intermodal freight, and, consequently, there is a greater need to schedule trains to achieve desired levels of customer service. Under conventional operations, some freight may wait until enough railcars accumulate to form a block. The first two factors reduce the number of decisions required for intermodal freight versus conventional freight, but the third factor dramatically increases the importance of careful train scheduling and routing decisions.

5.2.2. Intermodal Operation.

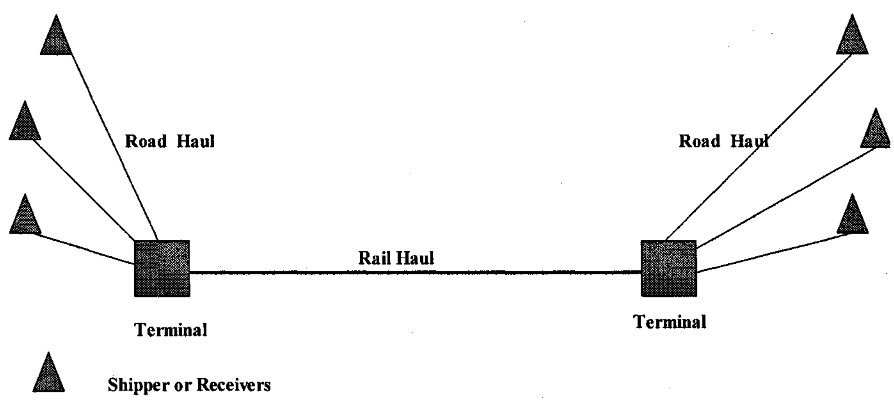


Figure 5.1: Rail-Truck Intermodal Freight Transport
(Adapted from Macharis and Bontekoning-2003)

Figure 5.1 provides a simple depiction of road-rail intermodal freight transport. A shipment that needs to be transported from a shipper to a receiver is first transported by truck to a rail intermodal terminal. There it is transshipped from truck to the second mode, in this instance a train. The train takes care of the terminal-to-terminal transport, called the *long-haul*. At the other end of the transport chain the shipment is transshipped from train to truck and delivered by truck to the receiver. The trucking part of the transport chain is called *drayage*, pre- and end-haulage or pick-up and delivery.

Intermodal transportation has definite advantages. Rail intermodal service on average uses less than half as much fuel as highway transport to move the same shipment the same distance. Intermodal combines the door-to-door convenience of trucks with the long-haul economy of rail service. As a result, trucking companies and intermodal marketing companies are forming productive partnerships to combine the best of both modes (for example, the partnership between *BNSF* and *J.B. Hunt*). The pollutant emission by moving a ton of freight by rail is less than one-third that of moving the same quantity by truck. A single intermodal train can take away as many as 280 trucks from the highways. Innovative Technology such as doublestack trains and roadrailers are in widespread use. *Doublestack trains* (with one container atop another) are in demand. *Roadrailers* look like conventional trailers but come equipped with both rubber tires and detachable steel wheels so they can ride directly on rails or on a highway.

Intermodal freight transport is only just starting to be researched seriously. Since 1990 a substantial number of analytical publications specifically addressing intermodal transport issues have appeared. Various intermodal freight transport decision problems to help in the application of operation research techniques have been presented. However, the use of OR in intermodal transport research is still limited. The intermodal transport system is more complex to model than the mono-modal one and thus more difficult to research. This gives rise to interesting and challenging tasks for the OR practitioners.

Macharis and Bontekoning (2003) categorize intermodal transportation based on the activities performed and the associated operators. They are of four types: *drayage* operators, *terminal* operators, *network* operators and *intermodal* operators.

Drayage operations involve the provision of an empty trailer or container to the shipper and the subsequent transportation of a full trailer or container to the terminal. The empty container may be picked up either at the terminal, at an empty depot or at a receiver. Delivery operations involve the distribution of a full container or trailer from the terminal to a receiver, followed by the collection of the empty container/trailer and its transportation to the terminal, an empty depot, or a shipper. Each drayage company faces a trip scheduling problem with trips between shippers, receivers and one or more terminals meeting several requirements, such as customer's pre-specified pick-up and delivery-times (time-windows), on-road travel times, and realistic limits on the length of the working day. The general problem of drayage operations is its cost in-effectiveness. Despite the relatively short distance of the truck movement compared to the rail or barge haul, drayage accounts for a large percentage (between 25% and 40%) of origin to destination expenses. High drayage costs seriously affect the profitability of an intermodal service, and also limit the markets in which it can compete with road transport. Consequently, alternative, less costly operations need to be designed to increase the competitiveness of intermodal transportation.

Transshipment is inherent to intermodal transportation. As figure 5.1 shows load units are transshipped at least twice between truck and train; once at a beginning terminal and once at an end terminal. This type of transshipment is called *road-rail exchange*. A road-rail terminal consists of: a road gate, where trucks enter and leave the terminal; a rail gate, where trains enter and leave the terminal; a storage area, for long-term storage of load units (24 hours or more); a buffer area, for temporary storage of load units; lifting equipment to unload and load trains, trucks and barges; and, storage and transport equipment. Trains arrive and depart according to a fixed timetable.

Depending on the consolidation concept additional intermediate transshipment can take place. This is called *rail-rail* exchange. Rail-rail terminals are a new concept and are still in the planning stage. Traditionally, shunting of railcars is applied to rail-rail exchange. Operations at a rail-rail terminal involve the exchange of load units between groups of related trains. When trains are in the terminal at the same time–this is called *simultaneous exchange*–cranes pick up load units from one train and drop them directly off onto another train, or onto the buffer or other transport system. When trains are not at the terminal at the same time but have an exchange correlation to each other, load units are *sequentially exchanged* via the buffer or storage area. The features of an optimally functioning terminal depend on demand volume and type of exchange. Exchange leads to an increase in chain lead time and total transport costs. Consequently, exchange operations need to be efficient and fast. Terminal operators have to make decisions on how to meet demand requirements.

Of course the transshipment points (terminals or yards) should provide multimodal facilities for container exchange. Multimodal facilities help firms achieve "*economies of conjunction*" derived from the capacity to conduct multiple events or transactions at the same time or place. Airports with large volumes of freight–in Atlanta, Dallas–Fort Worth, New York, Los Angeles and Chicago–are developing multimodal transportation facilities that attract private investment in warehouses, distribution services, and complementary transportation infrastructure such as trucking terminals and rail links, while seeking improved surface access to nearby martime ports. Maritme ports, like Vancouver's Deltaport combines ocean-going shipping facilities with a 64-acre container-yard, intermodal rail and trucking yards, and access lines to two off-site transcontinental rail yards.

The *network operator* faces decision problems concerning infrastructure planning, service schedules and pricing of services and daily operations of the services. The majority of the studies related to intermodal infrastructure decisions deal with the interconnectivity of modes in order to achieve intermodal transport chains and the location of intermodal terminals. *First* is to decide on the *consolidation method* (point-to-point, line, hub-and-spoke or collection-distribution) to use, which takes into account how to consolidate flows, the routing of the trains through the network and which nodes to serve. Although point-to-point method, in which train travels non-stop between two terminals, is the most popular but this method requires large volumes in order to offer a daily service. *Second* is the decision regarding the operation of trains. It involves decisions about frequency of service, train length, allocation of equipment to routes and capacity planning of equipment. The intermodal train system to be modeled is a fairly complicated one, and is quite distinct from the traditional rail carload service which has been the subject of much modeling in the last decade or so (see e.g. Assad (1980a), Cordeau et al. (1998)). A substantial difference is the interaction between a large variety of both trailers/containers and railcars, and the multiple levels of service classes, which must be considered. Pricing the intermodal transport product is a complicated issue. Gorman (2001) contends that it is imperative to adopt a global perspective, when establishing intermodal market prices, to improve network profitability.

The operational level involves the day-to-day management decisions about the load order of trains, redistribution of railcars, and load units (fleet management). A typical management problem in intermodal rail/road transport is the assignment of a set of trailers and containers to the available flatcars that can move this equipment.

Intermodal operators organize the transportation of shipments on behalf of shippers. Intermodal operators buy the services offered by drayage, terminal and network operators. Decisions made by intermodal operators deal with route and service choices in existing intermodal networks. This type of decision, by its nature, is an operational one, because it concerns the assignment of shipments to routes and carriers. Intermodal routing is rather more complex than the routing problems of road haulage.

5.3. Literature Review

As alluded to earlier, this is a rather nascent area which presents tremendous research potential. The intricacies of different units in an intermodal chain and their complexities make such problems very complex. Most of the work done focuses on one link or activity of the intermodal transport chain, and there is no work integrating each and every aspect of the chain. The papers referenced in the earlier sections of this chapter will not be repeated here, but they do form a part of the literature review. It is worth mentioning that we did **not** come across any work pertaining to hazardous materials transportation, which augments the importance of our current and intended future work.

Bontekoning et al. (2004) have identified the characteristics of the intermodal research community and scientific knowledge base. According to them, North American researchers place emphasis on the operational aspects of the intermodal chain, while their European counterparts focus more on the strategic and tactical aspects of intermodalism.

To reiterate, our intent is to review papers related to rail-truck intermodal transportation of hazardous materials, but there is not even a single relevant work. Although in this section we review papers related to different aspects of *rail-truck* intermodalism, here is the listing of some noteworthy contributions in others areas of intermodal transportation.

Barnhart and Schneur (1996), Kim et al. (1999), Armacost et al. (2002), Grunert and Sebastien (2000), Kozan (2000), Taylor et al. (2002), and Konings (2003), deal with the network design and terminal location decisions. Modesti and Sciomachen (1998), Lozano and Storchi (2001, 2002), Gedeon et al. (1993), and Kreutzberger (2003), address the different tactical aspects of an intermodal operation. Kozan and Preston (1999) tackle the operational efficiency of container transfer facility. Tsamboulas and Kapros (2000), Evers and Emerson (1998), Harper and Evers (1993), and Murphy and Daley (1998), deal with the issue of mode choice. Beuthe et al. (2001), Nierat (1997), Yan et al. (1995), DeCorla-Souza et al. (1997), and Taylor and Jackson, have addressed pricing strategy in an intermodal framework.

Macharis and Bontekoning (2003), and Bontekoning et al. (2004) provide excellent review for works related to intermodal transportation. We present the literature review under three categories: *drayage*, *rail-haul*, and *other*.

5.3.1 Drayage

As described above drayage operations take place by truck between a terminal and shippers or receivers. Drayage operations have some distinct features, which differ from simple pick up and delivery in rail and road transport. Despite the relatively short distance of the truck movement compared to rail line haul, drayage accounts for a large fraction (between 25% an 40%) of origin to destination expenses. High drayage costs seriously affect the profitability of intermodal service, and also limit the markets in which it can compete with road transport. Drayage is generally viewed as the weak link in the intermodal channel, and the entire drayage system is viewed as an opportunity for significant service improvement and cost reductions. A couple of relevant work aimed at better utilization of drayage resources are reviewed next.

Morlok and Spasovic (1995) identified and discussed approaches for improving service quality and cost of domestic intermodal service. The drayage or trucking portion of rail-truck intermodal service suffers from both productivity and service quality. The poor productivity effectively limits intermodal to longer hauls –generally greater than 600 miles, thus precluding it from capturing the higher volume shorter-haul domestic merchandise traffic markets. A promising approach to improvement is to reorganize the way different players combine to provide intermodal service related to one another and perform various tasks. This reorganization centered on drayage service must entail the use of information on the status of loads and customers' service expectations to achieve efficient scheduling and pricing of drayage movements.

Gooley (2001) contends that efficient drayage is a critical component of the chain. Drayage companies, which cluster by the dozen around U.S. container ports, provide the transportation link between the ports and inland distribution.

5.3.2 Rail-Haul

This is the terminal-to-terminal leg of the intermodal transport chain, which for our instance is the rail-haul. The railroad industry is a key intermediary in the rail-truck intermodal channel, since it plays a critical role in providing line-haul and terminal facilities, and in providing rail cars, domestic containers, trailers, and chassis.

Although there is a vast literature about rail modeling, intermodal rail transport is distinct from the traditional rail transport in four ways, and hence deserves a distinct literature review. *First*, in intermodal transport, fixed schedules are used, essentially without classification between origin and destination, while in traditional rail haul networks, trains run only when full and a lot of classification at intermediate nodes takes place. *Second*, fleet management issues in intermodal transport are more complex, because of the separation of the transport unit (rail flatcar) and the load unit (container/trailer). *Third*, because the transport unit can be separated from the local unit, rail-rail transshipment terminals can replace intermediate rail yards for classification. *Fourth*, location decisions for intermodal rail-road terminal are different from rail yards, as the former needs to connect two types of infrastructure. The main objective of intermodal rail haul research is to find solutions to the problem of organizing the rail haul in an efficient, profitable and competitive way. The planning and decision–making of rail-haul can be strategic, tactical or operational in nature.

At the *strategic level*, the configuration of the service network is determined. This includes decisions about which rail links to use, which origin and destination regions to serve, which terminals to use and where to locate new terminals. At the *tactical level* decisions about train scheduling and routing, which traffic (flows) to consolidate, frequency of service and train length are determined. At the *operational level* day-to-day management decisions about the load order of trains, redistribution of railcars and load units (fleet management) are taken.

The papers reviewed below are confined to different aspects of *rail-haul* of a rail-truck intermodal chain. The reviewed works are classified according to the type of decision (time-horizon) and will fall under strategic, tactical and operational.

Strategic Level:

Railroad companies are putting forth a lot more effort to design networks and provide services, to make it more like truck, even offering guaranteed service in specific lanes. If railroads had made these guarantees four years ago, everyone would have shipped intermodal, and all freight bills would have been refunded (Richardson (2002)). Burlington Northern Santa Fe Railway (*BNSF*) launched a guaranteed intermodal service in May 2000. Improvements in available technology have been a factor in Norfolk Southern's (*NS*) recent network redesign, which is yielding 10 to 30% faster rail transit times for single-carload merchandise customers. With classification and reporting systems that track individual car movements, NS is able to improve the way it builds trains, reduces or eliminates car handling in yards, and it even makes fewer stops per train. Union Pacific (*UP*) and NS jointly operated run-through trains, the Blue Streak, illustrates the current attitude toward cooperation between east and west railroads–an attitude that contributes to decreased transit times. Attractions are *pricing* that is about 10% lower than truckload and *transit-time* within a day of the coast-to-coast, single-driver truck load time.

Wiegmans et al. (1999) describe and analyze the freight terminal market with the help of Porter's model of five competitive forces. The five competitive forces are: industry *competitors*, *buyers* of terminal services, *suppliers* of terminal facilities, potential *entrants* into the freight terminal market and *substitutes* for the use of a freight terminal.

Priemus (1999) describes problems of multimodality in European freight transport and anticipates promising developments concerning terminals and networks. The twin criteria of sustainability and long term accessibility of economic centers require intermodal freight traffic, which necessitates new generation of terminals (in which automation and robotization are strongly featured).

Bontekoning (2000) presents an evaluation study of the newly developed terminal concepts, carried out as part of the EC project Terminet. The underlying idea being that, if such terminals can genuinely contribute to more efficient intermodal operations, then they should be implemented. The author goes on to assert that technically and operationally, the new-generation terminals are valuable for further development of intermodal transport, but admits to not having a detailed insight into the cost structure of these concepts.

Barton et al. (1999) describe a study undertaken in Minnesota to evaluate the need for new or expanded intermodal terminal facilities in the Twin Cities metropolitan area. In particular, the study investigated whether a multi-user intermodal terminal at a new location could provide high-quality service, reduce costs for carriers and shippers in the region, and relieve the issues of incompatible land uses at the present terminal sites. They contended that inappropriate location of an intermodal terminal and inadequate size of terminal facilities are the major impediments to intermodal transportation.

Arnold et al. (2003) present the problem of optimally locating rail/road terminals for freight transport. An alternative formulation to the hub-type formulation is used (0-1 linear program); it is based on multicommodity fixed-charge network design problems. The size of real-world intermodal transportation problems is often far beyond the present possibilities of ILP packages; therefore, the authors resorted to heuristic methods and proposed Intermodal Terminals Location Simulation System (*ITLSS*). ITLSS is based on a particular representation of the transportation system that explicitly uses the multimodality concept. The model is applied to the rail/road transportation system in the Iberian Peninsula.

Ballis and Golias (2004) present a modeling approach focusing on the comparative evaluation of conventional and advanced rail-road terminal equipment. A set of models for the investigation of selected innovative handling technologies and advanced operating forms that could lead to a more efficient operation of the combined terminals and the whole transport chain is proposed.

Southworth and Peterson (2000) describe the development and application of a single, integrated digital representation of a multimodal and transcontinental freight transportation network. The network was constructed to support the simulation of some five million origin-destination intermodal freight shipments reported as part of the 1997 United States Commodity Flow Survey.

Rizzoli et al. (2002) present a simulation model of the flow of intermodal units among and within inland intermodal terminals, wherein the residence time of intermodal units is much shorter. It is a part of the Platform project, initiated by the European Community to promote intermodal transport. This integrated simulation environment is composed of three modules: the road network planning and simulation module; the terminal simulation module; and, the corridor simulation module.

Evers (1994) empirically examined the extent to which statistical economies of scale are available to intermodal railroad-truck transportation firms. Four intermodal terminals in the US were visited to collect data and observe the operating characteristics of the individual terminals. The findings suggest that, by combining adjacent intermodal terminals, railroads can reduce their capital investment in trackage and parking lots, due to improved utilization and pooled uncertainty. Because of its high investment cost, lift equipment must be intensively used, and railroads improve equipment utilization by consolidating terminals and concentrating traffic through them. In doing so, railroads also reduce the amount of capital tied up in terminal infrastructure.

Tactical Level:

Newman and Yano (2000) address the problem of simultaneously determining train scheduling and container routing decisions in a rail intermodal setting. They have developed a decomposition procedure, which takes advantage of the embedded network structure, and yields near optimal solution in lesser time.

Bookbinder and Fox (1998) derive the optimal routings for intermodal containerized transport from Canada to Mexico. They summarize the links and routes to Mexico, on which one or more carriers now operate, and then determine the non-dominated tradeoffs between cost and service.

Nozick and Morlok (1997) present a model for the planning of operations for an intermodal rail-truck service. They concentrate on the line haul and terminal operations of the intermodal movement, with a view to aid medium-term operations planning. Within the two links, they focused on the trailer, container and railcar flows, as well as work estimation at terminals, given the expected traffic and service quality needs, and the capacity. The problem, quite complex, was solved heuristically.

Barnhart and Ratliff (1993) discuss methods for determining minimum cost intermodal routings to help shippers minimize total transportation costs. Routing problems with rail transportation costs expressed per trailer and per flatcar are described. While per trailer routing problem has a shortest path solution procedure, a solution procedure involving matching is introduced for the per flatcar routing problem.

Trip and Bontekoning (2002) explore the possibility of implementing innovative bundling models and new-generation terminals as a means to integrate small flows, mainly from outside the economic core areas, in the intermodal transport system. Any integration of these small flows would increase the transport volume that is potentially suitable for intermodal transportation, and could therefore add to the modal shift from road to rail.

Jourquin et al. (1999) present a methodology to model bundling operations, implemented in NODUS, a GIS like software, on large multimodal freight networks. The model deals with different modes and means of transport, and is based on the concept of the 'virtual network' that decomposes the successive operations involved in multimodal transport and includes a detailed analysis of all costs. The simulations that were performed with various sets of operating costs showed the possible impacts of the service on the transportation flows by the different modes and means.

Janic et al. (1999) evaluated the rail-based innovative freight bundling networks with an objective to identify the network with promising or preferable configuration and performance, which will be competitive to road haulage under given circumstances. The authors present 20 indicators (both quantitative and qualitative) to measure the performance of innovative bundling networks.

Operational Level:

Choong et al. (2002) present a computational analysis of the effect of planning horizon length on empty container management for intermodal transportation networks. The mathematical model seeks to minimize total costs related to moving empty containers, subject to meeting requirements for moving loaded containers. A general conclusion is that longer planning horizon allows better management of container outsourcing and encourages use of slower and cheaper transportation modes (e.g. barges).

Powell and Carvalho (1998) propose a dynamic model for optimizing the flows of flatcars that considers explicitly the broad range of complex constraints that govern the assignments of trailers and containers to a flatcar. The problem is formulated as a logistics queuing network which can handle a wide range of equipment types and complex operating rules. The complexity of the problem prevents a practical implementation of a global network optimization model. Instead, it is formulated as a global model with the specific goal of providing network information to local decision makers, regardless of whether they are using optimization models at the yard level.

5.3.3 Others :

There is a group of studies that deal with decision support tools for shippers in their selection of the optimal intermodal routing for a specific shipment. Some others deal with the behavioral aspects of different intermodal players, and does not fall under either of the aforementioned categories.

The intermodal choice is never a simple matter in international trade since it can be affected by a multitude of conflicting factors such as cost, on-time service and risk. Min (1991) developed a chance-constrained goal programming model to aid the distribution manager in choosing the most effective intermodal mix that not only minimizes the cost and risk, but also satisfies various on-time service requirements.

Boardman et al. (1997) describe a decision support system that implements a robust method to automate the determination of the least cost combination of transportation modes through a network, wherein now transfer costs are embedded into the network. This DSS is intended to be used by shippers in making the best selection of combinations of transportation modes on the basis of cost, service level, and the nature of the commodity being shipped.

Jervell III et al. (1997) concluded that significant amount of intermodal skills training was available for middle and upper middle management but not for the entry level professional.

Evers and Johnson (2000) undertook a study to determine the influence of shipper perceptions of intermodal railroad-truck services provided by specific railroads on the overall perception of carrier performance and then to link those overall shipper perceptions with shipper satisfaction and future usage intentions. They concluded that improving shipper perceptions of a railroad's intermodal service should over time lead to increased intermodal business for that railroad.

Furthermore, railroads need to cultivate stronger relations with their shippers; this could lead to continued business opportunities in the future and could represent an effective tool to counter the significant, negative relationship.

Stank and Roath (1998) undertook to empirically gauge shippers' feelings regarding the need and desirability of developing new transportation and logistics capabilities. More than one third of the firms surveyed favored such development, and only those services attracting a critical mass of customers to realize regional economies of scope and scale should be offered.

Evers et al. (1996) studied the shipper perceptions of transportation service, i.e. the level of service perceived by shippers. This research found that while firm contact, cost, restitution, and suitability may be important, shippers' overall perceptions are more greatly affected by timeliness and availability.

The literature review brings to fore numerous research opportunities in the area of intermodal transportation. It also points out the absence of any work done in the domain of rail-truck intermodal transportation of hazardous materials, which is the spirit of next section. In section 5.4, we describe a rail-truck intermodal transportation system; conduct risk-cost evaluation/analysis of a case example, driven by the aspect of "***time***" (service-level).

5.4 Rail-Truck Intermodal Transportation of Mixed Freight

The first part of this section describes a rail-truck intermodal transportation system. The second part makes use of a realistic-size case example and intelligent enumeration, to evaluate rail-truck intermodal shipments on a '*risk-cost-time*' dimension and presents the analyses and case-specific recommendations.

5.4.1 Rail-Truck Intermodalism: Description

As concluded in the literature review section, intermodal transportation research presents numerous opportunities, including work on rail-truck intermodal movement of hazardous materials. As mentioned earlier the U.N. approach towards intermodal transportation of dangerous goods is mode oriented, which translates into regulations for railroads and highway transportation for our instance. In light of our work in previous chapters we will adopt a *population exposure* approach towards risk assessment for both railroads and trucks.

We have built a railroad network to mimic *Canadian Pacific Railroad*'s (CPR) intermodal network in Canada. This network will be used to evaluate the rail-haul part of the intermodal chain, while road network was built to track the drayage aspect of the transport chain.

Hazardous materials will be shipped in ISO specified containers, special truck-trailer and undergo the usual crane operations at the intermodal yard, as illustrated in figure 5.2. Intermodal tanks, also referred to as ISO tanks, tank containers, or IMO portable tanks, are designed for international transportation by road, rail and ship. Specifically *IMO Type 1* tanks are used for hazardous product shipment, and hence would be the container for our study. On the other hand the non-hazardous cargo can be shipped in either trailer or container.

While the intermodal movement will be alike any other rail-truck intermodality, there are certain nuances specific to hazardous materials. The following description of rail-truck intermodalism is more detailed than the one before and sets the stage for further discussion.

Figure 5.2: Intermodal transportation of hazmats

Figure 5.3 (below) depicts a simplified representation of rail-truck intermodalism. The tractor-trailer pool is maintained near the Intermodal Yard, and an empty unit is dispatched when requested for by a shipper. Of course railroad companies offer different plans, whereby the intermodal unit (IMU; container / trailer)) can belong to the shipper, transport company or the railroad company. For example *Canadian Pacific Railroad* (CPR) offers six different plans in Canada: ramp-to-ramp; door-to-door; door-to-ramp; ramp-to-door; door-to-door (IMU belongs to shipper); and, ramp-to-door (unit belongs to shipper) (Calluri (2004)).

We are interested in the second plan, door-to-door, where everything belongs to CPR or the concerned railroad company. It is not widely known that CPR has a sizeable presence in the drayage business through contractors or transport companies. A well known example of a railroad company joining hands with drayage operator is the alliance between *Burlington Northern Sante Fe Railway* (BNSF) and *J. B. Hunt*, one of the largest trucking companies in North America. The two together are responsible for the entire intermodal transport chain, and also provide a basis for our work.

Based on the demand, *shipper (i)* requests IMUs from the nearest IM yard. If need be, the request will also contain certain ISO containers (tanks) for hazardous materials. On receiving the request, the IM yard will dispatch the specified trailer (container) along with the truck-driver from the pool. For the purpose of our analysis, we will assume that the "***time***" counter, specified by the receiver, for the shipper starts here. Obviously the driver will take the shortest (cheapest) path from *Pool-A* to *shipper (i)*. On reaching *shipper (i)*, the driver has two options: either to un-hitch the trailer (container) and *leave*, or to *stay-with*. For our analysis we will assume that the driver stays with the trailer (container) and waits for loading, and hence the "*time*" counter does not stop.

Once the IMU is ready to leave *shipper (i)*, the truck driver brings it to the IM yard for rail-haul of the journey. It goes without saying that the driver will again take the shortest (cheapest) path. This approach is alright if the concerned IMU contains non-hazardous cargo, but we will contend that a weighted shortest path must be followed when hazardous materials loads are involved.

We will elaborate on this in the following pages, but for now let us continue with the rail-haul movement. Using the overhead or gantry cranes, the IMUs are placed on the flat cars of the designated IM train. For the purpose of our analysis, the following assumptions have been made. These IMUs do not have to wait at the IM yard, and they are loaded onto the IM trains using a number of overhead or gantry cranes to adhere to the fixed-schedule of the IM trains.

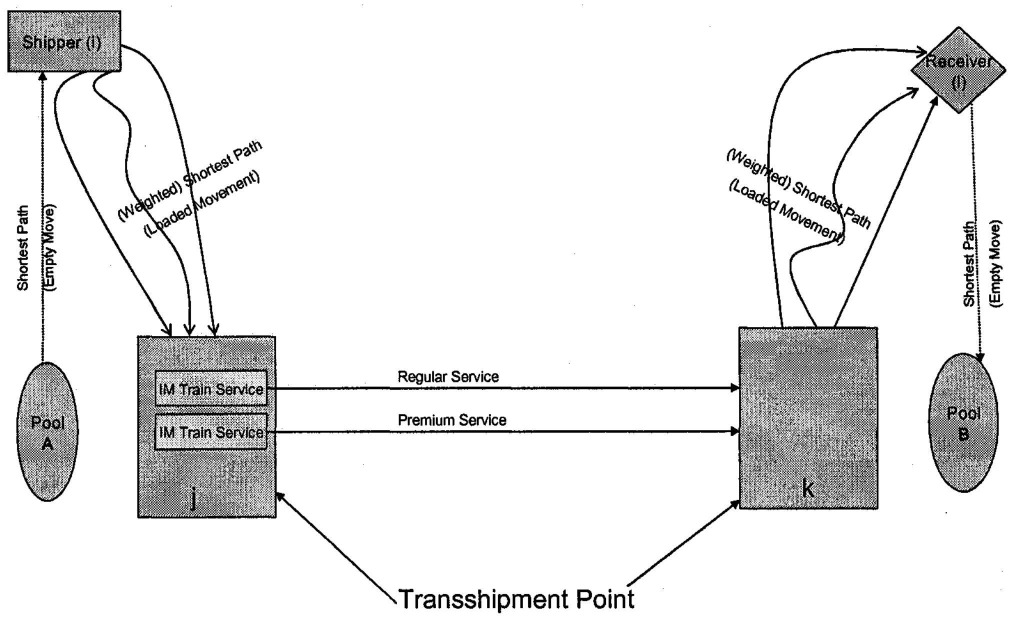


Figure 5.3: Rail-Truck Intermodalism

We know from previous sections, that in years past, IM traffic was carried in regular freight trains but now it is carried almost exclusively on separate IM trains. These trains operate between IM terminals and bypass classification yards entirely. The IM network is essentially distinct from that for other rail freight traffic, except the main line tracks. The rail portion begins and ends at IM terminals, whereby containers and trailers are loaded to/unloaded from special rail flatcars. This is different compared to normal railroad, where a railcar is typically loaded by the shipper at a private rail-siding and then moved by a local train to the classification yard.

At the origin-terminal *(j)*, the routing of traffic is determined. Given the sparse rail-network and even sparser IM terminal network, usually there is a single preferred routing to each destination but there will be time-of-departure options for all but the highest class of service. Lower service-level cargo implies lower shipping cost. In figure 5.3, *regular* service will be cheaper than *premium* service. Once routing decision is made, the trailer is loaded on a railcar. The operations are simpler and there is reduced interchange between IM trains. Most importantly IM trains offer a *fixed-schedule* and are quite *punctual*, which is far removed from the unreliability associated with regular freight trains.

At the destination-terminal *(k)*, cranes will be employed to transfer the IMUs from the IM train to the waiting trucks. The driver will take the shortest path to *receiver (l)*, unload the container and bring back the truck to *Pool-B*, again taking the shortest path. The elapsed "*time*" counter stops as soon as the driver reaches the receiver's site. Once again, taking the shortest path to the receiver is fine as long as the IMUs do not contain dangerous goods. At *receiver (l)*, the IMU could be left to be picked-up later, or the driver can wait for the contents to be unloaded and then bring back the IMU to *Pool–B*. We will assume that the driver waits for the contents to be emptied.

As mentioned above, ***punctuality*** and ***reliability*** of IM trains are the biggest sell. Shippers (Receivers) are willing to pay more to reduce the uncertainty in the supply chains. *Service Level* is the underpinning of IM operations, wherein the implied reliability and schedule based operations also distinguish the IM transportation from normal railroad transportation. For our instance, service-level translates into delivering the shipments before the specified "*time*" elapses.

It may be evident from figure 5.3 that there are 3 parts to this intermodal movement: *inbound drayage*, *rail-haul* and *outbound drayage*. The first is the empty trailer-tractor movement from the IM yard to the shipper; the second is the train movement between IM terminals; and, the third is the final leg of the journey from the IM terminus to the receiver. We know from previous sections that the drayage part of the intermodal transport chain is extremely expensive. It has been estimated that for a 1000 mile door-to-door option, drayage accounts for 40% of the cost. The section on literature review refers to the relevant work in this domain.

Subsection 5.4.2 presents three aspects of the intermodal problem. It builds a realistic case example, using hypothetical demand numbers and CPR's intermodal network in Canada; then it conducts a *risk-cost* shipment evaluation, dependent on the element of "***time***"; and, then presents an intelligent enumeration technique to solve the rail-truck intermodal movements of hazardous cargo.

5.4.2 Rail-Truck Intermodalism: Case Example

The set up for our problem is as follows. There are ten shippers in Quebec, distributed around Montreal, who have to fulfill orders of ten customers in British Columbia. The rationale for basing shippers in Quebec and receivers in British Columbia stemmed from the visit and discussion at the CPR's intermodal facility in Montreal (Calluri (2004)). Each shipper has to supply to each of the ten customers, and the demand will include both hazardous and non-hazardous materials.

- SHIPPERS: The ten shippers are situated at the centre of the 10 municipalities, arbitrarily selected, around Montreal. These are: *Repentigny*, *Boucherville*, *Saint Hubert*, *Brossard*, *Chateauguay*; *Beaconsfield*, *Kirkland*, *Saint-Eustache*, *Sainte-Therese*, and *Laval*.
- IM YARDS: The IM yard of CPR is in the Lachine municipality on the Island of Montreal. Delta Port in Vancouver is assumed to be the terminus for the IM train leaving Lachine for British Columbia.
- RECEIVERS: They are spread across the province of British Columbia, some in and around while others away from Vancouver. They are: *Kelowna*, *Kamloops*, *Burnaby*, *Surrey*, *Richmond*, *Haney*, *Coquitlam*, *Forest Hills*, *Prince George*, and *Prince Rupert*. Each receiver has ordered a combination of hazardous cargo and non-hazardous cargo from each of the ten shippers (suppliers), hence there are 100 supply-demand pairs. Corresponding to each demand order, a delivery "***time***" is specified. This time-counter will govern the routing decisions for both the rail-haul and trucking segment of the intermodal transport chain.

Inbound Drayage:

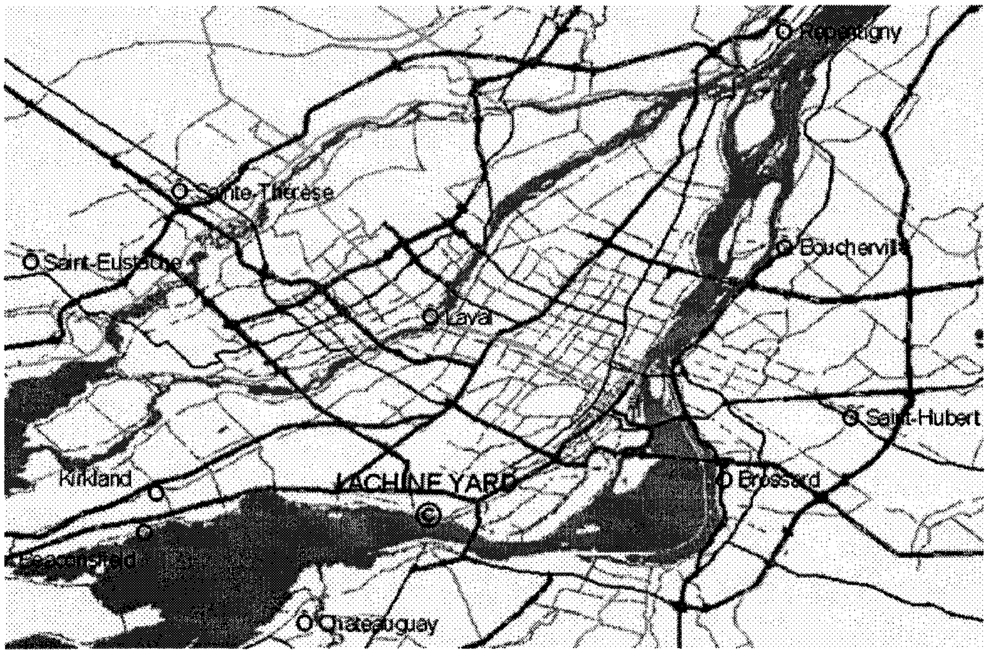


Figure 5.4: Inbound Drayage

Figure 5.4 has been created in GIS and has four layers. It contains the municipal territorial layer, road and highway network layer, water layer, and the location of the shippers. It is rather evident that each shipper is linked to Lachine yard via a number of alternate routes. As alluded to earlier the truck driver will always take the shortest path between the shipper and the IM yard, and we are fine with this approach as long as the cargo in question is non-hazardous. Obviously this part of the transport chain can be broken down by shipper-route combination for micro-analysis, and we will get to that shortly. For now, we continue with the next part of the chain the IM rail-haul.

IM Rail-Haul:

The IM train is formed at the Lachine yard in Montreal and terminates at Delta Port in Vancouver. We mentioned earlier that typically there is only one route between the IM terminals and that network is sparse. This observation stems from the expanse of railroad and intermodal network in North America. Figure 5.5 depicts only one route between Montreal and Vancouver, and this route goes through Edmonton. We have two types of IM services on this network. First is a *regular* service (***R-IM***) with a stop at Edmonton to pick-up and drop-off traffic. Second is the *premium* (***P-IM***) non-stop service, at a higher speed, between Montreal and Vancouver. Of course the regular service is cheaper and takes longer, while the premium one is faster but more expensive.

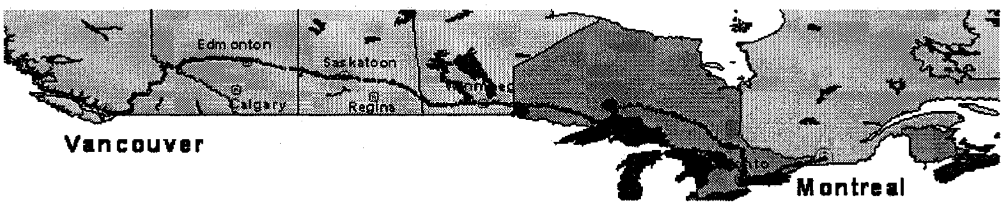
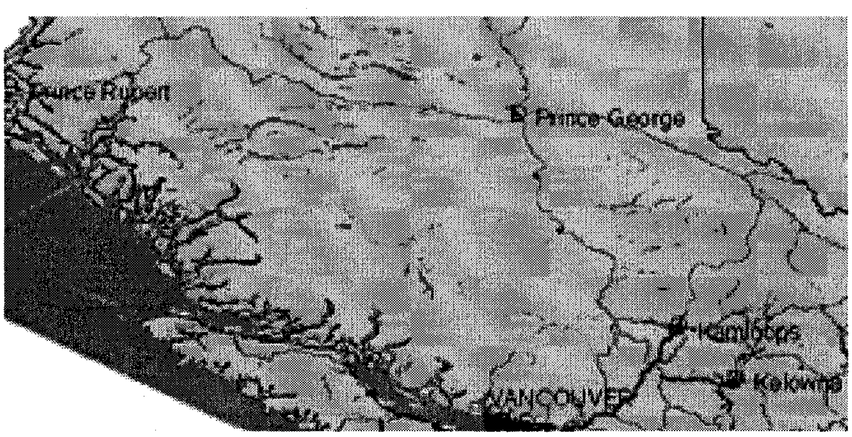


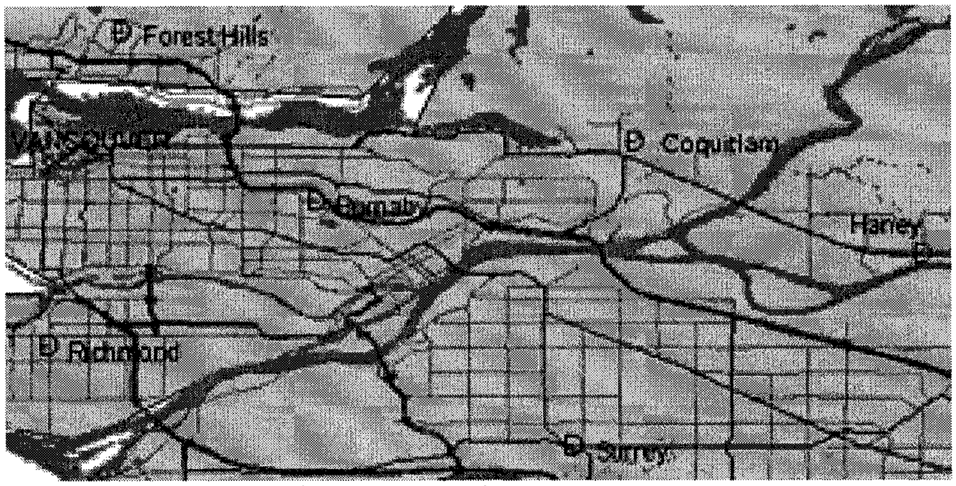
Figure 5.5: Intermodal route between Montreal & Vancouver

<u>Outbound Drayage:</u>

The receivers of the shipments are spread all over the province. As is evident from figure 5.6a and 5.6b, six of them are around the Greater Vancouver area, while four are further away. Once again there are a number of paths connecting the receivers to the IM yard at Delta Port in Vancouver. The rationale of choosing receivers from all over the province was to get additional insight into the outbound drayage link of the transport chain not possible with the points close by viz. the effect of longer traveling time by truck.



a: Distant Population Centers



b: Centers around Vancouver

Figure 5.6: Outbound Drayage

DEMAND

Table 5.1 depicts the demand, generated hypothetically, in terms of number of intermodal containers/trailers, and the breakdown for hazardous and non-hazardous cargo.

TOTAL DEMAND (in number of IM containers / trailers)										
From/To	Kelowna	Kamloops	Burnaby	Surrey	Richmond	Haney	Coquitlam	Forest Hills	Pr-George	Pr-Rupert
Repentigny	5	10	7	9	19	12	4	11	12	6
Boucherville	13	7	9	8	4	6	6	6	12	10
Saint Hubert	12	12	7	12	14	5	12	16	10	10
Brossard	14	6	13	19	23	8	5	5	12	17
Chateauguay	10	6	8	10	13	10	12	12	13	16
Beaconsfield	10	12	12	13	16	10	6	8	10	13
Kirkland	8	5	5	12	17	14	6	13	19	23
Saint-Eustache	5	12	16	10	10	12	12	7	12	14
Sainte-Therese	6	6	6	12	10	13	7	9	8	4
Laval	12	4	11	12	6	5	10	7	9	19
HAZMAT DEMAND (in number of ISO IM containers)										
From/To	Kelowna	Kamloops	Burnaby	Surrey	Richmond	Haney	Coquitlam	Forest Hills	Pr-George	Pr-Rupert
Repentigny	2	4	5	8	9	8	2	5	8	2
Boucherville	6	2	8	6	3	4	2	3	6	5
Saint Hubert	6	8	2	6	8	3	6	8	4	6
Brossard	8	4	6	9	11	4	2	3	6	9
Chateauguay	8	2	2	5	4	4	6	8	4	9
Beaconsfield	4	6	8	4	9	8	2	2	5	4
Kirkland	4	2	3	6	9	8	4	6	9	11
Saint-Eustache	3	6	8	4	6	6	8	2	6	8
Sainte-Therese	4	2	3	6	5	6	2	8	6	3
Laval	8	2	5	8	2	2	4	5	8	9
NON-HAZMAT DEMAND (in number of IM containers / trailers)										
From/To	Kelowna	Kamloops	Burnaby	Surrey	Richmond	Haney	Coquitlam	Forest Hills	Pr-George	Pr-Rupert
Repentigny	3	6	2	1	10	4	2	6	4	4
Boucherville	7	5	1	2	1	2	4	3	6	5
Saint Hubert	6	4	5	6	6	2	6	8	6	4
Brossard	6	2	7	10	12	4	3	2	6	8
Chateauguay	2	4	6	5	9	6	6	4	9	7
Beaconsfield	6	6	4	9	7	2	4	6	5	9
Kirkland	4	3	2	6	8	6	2	7	10	12
Saint-Eustache	2	6	8	6	4	6	4	5	6	6
Sainte-Therese	2	4	3	6	5	7	5	1	2	1
Laval	4	2	6	4	4	3	6	2	1	10

Table 5.1: Shipment Demand

Although the numbers have been generated hypothetically, the logic of westbound traffic is based on the feedback received at the intermodal yard of

Canadian Pacific Railroad (Calluri (2004)). The 10 shippers are listed in the first column, while the 10 receivers are listed across the table as column headings. Attached to each demand is a delivery date (time), and the shipper has to ensure that the said demand is met on or before the specified date (time). These delivery dates (times) are provided in table 5.3. It is essential to make the delivery date (time) assumption, otherwise there is no need to use IM train and pay a higher rate, when the same shipments could be moved by a normal freight train at a lower cost, and reach their destinations at a later time. Since ***reliability*** and ***punctuality*** are the cornerstones of intermodal operations, it is important to work with "***time***" specified by receivers. Simply put, the sum of times taken by each activity (drayage, transshipment, rail-haul, etc.) in the intermodal chain should not exceed the "***time***" specified by the receiver.

For our analysis, receivers at Kelowna and Kamloops want to receive their orders within 5 days (120 hrs) from the time an order has been placed. Receivers in and around Vancouver (Burnaby, Surrey, Richmond, Haney, Forest Hills and Coquitlam) have 4.5 days (108 hours) as the specified deadline. The two furthest points, Prince George and Prince Rupert, have specified 6 days for delivery. Based on these numbers the shippers (in conjunction with the drayage company and the IM operator) can decide when the shipments need to leave their warehouses. In addition the decision whether or not to use the *premium* service at a higher rate is needed.

Once again referring to figure 5.7 and focusing on the first shipper, i.e. *Repentigny*. The driver(s) leaves the Lachine yard with the empty truck-trailer(s) and takes the shortest path to the shipper location. Once again the moment the driver-trailer leaves the IM yard, the "***time***" counter starts for the shipper. It is reasonable to assume that the shipper has been apprised by the IM operator of the departure time of the IM train, and also the cut-off time to make it to that IM train. Moreover, the shipper is aware of the time it will take to complete the inbound drayage part of the intermodal transport chain, and hence when should the shipment(s) be ready to be able to make the specified IM train. It should be noted that three things are happening at this location: the container (trailer) is being loaded; driver-truck is waiting and adding to the cost; and, a portion of the specified "***time***" is elapsing.

5.4.2.1 Evaluation

There are 4 paths from the shipper to the *Lachine* yard as recreated in figure 5.7. It is expected that the driver will take the shortest path, since it is the cheapest.

Lachine Yard -- Repentigny -- Lachine Yard				
Paths	1	2	3	4
"Time" (hrs.)	2.08	2.28	2.12	3.00
Distance (km)	83	91	85	120
Cost ($)	254	264	256	300
Population Exposure (people)	2959	2787	2557	1266

Table 5. 2: Attributes of the routes to Repentigny

The distance of shortest path from the yard to this shipper is 41.5 km, and hence *path1* indicates using the shortest path for both segments of inbound drayage (41.5 * 2 =83). *Path2* through *Path4,* imply taking the shortest path to the shipper, and then a different one to get back to the IM yard. Associated with each path is a **cost** and a **risk** attribute. The cost numbers in dollars have been estimated to account for the following. In Quebec trucks can travel at a maximum speed of 50 km/hr in the city (http://www.mtq.gouv.qc.ca). Due to lights and traffic, an average speed of 40 km/hr is assumed. So the travel time on *path1* will be 2.1 hrs. Normally drayage is charged in terms of the amount of time the crew (driver-truck) is engaged. At a very conservative estimate of $50/hr, the crew-cost-fuel for the transportation part is $104. A conservative estimate of the time required to load and unload the containers (trailers) is considered. It takes approximately two hours to load the container at the shippers and an hour to unload it at the IM yard, for a combined crew cost of $150. So using *path1* a trailer (container) can be moved to the IM yard for $254, and similarly for the other paths. It should be noted that the 42 containers (trailers) originating at this shipper have non-hazardous cargo (table 5.1), and they are expected to take the shortest path i.e. *path1*.

Now for calculating ***population exposure*** (RISK), we have used the procedure described in the previous two chapters. Until this point, population exposure risk is at two points. At the shipper's site when the hazardous containers are being loaded (handled), and second while being transported. At the shipper's site, it is a straightforward generation of danger circle centered at the point of handling. Hazmat transportation on each path will result in sections of population centers being exposed, due to the airborne nature of toxins in consideration. It should be noted that the population exposure will arise only on the second leg of the inbound drayage, i.e. movement from the shipper to the IM yard. To be consistent with previous chapters and also to have a conservative estimate, we will work with propane as the hazmat in question.

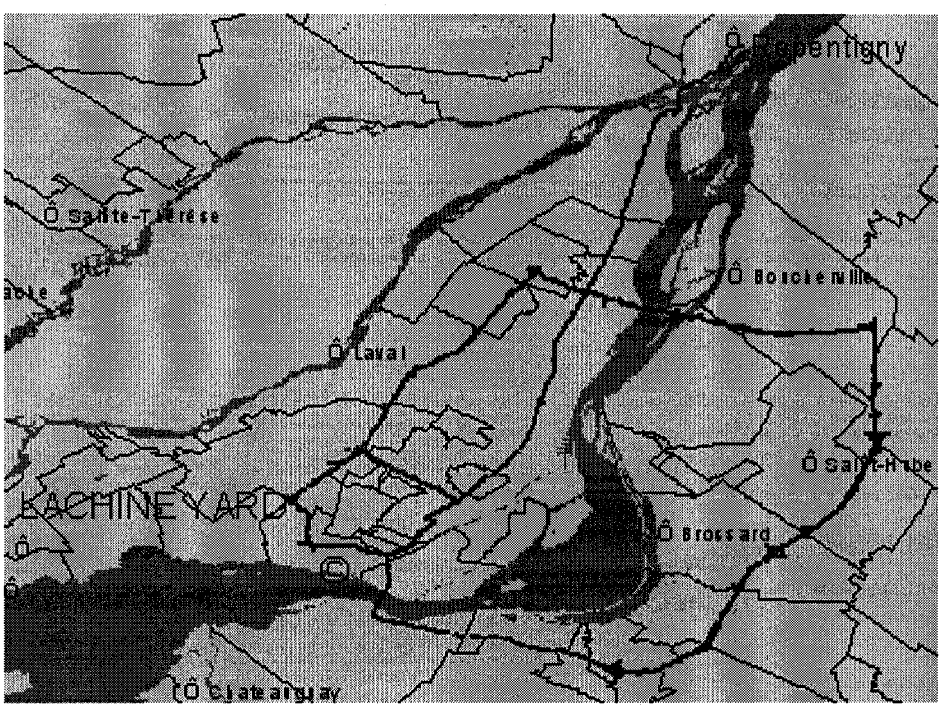


Figure 5.7: Drayage Paths from *Repentigny*

Gaussian Plume Model (GPM) was used to simulate concentrate levels and to calculate threshold distance for the severe-injury IDLH level of propane (600,000 ppm). Using the threshold distance, *danger circle* was created at the shipper's site and *exposure bands* were created along each possible path in *ArcView* GIS. Then using *Avenue Programming* in *ArcView* GIS, population exposure was calculated for each danger circle and for each path.

At *Repentigny* 1,557 people were exposed due to the handling of a single container with hazardous cargo. This shipper has to provide 53 containers (table 5.1) with hazardous cargo, and hence the cumulative exposure at this site is 82,521 people. There is nothing that can be done to reduce these numbers, except move the shipper to a less densely populated location. But the cumulative population exposure number does provide a basis for having emergency response planning in place. Appropriate emergency response systems can be planned based on cumulative demands for hazardous cargo originating at this shipper,

We see from Table 5.2 that *path1* has the highest population exposure while *path4* has the lowest, while the latter is the longest of the four available paths for this shipper. If hazardous material is being transported from the shipper to the yard, from a risk standpoint it is not prudent to take *path1*. The shortest path goes through downtown Montreal thereby exposing more than double the number than does *path4*, which bypasses downtown Montreal.

From our standpoint, a ***risk-cost*** tradeoff analysis on "***time***" dimension should be conducted. For our instance risk-cost evaluation will be done keeping in perspective the following: the departure times of the IM trains are fixed as they are *schedule-based*; and, the specified "***time***" at the receivers' site is a hard constraint. But by spending an extra $46 and taking *path4*, the risk to the population can be brought down by 1,693 people. Clearly this would mean that the shipper should have the shipments ready an hour earlier than when taking *path1*, in order to make the same IM train even after traveling on the longest route i.e. *path4*. As may be evident we are doing more than a typical risk-cost analysis. In here the increased cost and/or lower risk is acceptable only if the specified "*time*" element is not violated. We know from table 5.2 and figure 5.7 that the shipper at *Repentigny* has four paths, and each of the four is feasible if the shipments are readied at appropriate times. So in essence time-dimension drives determination of feasible routes and consequent selection of routes. We are incorporating a JIT approach wherein a tractor-trailer does not have to wait at shipper's site for loading, and at the intermodal yard for unloading. The activities in the intermodal chain are synchronized to eliminate waiting and congestion. We are assuming that there are enough flat-cars and IM trains for all the incoming IMUs, and that the number of trains is an operations decision to be taken by the yard-master and depends on the number of IMUs to be moved to a given intermodal terminus. It is a relevant assumption in light of two things: an IM train cannot be of infinite length; and, we are not aiming to capture the waiting (congestion) cost at the IM yards. We simply want to ensure that the rail-haul leg of the intermodal chain is executed as soon as the inbound-drayage leg finishes.

The cost increment versus risk reduction numbers above stems from only one trailer (container) with hazardous cargo. 53 trucks (containers) with hazardous cargo have been demanded from this shipper at *Repentigny*, and all of these are supposed to take one of the available paths. 89,729 more people are exposed, if all the 53 containers take *path1* compared to when they take *path4*. On the other hand, since *path4* is the longest it will mean having all the containers ready an hour early to be able to make to that IM train, and incurring an extra $2,438 ($15,900-$13,462) for the entire shipment.

Once the containers (trailers) reach the IM yard, they are placed on rail flatcars using a gantry or overhead crane as illustrated in figure 5.2. Barton et al. (1999) evaluated the feasibility of setting up an intermodal terminal, with public-private partnership, and have estimated the cost of one intermodal lift at the yards to be $140. We have taken a value of $150 / lift. All the 95 containers have to be placed on rail flatcars and each will add $150 to the intermodal movement cost. While the **cost** will be incurred for each container (trailer), **risk** will accrue only from containers with hazardous cargo due to additional handling at the yard. The risk stemming from each hazardous container will give rise to a danger circle centered at the point of handling. The number of people within this danger circle would constitute the population exposure resulting from the yard handling of the hazardous container. Co-incidentally the population density of *Lachine* municipality is the same as that of *Repentigny* area, and hence a total of 82,521 people would be exposed due to the handling of 53 containers with hazardous cargo with *Repentigny* origin. *Lachine* yard receives the containers (trailers) from other nine shippers as well, and hence the cumulative exposure from the hazardous cargo from all the ten shippers is 837,666 people. This is the risk stemming from handling 538 containers with hazardous cargo.

Figure 5.5 depict the IM train route between Montreal and Vancouver. Just to recollect both *regular* (***R-IM***) and *premium* (***P-IM***) services are available on this route, although at different costs. It is reasonable to assume that the shippers have been provided with the rates for the two IM trains and also which of the two has to be taken to meet the specified-time deadlines. Once that decision has been made, the said containers (trailers) would be placed on the rail flatcars of the chosen IM train.

The CPR intermodal network was re-created in *ArcView GIS* using the NTSB database. The intermodal rail length between Montreal and Vancouver was estimated, in *ArcView GIS*, at 2,920 miles. Intermodal train speed was calculated using information provided on CPR's website (www8.cpr.ca). The average IM train speed in 2004 is 28.5 miles per hour. This was rounded up to 30 miles per hour for ***R-IM***, and estimated the ***P-IM*** service rate @ 40 miles per hour. The ***R-IM*** train stops in Edmonton for traffic swaps, and the entire process is estimated to take 6 hours on average. The ***R-IM*** train will need 97 hours of travel time to reach Vancouver from Montreal, for a total yard-to-yard time of 103 hours. On the other hand ***P-IM* train**, being both non-stop and faster, will cover the same distance in 73 hours.

FEASIBLE ROUTES: Repentigny to various Receivers.

Regular Intermodal Servivce: 97 hrs. Lachine Yard Loading: 1 hr. Loading @ Shipper: 2 hrs.
Edmonton Swap Stop: 6 hrs. Vancouver Yard Unloading: 1 hr. Unloading @ Receiver: 2 hrs.

	INBOUND Drayage	Path 1					Path 2					Path 3					Path 4				
	Time in *HOURS*	2.08					2.28					2.12					3				
	OUTBOUND Drayage (Paths)	1	2	3	4	5	1	2	3	4	5	1	2	3	4	5	1	2	3	4	5
	Kelowna	9.70	7.35	7.34	7.37	7.46	9.70	7.35	7.34	7.37	7.46	9.70	7.35	7.34	7.37	7.46	9.70	7.35	7.34	7.37	7.46
	Kamloops	7.88	6.96	7.23	7.20	7.09	7.88	6.96	7.23	7.20	7.09	7.88	6.96	7.23	7.20	7.09	7.88	6.96	7.23	7.20	7.09
	Burnaby	0.26	0.35	0.32	0.47		0.26	0.35	0.32	0.47		0.26	0.35	0.32	0.47		0.26	0.35	0.32	0.47	
	Surrey	0.70	0.96	1.20	0.76	0.77	0.70	0.96	1.20	0.76	0.77	0.70	0.96	1.20	0.76	0.77	0.70	0.96	1.20	0.76	0.77
	Richmond	0.27	0.28	0.58	0.36		0.27	0.28	0.58	0.36		0.27	0.28	0.58	0.36		0.27	0.28	0.58	0.36	
	Haney	0.86	0.83	0.80			0.86	0.83	0.80			0.86	0.83	0.80			0.86	0.83	0.80		
	Coquitlam	0.57	0.60	0.74			0.57	0.60	0.74			0.57	0.60	0.74			0.57	0.60	0.74		
	Forest Hills	0.28	0.48	0.47			0.28	0.48	0.47			0.28	0.48	0.47			0.28	0.48	0.47		
	Pr-George	13.22	18.27	18.40	18.33	18.34	13.22	18.27	18.40	18.33	18.34	13.22	18.27	18.40	18.33	18.34	13.22	18.27	18.40	18.33	18.34
	Pr-Rupert	25.66	27.50	27.49	30.53	30.52	25.66	27.50	27.49	30.53	30.52	25.66	27.50	27.49	30.53	30.52	25.66	27.50	27.49	30.53	30.52
	Elapsed Time (in DAYS):	1	2	3	4	5	1	2	3	4	5	1	2	3	4	5	1	2	3	4	5
5.0 days	Kelowna	5.03	4.93	4.93	4.94	4.94	5.04	4.94	4.94	4.94	4.95	5.03	4.94	4.94	4.94	4.94	5.07	4.97	4.97	4.97	4.98
	Kamloops	4.96	4.92	4.93	4.93	4.92	4.96	4.93	4.94	4.94	4.93	4.96	4.92	4.93	4.93	4.93	4.99	4.96	4.97	4.97	4.96
4.5 days	Burnaby	4.64	4.64	4.64	4.65		4.65	4.65	4.65	4.66		4.64	4.64	4.64	4.65		4.68	4.68	4.68	4.69	
	Surrey	4.66	4.67	4.68	4.66	4.66	4.67	4.68	4.69	4.67	4.67	4.66	4.67	4.68	4.66	4.66	4.70	4.71	4.72	4.70	4.70
	Richmond	4.64	4.64	4.65	4.64		4.65	4.65	4.66	4.65		4.64	4.64	4.65	4.64		4.68	4.68	4.69	4.68	
4.0 days	Haney	4.66	4.66	4.66			4.67	4.67	4.67			4.67	4.66	4.66			4.70	4.70	4.70		
	Coquitlam	4.65	4.65	4.66			4.66	4.66	4.67			4.65	4.65	4.66			4.69	4.69	4.70		
	Forest Hills	4.64	4.65	4.65			4.65	4.66	4.66			4.64	4.65	4.65			4.68	4.69	4.69		
6.0 days	Pr-George	5.18	5.39	5.39	5.39	5.39	5.19	5.40	5.40	5.40	5.40	5.18	5.39	5.40	5.39	5.39	5.22	5.43	5.43	5.43	5.43
	Pr-Rupert	5.70	5.77	5.77	5.90	5.90	5.71	5.78	5.78	5.91	5.91	5.70	5.78	5.78	5.90	5.90	5.74	5.81	5.81	5.94	5.94

Table 5.3: *Regular* Intermodal Service & Route Feasibility

Table 5.3 provides the time elapsed (rounded to decimal places) at each stage of the movement, using ***R-IM***, of IMUs from the shipper at ***Repentigny*** till they reach their respective destinations. It is important to qualify that the time calculations in table 5.3 have been done assuming no waiting at any point in the intermodal chain, sort of a JIT approach towards the transfer and movement of IMUs.

The top of table 5.3 lists the different activities performed at the yards and sites, and the intermodal service times. These activities are common and constant for all shipments, irrespective of the destination or nature of cargo. Then we have the four possible paths and corresponding travel times for inbound drayage for the shipper at *Repentigny*. On termination of intermodal train journey in Vancouver, the outbound drayage will happen. This will take place, alike the inbound drayage, using one of the possible paths to the receiver's site.

Each link in the intermodal chain performs a task and consumes time, the sum of times at each link is the total time a container (trailer) spends traveling in the intermodal chain. The bottom half of the table provides the total time, in days, spent in the system. The text-boxes to the left of the receivers remind us of the time specified by each of the ten receivers, and will also enable a route-feasibility evaluation.

For visual and explanatory convenience the infeasible times have been shaded, and imply the un-viability of associated activities along the intermodal chain. For example, the value 5.03 is infeasible since the delivery requirement is on or before 5 days. This implies that a combination of *path1* of inbound drayage, ***R-IM***, and *path1* of outbound drayage is not a viable option since it violates the delivery specification. Similar argument will hold for all the other shaded numbers.

Table 5.3 also tells us that six receivers i.e. ones in *Surrey, Burnaby, Richmond, Forest Hills, Coquitlam* and *Haney* will not be able to receive their orders before the specified time. Although there are 20 possible route combinations to get to *Surrey*, not even one is feasible. There are 16 possible routes for *Burnaby* and also for *Richmond*, but not even one is feasible. The remaining three receivers have 12 possible routes each, but given the time constraint not even one is viable. It is the onus of the shipper (and the intermodal company) to deliver shipments before the scheduled delivery time. The rail-haul by being the longest part of this IM chain is also its bottleneck. There are two ways one of the infeasible routes can be made feasible: *first*, by moving traffic between Montreal and Vancouver at a faster pace; and *second* by relaxing the specified-time limit. The former can be done by employing faster trains, and the latter by penalizing late deliveries. Clearly shippers would want to avoid the latter option as far as possible.

FEASIBLE ROUTES: Repentigny to various Receivers. Premium Intermodal Service: 73 hours																					
	Elapsed Time (in DAYS):	1	2	3	4	5	1	2	3	4	5	1	2	3	4	5	1	2	3	4	5
5.0 days	Kelowna	4.03					4.04					4.03					4.07				
	Kamloops																				
4.5 days	Burnaby	3.64	3.64	3.64	3.65		3.65	3.65	3.65	3.66		3.64	3.64	3.64	3.65		3.68	3.68	3.68	3.69	
	Surrey	3.66	3.67	3.68	3.66	3.66	3.67	3.68	3.69	3.67	3.67	3.66	3.67	3.68	3.66	3.66	3.70	3.71	3.72	3.70	3.70
	Richmond	3.64	3.64	3.65	3.64		3.65	3.65	3.66	3.65		3.64	3.64	3.65	3.64		3.68	3.68	3.69	3.68	
4.0 days	Haney	3.66	3.66	3.66			3.67	3.67	3.67			3.67	3.66	3.66			3.70	3.70	3.70		
	Coquitlam	3.65	3.65	3.66			3.66	3.66	3.67			3.65	3.66	3.66			3.69	3.69	3.70		
	Forest Hills	3.64	3.65	3.65			3.65	3.66	3.66			3.64	3.65	3.65			3.68	3.69	3.69		
6.0 days	Pr-George																				
	Pr-Rupert																				

Table 5.4: *Premium* Intermodal Service

Focusing on the first way to expedite travel times, we introduce the *premium* IM train service (***P-IM***) on the same route. Table 5.4 provides the delivery times, in days, when ***P-IM*** is used to move the same shipments from Montreal to Vancouver. We observed in the previous paragraph that the delivery times specified by the receivers in *Surrey, Burnaby, Richmond, Forest Hills*, *Haney* and *Coquitlam* would be violated, if ***R-IM*** was used between Montreal and Vancouver. Now if these shipments were loaded onto the ***P-IM***, they would arrive at their destinations before the delivery cut-off time. It is not surprising to see that other shipments (shaded) are also reaching their destinations earlier than in table 5.3, since this is a faster train. What would be evident from earlier discussion, although not depicted in table 5.4, is the cost of using premium intermodal service. They are much more expensive than the regular intermodal service, and hence there is perhaps no need to load all the shipments on this service. Only the shipments destined to *Surrey, Burnaby, Richmond, Forest Hills, Haney* and *Coquitlam* would be loaded onto the ***P-IM***.

According to Morlok and Spasovic (1995), the rail-haul of intermodal cost is $0.70/mile. Since these numbers seemed a little old, we adjusted it to reflect changed conditions. We have taken it to be $0.875/mile for the rail-haul of ***R-IM***. Since there is no way of quantifying premium service, given that it is not public information, we have adopted a crude rule of thumb approach. The speed ratio between the two types of intermodal services provides us with an estimate for the travel-cost. A ratio of 1.33 yields \$1.164/mile as the rail-haul cost for *premium* intermodal service.

Vancouver Yard – Kelowna – Vancouver Yard					
Paths	1	2	3	4	5
Distance (km) - To the Receiver	485	368	367	369	373
Total Distance (km)	852	735	734	736	740
Cost ($)	1215	1068	1068	1070	1075
Population Exposure (people)	37	87	86	88	89
Cumul. Population Exposure	1961	4611	4558	4664	4717

Table 5.5: Outbound Drayage to *Kelowna*

On reaching the Vancouver yard, the intermodal train terminates and the containers (trailers) are unloaded from the rail flatcars and engaged to a drayage crew (truck-driver). Now, the truck driver has to move the container (trailer) to the receivers' location. Once again we would expect the truck driver to take the shortest route (cheapest) to the receiver site. Just to reiterate, this approach is fine as long as the containers do not contain any hazardous cargo. One would expect the driver to take any path except *path1* (is not just the longest, but also infeasible when used in conjunction with ***R-IM***), when going to *Kelowna*. If ***P-IM*** is used to move all the shipments destined for *Kelowna*, then *path1* will be feasible.

On reaching the location, the containers (trailers) are unloaded and the driver returns to the yard for future movement or waits in the region & awaits order for another inbound drayage. As far as the receiver is concerned the delivery of shipments indicates fulfillment of the purchase order, whereby the "*time*" elapsed counter stops.

Figure 5.8 presents the five possible ways to reach *Kelowna* from the Vancouver yard, and *path1* is the most expensive. The other four paths, while being very similar to each other from both cost and risk standpoint, expose roughly 2.5 times the number of people exposed if *path1* is used to move the hazardous cargo. The receiver at *Kelowna* needs 53 containers with hazardous cargo and the population exposure difference between *path1* and the best among the other four paths (namely, *path3*) is 49 people per container. 2,597 more people are exposed when all 53 containers move on *path3*, as opposed to when they move on *path1*. Of course not taking the shortest path will imply more travel cost. An additional $147/container will be incurred if the truck driver takes *path1* instead of the shortest path (*path3*). Hence, by spending an additional $7,791, the population exposure risk could be reduced by 2,597 people.

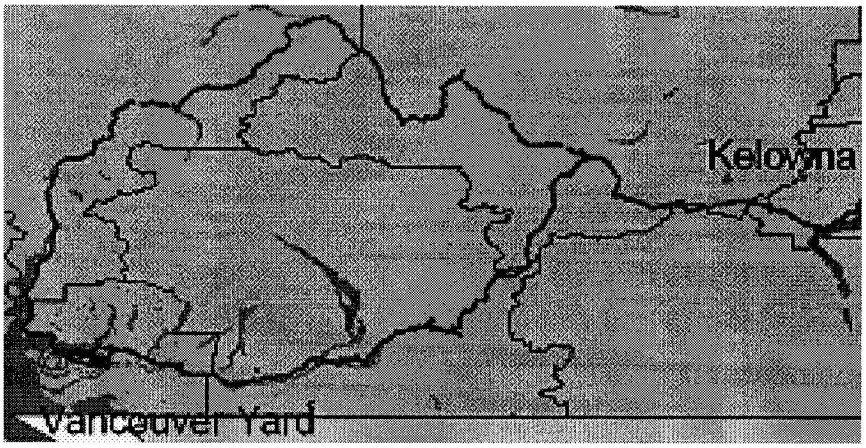


Figure 5.8: Outbound Drayage to *Kelowna*

Once the shipments have been delivered the dollar cost incurrence and the specified "***time***" counter stops, although the same cannot be said of population exposure. At the receiver's site, population exposure stems from the number of people within the danger circle centered at the point of container handling. This will be incurred for all the hazardous containers. At *Kelowna* 32 people are exposed due to the handling of a single hazardous container, which results in a cumulative total of 1,696 people for 53 containers.

For each shipper we have tables, such as, 5.2 to 5.5 for the one at *Repentigny*. **Appendix B** contains similar tables for the shippers at *Boucherville, Saint Hubert, Brossard, Chateauguay, Beaconsfield, Kirkland, Saint Eustache, Saint Therese,* and *Laval*.

5.4.2.2 Analysis

Although mentioned earlier, it is worth repeating that among all the activities being performed along the intermodal chain, only <u>two</u> has hard time constraints. *First* is the departure of the intermodal train from Lachine yard; and, s*econd* is the "***time***" specified by the receiver. All of the other links (activities) in the intermodal chain have to be maneuvered around these two, while maintaining feasibility and ensuring minimum monetary (and societal) costs.

Given the two types of IM train services and the multiple drayage paths, one can decide the paths for the trucking segment and the loadings on each type of IM train service. As mentioned before, the truck driver will take the shortest paths for yard - shipper/receiver - yard movements. We will evaluate the efficacy of this approach from a **cost-risk** standpoint against "***time***" dimension, and argue that intelligent enumeration would facilitate realizing weighted minimum of monetary and societal costs rather than just minimum dollar cost.

Population Exposure (PE) from Loading / Unloading of Hazardous Containers							
	Exposure				Exposure		
Yard / Shippers	Single IMU	All IMUs		Yard / Receivers	Single IMU	All IMUs
Lachine Yard	1557	837666		*Vancouver Yard*	447	240486
Repentigny	1557	82521		*Kelowna*	32	1696
Boucherville	343	15435		*Kamloops*	2	76
Saint Hubert	824	46968		*Burnaby*	447	22350
Brossard	1019	63178		*Surrey*	447	27714
Chateauguay	794	41288		*Richmond*	447	29502
Beaconsfield	1238	64376		*Haney*	447	23691
Kirkland	1705	105710		*Coquitlam*	447	16986
Saint-Eustache	401	22857		*Forest Hills*	447	22350
Sainte-Therese	1668	75060		*Pr-George*	1	62
Laval	1416	75048		*Pr-Rupert*	1	66

Table 5.6: Exposure from Container Handling

Table 5.6 presents the population exposure due to the handling of hazardous containers at the two yards, and at the shipper's and receiver's locations. A total of 1036 containers (trailers) have been demanded by the receivers, of which 538 contain hazardous cargo (table 5.1). Table 5.1 also presents the breakdown of total demand by shipper, receiver and commodity type.

As mentioned earlier the cumulative population exposure for Lachine IM yard is 837,666 persons. On the other hand at the Vancouver yard the same number of hazardous containers will be handled, but since the population density of British Columbia is lower than that of Quebec, the cumulative exposure at this yard is 240,486 people. The interpretation is similar for the exposure numbers at the ten shippers and the ten receivers. In general we notice that the exposure is higher in Quebec (at the shippers) than in British Columbia (at the receivers), and the higher population density in the former is the reason for the difference. It should also be noted that the exposure zone around the yard and the six centers around Vancouver contains the same number of people. All these six points of interest are situated in Greater Vancouver area, and that is the level of detail provided in the *ArcView GIS* database in our possession. It would not be incorrect or unreasonable to assume that population density will be higher in downtown Vancouver and around the Delta Port area, compared to the six receivers' location.

Exposure numbers in table 5.6 cannot be eliminated or reduced without a corresponding decrement in supply thereby only meeting partial demand. Hence the exposure numbers at the shippers' will be incurred if the demands have to be met. A very sparse intermodal terminal network and the business of meeting demand imply that the exposure at the Lachine and Vancouver yards cannot be reduced or eliminated. While the first point almost always translates into a single routing option, the second issue penalizes contract violations.

Table 5.7 presents the cost and risk numbers for one shipment and all shipments on a single path from the IM yard to the shipper and back. Once again dollar cost will incur for the entire trip, but risk will accrue only on the return trip and only when hazardous cargo is involved.

INBOUND DRAYAGE: Cost of One Shipment - Risk from One Hazardous Container										
PATHS	Repentigny	Boucherville	Saint Hubert	Brossard	Chateauguay	Beaconsfield	Kirkland	Saint-Eustache	Sainte-Therese	Laval
Cost ($)										
1	254	242	236	229	229	220	223	241	234	224
2	264	240	254	242	235	273	228	240	240	235
3	256	264	250	253	239	268	229	238	241	233
4	300	275	266		268	285	241	255	242	233
5						288	242	265	262	
6									251	
Risk (People)										
1	2959	2902	2548	2602	867	1089	1331	893	1044	2136
2	2787	2609	996	862	695	824	1223	903	1470	1626
3	2557	1174	797	857	634	837	1343	962	1067	1110
4	1266	716	2050		1363	1260	1999	1202	1438	3237
5						1304	2056	1654	2142	
6									1924	

INBOUND DRAYAGE: COST & RISK of ALL SHIPMENTS on that Path										
PATHS	Repentigny	Boucherville	Saint Hubert	Brossard	Chateauguay	Beaconsfield	Kirkland	Saint-Eustache	Sainte-Therese	Laval
Cost ($)										
1	24130	19602	25960	27987	25234	24156	27191	26538	18975	21242
2	25080	19408	27940	29573	25828	30052	27816	26400	19463	22325
3	24320	21384	27500	30890	26312	29480	27962	26224	19492	22097
4	28500	22275	29260		29524	31361	29426	28094	19602	22173
5						31680	29524	29172	21190	
6									20350	
Risk (People)										
1	156827	130590	145236	161324	45084	56628	82522	50901	46980	113208
2	147711	117405	56772	53444	36140	42848	75826	51471	66150	86178
3	135521	52830	45429	53134	32968	43524	83266	54834	48015	58830
4	67098	32220	116850		70876	65520	123938	68514	64710	171561
5						67808	127472	94278	96390	
6									86580	

Table 5.7: Cost-Risk attributes for Inbound Transport

To recollect, given the **fixed** departure time of the IM train, the onus of readying the shipments is on the shippers. The shippers are normally provided with the cut-off time for loading an IM train, and they are also aware of the travel time back to the IM yard. Against this backdrop, the containers or trailers have to be ready to be moved to the IM yard for appropriate connection.

Once again it goes without saying that the driver will take the shortest path, since the shipper is being billed on that basis. So in table 5.7 all the shipments originating at *Repentigny* will take *path1* to the yard; the ones at *Boucherville* will take *path-2*; *Saint Hubert: path1*; *Brossard: path1*; *Chateauguay: path1*; *Beaconsfield: path1*; *Kirkland: path1*; *Saint Eustache: path3*; *Sainte Therese: path1*; and, *Laval: path1*. This approach is justified from purely a cost standpoint. For example, if all the 95 containers / trailers originating at *Repentigny* contain regular freight, then the driver (shipper/drayage company) is right to take the shortest path back to the yard. In our opinion the efficacy of this approach is undermined when hazardous contents are involved. We see from the same table that shortest routes are not necessarily the least risky, since most of these routes traverse the densest population centers and hence are extremely risky. But on the other hand some of the longest paths are most risky since they expose more people along the length of the route. For example, the longest paths for the shippers at *Saint Hubert, Chateauguay, Beaconsfield, Kirkland, Saint Eustache* and *Sainte Therese*, are also the ones with maximum population exposure. We note from above that cost & risk may or may not be in conflict with each other.

It is our contention that a *weighted shortest path* strategy, evaluated against the specified "***time***", be employed in these situations. This strategy will aim to realize the weighted minimum of monetary and societal costs, while adhering to the time specifications. Our approach takes a middle path to the concerns of intermodal players (parties) and the society at large. We realize that in some instances nothing can be done to bring down the risk, unless one is willing to default on the shipment orders. But here the risk element can be brought down if the intermodal parties are willing to collaborate in the interest of reducing societal cost either by spending more money or by planning related activities more efficiently. By spending a little more money, societal risk can be reduced by traveling on a marginally longer but route with less exposure risk. But this longer route can be taken only if the hazardous shipments can be readied earlier than usual since the cut-off time for loading the IM train is fixed.

Numerous works have been done in the domain of bi- and multi-objective problems. Broadly speaking there are two stakeholders in our problem: *government agencies* and *intermodal parties* (players). They can arrive at mutually agreeable weights for cost and risk measures, and work forward.

INBOUND DRAYAGE: Weighted Objective Values										
Cost = 1.0 and Risk =1.0										
PATHS	Repentigny	Boucherville	Saint Hubert	Brossard	Chateauguay	Beaconsfield	Kirkland	Saint-Eustache	Sainte-Therese	Laval
1	3213	3144	2784	2831	1096	1309	1554	***1134***	***1278***	2360
2	3051	2849	1250	***1104***	930	***1097***	***1451***	1143	1710	1861
3	2813	1438	***1047***	1110	***873***	1105	1572	1200	1308	***1343***
4	***1566***	***991***	2316		1631	1545	2240	1457	1680	3470
5						1592	2298	1919	2404	
6									2175	
Normalized: Largest *Cost* and *Risk* numbers										
1	5700	5513	5094	5077	3342	***3458***	3736	3496	***3572***	4549
2	5636	5194	3737	***3477***	3228	3772	***3683***	***3493***	4063	4162
3	5319	4023	***3495***	3589	***3215***	3729	3816	3534	3664	***3620***
4	***4503***	***3683***	4920		4259	4336	4602	3958	4049	5755
5						4412	4667	4516	4965	
6									4635	
Normalized: Smallest *Cost* and *Risk* numbers										
1	3692	3601	3229	3264	1529	1723	1974	***1590***	***1720***	2782
2	3549	3301	1729	***1562***	1373	1613	***1881***	1596	2164	2304
3	3296	1936	***1519***	1588	***1325***	***1611***	2005	1650	1762	***1782***
4	***2132***	***1510***	2818		2138	2083	2695	1939	2137	3911
5						2135	2755	2420	2897	
6									2649	

Table 5.8: Weighted Paths for Inbound Drayage

Continuing with our analysis, we present three different weight scenarios in table 5.8. *First*, a scenario wherein both cost and risk measures have equal weight, hence it is straightforward summation of corresponding cells from table 5.7. The minimum from each column represents the best weighted path from that shipper to the Lachine yard. *Second* scenario presents normalized numbers. The ratio between the maximum risk value and the maximum cost value is 10.79, and hence each cost data is multiplied by this ratio. Once again the minimum in each column yields the best weighted paths from the shipper to Lachine yard. *Third* scenario is another instance of normalization, but now the multiplier is the ratio between the minimum risk and cost values, i.e. 2.89. It returns a set of weighted minimum cost-risk paths as well.

It should be noted from table 5.8 that except for the shippers at *Beaconsfield* and *Saint Eustache*, the best weighted solution in each of the three scenarios is consistent for the other eight shippers. Even in *Saint Eustache* two of three scenarios yield the same result, which can be assumed to be the best possible path. *Beaconsfield* is an exception where the routing should be decided either by additional weight analysis or by the preferences of the stakeholders.

It should also be noted that the suggested action from table 5.8 corresponds to what the driver would have done in only one instance. The route from *Sainte Therese* to *Lachine* yard, is the minimum cost and also the minimum risk path, and hence is the best available path from either standpoint.

Table 5.8 recommends the following (Shipper-Path# (# of containers): *Repentigny-Path4* (53); *Boucherville-Path4* (45); *Saint Hubert-Path3* (57); *Brossard- Path2* (62); *Chateauguay-Path3* (52); *Kirkland-Path2* (62); *Saint Eustache-Path1* (57); *Sainte Therese-Path1* (45); *Laval-Path3* (53); and finally, *Beaconsfield*: more analysis or negotiation (52 containers).

For containers (trailers) without hazardous content, the shortest path should be followed as in table 5.7. Hence the respective combinations and number of containers (trailers) are: *Repentigny-Path1* (42); *Boucherville-Path2* (36); *Saint Hubert-Path1* (53); *Brossard- Path1* (60); *Chateauguay-Path1* (58); *Beaconsfield-Path1* (58); *Kirkland-Path1* (60); *Saint Eustache-Path3* (53); *Sainte Therese-Path1* (36); and, *Laval-Path1* (42).

Now that the best weighted paths have been ascertained for inbound drayage, we move to the next link in the IM transport chain viz. rail-haul.

Route Length: 2920 miles.			
	Time (hrs.)	Rate ($/mile)	Cost ($) / IMU
Intermodal			
Regular Service	97	0.875	2555
Premium Service	73	1.164	3399
		Dollar Cost (All Shipments)	
Shipper	# of IMUs	Regular	Premium
Repentigny	95	242725	322894
Boucherville	81	206955	275309
Saint Hubert	110	281050	373877
Brossard	122	311710	414663
Chateauguay	110	281050	373877
Beaconsfield	110	281050	373877
Kirkland	122	311710	414663
Saint-Eustache	110	281050	373877
Sainte-Therese	81	206955	275309
Laval	95	242725	322894

Table 5.9: Cost of using Intermodal Services

Table 5.9 details the cost and operating characteristics of intermodal train service between *Lachine Yard* (Montreal) and *Delta Port* (Vancouver). The length of the CPR as re-created in *ArcView GIS* is 2920 miles. The ***R-IM***, with a six hour IMU swap in Edmonton, will take 103 (97+6) hours to traverse this route. On the other hand the ***P-IM*** will cover the distance in 73 hours. The IMUs from various shippers will be moved at the same $ rate between the IM terminals, although the total for each shipper will depend on the number of IMUs to be moved.

Furthermore the decision about the type of IM train service will be made by folding back the specified-time line. More specifically how long will the outbound drayage take once the containers (trailers) have reached the Delta Port in Vancouver. As detailed earlier in tables 5.3 to 5.6 (and **Appendix B**), we can enumerate the feasible and infeasible routes.

We recall that in tables 5.3 through 5.6 (and in **Appendix B**) none of path-combinations using ***R-IM*** was feasible for receivers in and around Vancouver. Orders of the six receivers at *Burnaby, Surrey, Richmond, Haney, Coquitlam* and *Forest Hills* cannot be delivered within the specified time, if ***R-IM*** is used between Montreal and Vancouver. Hence these are clear cases where ***P-IM*** would have to be employed, albeit at a higher shipping cost. Out of the 1036 containers (trailers) to be moved west, 612 are destined to these six centers and hence would be moved on premium train service for a total cost of $ 2,080,188. The remaining 424 will take the ***R-IM***, thereby incurring a cost of $ 1,083,320. So the total cost of moving the 1036 containers (trailers) from Lachine yard to Vancouver yard is $ 3,163,508.

Now for the *population exposure* of the rail-haul part of the intermodal chain, we need to know the number of hazardous containers traveling together and also draw upon our work from the previous two chapters.

Based on the arrival times at their receivers', 424 containers (trailers) are going to be loaded on the ***R-IM***. 219 containers have hazardous cargo, while the remaining 205 IMUs contain non-hazardous cargo. On the other hand the ***P-IM*** has to move 612 containers (trailers), of which 319 have hazardous content. Although the length of the train can be played with, to be consistent with our work in previous chapter, we will assume a space for 120 containers

(IMU) originating at Lachine Yard and destined for Vancouver, and the remaining slots are made available to Edmonton traffic.

Shippers / IM Train	Regular Service			Premium Service		
	HazMat	*Non-HazMat*	Total	*HazMat*	*Non-HazMat*	Total
Repentigny	16	17	**33**	37	25	**62**
Boucherville	19	23	**42**	26	13	**39**
Saint Hubert	24	20	**44**	33	33	**66**
Brossard	27	22	**49**	35	38	**73**
Chateauguay	23	22	**45**	29	36	**65**
Beaconsfield	19	26	**45**	33	32	**65**
Kirkland	26	29	**55**	36	31	**67**
Saint-Eustache	23	20	**43**	34	33	**67**
Sainte-Therese	15	9	**24**	30	27	**57**
Laval	27	17	**44**	26	25	**51**

Table 5.10: Traffic for the Two Intermodal Services

Table 5.10 provides further breakdown by shipper and type of freight. To recollect, it is assumed that the IM service provider has the capacity and equipment to move shipments as per demand, and hence these containers (trailers) will not be stranded at the yards waiting to be westbound. Although we are assuming that each shipment will arrive at their destinations on schedule, we still need to ascertain the loading of IM trains in order to calculate the rail-haul *population exposure*. It is here that we draw upon our earlier works from chapters 3 and 4.

It is worth recollecting the *economies of risk* phenomenon discussed in earlier chapters. Intuitively it would seem that population exposure should be from moving 538 containers of hazardous cargo, which is correct but it would be fallacious to determine exposure based on this number alone. This is the total number of hazardous containers being transported, but we need the number of containers with hazardous cargo on each IM train to be able to arrive at the exact population exposure number for that train. What is the exposure stemming from each IM train?

The assignment of containers (trailers) to each train will determine this. One could use a heuristic whereby as far as possible the entire block of traffic from a particular shipper will be assigned to only one train. For example the 33 containers (trailers) from *Repentigny* will be loaded on one ***R-IM***, and so on.

To move 424 containers (trailers) we need four regular intermodal trains. One way to assign traffic could be:

- Train 1: *Repentigny* and *Bouchverville* and *Saint Hubert* traffic. This totals 119 containers (trailers), with 59 hazardous containers and 60 non-hazardous.
- Train 2: *Brossard* and *Chateauguay* and *Sainte Therese* traffic. This totals 118 containers (trailers), with 65 hazardous containers and 53 non-hazardous.
- Train 3: *Beaconsfield* and *Kirkland* traffic. This totals 100 containers (trailers), with 45 hazardous and 55 non-hazardous units. Fill the rest of the space with Edmonton traffic.
- Train 4: *Saint Eustache* and *Laval* traffic. This totals 87 containers (trailers), with 50 hazardous and 37 non-hazardous IMUs. Fill the rest of the space with Edmonton traffic.

An alternate way could be to allow breaking consignment from one shipper, knowing that all the trains are arriving in Vancouver one after the other (around the same time).

- Train 1: *Repentigny* and *Bouchverville* and *Saint Hubert* traffic. This totals 119 containers (trailers), with 59 hazardous containers and 60 non-hazardous.
- Train 2: *Brossard* and *Chateauguay* and *Sainte Therese* traffic. This totals 118 containers (trailers), with 65 hazardous containers and 53 non-hazardous.
- Train 3: *Beaconsfield* and *Kirkland.* This totals 120 containers (trailers), with 45 hazardous and 75 non-hazardous units. Fill the rest of the space with Edmonton traffic.
- Train 4: *Saint Eustache* and *Laval.* This totals 67 containers (trailers), with 50 hazardous and 17 non-hazardous IMUs. Fill the rest of the space with Edmonton traffic.

It should be noted that above two are the not the only ways to load the IM trains, they are just representative of two assignments.

A very interesting IM train makeup motivated by our work in Chapter 3 could be to form the IM train on the lines of a *unit-train*. Specifically there could be two types of ***R-IM***, characterized by the type of freight being hauled. One will almost exclusively carry hazardous containers, while the other can carry non-hazardous containers/trailers. We can resort to this, since the trains arrive in Vancouver one after the other. Using this assignment scheme, once again there would be four ***R-IM*** trains.

- HazMat Train # 1: Train #1 will carry 109 hazardous containers from shippers at *Repentigny, Boucherville, Saint Hubert, Brossard* and *Chateauguay.*
- HazMat Train # 2: It will carry the remaining 120 hazardous containers from the shippers at the other five locations i.e. *Beaconsfield, Kirkland, Saint Eustache, Sainte Therese,* and *Laval.*
- Train # 3: Can haul the 104 non-hazardous containers and trailers from the shippers at *Repentigny, Boucherville, Saint Hubert, Brossard* and *Chateauguay.*
- Train # 4: Will carry the remaining 101 non-hazardous containers and trailers from the shippers at *Beaconsfield, Kirkland, Saint Eustache, Sainte Therese*, and *Laval.*

The corresponding population exposure[7] from each of the three train makeup policies are as follows:

Train #	Plan 1	Plan 2	IM unit Trains
1	328	328	460
2	350	350	501
3	280	280	
4	300	300	

Table 5.11: Population Exposure of IM regular service

The threshold distances for the four trains in Plan 1 and Plan 2 are 4.36, 4.71, 3.62 and 3.89 miles respectively. Using these as radii, four different exposure bands were created along the IM train lines between Montreal and Vancouver. There will be no exposure difference between ***Plan 1*** and ***Plan 2***, since only the non-hazmat containers / trailers are changing trains (20 regular containers /

[7] These *population exposure* numbers are rather low. The GIS provincial population data in our possession provides more detailed layers for the provinces of Quebec and Ontario than for other Canadian provinces. Sub-division level population data have been provided for these two provinces, while municipal level data for the others.

trailers from the shipper at Saint Eustache). The total population exposure carved out by the ***R-IM*** is 1,258 people under both ***Plan 1*** and ***Plan 2***.

The threshold distances for the IM unit trains are 6.68 and 7.33 miles. Once again exposure bands were created using these numbers. Not surprisingly the population exposure when unit train equivalent of IM service is used goes down to 961 persons. The usage of hazmat unit train reduces the exposure by roughly 24%. It should be noted that the cost of operating IM services under each of the three plans in table 5.11 is the same, and hence is makes sense to implement a load-assignment strategy that can bring down the **risk** (population exposure). We have seen in the two previous chapters that when hazardous cargo, with airborne characteristics travel together, they yield *economies of risk* due to non-linear nature of the resulting concentration curves.

On the other hand 612 containers (trailers) need to be moved by ***P-IM***, of which 319 contain hazardous cargo. Once again any assignment heuristic can be used to load these trains. All we know is that roughly 5 trains will be required, and since there is no Edmonton traffic we can accommodate between 130 and 140 containers (trailers) in each IM train service. Once again these numbers are mere parameters, which could be varied.

We have justified (above and in the last two chapters) the usage of *unit-train* equivalent of IM service, since that reduces the risk by a substantial amount. Once again assuming everything else being constant it makes sense to assign traffic, in the formation of ***P-IM***, to result in ***unit*** trains. The 5 trains and their cargo mix would be as follows:

- HazMat Train # 1: It will carry the 118 containers with hazardous cargo. These belong to shippers at *Repentigny, Boucherville, Chateauguay* and *Laval*.
- HazMat Train # 2: It will carry 131 containers with hazardous cargo. These belong to shippers at *Saint Hubert, Brossard, Beaconsfield* and *Sainte Therese*.
- Mixed Train # 3: It will carry 70 hazardous containers and 13 regular trailers (containers). The hazardous containers belong to the shippers at

Kirkland and *Saint Eustache*, while the regular trailers (containers) belong to the shipper at *Boucherville*.

- Train # 4 and Train # 5: The two together will move 280 containers (trailers), without any hazardous content.

Of course the Mixed Train has enough room to accommodate more containers (trailers), and something can be moved from regular IM service. Even though it is a possibility, moving anything from regular service to premium is unlikely because of the cost involved, but then it is not impossible. Such decisions are made by the IM operator and would be based on marginal *cost–benefit* analysis.

The threshold distances for the two hazmat and one mixed trains are 7.28, 7.67 and 4.91 miles, respectively. The population exposures due to the three trains are as follows: HazMat Train # 1 exposes 498 people; HazMat Train # 2 exposes 522 people; and, the Mixed Train # 3 exposes 365 people. The total population exposure from the premium IM train services is 1,385 people.

Population Exposure due to the rail-haul movement of 538 hazardous IMUs, by the two types of IM train services, is 2,346 people. A total of nine IM trains will be required to move all the shipments from *Lachine Yard* in Montreal to the *Delta Port Yard* in Vancouver. Furthermore four ***R-IM*** and five ***P-IM*** would have to be employed for these shipments.

Now the containers (trailers) have reached Vancouver, but still need to cover the last-leg of their journey viz. outbound drayage.

It is logical that the driver will take the shortest (cheapest) routes to get to the receiver's location. We recollect that some routes are infeasible, since they are likely to violate the delivery specifications. For example, *path1* to *Kelowna* is infeasible given that the load destined for *Kelowna* from all shippers have arrived on the ***R-IM***. As this was the longest path from Vancouver yard to *Kelowna*, the driver wouldn't have taken this path anyway.

From a pure *cost* standpoint (table 5.12), for the traffic from *regular* IM service, the receiver and outbound drayage path to be taken are: *Kelowna-Path2* or *Path3*; *Kamloops- Path2*; *Prince George-Path1*; and, *Prince Rupert-Path4*. On the other hand for the traffic from *premium* IM service, the corresponding *cost-based* combinations are: *Burnaby- Path1*; *Surrey-Path5*; *Richmond-Path1*; *Haney-Path3*; *Coquitlam-Path1*; and, *Forest Hills-Path1*.

OUTBOUND DRAYAGE: Cost of One Shipment - Risk from One Hazardous Container										
PATHS	Kelowna	Kamloops	Burnaby	Surrey	Richmond	Haney	Coquitlam	Forest Hills	Pr-George	Pr-Rupert
$ (Cost)										
1	1065	928	33	88	34	104	71	36	1653	3208
2	918	870	38	104	35	102	73	49	1968	3323
3	918	887	36	119	53	100	82	47	1976	3322
4	920	885	45	91	39				1972	2343
5	925	878		63					1974	3511
Risk (People)										
1	37	47	447	625	460	462	451	535	31	16
2	87	90	528	738	465	454	460	612	39	26
3	86	96	499	846	701	447	512	595	41	32
4	88	112	625	647	522				47	25
5	89	92		500					49	21

OUTBOUND DRAYAGE: Cost & Risk of ALL SHIPMENTS on that Path.										
PATHS	Kelowna	Kamloops	Burnaby	Surrey	Richmond	Haney	Coquitlam	Forest Hills	Pr-George	Pr-Rupert
$ (Cost)										
1	101175	74200	3057	10301	4446	9855	5696	3346	193350	423403
2	87248	69629	3613	12170	4620	9684	5856	4583	230300	438573
3	87210	70960	3410	13949	6975	9527	6530	4457	231208	438454
4	87372	70821	4273	10673	5188				230719	309276
5	87888	70248		7371					230929	463476
Risk (People)										
1	1961	1786	22350	38729	30360	24508	17138	26750	1922	1056
2	4611	3420	26419	45759	30658	24083	17463	30606	2418	1716
3	4558	3648	24934	52445	46285	23691	19472	29771	2542	2112
4	4664	4256	31243	40128	34425				2914	1650
5	4717	3496		31000					3038	1386

Table 5.12: Cost-Risk attributes of Outbound Drayage

OUTBOUND DRAYAGE: Weighted Objective Values. Cost = 1.0 and Risk = 1.0										
PATHS	Kelowna	Kamloops	Burnaby	Surrey	Richmond	Haney	Coquitlam	Forest Hills	Pr-George	Pr-Rupert
1	1102	975	***480***	713	***494***	566	***522***	***571***	***1684***	3224
2	1005	***980***	567	842	500	556	533	661	2007	3349
3	***1004***	983	535	965	754	***547***	594	643	2017	3354
4	1008	997	670	738	561				2019	***2368***
5	1014	970		***563***					2023	3532
Normalized: Largest *Cost* & *Risk* Numbers										
1	***1219***	***1123***	***1888***	2681	***1943***	2023	***1943***	***2256***	***1781***	3274
2	1280	1244	2232	3168	1963	1988	1981	2590	2130	3430
3	1275	1285	2106	3630	2964	***1956***	2209	2519	2146	3454
4	1285	1350	2639	2778	2204				2167	***2447***
5	1295	1260		***2138***					2177	3598
Normalized: Smallest *Cost* & *Risk* Numbers										
1	1140	***1023***	***941***	1358	***969***	1044	***988***	***1123***	***1716***	3240
2	1095	1053	1112	1604	979	1026	1007	1293	2048	3375
3	***1093***	1082	1050	1839	1478	***1009***	1123	1258	2059	3387
4	1099	1113	1315	1407	1099				2067	***2394***
5	1106	1065		***1079***					2073	3554

Table 5.13: Weighted Paths for Outbound Drayage

Once again we contend that taking the shortest path is fine as long as hazardous cargo is not being moved. It should be noted that population density of British Columbia is lower than that of Quebec, and hence the numbers are expected to be lower. Just like in inbound drayage, the weight based numbers are provided for outbound drayage in table 5.13. The top block is the result of one to one summation of cost and risk numbers from table 5.12, for a single shipment. The middle block contains the summation of normalized values, wherein the risk numbers are multiplied by the ratio of maximum cost to maximum risk. The third block has normalization based on the ratio of minimum cost to minimum risk.

Kelowna and *Kamloops* contain two different paths in the 3 scenarios presented. For *Kelowna* we know from before that *path1* is infeasible if ***R-IM*** is used between Montreal and Vancouver, and hence the recommendation in the middle block can be neglected thereby leaving *path3* as the suggested path. For *Kamloops*, two of the three instances contain *path1* as the suggested path and hence can be taken or further weight analysis can be conducted.

Just like in inbound drayage, some shipments could be routed in better ways to further minimize risk. For example, the shipments to *Kelowna* from each of the ten shippers are moved between the IM yards by ***R-IM***. This loading is dictated purely by cost considerations. Let us assume that all the hazardous containers to *Kelowna* are moved by the ***P-IM***, thereby reaching Vancouver yard in roughly 4.2 days.

Given that the truck drivers have more time before the 5 day cut-off period. Now they can take *path1* which although being a little bit more expensive has the least population exposure. For an extra $147/IMU the exposure can be reduced by 49 persons, a 57% reduction in risk. For the entire hazardous shipments bound for Kelowna, it will cost $7,791 more but the exposure risk comes down by 2,597 people. Of course these are just the numbers for outbound drayage.

One has to pay to use the ***P-IM*** and that will cost an extra 53*2920*0.289 = $44,725. The 53 hazardous containers can be moved on Mixed Train # 3 (premium service), which will make it the HazMat Train # 3 with 123 hazardous containers. The 13 regular freight cars on Mixed Train # 3 could be allocated to HazMat Train # 1, bringing its total loading to 131 containers (trailers).

Of course doing so reduces the number of hazardous containers moving by ***R-IM*** by the corresponding number. ***R-IM*** HazMat Train # 1 will now carry 79 hazardous containers (109-30), while HazMat Train # 2 will carry 97 hazardous containers (120-23). Now we have some open slots in HazMat Trains # 1 and 2, which could be filled. The two HazMat trains have 64 available slots (53 hazardous containers destined for *Kelowna* from above, and 11 open slots in HazMat Train #1's original configuration). This new assignments should eliminate the need to form and run the fourth train, but now Train # 3 will have 141 containers (trailers).

Normally the IM operator should be able to accommodate the 21 extra containers in the same train, but if not these containers can always be loaded on to ***P-IM*** HazMat Train # 1, which has 22 open slots. Although it will be expensive to the IM operator, it eliminates the need for a fourth train. The shipper will have no problem with this revised loading, since the load is reaching Vancouver well before the scheduled time. Normally this will be done without the knowledge of the shipper, who is only concerned about the safe and timely delivery of the shipments. Moreover the shippers have no say in the assignments / loading of IM trains, it is the exclusive domain of the IM operators (railroad companies).

In conclusion, it can be said that it is possible to reduce population exposure risk by spending more money and/or readying the shipments at an earlier time in the event of inbound drayage, and by taking the faster IM train (premium) service for the rail-haul in order to enable the outbound drayage to take a risk-cost weighted path to the receiver's site. In addition, population exposure stemming from IM trains can be reduced by implementing a train make-up scheme on lines of (hazardous) unit-trains. We also noticed that train exposure numbers were rather low because of the provincial level data in GIS. In general, risk reduction is possible only when all the IM parties are concerned about safety and not driven just by the desire to minimize cost.

<u>SOUTHERN InterModal Route:</u>

Now suppose the IM operator has another intermodal train, running between *Lachine* yard in Montreal and *Delta Port* in Vancouver as, re-created in *ArcView GIS*, in figure 5.9. This train has the same characteristics as the other two IM trains, except that it goes through Calgary, and departs from Lachine yard <u>two hours</u> later than the one through Edmonton. We would like to differentiate the two routes, and hence the one going through Edmonton will be called the *North Route* and the one through Calgary the *South Route*.

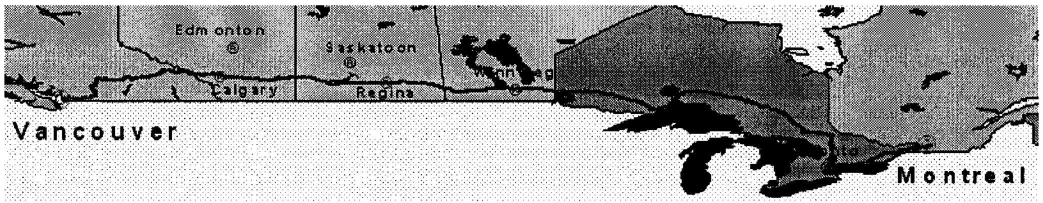


Figure 5.9: Alternate Intermodal Route

The length of this route (*South Route*) as measured in *ArcView GIS* is 2,713 miles, which is a full 207 miles shorter than the North Route. A ***R-IM*** will cover the yard to yard distance in 96 hours, including the 6 hour for container swap at Calgary. On the other hand, a ***P-IM*** through the *South Route* will have a 68 hour yard to yard run time. All the calculations are based on the IM train speeds introduced earlier, i.e. 30 miles per hour for regular service, and 40 miles per hour for premium service.

Tables 5.3 through 5.6 were re-created with the new IM travel times. The sample for the shippers at *Repentigny* is produced in table 5.14. The corresponding tables for the other nine shipper locations are presented in **Appendix B**.

One thing we notice immediately is that there are no infeasible routes. All the demands can be met on time using ***R-IM***, thereby ruling out the possibility of employing ***P-IM*** to move any traffic. Since this is a shorter route it would be cheaper to move traffic in this lane as opposed to the North Route, but the IM operator will split traffic between the two lanes.

A shipper will approach an IM operator (IMC) with the delivery date and service type preferences. Based on the delivery date the IM operator (railroad operator) will quote a price and the time of delivery. The shippers are only interested in the timely and safe arrival of their shipments, without worrying about the route a shipment may take. As soon as a container (trailer) leaves a shippers' location, almost simultaneously information regarding the destination and content (if hazardous) of the shipment is generated (Nozick and Morlok

(1997)). So in essence a route plan has been prepared for the shipment, without the knowledge of the shipper, even before the shipment reaches the nearest IM yard.

FEASIBLE ROUTES: Repentigny to various Receivers

Regular Intermodal Servivce:	90 hrs.				Lachine Yard Loading:	1 hr.									Loading @ Shipper:	2 hrs.				
Edmonton Swap Stop:	6 hrs.				Vancouver Yard Unloading:	1 hr.									Unloading @ Receiver:	2 hrs.				
INBOUND Drayage	Path 1					Path 2					Path 3					Path 4				
Time in *HOURS*	2.08					2.28					2.12					3				
OUTBOUND Drayage (Paths)	1	2	3	4	5	1	2	3	4	5	1	2	3	4	5	1	2	3	4	5
Kelowna	9.70	7.35	7.34	7.37	7.46	9.70	7.35	7.34	7.37	7.46	9.70	7.35	7.34	7.37	7.46	9.70	7.35	7.34	7.37	7.46
Kamloops	7.88	6.96	7.23	7.20	7.09	7.88	6.96	7.23	7.20	7.09	7.88	6.96	7.23	7.20	7.09	7.88	6.96	7.23	7.20	7.09
Burnaby	0.26	0.35	0.32	0.47		0.26	0.35	0.32	0.47		0.26	0.35	0.32	0.47		0.26	0.35	0.32	0.47	
Surrey	0.70	0.96	1.20	0.76	0.77	0.70	0.96	1.20	0.76	0.77	0.70	0.96	1.20	0.76	0.77	0.70	0.96	1.20	0.76	0.77
Richmond	0.27	0.28	0.58	0.36		0.27	0.28	0.58	0.36		0.27	0.28	0.58	0.36		0.27	0.28	0.58	0.36	
Haney	0.86	0.83	0.80			0.86	0.83	0.80			0.86	0.83	0.80			0.86	0.83	0.80		
Coquitlam	0.57	0.60	0.74			0.57	0.60	0.74			0.57	0.60	0.74			0.57	0.60	0.74		
Forest Hills	0.28	0.48	0.47			0.28	0.48	0.47			0.28	0.48	0.47			0.28	0.48	0.47		
Pr-George	13.22	18.27	18.40	18.33	18.34	13.22	18.27	18.40	18.33	18.34	13.22	18.27	18.40	18.33	18.34	13.22	18.27	18.40	18.33	18.34
Pr-Rupert	25.66	27.50	27.49	30.53	30.52	25.66	27.50	27.49	30.53	30.52	25.66	27.50	27.49	30.53	30.52	25.66	27.50	27.49	30.53	30.52

	Elapsed Time (in DAYS):	1	2	3	4	5	1	2	3	4	5	1	2	3	4	5	1	2	3	4	5
5.0 days	Kelowna	4.74	4.64	4.64	4.64	4.65	4.75	4.65	4.65	4.65	4.66	4.74	4.64	4.64	4.65	4.65	4.78	4.68	4.68	4.68	4.69
	Kamloops	4.66	4.63	4.64	4.64	4.63	4.67	4.64	4.65	4.65	4.64	4.67	4.63	4.64	4.64	4.63	4.70	4.67	4.68	4.68	4.67
	Burnaby	4.35	4.35	4.35	4.36		4.36	4.36	4.36	4.36		4.35	4.35	4.35	4.36		4.39	4.39	4.39	4.39	
4.5 days	Surrey	4.37	4.38	4.39	4.37	4.37	4.37	4.39	4.40	4.38	4.38	4.37	4.38	4.39	4.37	4.37	4.40	4.42	4.43	4.41	4.41
	Richmond	4.35	4.35	4.36	4.35		4.36	4.36	4.37	4.36		4.35	4.35	4.36	4.35		4.39	4.39	4.40	4.39	
	Haney	4.37	4.37	4.37			4.38	4.38	4.38			4.37	4.37	4.37			4.41	4.41	4.41		
4.0 days	Coquitlam	4.36	4.36	4.37			4.37	4.37	4.38			4.36	4.36	4.37			4.40	4.40	4.41		
	Forest Hills	4.35	4.36	4.36			4.36	4.37	4.36			4.35	4.36	4.36			4.39	4.40	4.39		
6.0 days	Pr-George	4.89	5.10	5.10	5.10	5.10	4.90	5.11	5.11	5.11	5.11	4.89	5.10	5.10	5.10	5.10	4.93	5.14	5.14	5.14	5.14
	Pr-Rupert	5.41	5.48	5.48	5.61	5.61	5.41	5.49	5.49	5.62	5.62	5.41	5.48	5.48	5.61	5.61	5.44	5.52	5.52	5.65	5.65

FEASIBLE ROUTES: Repentigny to various Receivers

Premium Intermodal Service: 68 hours

	Elapsed Time (in DAYS):	1	2	3	4	5	1	2	3	4	5	1	2	3	4	5	1	2	3	4	5
5.0 days	Kelowna	3.82	3.73	3.73	3.73	3.73	3.83	3.73	3.73	3.74	3.74	3.83	3.73	3.73	3.73	3.73	3.86	3.76	3.76	3.77	3.77
	Kamloops	3.75	3.71	3.72	3.72	3.72	3.76	3.72	3.73	3.73	3.72	3.75	3.71	3.72	3.72	3.72	3.79	3.75	3.76	3.76	3.75
	Burnaby	3.43	3.43	3.43	3.44		3.44	3.44	3.44	3.45		3.43	3.44	3.44	3.44		3.47	3.47	3.47	3.48	
4.5 days	Surrey	3.45	3.46	3.47	3.45	3.45	3.46	3.47	3.48	3.46	3.46	3.45	3.46	3.47	3.45	3.45	3.49	3.50	3.51	3.49	3.49
	Richmond	3.43	3.43	3.44	3.43		3.44	3.44	3.45	3.44		3.43	3.43	3.45	3.44		3.47	3.47	3.48	3.47	
	Haney	3.46	3.45	3.45			3.46	3.46	3.46			3.46	3.46	3.46			3.49	3.49	3.49		
4.0 days	Coquitlam	3.44	3.45	3.45			3.45	3.45	3.46			3.45	3.45	3.45			3.48	3.48	3.49		
	Forest Hills	3.43	3.44	3.44			3.44	3.45	3.45			3.43	3.44	3.44			3.47	3.48	3.48		
6.0 days	Pr-George	3.97	4.18	4.19	4.18	4.18	3.98	4.19	4.19	4.19	4.19	3.97	4.18	4.19	4.19	4.19	4.01	4.22	4.22	4.22	4.22
	Pr-Rupert	4.49	4.57	4.57	4.69	4.69	4.50	4.57	4.57	4.70	4.70	4.49	4.57	4.57	4.69	4.69	4.53	4.60	4.60	4.73	4.73

Table 5.14: For Shipper at *REPENTIGNY*

The terminal to terminal routes of these IM trains are fixed, and could safely be assumed to be the shortest. In other words, an IM operator knows that if a ***R-IM*** on *South Route* can enable meeting demands on time, then there is very little motivation to use ***R-IM*** on *North Route*. The only motivation can stem from the fact when there is a less-than-train-load traffic for Edmonton and something else needs to be moved from Edmonton to Vancouver, these two factors together could justify traffic over the longer *North Route*. Of course only the shipments with enough buffer time would be consolidated with the Edmonton traffic and dispatched on *North Route*.

As far as the cost component goes, the IM operator will not quote two different costs for the ***R-IM*** on two routes. It is so because the shorter route will always be preferred by the shippers, and it will also be less expensive. Hence, irrespective of the routes, the IM operator (railroad) company will quote only two rates, one for *regular* and the other for *premium* service. We have already qualified that almost always there will be only one route, but in instances with multiple routes one would expect the quotes to be based on the longest route. Although the quotes will be based on the longest route, the option to ship traffic destined for areas in and around Vancouver (*Burnaby, Surrey, Richmond, Haney, Coquitlam* and *Forest Hills*) is no longer limited to only *premium service* on the *North Route.* Now the shippers have the option to use ***R-IM*** on the *South Route* and still make to the receiver by the specified "***time***". So moving 1036 containers (trailers) on ***R-IM*** on this route will cost \$ 2,646,980, which is \$ 516,600 lower when a combination of regular and premium service on *North Route* was being used to move the shipments.

The rail-haul cost savings, indicated above, is possible only when the cost structure and routes are transparent to each and every player in the system. This is never the case, and hence we should not read too much into the cost savings above.

Now what will be the impact on *population exposure*, given that this new route is being taken? From table 5.15 we know that none of the shipment needs to be connected to ***P-IM*** on this route. All the 538 hazardous containers will travel on ***R-IM***, and so would the 498 regular freight containers (trailers). Since the arrival of all the trains is assumed to be back-to-back in Vancouver, we can resort to a simple loading of traffic in the Lachine yard without worrying about any delay.

The 538 hazardous containers will be assigned to four hazmat unit trains, and the remaining 58 to what would be a mixed train. 480, of the 498 regular freight containers (trailers), would be allotted to 4 regular IM trains, and the remaining 18 to the mixed train. Each of the four HazMat train carries 120 hazardous containers, and carves a band of radius 7.33 miles thereby exposing 548 people. The mixed train has 58 hazardous containers and exposes 358 people. The population exposure on the *South Route* is 2,550 people, while 2,340 people were exposed on the *North Route*. It appears that the route through Calgary passes through denser population centers than the route through Edmonton.

Roughly speaking the IM operator (shippers) can save a combined total of $516,600 by taking this *South Route*, but now 210 more persons are being exposed.

We mentioned earlier that this train leaves two-hours later than the one taking the *North Route*. This translates into more time for inbound drayage, specifically the cut-off time for the shippers. Now the shippers have more time, and if the containers have been loaded, then the extra time could be used to route the loaded truck via a weighted minimum path rather than the conventional least costly one.

On the outbound drayage end, we noticed that *path1* to *Kelowna* was infeasible when used in conjunction with ***R-IM*** on the *North Route*. But if ***R-IM*** on the *South Route* is being used, this is a feasible path. Moreover this path has the least risk, and hence presents a good possibility of being followed if risk consideration outweighs cost concerns.

It is worth reiterating that specified-time or service level as demanded by the receivers dictates the paths and train service to be taken in order to adhere to the specifications. If the specified-time allows some flexibility, a longer but less risky route can be taken for drayage purposes.

In conclusion, the introduction of *South Route* between Montreal and Vancouver increases the number of options for the IM operator. Although it is shorter and hence takes less time to be traversed, it is riskier due to higher population density around the Calgary sector. This route eliminates the need to use ***P-IM*** on either of the two routes, since all demand can be fulfilled within the specified "***time***" using ***R-IM***. Perhaps a bigger advantage of this route is the additional time both inbound and outbound drayage has to travel to the IM yard and the receiver's site, respectively. This additional time opens up the option to take routes, which although a little longer are less risky. The shippers do not have any say in the routing of intermodal traffic as it is the domain of the yard-master, who makes a decision based on the *time* left and *volume* of traffic to be moved.

5.5 Mathematical Model: Development

This section develops a mathematical model for a rail-truck intermodal transportation system. A small case example will be used to develop a simple instance of the model called *Special Case#1*, which will then be extended into another variation called *Special Case#2*, before leading to a *General Case* Model. **Appendix-B**, under *Special Case#1* and *Special Case#2* in the ***Intermodal Model Development*** section, provides the other details used to set up the special cases of the model. *Special Case#1* is a simplified instance and involves a single pair of intermodal terminals and only one type of intermodal train service between them. *Special Case#2* has only one pair of intermodal terminals, just like case#1, but a number of different types of intermodal train services between these two terminals. The *General Case* will involve multiple intermodal terminal pairs, and a number of train services between each pair of terminals.

5.5.1 Special Case#1:

Figure 5.10 is intended to aid the development of a mathematical model for time-based rail-truck intermodal transportation system. There are two shippers and two receivers, wherein each of the former has to supply to each of the latter. There is only one IM train service between the two terminals. This service takes 80 hours to cover its journey.

The demand from each receiver consists of both *hazardous* cargo and *regular* freight, to be moved in intermodal units (IMUs). For our purposes, demand is expressed in terms of IMUs with hazardous cargo and IMUs with regular freight. Each of the two shippers specifies a delivery time of 4 days (96 hours), after placing an order on Monday @ 10:00 am.

Figure 5.10: Available Network for illustrative example

	Hazmat	Regular	Total
1 to A	2	5	7
1 to B	1	8	9
2 to A	1	8	9
2 to B	2	6	8

IM terminus -Shipper 1 - IM terminus			
	1	2	3
Time (hrs.)	2.08	2.28	2.12
Cost ($)	254	264	256
P.E. (people)	2959	2787	2557

IM terminus -Receiver A - IM terminus			
	1	2	3
Time (hrs.)	0.26	0.35	0.32
Cost ($)	33	38	36
P.E. (people)	447	528	499

IM terminus -Shipper 2 - IM terminus			
	1	2	3
Time (hrs.)	1.84	1.79	2.28
Cost ($)	242	240	264
P.E. (people)	2902	2609	1174

IM terminus -Receiver B - IM terminus			
	1	2	3
Time (hrs.)	0.7	0.96	1.2
Cost ($)	88	104	119
P.E. (people)	625	738	846

Table 5.15: Time, Cost and Risk for Drayage

There are three paths from each of the two shippers to the IM terminus and also three paths from the IM terminus (at the end of journey) to each of the two receivers (Table 5.15). The time to complete the inbound/ outbound drayage, cost and associated population exposure (risk) of each path are produced. The figures corresponding to unit weight on both objectives are produced below in Table 5.16.

Weighted Cost + Risk ($ + people)							
	1	2	3		1	2	3
Shipper 1	3213	3051	2813	Receiver A	480	566	535
Shipper 2	3144	2849	1438	Receiver B	713	842	965

Table 5.16: Drayage with unit weights

The two shippers receive the demand orders from the two receivers on Monday 10:00 am for delivery by Friday 10:00 am. The IM train, needed to meet the specified deadline, departs at 6:00 pm from the nearest terminus, and it takes a total of three hours /IMU (two hours at the shipper and one hour at the IM yard) to complete the loading and transfer operations at the two sites (Figure 5.11). Moreover, there is a cut-off time after which an IMU will not be able to make to this train. The cut-off time is Monday 5:00 pm and hence the *inbound drayage* must be completed by then to make to the Monday evening train.

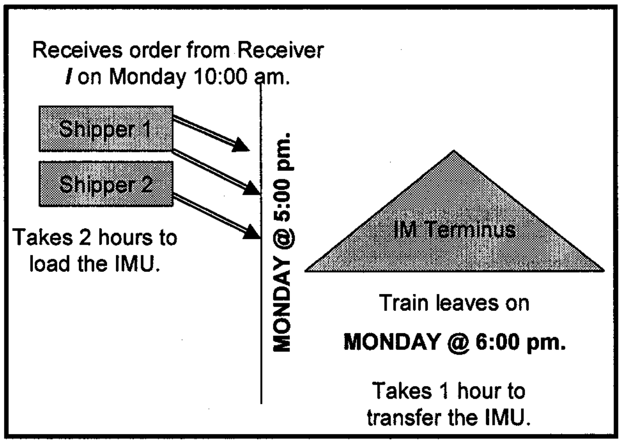


Figure 5.11: Inbound Drayage & Cut-Off Time

The IM train will arrive at its destination on Friday morning @ 2:00 am. It will take an hour to transfer the IMUs to the waiting trucks, and hence the *outbound drayage* can start at 3:00 am on Friday (Figure 5.12).

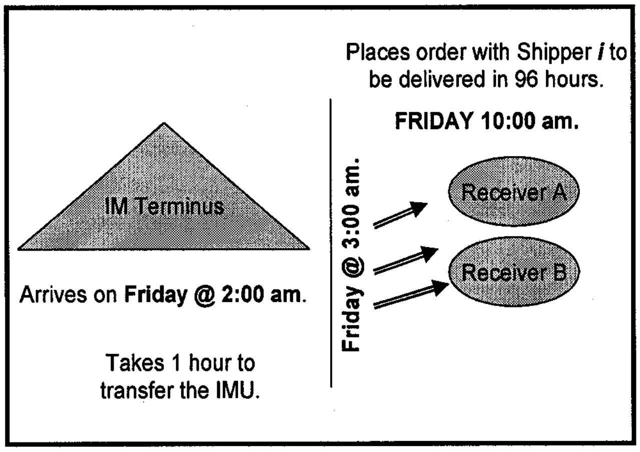


Figure 5.12: Earliest Outbound Drayage

It is convenient to visualize the entire intermodal chain as a series of just-in-time activities, which may never be delayed. After factoring in an hour each for loading and unloading the IMUs from the IM train, we will assume a total rail-haul time of 82 hours (80+1+1).

A mathematical model of the above system will involve the following.

<u>*Constraints:*</u>

- Two sets of *transshipment constraints* corresponding to the two IM terminals.
- *Demand constraints* at each receiver from each shipper.
- *Capacity constraint* for the IM train between the two IM terminals.
- *Lead-time constraints* to ensure that delivery takes place by the specified deadline. These constraints would evaluate, based on travel times, the feasibility of the three transport links of the intermodal chain viz. *inbound drayage–IM train–outbound drayage,* and keep the solution confined to the combinations of feasible transport links.
- *Forcing constraints* for indicator variables. These constraints will enable the above feasibility evaluation, and would be activated by the flow variables. If flow variable moves on path 1, then the indicator variable corresponding to path 1 will be activated to evaluate feasibility for the complete intermodal route, given that path 1 has been chosen.
- *Sign Restrictions* constraints.

Variables:

- Flow variables for hazmat IMUs and regular IMUs.
- Number of IM trains.
- Indicator variables for time-feasibility constraints. Are binary in form, and would be activated by the flow variables (both hazmat IMUs and regular IMUs).

Sets:

I: Set of shippers = {1, 2}.

L: Set of receivers = {A, B}.

P_1: Set of paths between shipper *1* and originating IM terminal = {1, 2, 3}.

P_2: Set of paths between shipper *2* and originating IM terminal = {1, 2, 3}.

Q_A: Set of paths between terminating IM terminal and receiver A = {a, b, c}.

Q_B: Set of paths between terminating IM terminal and receiver B = {a, b, c}.

IM : IM train service between the IM terminals = {1}.

Variables:

For Inbound Drayage:

$X(h)^p_{1A}$: number of hazmat IMUs demanded by receiver A from shipper 1 using paths = {1, 2, 3} for inbound drayage.

$X(nh)^p_{1A}$: number of regular IMUs demanded by receiver A from shipper 1 using paths = {1, 2, 3} for inbound drayage.

$X(h)^p_{1B}$: number of hazmat IMUs demanded by receiver B from shipper 1 using paths = {1, 2, 3} for inbound drayage.

$X(nh)^p_{1B}$: number of regular IMUs demanded by receiver B from shipper 1 using paths = {1, 2, 3} for inbound drayage.

➔ **12 variables.**

$X(h)^p_{2A}$: number of hazmat IMUs demanded by receiver A from shipper 2 using paths = {a, b, c} for inbound drayage.

$X(nh)^p_{2A}$: number of regular IMUs demanded by receiver A from shipper 2 using paths = {a, b, c} for inbound drayage.

$X(h)^p_{2B}$: number of hazmat IMUs demanded by receiver B from shipper 2 using paths = {a, b, c} for inbound drayage.

$X(nh)^p_{2B}$: number of regular IMUs demanded by receiver B from shipper 2 using paths = {a, b, c} for inbound drayage.

➔ **12 variables.**

For IM train service:

Since there is only one IM train service, hence all the IMUs from the two shippers to the two receivers will be loaded on this train to be moved to the terminating IM yard.

$X(h)_{1A}$: number of hazmat IMUs demanded by receiver *A* from shipper *1* using IM train service.

$X(nh)_{1A}$: number of regular IMUs demanded by receiver *A* from shipper *1* using IM train service.

$X(h)_{1B}$: number of hazmat IMUs demanded by receiver *B* from shipper *1* using IM train service.

$X(nh)_{1B}$: number of regular IMUs demanded by receiver *B* from shipper *1* using IM train service.

➔ **4 variables.**

$X(h)_{2A}$: number of hazmat IMUs demanded by receiver *A* from shipper *2* using IM train service.

$X(nh)_{2A}$: number of regular IMUs demanded by receiver *A* from shipper *2* using IM train service.

$X(h)_{2B}$: number of hazmat IMUs demanded by receiver *B* from shipper 2 using IM train service.

$X(nh)_{2B}$: number of regular IMUs demanded by receiver *B* from shipper *2* using IM train service.

➔ **4 variables.**

For Outbound Drayage:

$X(h)_{1A}^{q}$: number of hazmat IMUs demanded by receiver *A* from shipper *1* using paths = {a, b, c} for outbound drayage.

$X(nh)_{1A}^{q}$: number of regular IMUs demanded by receiver *A* from shipper *1* using paths = {a, b, c} for outbound drayage.

$X(h)_{1B}^{q}$: number of hazmat IMUs demanded by receiver *B* from shipper *1* using paths = {a, b, c} for outbound drayage.

$X(nh)^{q}_{1B}$: number of regular IMUs demanded by receiver *B* from shipper *1* using paths = {a, b, c} for outbound drayage.

➔ **12 variables.**

$X(h)^{q}_{2A}$: number of hazmat IMUs demanded by receiver *A* from shipper *2* using paths = {a, b, c} for outbound drayage.

$X(nh)^{q}_{2A}$: number of regular IMUs demanded by receiver *A* from shipper *2* using paths = {a, b, c} for outbound drayage.

$X(h)^{q}_{2B}$: number of hazmat IMUs demanded by receiver *B* from shipper *2* using paths = {a, b, c} for outbound drayage.

$X(nh)^{q}_{2B}$: number of regular IMUs demanded by receiver *B* from shipper *2* using paths = {a, b, c} for outbound drayage.

➔ **12 variables.**

Corresponding to each variable for inbound and outbound drayage, there will be an indicator variable. These variables will be activated depending on the paths taken by the hazardous and regular IMUs, and a complete path from shipper to receiver will be evaluated for lead-time feasibility.

CONSTRAINTS: Please refer to **Appendix B** under ***Special Case#1*** for the detailed constraint listing.

Transshipment Constraints:

First Set: The total number of hazmat or regular IMUs coming into the origin IM yard using the three specified paths, with unique *shipper-receiver-commodity type* identifier, is equal to the number of IMUs departing on the **only** IM train service *SL*. They would be represented as follows:

➔ $\sum_{p=1,2,3} X(h)^{p}_{il} = X(h)_{il} \quad \forall i = \{1,2\},\ l = \{1,2\}.$

➔ $\sum_{p=1,2,3} X(nh)^{p}_{il} = X(nh)_{il} \quad \forall i = \{1,2\},\ l = \{1,2\}.$

Second Set: The total number of hazmat or regular IMUs coming into the destination IM yard from origin yard using the **only** IM train service *SL*, with unique *shipper-receiver-commodity type* identifier, is equal to the number of IMUs leaving for receivers using the three specified paths. They would be represented as follows:

➔ $X(h)_{il} = \sum_{q=a,b,c} X(h)_{il}^{q} \quad \forall i = \{1,2\}, l = \{1,2\}$

➔ $X(nh)_{il} = \sum_{q=a,b,c} X(nh)_{il}^{q} \quad \forall i = \{1,2\}, l = \{1,2\}$

Demand Constraints: The demand (hazmat and non-hazmat) at each receiver is fulfilled using one and/or more paths available for outbound drayage. The demand for hazmat and non-hazmat cannot be combined since they have different moving cost(s). The hazmat movement will also result in societal cost in the form of population exposure, while the regular freight incurs only the dollar cost. If the two are combined to meet the total demand in the same constraint, this distinction is blurred, and the regular shipments may take the minimum risk route or the hazmat shipments may take the minimum cost route, and not the intentioned weighted cost-risk route. They would be represented as follows:

➔ $\sum_{q=a,b,c} X(h)_{il}^{q} = D(h)_{li} \quad \forall\, i = \{1,2\},\ l = \{1,2\}$

➔ $\sum_{q=a,b,c} X(nh)_{il}^{q} = D(nh)_{li} \quad \forall\, i = \{1,2\},\ l = \{1,2\}$

Capacity Constraint: There is only one train service between the two IM yards, and hence only one capacity constraint will be required, which is as follows:

➔ $\sum_{i} \sum_{l} [X(h)_{il} + X(nh)_{il}] \le U\ N \quad \forall\ IM$.

Lead-Time Constraints: The total intermodal journey has to be completed in 96 hours so as to be feasible. This implies that the sequence of activities forming an intermodal chain should be completed by the specified deadline. The three components of the chain are *inbound drayage*, *rail haul service*, and *outbound drayage*. Since there is only one rail haul service and each IMU container has to take this IM service, there is no need for indices for distinguishing IM train services.

This is one of the two sets of constraints using indicator (binary) variables. So depending on the paths chosen for inbound and outbound drayage, the two together will be evaluated with the train service time for feasible-routing possibilities. It also implies that only the feasible sequence of combinations will be chosen, irrespective of the cost or risk factors.

So we introduce Y variables corresponding to each inbound and outbound drayage paths, and the intermodal train service. Three Y variables will be used to build an intermodal chain, and all the possible chains have to be enumerated. The variables corresponding to inbound drayage will be defined as follows:

$$Y_{il}^{p} = \begin{cases} 1 \text{ if } X(h)_{il}^{p} > 0 \text{ OR } X(nh)_{il}^{p} > 0 \\ 0 \text{ otherwise} \end{cases}$$

There is no need to develop separate indicator variables for hazardous and regular IMUs, since a complete path and hence adhering to lead-time constraints is independent of the commodity type. In other words, travel time on an intermodal path (drayage or rail haul) is not influenced by the content of the intermodal units, and hence a common indicator variable could be used for the lead-time evaluation for the intermodal movement of both hazardous and regular IMUs.

There will be similar representations for the outbound drayage. There is only one type of intermodal train to which all the IMUs will be connected, and hence we need only one Y variable for train. The lead-time specified by the receivers is 96 hours. These constraints will be of the following form:

➔ $t(in)_{il}^{p} Y_{il}^{p} + t(IM)_{il} Y + t(out)_{il}^{q} Y_{il}^{q} \leq 96 \qquad \forall\, p, i, IM, l, q.$

<u>Forcing Constraints:</u> The ***Y*** variables in the feasible time constraints are indicator variables, activated by the flow variables ***X***. The activation of ***Y*** variables and consequent feasibility evaluation of an intermodal route stems

from the movement of IMU containers on paths for inbound and outbound drayage, and IM train service.

There will be 24 forcing constraints for *inbound drayage*, one corresponding to each of the 24 inbound drayage variables. These constraints will be of the form:

$$MY_{1A}^{1} \geq X(h)_{1A}^{1}$$

This says that if IMUs, destined for receiver *A* from shipper *1*, follow path *1* for inbound drayage then the associated indicator variable for path *1* will assume a value of *1*. '*M*' can be large number, in here it is 35 (total demand for the two receivers is 33).

These 24 constraints can be compactly represented as follows:

➔ $MY_{il}^{p} \geq X(h)_{il}^{p} \quad \forall\ p = \{1,2,3\}, i = \{1,2\},\ l = \{1,2\}.$

➔ $MY_{il}^{p} \geq X(nh)_{il}^{p} \quad \forall\ p = \{1,2,3\}, i = \{1,2\},\ l = \{1,2\}.$

There will be 24 forcing constraints for *outbound drayage*, one corresponding to each of the 24 outbound drayage variables. These constraints will be of the form:

$$MY_{1A}^{a} \geq X(h)_{1A}^{a}$$

This says that if IMUs, destined for receiver *A* from shipper *1*, follow path *a* for outbound drayage then the associated indicator variable for path a will assume *a* value of *1*. '*M*' is a large number, in here it is 35 (total demand for the two receivers is 33). These 24 constraints can be represented in compact form as follows:

➔ $MY_{il}^{q} \geq X(h)_{il}^{q} \quad \forall\ q = \{1,2,3\}, i = \{1,2\},\ l = \{1,2\}.$

➔ $MY_{il}^{q} \geq X(nh)_{il}^{q} \quad \forall\ q = \{1,2,3\}, i = \{1,2\},\ l = \{1,2\}.$

Since there is only one *IM train service*, which all IMUs are going to be connected to, the value of ***Y*** in the feasible-time constraints will be *1*. But if we had choices of train services then we can insert indices to the ***Y*** variable, as was done for inbound and outbound drayage.

Sign Restrictions: The ***X*** variables are non-negative integer variables, while the ***Y*** variables are binary indicator variables.

Objectives: It is a multi-criteria problem, with *risk* and *cost* as the two objectives. The demand fulfillment is driven by the element of time, and hence just minimizing the cost and/or risk may not be a feasible option. The compact expression for our instance is below. There is only one origin terminal (*J={1}*), only one destination terminal (*K={1}*), and only one IM train service ($IM = \{1\}$), which simplifies the illustrative problem.

Min

$$\sum_i \sum_p \sum_l \left[C(h)^p_{il} X(h)^p_{il} + C(nh)^p_{il} X(nh)^p_{il} \right] + \sum_i \sum_l \left[C(h)_{il} X(h)_{il} + C(nh)_{il} X(nh)_{il} \right] + \sum_i \sum_q \sum_l \left[C(h)^q_{il} X(h)^q_{il} + C(nh)^q_{il} X(nh)^q_{il} \right] + C(IM)N$$

$$\sum_i \sum_p \sum_l CE(h)^p_{il} X(h)^p_{il} + CE(h)_{il} \left(\sum_i \sum_l X(h)_{il} \right) + \sum_i \sum_q \sum_l CE(h)^q_{il} X(h)^q_{il}$$

Once again, just like in the Tactical Planning instance in Chapter 4, the *population exposure* risk stemming from the rail-transport of IMUs with hazardous cargo is due to multiple sources of release, and hence the aggregate concentration curves will be non-linear. Typically these two also imply absence of any closed form expression for risk, and the consequent inability to use a commercial solver.

But in here, there is only one train between the two terminals and hence we could solve the example using a commercial solver. One train implies that all the IMUs moving from the two shippers to the two receivers have to be loaded on this very train, and hence we know the exact number of IMU with hazardous cargo. Earlier this was precisely the reason for the absence of any closed form expression, but now since we know the exact number of IMUs with hazardous cargo, we can calculate the corresponding *population exposure* risk.

The above problem was solved (in LINDO) without the '*risk*' expression for IM train-loading, thereafter the exact amount of risk accruing from train movement of these hazardous IMUs was added to the answer to result in a weighted solution. This solution is optimum since we know that all IMUs are loaded on this very train, and hence adding the risk value consequent to the solution returned by a solver is not inappropriate.

LINDO solved several instances of the problem, a **base case** where both cost and risk have equal weight, and a *risk-cost* analysis, as detailed below. **Base Case** optimum solution had a weighted objective value of 109,267 (People+$), and used the following variables for inbound and outbound drayage.

Shipper 1 used the third path for hazardous IMUs and first path for regular IMUs for inbound drayage destined for both receivers. *Shipper 2* used the third path for hazardous IMUs and second path for regular IMUs for inbound drayage. There is a single intermodal train and all the IMUs are loaded on this train. Both the hazardous IMUs and regular IMUs (from both shippers) are taking path 1 for outbound drayage to *Receiver 1*, and this makes sense since path 1 is both the least risky and cheapest. The outbound drayage to *Receiver 2* from both the shippers and for both hazardous and regular freight takes the first path, since it is the safest and the cheapest.

The snapshot of the solution obtained by attaching different weights to the cost and risk objective in this special case is presented in Figure 5.13 and Table 5.17. **Base Case** has a unit weight attached to both objectives. ***"A"*** is derived by attaching unit weight to cost and zero to risk, while ***"B"*** has a 90% weight on cost and 10% on risk, and so on with ***"K"*** being the minimum risk solution. These objectives values were used to generate Figure 5.13 in and discuss incremental changes, if any. Only the variants to the base case will be presented here, while the solution details are provided in Appendix-B.

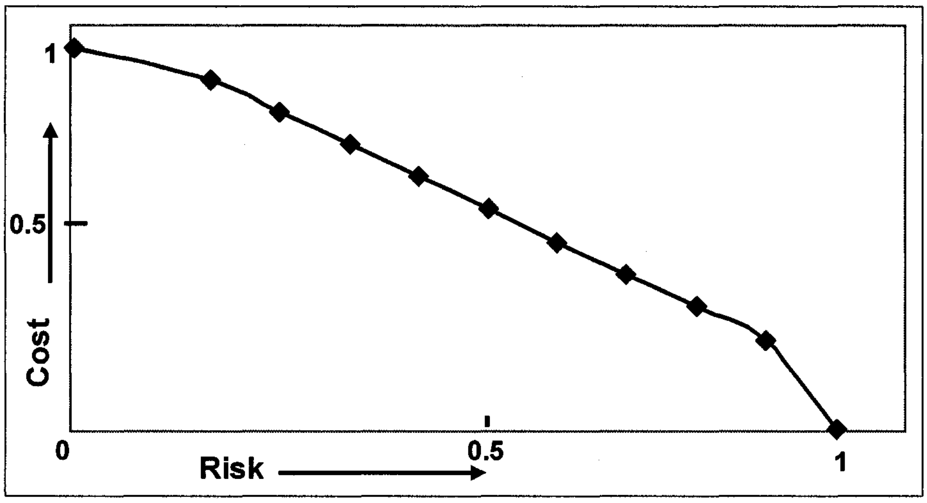


Figure 5.13: Risk-Cost Analysis for Special Case # 1

According to Table 5.17 the inbound drayage for hazardous IMUs from the first shipper does not vary from the **Base Case** under any weight combination except under the minimum cost instance (point K), when it expectedly moves to the cheapest routes. The same pattern is exhibited in the case of the second shipper as well. The regular IMUs as anticipated take the minimum cost routes.

The outbound drayage for hazardous IMUs is more interesting, since the paths taken under each of the eleven cases in figure 5.13 (from minimum risk to minimum cost) are the same (also same as the Base Case). Again this is not unexpected since path 1 to both the receivers is the cheapest and the least risky. However this is not the case for regular IMUs under a risk coefficient weight of 1. Since no weight is attached to cost, hence the costliest path is taken to Receiver A, and the second costliest path to the second receiver.

After considering the solutions, it is reasonable to conclude that the **Base Case** indeed presents a weighted perspective of both cost and risk, since it does not contain exactly the same variables as either the *minimum cost* or *minimum risk* solutions.

Please refer to **Appendix-B** (*Special Case#1*) for the pertinent decoding of the variables appearing in Table 5.17. It should be noted that while having only one intermodal train makes the problem solvable by a commercial package, it also makes it less interesting since we already know the train make-up plan. Moreover since the cost to move a single IMU on the train is the same, irrespective of the shipper, receiver or commodity type, and the total number of hazardous IMUs is the same, it makes no difference which variable corresponding to the rail-haul part enters the solution. Although in Table 5.17 different variables corresponding to the rail-haul part are of the optimal solution, but because of the above reason, any combination of these variables will yield the same weighted value for this part of the intermodal chain.

Weights	Base-Case		A		B		C		D		E		F		G		H		I		J		K	
Obj. Val.	109267		94583		86678		78649		70756		62640		54680		46697		38802		30632		22484		14694	
	Var.	Val.	Var.	Val.	Var.	Val.	Var.	Val.	Var.	Val.	Var.	Val.	Var.	Val.	Var.	Val.	Var.	Val.	Var.	Val.	Var.	Val.	Var.	Val.
Indicator Variables	Y1	1	Y1	1	Y1	1	Y1	1	Y1	1	Y1	1	Y1	1	Y3	1	Y1	1	Y3	1	Y1	1	Y2	1
	Y3	1	Y5	1	Y3	1	Y3	1	Y3	1	Y3	1	Y3	1	Y5	1	Y3	1	Y5	1	Y3	1	Y3	1
	Y4	1	Y11	1	Y5	1	Y5	1	Y4	1	Y4	1	Y4	1	Y6	1	Y4	1	Y6	1	Y4	1	Y4	1
	Y5	1	Y12	1	Y6	1	Y6	1	Y5	1	Y5	1	Y5	1	Y11	1	Y5	1	Y11	1	Y6	1	Y6	1
	Y6	1	Y13	1	Y11	1	Y11	1	Y6	1	Y6	1	Y6	1	Y12	1	Y6	1	Y12	1	Y11	1	Y11	1
	Y11	1	Y14	1	Y12	1	Y12	1	Y11	1	Y11	1	Y11	1	Y14	1	Y11	1	Y14	1	Y12	1	Y12	1
	Y12	1			Y14	1	Y14	1	Y12	1	Y12	1	Y12	1			Y12	1			Y14	1	Y14	1
	Y14	1							Y14	1	Y14	1	Y14	1			Y14	1					Y15	1
											Y16	1					Y15	1						
Inbound Drayage Variables	X3	2	X1	2	X3	2	X3	2	X3	2	X3	2	X3	2	X3	2	X3	2	X3	2	X3	2	X3	2
	X5	5	X5	5	X5	5	X5	5	X5	5	X5	5	X5	5	X7	5	X5	5	X7	5	X5	5	X6	5
	X11	1	X9	1	X11	1	X11	1	X11	1	X11	1	X11	1	X11	1	X11	1	X11	1	X11	1	X11	1
	X13	8	X13	8	X13	8	X13	8	X13	8	X13	8	X13	8	X15	8	X13	8	X15	8	X13	8	X15	8
	X19	1	X18	1	X19	1	X19	1	X19	1	X19	1	X19	1	X19	1	X19	1	X19	1	X19	1	X19	1
	X22	8	X22	8	X22	8	X22	8	X22	8	X22	8	X22	8	X22	8	X22	8	X22	8	X21	8	X23	8
	X27	2	X26	2	X27	2	X27	2	X27	2	X27	2	X27	2	X27	2	X27	2	X27	2	X27	2	X27	2
	X30	6	X30	6	X30	6	X30	6	X30	6	X30	6	X30	6	X30	6	X30	6	X30	6	X31	6	X31	6
IM Train Variables	X331	2	X331	2	X331	2	X33	2	X331	2	X331	2	X331	2	X331	2	X331	2	X331	2	X331	2	X331	2
	X34	5	X34	5	X34	5	X34	5	X34	5	X34	5	X34	5	X34	5	X34	5	X341	5	X342	5	X342	5
	X352	1	X352	1	X352	1	X352	1	X35	1	X352	1	X352	1	X352	1	X35	1	X35	1	X351	1	X352	1
	X362	8	X361	8	X362	8	X362	8	X36	8	X361	8	X361	8	X362	8	X36	8	X361	8	X36	8	X361	8
	X371	1	X371	1	X371	1	X372	1	X371	1	X371	1	X371	1	X371	1	X371	1	X371	1	X371	1	X37	1
	X381	8	X382	8	X382	8	X382	8	X382	8	X381	8	X381	8	X381	8	X381	8	X382	8	X381	8	X381	8
	X391	2	X391	2	X391	2	X391	2	X391	2	X391	2	X391	2	X391	2	X391	2	X391	2	X391	2	X391	2
	X401	6	X401	6	X401	6	X401	6	X401	6	X401	6	X401	6	X401	6	X401	6	X401	6	X401	6	X40	6
Outbound Drayage Variables	X41	2	X41	2	X41	2	X41	2	X41	2	X41	2	X41	2	X41	2	X41	2	X41	2	X41	2	X41	2
	X45	5	X45	5	X45	5	X45	5	X45	5	X45	5	X45	5	X45	5	X45	5	X45	5	X45	5	X46	5
	X49	1	X49	1	X49	1	X49	1	X49	1	X49	1	X49	1	X49	1	X49	1	X49	1	X49	1	X49	1
	X54	8	X54	8	X54	8	X54	8	X54	8	X54	8	X54	8	X54	8	X54	8	X54	8	X54	8	X55	8
	X59	1	X59	1	X59	1	X59	1	X59	1	X59	1	X59	1	X59	1	X59	1	X59	1	X59	1	X59	1
	X63	8	X63	8	X63	8	X63	8	X63	8	X63	8	X63	8	X63	8	X63	8	X63	8	X63	8	X64	8
	X67	2	X67	2	X67	2	X67	2	X67	2	X67	2	X67	2	X67	2	X68	2	X67	2	X67	2	X67	2
	X72	6	X72	6	X72	6	X72	6	X72	6	X72	6	X72	6	X72	6	X72	6	X72	6	X72	6	X73	6
	N	1	N	1	N	1	N	1	N	1	N	1	N	1	N	1	N	1	N	1	N	1	N	1
	Y	1	Y	1	Y	1	Y	1	Y	1	Y	1	Y	1	Y	1	Y	1	Y	1	Y	1	Y	1

Table 5.17: Weighted Objective Value for Special Case#1

Given the size of this example, it is not unusual to not see marked variance from the base case and between different weights. After all only three paths each for inbound and outbound drayage, and only one intermodal train service were available to each shipper. A larger example is conceivably limited by the length of an intermodal train, which leads us to the next special case.

5.5.2 Special Case #2:

In here although there is only **one** intermodal terminal in the vicinity of both the shipper and the receiver; but there are **more** than one types of train service between the two intermodal terminals. This was the setting for the small case example illustrated in **Appendix-B** under section ***Special Case #2***.

Such a network will have one origin terminal, one destination terminal, and different types of train services between these terminals. But now we will use an index, *'SL'*, to distinguish between the train services. So the variables corresponding to the rail-haul part will be subscripted as follows:

$X(h)_{il}^{SL}$: number of hazmat IMU tanks demanded by receiver *l* from shipper *i* using IM train service ***SL*** between the two intermodal terminals.

Now we have more than one intermodal train, differentiated by route and/or speed, between the two terminals. This implies that we would not know a priori the train make-up as in the first special case, and hence we will not have a closed form expression for the risk objective. The latter, just like the tactical model instance in chapter 4 and ***(IMM)*** above, rules out the usage of any commercial package to return a solution.

This model (other details in Appendix-B) is more complicated than the one derived for the first special case. We are inspired by the efficiency of the enumeration technique illustrated in the previous section of this chapter, and expect a local (neighbourhood) search based solution technique for this case. Clearly the general case model will be more complicated than this instance, and that is presented next.

5.5.3 General Case:

Figure 5.14 is a generic representation of a rail-truck intermodal network to aid the development of the general case model. There are a number of shippers and receivers, wherein each of the former has to supply to each of the latter. There are a number of IM train services in a network. Each of these IM train service has a scheduled departure and arrival times. There could be more than one type of IM train service between the same two terminals, and we will distinguish these services by an index denoted as *'SL'*. This index distinguishes IM train services based on speed, route, and stops, between the same pair of terminals.

Just like in the two special cases, demand from each receiver consists of both *hazardous* cargo and *regular* freight, to be moved in intermodal units (IMUs). For our purposes, demand is expressed in terms of IMUs with hazardous cargo and IMUs with regular freight. Each of the receivers specifies a delivery time after placing an order with the shipper. Each shipment has a number of possible paths for both inbound and outbound drayage. Each path has three attributes attached to it: dollar cost, exposure risk, and time needed.

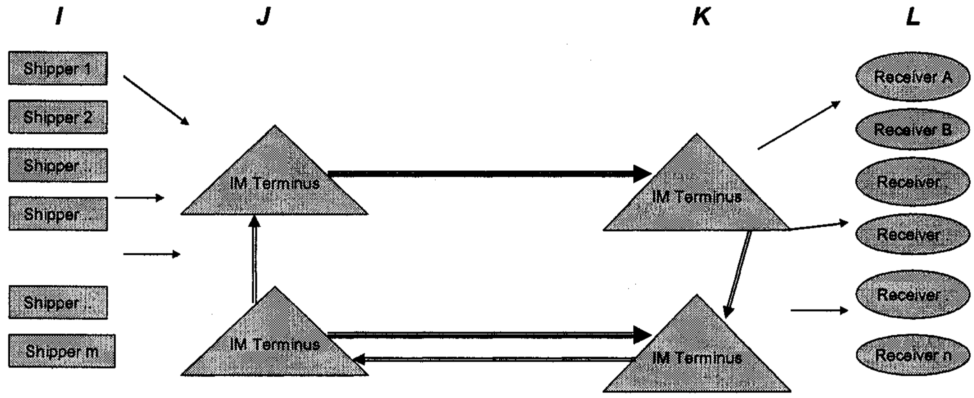


Figure 5.14: Intermodal Network

It is convenient to visualize the entire intermodal chain as a series of just-in-time activities, which may never be delayed. The total rail-haul time will constitute the travel time plus an hour each of loading and unloading at the two IM terminals. We develop the general case model next.

Mathematical Model:

Sets and Indices:

I : Set of shippers, indexed by i.

J : Set of originating IM terminus, indexed by j.

K : Set of terminating IM terminus, indexed by k.

L : Set of receivers, indexed by l.

P_{ij} : Set of paths between shipper i and originating terminus j, indexed by p.

Q_{kl} : Set of paths between terminating terminus k and receiver l, indexed by q.

IM_{jk}^{SL} : Set of IM train services belonging to different services classes between terminus j and terminus k.

Decision Variables:

$X(h)_{ijkl}^{p}$: number of hazmat IMUs demanded by receiver ***l*** from shipper ***i*** using path ***p*** of inbound drayage ***i-j***.

$X(nh)_{ijkl}^{p}$: number of regular IMUs demanded by receiver ***l*** from shipper ***i*** using path ***p*** of inbound drayage ***i-j***.

$X(h)_{ijkl}^{SL}$: number of hazmat IMU tanks demanded by receiver ***l*** from shipper ***i*** using IM train ***SL*** between ***j-k***.

$X(nh)_{ijkl}^{SL}$: number of regular IMU tanks demanded by receiver ***l*** from shipper ***i*** using IM train ***SL*** between ***j-k***.

$X(h)_{ijkl}^{q}$: number of hazmat IMUs demanded by receiver ***l*** from shipper ***i*** using path ***q*** of outbound drayage ***k-l***.

$X(nh)_{ijkl}^{q}$: number of hazmat IMUs demanded by receiver ***l*** from shipper ***i*** using path ***q*** of outbound drayage ***k-l***.

N_{jk}^{SL} : number of IM train service ***SL*** needed between ***j-k***.

Inbound Drayage

$$Y_{ijkl}^{p} = \begin{cases} 1, \text{if } X(h)_{ijkl}^{p} > 0 \text{ OR } X(nh)_{ijkl}^{p} > 0 \\ 0 \text{ otherwise} \end{cases}$$

IM train service

$$Y_{ijkl}^{SL} = \begin{cases} 1, \text{if } X(h)_{ijkl}^{SL} > 0 \text{ OR } X(nh)_{ijkl}^{SL} > 0 \\ 0 \text{ otherwise} \end{cases}$$

Outbound Drayage

$$Y_{ijkl}^{q} = \begin{cases} 1, \text{if } X(h)_{ijkl}^{q} > 0 \text{ OR } X(nh)_{ijkl}^{q} > 0 \\ 0 \text{ otherwise} \end{cases}$$

Parameters:

$C(h/nh)^{p}_{ijkl}$: Cost of moving one IMU on inbound drayage ***i-j*** using path ***p***.

$C(h/nh)^{SL}_{ijkl}$: Cost of moving one IMU on IM train service ***SL*** between ***j-k***.

$C(h/nh)^{q}_{ijkl}$: Cost of moving one IMU on outbound drayage ***k-l*** using path ***q***.

$CE(h)^{p}_{ijkl}$: Population Exposure due to moving one hazmat IMU on inbound drayage ***i-j*** using path ***p***.

$CE(h)^{SL}_{ijkl}$: Population Exposure due to moving one hazmat IMU on IM train service ***SL*** between ***j-k***.

$CE(h)^{q}_{ijkl}$: Population Exposure due to moving one hazmat IMU on outbound drayage ***k-l*** using path ***q***.

$t(in)^{p}_{ijkl}$: Time to complete inbound drayage ***i-j*** using path ***p***.

$t(IM)^{SL}_{ijkl}$: Time to complete IM rail-haul ***SL*** between ***j-k*** (plus 2 hours of loading & unloading).

$t(out)^{q}_{ijkl}$: Time to complete outbound drayage ***k-l*** using path ***q***, after transfer.

$T(l)_i$: Time specified by receiver ***l*** to shipper ***i***.

$D(h)_{l_i}$: # of IMU with hazmat cargo demanded by receiver ***l*** from shipper ***i***.

$D(nh)_{l_i}$: # of IMU with regular freight demanded by receiver ***l*** from shipper ***i***.

$C(IM)^{SL}_{jk}$: Fixed cost of operating IM train service ***SL*** between ***j-k***.

(IMM)

Min

$$\sum_{i}\sum_{p}\sum_{j}\sum_{k}\sum_{l}\left[C(h)^{p}_{ijkl}X(h)^{p}_{ijkl}+C(nh)^{p}_{ijkl}X(nh)^{p}_{ijkl}\right]$$
$$+\sum_{i}\sum_{j}\sum_{SL}\sum_{k}\sum_{l}\left[C(h)^{SL}_{ijkl}X(h)^{SL}_{ijkl}+C(nh)^{SL}_{ijkl}X(nh)^{SL}_{ijkl}\right]$$
$$+\sum_{i}\sum_{q}\sum_{j}\sum_{k}\sum_{l}\left[C(h)^{q}_{ijkl}X(h)^{q}_{ijkl}+C(nh)^{q}_{ijkl}X(nh)^{q}_{ijkl}\right] \qquad \text{(a)}$$
$$+\sum_{SL}\sum_{j}\sum_{k}C(IM)^{SL}_{jk}N^{SL}_{jk}$$

$$\sum_{i}\sum_{p}\sum_{j}\sum_{k}\sum_{l}CE(h)^{p}_{ijkl}X(h)^{p}_{ijkl}$$
$$+\sum_{j}\sum_{k}\sum_{SL}CE(h)^{SL}_{ijkl}\left(\sum_{i}\sum_{l}X(h)^{SL}_{ijkl}\right) \qquad \text{(b)}$$
$$+\sum_{i}\sum_{j}\sum_{k}\sum_{q}\sum_{l}CE(h)^{q}_{ijkl}X(h)^{q}_{ijkl}$$

(5.1)

Subject to:

$$\sum_{p}X(h)^{p}_{ijkl}=\sum_{k}\sum_{SL}X(h)^{SL}_{ijkl} \qquad \forall i,j,l \qquad \text{(a)}$$

$$\sum_{p}X(nh)^{p}_{ijkl}=\sum_{k}\sum_{SL}X(nh)^{SL}_{ijkl} \qquad \forall i,j,l \qquad \text{(b)}$$

$$\sum_{j}\sum_{SL}X(h)^{SL}_{ijkl}=\sum_{q}X(h)^{q}_{ijkl} \qquad \forall i,k,l \qquad \text{(c)}$$

$$\sum_{j}\sum_{SL}X(nh)^{SL}_{ijkl}=\sum_{q}X(nh)^{q}_{ijkl} \qquad \forall i,k,l \qquad \text{(d)}$$

Transshipment Constraints (5.2)

$$\sum_j \sum_k \sum_q X(h)^q_{ijkl} = D(h)_{l_i} \qquad \forall i,l$$

$$\sum_j \sum_k \sum_q X(h)^q_{ijkl} = D(nh)_{l_i} \qquad \forall i,l$$

Demand Constraints (5.3)

$$\sum_i \sum_l \left(X(h)^{SL}_{ijkl} + X(nh)^{SL}_{ijkl} \right) \le U_{SL} N^{SL}_{jk} \qquad \forall IM^{SL}_{jk}, j, k$$

Capacity Constraints (5.4)

$$t(in)^p_{ijkl} Y^p_{ijkl} + t(IM)^{SL}_{ijkl} Y^{SL}_{ijkl} + t(out)^q_{ijkl} Y^q_{ijkl} \le T(l)_i \qquad \forall p, i, IM^{SL}_{ijkl}, l, q \qquad (5.5)$$

$$MY^p_{ijkl} \ge X(h)^p_{ijkl} \qquad \forall p,i,l. \qquad \text{(a)}$$

$$MY^p_{ijkl} \ge X(nh)^p_{ijkl} \qquad \forall p,i,l. \qquad \text{(b)}$$

$$MY^{SL}_{ijkl} \ge X(h)^{SL}_{ijkl} \qquad \forall IM^{SL}_{jk},i,l. \qquad \text{(c)}$$

$$MY^{SL}_{ijkl} \ge X(nh)^{SL}_{ijkl} \qquad \forall IM^{SL}_{jk},i,l. \qquad \text{(d)}$$

$$MY^q_{ijkl} \ge X(h)^q_{ijkl} \qquad \forall q,i,l. \qquad \text{(e)}$$

$$MY^q_{ijkl} \ge X(nh)^q_{ijkl} \qquad \forall q,i,l. \qquad \text{(f)}$$

Forcing Constraints (5.6)

$$X \ge 0 \quad \text{INTEGER} \qquad \textbf{(5.7)}$$

$$Y = \{0,1\}. \qquad (5.8)$$

(IMM), a general case model, is intended to capture the time-based movement of rail-truck intermodal traffic, wherein both regular and hazardous cargo is involved. It is a bi-objective model with dollar *cost* and population exposure *risk* as the two objectives.

Objectives:

Cost Objective: consists of four components, one for inbound drayage, one for outbound drayage, one for IM train service, and one for the number of IM trains of different types required in the network.

First component calculates the cost of all the shipments from different shippers using all of the available paths and destined for different receivers via the origin and terminating IM terminals in the network.

Second component calculates the cost of moving, all IMUs coming from different shippers and destined for different receivers, to the origin IM terminals to be moved to the terminating IM terminals in the network.

Third component calculates the cost of outbound drayage, as first one does for inbound drayage.

The cost of providing a specific type of IM train service has a fixed cost, and this is accounted for by the final cost component.

Risk Objective: will stem only from the movement of IMUs with hazardous cargo on inbound drayage, rail haul, and outbound drayage.

Population Exposure due to the transportation of IMUs, from different shippers using all the available paths, and destined for different receivers, going through the different origin and terminating terminals in the network.

This second component intends to capture population exposure from the movement of IMUs, from different shippers and for various receivers, with hazardous cargo on a particular IM train service and all such movements in the network. This lacks a closed form expression thereby ruling out the usage of commercial solver for IMM, and underlining the need to develop a solution methodology for IMM.

The third component is the risk expression from the outbound drayage activity, just as the first was for inbound drayage.

Transshipment Constraints: will be for the two terminals. Since we intend to maintain the distinction between hazardous and regular IMUs, we will have four sets of transshipment constraints.

(a) tells us that the total number of hazmat IMUs coming into the origin terminal from different paths from a shipper destined for a receiver is equal to the total number of hazmat IMUs leaving the origin terminal on different IM train services destined for terminating yards.

(b) implies the same as above, but for regular IMUs.

(c) says that the total number of hazmat IMUs coming from a shipper via different origin yards and on different train services, is equal to that leaving from different paths to a receiver.

(d) implies the same as (c), but only for regular IMUs.

Demand Constraints: for each shipper and receiver should be written both in terms of hazmat and regular IMUs.

(a) says that the number of hazmat IMUs (from a shipper) coming from different paths and from different terminating intermodal yards, to a receiver is equal to what was demanded by the receiver from a shipper.

(b) implies the same as (a), but for non-hazardous cargo.

Capacity Constraints: It says that the number of IM train service of a specific type between two terminals will be decided by the total number of IMUs (hazardous & regular) to be moved between these terminals.

Lead-Time Constraints: These constraints will evaluate the time-based feasibility of a particular intermodal routing combination involving *inbound drayage-IM train service–outbound drayage.*

It says that the time taken by (hazmat or regular) IMUs to travel an intermodal chain comprising of inbound drayage, IM train service, and outbound drayage should be within the time specified by a receiver to a shipper.

Forcing Constraints: The feasible-time constraints contain indicator variables, which have to be activated for feasibility evaluation. This activation will be done by the flow variables under this block of constraints.

(a) says that if hazmat IMUs, from a shipper to a receiver, take a specific path on inbound drayage, then the indicator variable associated with that path will be forced to take on a value 1. This will in turn lead to the evaluation of feasible-time constraints.

(b) does the same thing as (a), but for regular IMUs.

(c) implies that the hazmat IMUs, demanded by a receiver from a shipper, traveling on a particular IM train service will force the evaluation of this service with the inbound and outbound drayage activities.

(d) says the same as (c), but for regular IMUs.

(e) and (f) say for outbound drayage, what (a) and (b) said for inbound drayage.

Sign Restrictions: The flow variables are non-negative, while the indicator variables are binary.

How Different from Tactical Planning Model?

While the Tactical Planning project had its own intricacies and complications, ***(IMM)*** is not straightforward as well. This complexity is not unexpected since we are targeting to capture a number of facets such as element of time, trucking operations, and intermodal train service; and their operational (tactical) attributes like routing, loading, assignment, etc.

The solution methodology we developed for the Tactical Planning model was decomposition followed by *Memetic Algorithm*. For that purpose, we were able to combine genetic algorithm (*GA*) with a local search since the number of variables far outnumbered the number of constraints. Moreover, our encoding scheme enabled us to not worry about the demand constraints, and be concerned only about the capacity constraints.

A *GA* based solution methodology may not be appropriate for ***(IMM)***, given its structure. Even the small illustrative example (Appendix-B) has 57 decision variables (excluding indicator variables) and 146 constraints (excluding the sign restrictions). *GA* is not suitable when constraints far outnumber variables as is the case with ***(IMM)***, and hence we need to develop a search technique more appropriate for ***(IMM)***.

The effectiveness of intelligent enumeration, used to solve 100 supply-demand pairs problem, has impressed and inspired us. We need to develop a solution methodology for (IMM) based on some form of local/neighborhood search.

5.6 Conclusion

This chapter starts with a conceptual explanation of attributes relevant to a new form of transportation viz. intermodal transportation, which involves combination of more than one mode. This chapter was motivated by the desire to combine the advantages of rail and truck transportation into producing something better than the sum of two individual modes. The ever increasing popularity of intermodal transportation coupled with its revenue contribution makes it an extremely important segment for the railroad industry. We made use of intelligent enumeration to solve a 100 supply-demand pair problem, and demonstrated societal risk reduction given flexibility in specified-time. We drew upon our previous work and illustrated another way to reduce societal risk i.e. by sending hazmat unit-trains between Montreal and Vancouver. Finally, we made use of an illustrative example to develop a mathematical model for the special case of rail-truck intermodal transportation, wherein there is only one set of intermodal terminals and train service between these terminals. This mathematical model is then extended for general case instances of "***time***" driven rail-truck intermodal transportation of hazardous cargo and regular freight. While noting the differences between this mathematical model and the Tactical Planning Model in Chapter 4, we suggest a neighborhood based heuristic search technique would be more appropriate than a population based search. Although this chapter developed a strategic framework for routing intermodal shipments, it also provided answers to tactical questions about equipment and resource requirements along the intermodal transport chain.

In closing of Chapter 4 we noted that a hazmat railcar is subject to the conventional destination-based blocking phenomenon just like any other railcar, and this phenomenon does not decrease the risk of release since each of these railcars is brought down a hump and grouped with other railcars bound for the common handling points. Although it is true that loading/unloading of ISO tanks at the intermodal yards do increase the risk of release, but which of the two operations (loading/unloading or destination-based blocking) entail a lesser chance of release is the real question and one that requires further investigation. It has been established that from a cost perspective rail-truck intermodal transportation becomes more competitive than trucks for distances over 550 miles. Although a comparable threshold distance from (both *cost* and) *risk* perspective has not been identified, we anticipate that rail-truck intermodal transportation will become competitive for distances over 1000 miles thanks to the *economies of risk* associated with the rail-haul, and the benefits accruing from it will outweigh the incremental risk due to loading/unloading at the yards.

The contribution of this chapter is ***fourfold***. *First*, it studies rail-truck intermodal transportation of hazardous and regular freight, the first of its kind. *Second*, a relatively large realistic case example is built and presented for evaluation, consequent analysis, and possible future work. *Third*, a '*risk-cost*' tradeoff driven by the element of ***"time"*** as service level is presented. *Finally* a bi-objective mathematical model, with risk and cost objectives, intended to capture time-driven rail-truck intermodal movement of hazardous and non-hazardous cargo is presented. The final section also contains two special cases of the general case intermodal transportation model.

There are a number of future directions of research. For us, the work in the immediate future is to develop a solution methodology for ***(IMM)***. One possible extension could be incorporation of accident rate probabilities, and not population exposure, in the computation of risk. Identifying the dominance of intermodal transportation over rail and/or trucks from a risk-cost perspective is another immediate research area for us. Investigating the prevalent assignment of IMUs to flat railcars and make-up of intermodal train service when hazardous cargo is involved, could be an interesting topic to provide further insights and hopefully identify alternative IM train make-up plan. Most importantly now we have a strategic framework which can be tailored to evaluate other forms of intermodal transportation system.

CHAPTER 6

Conclusion and Future Research

The 70,000 daily shipments in Canada and 800,000 in the U.S.A. are testament to the integrality of hazardous materials to industrialized societies. Out of these roughly 94% in United States and 92% in Canada, are carried by trucks and trains, thereby rendering these two modes as the biggest sources of hazmat transportation risk. Decisions involving hazardous materials are extremely difficult due to the potential for spectacular accidents, public sensitivity, and the presence of multiple stakeholders driven primarily by the perception of risk.

My *Doctoral Thesis* addressed two sources of transportation risk and the interests of two stakeholders, notably regulatory agencies and transport companies. The risk assessment methodology ensured conservative estimation of risk, which in turn can facilitate adequate emergency response planning. It answered the following three research questions:

The **first** question: *"Development of a risk assessment methodology for train transportation of hazardous materials, one that captured the distinct features of railroad operations."*

The **second** question: *"Given the risk assessment methodology developed earlier and a realistic railroad operation, conceptualization and development of an optimization model and a Memetic Algorithm based solution methodology to facilitate railroad transportation of both hazardous and non-hazardous materials."*

The **third** question: *"Combined the advantages of rail and truck to move both dangerous goods and regular shipments. Proposed a series of mathematical models to enable rail-truck intermodal routing?"* The in-progress solution methodology for the general case will also enable us answer the comparative performance of uni-modes like trucks and rails, and rail-truck intermodal movements.

Chapter 2 presented a detailed literature review of relevant works on hazardous materials logistics, particularly risk accruing from hazardous facilities and from transporting hazardous cargo. The obnoxious facility mimics the risk posed by handling of hazardous cargo at rail yards, intermodal terminals and other transfer stations. Speed, accessibility and volume flexibility are some of the benefits of truck transportation, which in turn explains the intense research activity in this area over the past two decades. Railroads, despite moving comparable hazmat volume, have very few (published) works, and almost all of them approach risk assessment from an accident rate perspective. There was no work that established any relationship between volume (type) of hazmat released and the resulting consequence. The last two points motivated me to contribute in this area, and also laid the foundation for my doctoral work.

In *Chapter 3*, *population exposure* was used as a measure of risk. This enabled us to tide over the limitations associated with accident rate analysis, and also facilitated conservative risk assessment which is very important for planning emergency response systems. An assessment measure, based on air-dispersion modeling, was developed to capture concentrate level from multiple sources such as train, wherein the aggregate concentrate level is a function of hazmat volume. In addressing the multiple release-source nature of train accidents, the use of *hazmat-median* as the reference point of the train is proposed, which also provides a good basis for approximating threshold distances for different consequences. An approximation method that is robust to both the design of train and atmospheric stability category is presented. A number of insights into the nature of railroad transport risk, and a conflict among the people living nearby railroad tracks and those not in the immediate vicinity, are presented. The methodology and *GIS ArcView* environment was used to assess the transport risk posed by the daily Ultra-train between Quebec City and Montreal.

A paper based on this chapter is a standalone contribution entitled "Railroad Transportation of Dangerous Goods: Population Exposure to Airborne Toxins" by *Manish Verma* and *Vedat Verter*, August 2003, August 2004 (Accepted December 2004), and is forthcoming in ***Computers and Operations Research***.

Verter and Erkut (1997) have suggested insurance as a proxy to measure risk, and demonstrated its applicability in context of highway transportation. Given the practice of reinsurance in the railroad industry, the significance of insurance as a measure of risk is undermined in railroad transportation. Reinsurance motivates a railroad company to under declare risk posed by hazmat shipments, which in turn skews the premiums thereby inhibiting correct quantification of risk. We acknowledge that this is an interesting approach to tackle risk and a subject of definite future research, and one wherein we will aim to deliver more positive results than has been the case to date.

Evidently population exposure risk assumes that the general populace is risk-neutral, which is never the case. It would be interesting to breakdown an exposed population center into risk-neutral and risk-averse components, whereby an individual's attitude can be captured. This is a rather challenging proposition, one that requires evaluating individual risk profiles of the entire populace, and perhaps is equivalent to the work of Barberis and Thaler (2003) in the context of behavioral finance, wherein they tackle ambiguity aversion from investor psychology perspective. However it is an extremely interesting research area and one that will require learning more about the state of behavioral research in the domain of risk, and a possible area of investigation in the future.

Chapter 4 incorporated the risk assessment methodology from chapter three and the intricacies of railroad freight operations to develop an optimization model with *risk* and *cost* objectives. This bi-objective tactical planning model was used to determine the routes of mixed traffic, yard activities (classification, blocking, transfer), and the frequency of different train types. This model was distinct, from the classical ones, in that its form was motivated by and enabled us to capture *economies of risk*. A *Memetic Algorithm* based solution methodology was developed for the tactical planning model, as the absence of a closed form expression for the objective function ruled out the usage of any commercial solvers. A number of scenarios were presented to discuss algorithmic efficiency and gain numerical insights into the problem.

This piece of work has a ***four-fold*** contribution: ***first***, this is the only work that uses population exposure as a measure of risk and captures release effect from multiple sources as in a train; ***second***, this is the first risk-cost model for railroad transportation of mixed freight; ***third***, only work that constructs a *Quasi-Pareto* frontier on which every point contains a set of solution for the underlying railroad transportation problem; and ***fourth***, the only work that compares risk stemming from the railroad transportation of propane and chlorine.

There are a number of future research directions coming out of this chapter. *First*, extend the bi-criteria model to a tri-criteria model, wherein the accident rate probabilities could be the third criterion. *Second*, relax the no interaction assumption and develop a form or an expression that captures interaction among the hazmats being transported. *Third*, investigate whether an alternate blocking technique that dominates the prevalent destination based blocking is feasible. *Fourth*, development of a Decision Support System (*DSS*) that could be used by the regulators and transport companies to plan, monitor, and manage hazardous shipments.

Chapter 5 was motivated by the desire to combine the advantages of two transportation modes, viz., trucks and trains, and also to gain an insight into the safety of each of these modes. Intermodal transportation system was introduced, and its importance in context of railroad industry was pointed out. Intelligent enumeration was used to solve a 100 supply-demand pair problem, wherein risk reduction was demonstrated if there is flexibility in specified delivery time. Unit train formation as another way to reduce societal risk was demonstrated. Two special cases and a general case mathematical model for the ***"time"*** driven rail-truck intermodal transportation of mixed freight were presented. A number of scenarios related to the first special case are presented. The structure of general case model (also special case#2) and the efficacy of intelligent enumeration suggest that a neighborhood-based heuristic search technique may be appropriate for this model.

This chapter has a four-fold contribution: ***first***, this is the only study of rail-truck intermodal transportation of hazardous and regular freight; ***second***, the first relatively large realistic case example is built and presented for evaluation and consequent analysis; ***third***, only work wherein a risk-cost tradeoff curve driven by the element of "time" as the proxy for service-level is presented; and ***fourth***, only work to present a multi criteria mathematical model intended to model *time*-driven rail-truck intermodal movement of mixed freight.

There are a number of possible research avenues coming out of this chapter. Our ongoing work is focused on the development of a solution methodology for ***(IMM)***, and model refinements if necessary. *Second*, the incorporation of accident rate probabilities, and not population exposure, in the computation of risk, and compare how different the results are to ***(IMM)***. *Third*, investigate the position of rail-truck intermodalism from a risk-cost perspective vis-à-vis uni-modes like truck and trains. *Fourth*, explore whether any other Intermodal train make-up plan is better than the existing plan when hazardous goods are involved. *Fifth* and perhaps the most important, extend the (modified) strategic framework to evaluate other forms of intermodalism.

x------x------x

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APPENDICES

Appendix A: Chapter 4

4-A.1: *Base Case Solution*

What follows is the decoded detail of each itinerary in the base case solution. They have been explained in the order in which they appear in the solution.

Sarnia:

SL1: Classification / Blocking @ Sarnia → Take-List of train N(96) → Transfer @ Toronto to train N(82) until London.

ST1: Classification / Blocking @ Sarnia → Take-List of train N(96) to Toronto.

SK1: Classification / Blocking @ Sarnia → Take-List of train N(96) → Transfer @ Toronto to train N(90) to Kingston.

SO1: Classification / Blocking @ Sarnia → Take-List of train N(96) → Transfer @ Toronto to train N(80) to Ottawa.

SM1: Classification / Blocking @ Sarnia → Take-List of train N(96) → Transfer @ Toronto to train N(90) to Montreal.

STR1: Classification / Blocking @ Sarnia → Take-List of train N(96) → Transfer @ Toronto to train N(80) to Trois-Rivieres.

SSH1: Classification / Blocking @ Sarnia → Take train N(96) to Sherbrooke.

SQC1: Classification / Blocking @ Sarnia → Take train N(96) to Quebec City.

London:

LS1: Classification / Blocking @ London → Take-List of train N(80) → Transfer @ Ottawa to train N(62) and travel to Sarnia.

LT1: Classification / Blocking @ London → Take-List of train N(80) to Toronto.

LK1: Classification / Blocking @ London → Take-List of train N(80) → Transfer @ Toronto to train N(90) and travel to Kingston.

LO1: Classification / Blocking @ London → Take-List of train N(80) to Ottawa.

LC1: Classification / Blocking @ London → Take-List of train N(80) → Transfer @ Toronto to train N(90) and travel to Cornwall.

LM1: Classification / Blocking @ London → Take-List of train N(80) → Transfer @ Toronto to train N(90) and travel to Montreal.

LTR1: Classification / Blocking @ London → Take-List of train N(80) to Trois-Rivieres.

LSH1: Classification / Blocking @ London → Take-List of train N(80) → Transfer @ Toronto to train N(96) and travel to Sherbrooke.

LQC1: Classification / Blocking @ London → Take-List of train N(80) → Transfer @ Toronto to train N(96) and travel to Quebec City.

Trois-Rivieres:

TRS2: Classification / Blocking @ Trois-Rivieres → Take-List of train N(82) → Transfer @ Ottawa to train N(62) and travel to Sarnia.

TRL1: Classification / Blocking @ Trois-Rivieres → Take-List of train N(82) to London.

TRT1: Classification / Blocking @ Trois-Rivieres → Take-List of train N(82) to Toronto.

TRK1: Classification / Blocking @ Trois-Rivieres → Take-List of train N(82) → Transfer @ Toronto to train N(90) and travel to Kingston.

TRO1: Classification / Blocking @ Trois-Rivieres → Take-List of train N(82) to Ottawa.

TRC1: Classification / Blocking @ Trois-Rivieres → Take-List of train N(82) → Transfer @ Sherbrooke to train N(62) →Classification / Blocking @ Montreal → Take-List of train N(72).

TRM1: Classification / Blocking @ Trois-Rivieres → Take-List of train N(82) → Transfer @ Sherbrooke to train N(62) and travel to Montreal.

TRSH1: Classification / Blocking @ Trois-Rivieres → Take-List of train N(82) to Sherbrooke.

TRQC1: Classification / Blocking @ Trois-Rivieres → Take-List of train N(82) → Transfer @ Toronto to train N(96) and travel to Quebec City.

<u>*Quebec City:*</u>

QCS1: Classification / Blocking @ Quebec City → Take-List of train N(62) to Sarnia.

QCL1: Classification / Blocking @ Quebec City → Take-List of train N(62) → Transfer @ Sherbrooke → train N(82) to London.

QCT1: Classification / Blocking @ Quebec City → Take-List of train N(62) → Transfer @ Sherbrooke → train N(82) to Toronto.

QCK1: Classification / Blocking @ Quebec City → Take-List of train N(62) → Transfer @ Montreal → train N(72) to Kingston.

QCO1: Classification / Blocking @ Quebec City → Take-List of train N(62) to Ottawa.

QCC1: Classification / Blocking @ Quebec City → Take-List of train N(62) → Transfer @ Montreal → train N(72) to Cornwall.

QCM1: Classification / Blocking @ Quebec City → Take-List of train N(62) to Montreal.

QCTR1: Classification / Blocking @ Quebec City → Take-List of train N(62) → Transfer @ Ottawa → train N(80) to Trois-Rivieres.

QCSH1: Classification / Blocking @ Quebec City → Take-List of train N(62) to Sherbrooke.

<u>*Cornwall:*</u>

CS1: Pick-up @ Cornwall by train N(90) → Classification / Blocking @ Montreal & connected to train N(62) to Sarnia.

CL2: Pick-up @ Cornwall by train N(72) → Transfer @ Toronto & connected to train N(82) to London.

CT1: Pick-up @ Cornwall by train N(72) and delivered to Toronto.

CK1: Pick-up @ Cornwall by train N(72) and delivered to Kingston.

CO4: Pick-up @ Cornwall by train N(90) → Classification / Blocking @ Montreal & connected to train N(62) to Ottawa.

CM1: Pick-up @ Cornwall by train N(90) and delivered to Montreal.

CTR2: Pick-up @ Cornwall by train N(72) → Transfer @ Toronto & connected to train N(80) to Trois-Rivieres.

CSH2: Pick-up @ Cornwall by train N(72) → Transfer @ Toronto & connected to train N(96) to Sherbrooke.

CQC2: Pick-up @ Cornwall by train N(72) → Transfer @ Toronto & connected to train N(96) to Quebec City.

Kingston:

KS1: Pick-up @ Kingston by train N(90) → Classification / Blocking @ Montreal & connected to train N(62) to Sarnia.

KL2: Pick-up @ Kingston by train N(72) → Transfer @ Toronto & connected to train N(82) to London.

KT1: Pick-up @ Kingston by train N(72) and delivered to Toronto.

KO2: Pick-up @ Kingston by train N(72) → Transfer @ Toronto & connected to train N(80) to Ottawa.

KC1: Pick-up @ Kingston by train N(90) and delivered to Cornwall.

KM1: Pick-up @ Kingston by train N(90) and delivered to Montreal.

KTR4: Pick-up @ Kingston by train N(90) → Transfer @ Montreal & connected to train N(62) → Transfer @ Ottawa & connected to N(80) to Trois-Rivieres.

KSH2: Pick-up @ Kingston by train N(72) → Transfer @ Toronto & connected to train N(96) to Sherbrooke.

KQC2: Pick-up @ Kingston by train N(72) → Transfer @ Toronto & connected to train N(96) to Quebec City.

Ottawa:

OS1: Pick-up @ Ottawa by train N(62) and delivered to Sarnia.

OL1: Pick-up @ Ottawa by train N(82) and delivered to London.

OT1: Pick-up @ Ottawa by train N(82) and delivered to Toronto.

OK2: Pick-up @ Ottawa by train N(82) → Transfer @ Toronto & connected to train N(90) and delivered to Kingston.

OC2: Pick-up @ Ottawa by train N(82) → Transfer @ Toronto & connected to train N(90) and delivered to Cornwall.

OM2: Pick-up @ Ottawa by train N(82) → Transfer @ Toronto & connected to train N(90) and delivered to Montreal.

OTR1: Pick-up @ Ottawa by train N(80) and delivered to Trois-Rivieres.

OSH2: Pick-up @ Ottawa by train N(82) → Transfer @ Toronto & connected to train N(96) and delivered to Sherbrooke.

OQC2: Pick-up @ Ottawa by train N(82) → Transfer @ Toronto & connected to train N(96) and delivered to Quebec City.

<u>Sherbrooke:</u>

SHS1: Pick-up @ Sherbrooke by train N(62) and delivered to Sarnia.

SHL1: Pick-up @ Sherbrooke by train N(82) and delivered to London.

SHT1: Pick-up @ Sherbrooke by train N(82) and delivered to Toronto.

SHK1: Pick-up @ Sherbrooke by train N(62) → Transfer @ Montreal & connect to train N(72) and delivered to Kingston.

SHO2: Pick-up @ Sherbrooke by train N(62) and delivered to Ottawa.

SHC1: Pick-up @ Sherbrooke by train N(62) → Transfer @ Montreal & connect to train N(72) and delivered to Cornwall.

SHM1: Pick-up @ Sherbrooke by train N(62) and delivered at Montreal.

SHTR1: Pick-up @ Sherbrooke by train N(82) → Transfer @ Toronto & connect to train N(80) and delivered to Trois-Rivieres.

SHQC1: Pick-up @ Sherbrooke by train N(96) and delivered to Quebec City.

<u>Toronto:</u>

TS1: Classification / Blocking @ Toronto → Connected to train N(8)) → Transfer @ Ottawa & connected to train N(62) → Delivered to Sarnia.

TL1: Pick-up @ Toronto by train N(82) and delivered to London.

TK1: Classification / Blocking @ Toronto & connected to train N(90) → Delivered to Kingston.

TO1: Pick-up @ Toronto by train N(80) and delivered to Ottawa.

TC1: Classification / Blocking @ Toronto & connected to train N(90) → Delivered to Cornwall.

TM1: Classification / Blocking @ Toronto & connected to train N(90) → Delivered to Montreal.

TTR1: Pick-up @ Toronto by train N(80) and delivered to Trois-Rivieres.

TSH1: Pick-up @ Toronto by train N(96) and delivered to Sherbrooke.

TQC1: Pick-up @ Toronto by train N(96) and delivered to Quebec City.

Montreal:

MS2: Pick-up @ Montreal by train N(62) and delivered to Sarnia.

ML4: Classification / Blocking @ Montreal → Connected to train N(72) → Transfer @ Toronto → Connected to train N(82) and delivered to London.

MT1: Classification / Blocking @ Montreal → Connected to train N(72) and delivered to Toronto.

MK1: Classification / Blocking @ Montreal → Connected to train N(72) and delivered to Kingston.

MO1: Pick-Up @ Montreal by train N(62) and delivered to Ottawa.

MC1: Classification / Blocking @ Montreal → Connected to train N(72) and delivered to Cornwall.

MTR2: Pick-Up @ Montreal by train N(62) → Transfer @ Ottawa → Connected to train N(80) and delivered to Trois-Rivieres.

MSH1: Classification / Blocking @ Montreal → Connected to train N(72) → Transfer @ Toronto → Connected to train N(96) and delivered to Sherbrooke.

MQC1: Classification / Blocking @ Montreal → Connected to train N(72) → Transfer @ Toronto → Connected to train N(96) and delivered to Quebec City.

4-A.2: ***Scenario # 1***

The figures reported in table A.1 (below) are distinct from those reported for the base case, as it should be, since the hazmat demand has increased across the board. It has gone up by 25% at each of the 10-nodes, and hence there is a different best solution value.

	100 (Population Pool Size)		
Mask Local Search			
CPU Time:	48	54	84
Best Solution:	1168746	1168746	1168746
Generation # :	9	14	19
One-bit Local Search			
CPU Time:	60	72	108
Best Solution:	1169396	1168746	1168746
Generation # :	9	14	19

Table A. 1: Scenario # 1

Under the *Mask-based* local search section, the solution continued to improve till hitting the 9th generation. In here the best solution, 1,168,746 ($+People), was returned in 5 of the 50 runs, or 10% of the time. On average it took 48 seconds to run a single set-up for the 9th generation. The solution did not improve for another five generations, although the frequency of occurrence of the '*best yet*' double to 20%. In addition two solution ***convergence*** (only two different solutions left in the gene-pool on algorithm termination) was noticed in some instances at this generation. We implemented the other stopping condition, and the 2 solution convergence became quite pronounced in the 19th generation. Interestingly although 80% of the solutions in this generation were the '*best yet*', there was no improvement in the previous 10 generations. Hence the algorithm was terminated.

Under the *One-Bit* local search, there was no occurrence of '*best yet*' solution until the 14th generation. It should also be noted that the CPU times are higher than those under the mask-based local search. Although the '*best yet*' solution was reached at a later generation and used more CPU time at 72 seconds, the frequency of occurrence was a healthy 40% instances. Since no convergence was noticed, further iteration was introduced. But the '*best yet*' solution did not improve until the 19th generation, after which it started deteriorating. In the 19th generation, 20% of the instances had '*best yet*' solutions, although significant convergence of solutions was noticed as well.

The one-bit local search, as before, appears more effective in later generations or deep into the search process, given a gene-pool size of 100. The mask-based search tends to return '*best yet*' solutions more consistently in earlier generations than the other type of local search. As alluded to earlier, it is perhaps due to the multi-step jump for mask-based search. Moreover, this type of jump appears to be more effective in earlier generations, when the starting points are all over the search space. On the other hand, the one-bit local search is more efficient in combing the neighborhood of solutions in later stages viz. when they are in the vicinity of the best-possible solution, due to its tendency to search one-step at a time in a relatively smaller search space.

It should be noted that the 300 runs produced 95 instances of the best possible solution for this scenario. On average, one could expect to end up with the best possible solution once every three runs. It is a rather healthy rate and underlines the efficiency and effectiveness of our algorithm.

The best possible weighted objective value for this scenario has been represented in Table A.2. There is no interpretational difference between this scenario and the **base case**, except that the cost and risk numbers have increased to adjust for the increased demand. The number of railcars with hazardous cargo is 25% higher than in the base-case, thereby affecting the cost. Also corresponding to the increment, the population exposure at the yards and along the service legs have increased. It needs to be reiterated that, due to *non-linearity* and *economies of risk*, the increment in *population exposure* risk is not 25%. The best possible solution for this scenario is 115,548 ($ + People) more than the best possible solution of the **base case**. This increment from the **base case** accounts for both *'cost'* and *'risk'*. The decoded results for Table A.2 are exactly the same as that for the **base case**, and hence there is no interpretational difference.

25% Increment in Hazmat Demand for All Nodes											
Weighted Objective Value: 1168746											
SL1	=	1	TTR1	=	1	CK1	=	1	SHS1	=	1
ST1	=	1	TSH1	=	1	CO4	=	1	SHL1	=	1
SK1	=	1	TQC1	=	1	CM1	=	1	SHT1	=	1
SO1	=	1	KS1	=	1	CTR2	=	1	SHK1	=	1
SC1	=	1	KL2	=	1	CSH2	=	1	SHO2	=	1
SM1	=	1	KT1	=	1	CQC2	=	1	SHC1	=	1
STR1	=	1	KO2	=	1	MS2	=	1	SHM1	=	1
SSH1	=	1	KC1	=	1	ML4	=	1	SHTR1	=	1
SQC1	=	1	KM1	=	1	MT1	=	1	SHQC1	=	1
LS1	=	1	KTR4	=	1	MK1	=	1	QCS1	=	1
LT1	=	1	KSH2	=	1	MO1	=	1	QCL1	=	1
LK1	=	1	KQC2	=	1	MC1	=	1	QCT1	=	1
LO1	=	1	OS1	=	1	MTR2	=	1	QCK1	=	1
LC1	=	1	OL1	=	1	MSH1	=	1	QCO1	=	1
LM1	=	1	OT1	=	1	MQC1	=	1	QCC1	=	1
LTR1	=	1	OK2	=	1	TRS2	=	1	QCM1	=	1
LSH1	=	1	OC2	=	1	TRL1	=	1	QCTR1	=	1
LQC1	=	1	OM2	=	1	TRT1	=	1	QCSH1	=	1
TS1	=	1	OTR1	=	1	TRK1	=	1	N(96)	=	3
TL1	=	1	OSH2	=	1	TRO1	=	1	N(80)	=	2
TK1	=	1	OQC2	=	1	TRC1	=	1	N(90)	=	2
TO1	=	1	CS1	=	1	TRM1	=	1	N(72)	=	2
TC1	=	1	CL2	=	1	TRSH1	=	1	N(82)	=	3
TM1	=	1	CT1	=	1	TRQC1	=	1	N(62)	=	2

Table A. 2: Best Solution for Scenario # 1

4-A.3: *Scenario # 2*

	100 (Population Pool Size)		
Mask Local Search			
CPU Time:	48	60	65
Best Solution:	1175669	1175669	1175669
Generation # :	9	14	19
One-bit Local Search			
CPU Time:	48	60	72
Best Solution:	1176293	1175669	1175669
Generation # :	9	14	19

Table A. 3: Scenario#2

Table A.3 is the report on the second scenario, whereby just the non-hazmat demand increases at all the 10 nodes in the network. The increment is a constant 25% from the regular freight demand in the base case presented earlier.

In here the best solution reported on the basis of 300 runs is distinct from the best solution encountered for the **base case** and *scenario # 1*. It should also be noted that the CPU times have not changed as much from the base case, as they did for the first scenario. This can be explained using the cost–dominance argument. Since only the regular freight demand went up, the algorithm did not have to embark on extra search to return a best weighted risk-cost solution. It just adjusted the cost-values for increased demand, possibly without foraying into readjustment of risk. One of the possible reasons that CPU times went up in scenario #1, was that both cost and risk values had to be readjusted followed by the exploration for the best-possible solution.

Under the *Mask-based* local search section, the solutions exhibited improvement till hitting the 9th generation. The best solution for this generation took an average time of 48 seconds to complete a run, and returned a weighted objective value of 1,175,669 ($+People). Moreover this solution was returned 20% of the time. Although there was no improvement in the '*best yet*' solution, the frequency of its occurrence continued to climb. The 14th generation returned the '*best yet*' solution in 70% instances or 35 of the 50 runs. This generation also brought to fore some solution convergences, implying fulfillment of our second stopping condition. The 19th generation took about the same average time as 14th generation and returned the '*best yet*' solution, although only in 40% instances. Not only had the frequency of returning the '*best yet*' solution gone down, but also the two solution convergence became remarkably pronounced. By the 19th generation both the stopping conditions were met, and hence we stopped the algorithm.

Under the *One-Bit* local search although the best solutions in each generation showed improvement, it did not return any '*best yet*' in the 9th generation. The 9th generation runs took an average of 48 seconds, alike the other local search, and contained the best objective value of 1,176,293 ($+People). This solution was returned in 10% of the runs. Since there was improvement, we introduced additional iteration. Although the best solution continued improving in the subsequent generations, with a couple of '*best yet*' solutions in the 12th and 13th generations, it was not before the 14th generation that the same occurred with regularity. The 14th generation took an average CPU time of 60 seconds and contained 60% instances of '*best yet*' solutions. It also exhibited some solution convergences. The '*best yet*' solution was not beaten for 3 generations, and hence we could have stopped the algorithm as per the first stopping criterion. We persisted for another four generations with absolutely no improvement in the best solution, although the frequency of occurrence of *'best yet'* started going down. It went down to 20% instances in the 19^{th} generation, wherein the average CPU time was 72 seconds/run. In addition there was significant convergence to two solutions and some instances of one solution. Since both stopping conditions were met, we stopped the algorithm. Evidently the average CPU time was higher for the 19^{th} generation under this type of local search compared to the other type.

Once again it should be noted that the one-bit exchange local search becomes more effective in later generations as opposed to the mask-based local search. The latter, owing to multi-step jumps, has a higher probability of hitting the '*best yet*' solutions earlier than the former, which is limited by single-step jumps.

25% Increment in Non-Hazmat Demand for All Nodes Weighted Objective Value: 1175669											
SL1	=	1	TTR1	=	1	CK1	=	1	SHS1	=	1
ST1	=	1	TSH1	=	1	CO4	=	1	SHL1	=	1
SK1	=	1	TQC1	=	1	CM1	=	1	SHT1	=	1
SO1	=	1	KS1	=	1	CTR2	=	1	SHK1	=	1
SC1	=	1	KL2	=	1	CSH2	=	1	SHO1	=	1
SM1	=	1	KT1	=	1	CQC2	=	1	SHC1	=	1
STR1	=	1	KO2	=	1	MS2	=	1	SHM1	=	1
SSH1	=	1	KC1	=	1	ML4	=	1	SHTR1	=	1
SQC1	=	1	KM1	=	1	MT1	=	1	SHQC1	=	1
LS1	=	1	KTR4	=	1	MK1	=	1	QCS1	=	1
LT1	=	1	KSH2	=	1	MO2	=	1	QCL1	=	1
LK1	=	1	KQC2	=	1	MC1	=	1	QCT1	=	1
LO1	=	1	OS1	=	1	MTR2	=	1	QCK1	=	1
LC1	=	1	OL1	=	1	MSH1	=	1	QCO1	=	1
LM1	=	1	OT1	=	1	MQC1	=	1	QCC1	=	1
LTR1	=	1	OK2	=	1	TRS2	=	1	QCM1	=	1
LSH1	=	1	OC2	=	1	TRL1	=	1	QCTR1	=	1
LQC1	=	1	OM2	=	1	TRT1	=	1	QCSH1	=	1
TS1	=	1	OTR1	=	1	TRK1	=	1	N(96)	=	3
TL1	=	1	OSH2	=	1	TRO1	=	1	N(80)	=	2
TK1	=	1	OQC2	=	1	TRC1	=	1	N(90)	=	2
TO1	=	1	CS1	=	1	TRM1	=	1	N(72)	=	2
TC1	=	1	CL2	=	1	TRSH1	=	1	N(82)	=	3
TM1	=	1	CT1	=	1	TRQC1	=	1	N(62)	=	2

Table A. 4: Best Solution for Scenario#2

It is important to underline the efficiency and effectiveness of the algorithm. Although in scenario#2 the algorithm was run roughly 350 times, table A.3 reports 300 runs. Out of the 300 runs, there were 105 instances of the '*best yet*' solution. In spite of the *triple-randomization* feature, inherent to our **memetic-**

algorithm, the frequency with which '*best yet*' solution is returned is encouraging.

The solution in Table A.4 is different than that in the **base case**. Two itineraries have changed from the ones in **base case**. '*MO2*' and '*SHO1*' have respectively replaced '*MO1*' and '*SHO2*'. The effect of the above changes would be at the corresponding yards and service legs. Further analysis revealed that Montreal and Sherbrooke yards, and train services N(62) and N(82) would be affected due to the above changes.

SHO1: Pick-Up @ Sherbrooke by train N(82).

At the Sherbrooke yard, the population exposure stemming from the pick-up will be the same, although the train service will change. In the **base case**, train N(62) was picking-up 85 railcars while N(82) was picking-up 51. Now that '*SHO1*' is entering the solution, the appropriate number of railcars (i.e. 15) corresponding to '*SHO2*' will be removed from N(62) and added to N(82).

MO2: Classification / Blocking @ Montreal → Connected to train N(96).

At the Montreal yard, two functions are affected: classification / blocking and pick-up traffic for N(62). 'MO2' implies classification / blocking at Montreal, while 'MO1' was simple pick-up by N(62). So now the risk at the yard has increased, since classification and blocking are required. The earlier option, although being cheaper and involving less exposure cannot be sustained, since higher traffic to be moved forces that itinerary out of the best solution. The pick-up of traffic for N(62) goes down to 49 railcars, wherein 26 contains hazardous cargo.

4-A.4: ***<u>Scenario#3</u>***

Table A.5 presents the snapshot of important results for scenario # 3. In this scenario the demand for both hazardous and non-hazardous materials increases at all the nodes in the network. The increment is 25% across the board.

The CPU times for the two types of local searches are different. In general, beyond the 10^{th} generation, the second type of local search takes longer to run.

	100 (Population Pool Size)		
Mask Local Search			
CPU Time:	40	48	65
Best Solution:	1295984	1295345	1296486
Generation # :	9	14	19
One-bit Local Search			
CPU Time:	40	56	82
Best Solution:	1296139	1295345	1295345
Generation # :	9	14	19

Table A. 5: Scenario#3

Under the *Mask-based* local search, there was continual solution improvement till about the 14th generation. The 9th generation runs on average took 40 seconds, and the best solution of 1,295,984 ($+People) was returned 10% of the time. Since there was improvement, further iteration was introduced. The best solutions in each of the subsequent generation showed improvement till hitting the 14th generation. This generation returned the '*best yet*' solution of 1,295,345 ($+People) in 30 out of the 50 runs. Since there was improvement further iteration was introduced. The 15th and 16th generation did not return anything better than the '*best yet*', and the subsequent generations had worse best-solutions. Same results in the three previous generations met our first stopping criterion, but the effect of the second criterion had to be evaluated. The 19th and the 20th generation returned, not only two solutions i.e. no diversity in population pool, but also worse-off solutions. The best-solution between the two generations was 1,296,486 ($+People), far removed from the '*best yet*' solution. Hence the algorithm was terminated.

It is worth noting that this is the first instance when the *Mask-based* local search has been unable to return any to be '*best yet*' solution before the 14th generation. It is in contrast to the **base case** and the first two scenarios, wherein the '*best yet*' started occurring in the 9th generation. Perhaps the uniform increment in both hazmat and regular freight, across the board, implies the presence of good solutions relatively deeper than in earlier instances for the mask-based local search. The other reason could be that the population pool does not contain a starting solution, that would facilitate the occurrence of '*best yet*' at an earlier stage.

Furthermore, the '*best yet*' is not present in the 19th generation which was the case until now. The best solution in this generation was much worse than some of the starting solutions in the initial gene pool. For this scenario, it appears that mask-based local search is not effective over a wide-range as in the base-case and the previous two scenarios. The *'best yet'* occurs within a very narrow range of iterations.

Once again the *One-Bit* exchange local search takes longer to iterate and provides better solutions in later generations. There was some improvement in the end result till the start of 9th generation. The 9th generation, took an average of 40 seconds to run, and returned the best solution of 1,296,139 ($+People). Since there was improvement, further generations were created. The solution quality improved until the 14th generation. This generation took an average of 56 seconds/ run for 50 runs, and yielded the '*best yet*' as the best solution. Moreover the occurrence was a healthy 60% of the 50 runs i.e. 30 instances. Very little convergence was noticed. The regularity with which the '*best yet*' solution occurred went up in the subsequent generations, maxing-out at 80% in the 19th generation. The 19th generation runs took an average of 82 seconds, relatively higher than in the other type of local search. While this was very promising, substantial convergence of solution was also noted. There were instances of perfect convergence in the 20th and 21st generation. Since both the stopping criteria were met the algorithm was terminated. This CPU time increment, in later generations, seems common in all the 3 scenarios discussed so far, and can be attributed to the one step local search. It takes longer to search one step at a time, although the results are very healthy.

Once again it should be noted that the one-bit local search has a higher rate of convergence towards the '*best yet*' solution in later generations compared to the mask-based local search. Secondly, it rarely zeroes in around the '*best yet*' in early generations, wherein mask-based local search has a higher probability of convergence.

This scenario was run 350 times, with table A.5 reporting 300 runs. Between the two types of local searches, the '*best yet*' was returned in 100 of the 300 instances for a very healthy 33.33%. As alluded to earlier, this set up seems to work in favor of the one-bit local search, with 70% of the *'best yet'* instances coming from it. Nevertheless, the 1 in 3 occurrence of the '*best yet*' solution underlines the efficiency and effectiveness of our *MA*.

The itineraries in Table A.6 are exactly as the ones in the **base case**, except that the number of trains of type N(82) has increased by one unit to 4 from the base case value of 3. With a uniform demand increase of 25% across the board, an additional train of type N(82) has to be employed every week in order to meet the increased load. Now, the total number of trains of different types is 15 as opposed to 14 in the base-case and the two previous scenarios. The other train services were not operating at capacity in the **base-case**, and hence the increased demand did not warrant higher frequency for those train services.

There is no interpretational difference between this scenario and the **base case**, except that the cost and risk numbers have increased to adjust for the increased demand. The number of railcars with hazardous cargo and non-hazardous cargo is 25% higher than in the base case, thereby affecting the cost. Also corresponding to the increment, population exposure at the yards and along the service legs have increased. Just like in scenario # 1, the increment in risk is not 25%. The best possible solution for this scenario is 242,147 ($+People) more than the best possible solution of the best-case. Once again this increment includes both '$' and 'people'.

25% Increment in Both Hazmat & Non-Hazmat Demand for All Nodes											
Weighted Objective Value: 1295345											
SL1	=	1	TTR1	=	1	CK1	=	1	SHS1	=	1
ST1	=	1	TSH1	=	1	CO4	=	1	SHL1	=	1
SK1	=	1	TQC1	=	1	CM1	=	1	SHT1	=	1
SO1	=	1	KS1	=	1	CTR2	=	1	SHK1	=	1
SC1	=	1	KL2	=	1	CSH2	=	1	SHO2	=	1
SM1	=	1	KT1	=	1	CQC2	=	1	SHC1	=	1
STR1	=	1	KO2	=	1	MS2	=	1	SHM1	=	1
SSH1	=	1	KC1	=	1	ML4	=	1	SHTR1	=	1
SQC1	=	1	KM1	=	1	MT1	=	1	SHQC1	=	1
LS1	=	1	KTR4	=	1	MK1	=	1	QCS1	=	1
LT1	=	1	KSH2	=	1	MO1	=	1	QCL1	=	1
LK1	=	1	KQC2	=	1	MC1	=	1	QCT1	=	1
LO1	=	1	OS1	=	1	MTR2	=	1	QCK1	=	1
LC1	=	1	OL1	=	1	MSH1	=	1	QCO1	=	1
LM1	=	1	OT1	=	1	MQC1	=	1	QCC1	=	1
LTR1	=	1	OK2	=	1	TRS2	=	1	QCM1	=	1
LSH1	=	1	OC2	=	1	TRL1	=	1	QCTR1	=	1
LQC1	=	1	OM2	=	1	TRT1	=	1	QCSH1	=	1
TS1	=	1	OTR1	=	1	TRK1	=	1	N(96)	=	3
TL1	=	1	OSH2	=	1	TRO1	=	1	N(80)	=	2
TK1	=	1	OQC2	=	1	TRC1	=	1	N(90)	=	2
TO1	=	1	CS1	=	1	TRM1	=	1	N(72)	=	2
TC1	=	1	CL2	=	1	TRSH1	=	1	N(82)	=	4
TM1	=	1	CT1	=	1	TRQC1	=	1	N(62)	=	2

Table A. 6: Best Solution for Scenario#3

4-A.5: *Scenario#4*

	100 (Population Pool Size)		
Mask Local Search			
CPU Time:	36	48	72
Best Solution:	1139097	1137923	1137923
Generation #:	9	14	19
One-bit Local Search			
CPU Time:	36	48	60
Best Solution:	1137923	1137923	1137923
Generation #:	9	14	19

Table A. 7: Scenario#4

Table A.7, above, reports the result of 300 runs for the fourth scenario. The CPU times are comparable for the two types of local searches till about the 18^{th} generation. The *'best yet'* solution for this scenario is distinct from the others above.

Under *Mask-based* local search the solution showed improvement until the 12^{th} generation. The 9^{th} generation runs took an average of 36 seconds and yielded the best solution of 1,139,097 ($+People). As has been the case in the previous scenarios, 10% of the instances in this generation returned the best-solution. Since there was improvement, we introduced further iteration. The best solution improved until the 12th generation, but its occurrence frequency within a generation was rather poor. The 14th generation runs took an average of 48 seconds and retained the '*best yet*' solution of 1,137,923 ($+People). This solution occurred in 20% of the 50 instances run for this generation. Furthermore there was distinct convergence, although not in all instances. Although the '*best yet*' was not surpassed for the past three generations implying meeting the first stopping criterion, the effect of the second stopping criterion still had to be ascertained. Hence we introduced additional iteration, but unfortunately the *'best-yet'* did not improve in the subsequent generations. Moreover 40% of the runs, in the 19th generation, returned one or two solution convergence, implying absence of diversity and fulfillment of the second stopping condition. This generation took an average of 72 seconds to complete a run. Once again as in Scenario # 3, it should be noted that the mask-based local search is unable to return any to be '*best yet*' solution before the 10th generation. Moreover the CPU time for later generations are higher under this type of search, substantiating our earlier assertion that mask-based local search is more effective and efficient in earlier generations than in later ones.

Under the *One-Bit Exchange Local Search* the '*best yet*' solution was reached in the 8th generation. The 9th generation has 10% instances of '*best yet*' solution, and it took an average of 36 seconds for one run. Further iteration was introduced in search of beating the '*best yet*' solution. The 14th generation took an average of 48 seconds per run and contained the '*best yet*' in 10% instances. Once again our first stopping condition was met, but we wanted to explore the effect of the second one. The frequency of occurrence of the '*best yet*' went up to 40% in the 19th generation, and also one solution convergence became pronounced thereby meeting our second stopping criterion. As in scenario # 3, the one-bit local search seems effective over a wider range of generations compared to the other type of local search. Perhaps the one-step local search is more effective and efficient in this problem setup, since the search has to be confined only around the attributes of the two nodes at Montreal and Toronto.

Out of a total of 300 runs reported in table A.7, the *'best yet'* solution was returned in 55 runs. Although the ratio is not as healthy as in the previous scenarios, it is satisfactory. On average the *'best yet'* solution was returned in 18% of the runs conducted.

25% Increment in Hazmat & Non-Hazmat Demand at T & M Weighted Objective Value: 1137923											
SL1	=	1	TTR1	=	1	CK1	=	1	SHS1	=	1
ST1	=	1	TSH1	=	1	CO4	=	1	SHL1	=	1
SK1	=	1	TQC1	=	1	CM1	=	1	SHT1	=	1
SO1	=	1	KS1	=	1	CTR2	=	1	SHK1	=	1
SC1	=	1	KL2	=	1	CSH2	=	1	SHO2	=	1
SM1	=	1	KT1	=	1	CQC2	=	1	SHC1	=	1
STR1	=	1	KO2	=	1	MS2	=	1	SHM1	=	1
SSH1	=	1	KC1	=	1	ML3	=	1	SHTR1	=	1
SQC1	=	1	KM1	=	1	MT1	=	1	SHQC1	=	1
LS1	=	1	KTR4	=	1	MK1	=	1	QCS1	=	1
LT1	=	1	KSH2	=	1	MO1	=	1	QCL1	=	1
LK1	=	1	KQC2	=	1	MC1	=	1	QCT1	=	1
LO1	=	1	OS1	=	1	MTR2	=	1	QCK1	=	1
LC1	=	1	OL1	=	1	MSH1	=	1	QCO1	=	1
LM1	=	1	OT1	=	1	MQC1	=	1	QCC1	=	1
LTR1	=	1	OK2	=	1	TRS2	=	1	QCM1	=	1
LSH1	=	1	OC2	=	1	TRL1	=	1	QCTR1	=	1
LQC1	=	1	OM2	=	1	TRT1	=	1	QCSH1	=	1
TS1	=	1	OTR1	=	1	TRK1	=	1	N(96)	=	3
TL1	=	1	OSH2	=	1	TRO1	=	1	N(80)	=	2
TK1	=	1	OQC2	=	1	TRC1	=	1	N(90)	=	2
TO1	=	1	CS1	=	1	TRM1	=	1	N(72)	=	2
TC1	=	1	CL2	=	1	TRSH1	=	1	N(82)	=	3
TM1	=	1	CT1	=	1	TRQC1	=	1	N(62)	=	2

Table A. 8: Best Solution for Scenario#4

The itineraries contained in table A.8 are different than the ones in the **base case**. In here, '*ML3*' replaces '*ML4*' in the best solution. The change in this context is appropriate, since the demand increment was occurring only at the Toronto and Montreal yards.

ML3: Classification / Blocking @ Montreal → Connected to train N(72) → Classification / Blocking @ Toronto → Connected to train N(82) → Delivered to London.

Both '*ML3*' and '*ML4*' itineraries were slated to take train N(72) after classification / blocking operation at the Montreal yard. Hence that part does not change. But there is a consequent effect in the Toronto yard. At the Toronto yard, the traffic coming from Montreal will be classified and blocked with other traffic for London. Earlier the same traffic was just transferred to train N(82). Now, the Toronto yard will classify the incoming traffic and prepare a block for London, which will contain 16 railcars (10 with hazmat cargo). Although this block is still picked-up by train N(82), but the yard operations go up.

The demand increment at these two nodes affects both of them. Although the load at Montreal yard does not change (except for the higher population exposure stemming from an increased number of hazmat railcars), '*ML3*' necessitates a more intensive operation in Toronto as opposed to a simple transfer as in the **base case**.

4-A.6: Cost-Risk Analysis

'A': The minimum cost solution

With a weight of 1 against the cost objective, it is not surprising to have the minimum cost solution being returned as the best solution. It is indeed the minimum solution, and has been verified independently using CPLEX. The minimum cost solution, returned by our ***Visual Basic 6.0*** program, contains, as it should, the least-costly itineraries to meet different demands in the system. The efficiency and the effectiveness of the code can be gauged from the fact that the minimum cost solution was being returned in every generation with satisfactory regularity.

'B': Cost is 0.9 & Risk is 0.1.

As alluded to earlier, each weight combination was run 300 times with a population pool size of 100 strings. Under this weight combination, the CPU time for mask-based local search was relatively higher than for one-bit exchange.

The *Mask-based* local search returns the '*best solution*' starting in the 9^{th} generation. In here, 40 of the 50 instances contained this solution. The best-solution did not improve until the 14^{th} generation, although there was significant convergence to only one solution in later generations.

The '*best solution*' was also returned in the 9^{th} generation under the *One-Bit* local search. This generation on average consumed less CPU time than the other search type, although the frequency of occurrence was relatively low at

20%. Once again, no improvement was observed in the subsequent generations. Numerous instances of one solution convergence were noticed after the 17th generation.

In here both local search types with the two stopping conditions yielded the same best-solution. The '*best solution*' contains exactly the same itineraries as the minimum cost solution, which is not surprising given the weight attached to the cost component of the problem. The only difference between points A and B is the weighted objective value, with the number of trains and itinerary types remaining unchanged.

'C': Cost is 0.8 & Risk is 0.2.

Just like in *'B'*, on average, the CPU times were higher for the mask-based local search. Besides that both the local search types, used in conjunction with the two stopping conditions, yields the same best solution.

Under the *Mask-based* local search, the '*best solution*' was reached in the 9th generation. This generation, on average, took 50 seconds for each run and contained the best solution in 25 of the 50 instances. Further iterations did not improve results, although two solution convergences occurred with regularity after the 15th generation. The 14th generation contained the *'best solution'* in 90% instances.

The occurrence of the '*best solution*' was equally impressive under the other local search and at a lower CPU time. 30 of the 50 runs in the 9th generation contained the '*best solution*'. Further iterations conducted until the 14th generations did not result in any improvements, although the occurrence of '*best solution*' instances went up to 95%. The 16th generations also resulted in substantial convergence thereby implying algorithm termination.

The '*best solution*' still contains the least costly itineraries, and is the same as those in *'A'* and *'B'*. It is not surprising since cost still carries a larger weight, and the current weight increment for the risk objective is not enough to force different itineraries to enter the '*best solution*'.

'D': Cost is 0.7 & Risk is 0.3.

Under this weight combination there is very little difference under the two types of local searches. The mask-based local search requires a little bit more CPU time.

Under the *Mask-based* local search, the '*best solution*' was reached in the 9th generation, taking an average of 60 seconds per run. The '*best solution*' occurred in 30% of the 50 instances. Although introducing further iterations did not improve the solution, the '*best solution*' was returned in 90% of the runs. The 15th and 16th generations exhibited substantial convergence, whereby the algorithm was terminated.

The '*best solution*' under the *One-Bit Local Search* was returned in the 9th generation as well, coincidentally with the same frequency. Yet again, there was no solution improvement. While the 14th generation returned the '*best solution*' in 90% instances, the subsequent generations led to convergence.

The itineraries contained in the *'best solution'* are not different than those in *'A'*, *'B'* and *'C'*. It still seems that the effect of cost coefficient far outweighs that of risk coefficient.

Before moving on with the *cost-risk* evaluation of other points in the figure, let us study the solution returned in each of the four cases discussed until now. Table A.9 (below) depicts the best possible solution and the corresponding objective values for the four cases above.

The itineraries in the *best possible solution*, returned independently by our algorithm for points *'A'*, *'B'*, *'C'* and *'D'* are the same. '*A*' is the minimum cost solution wherein risk has a weight of zero. Hence the minimum cost itineraries were chosen, which was validated using CPLEX (alluded to earlier). Points *'B'*, *'C'* and *'D'* place a huge proportion of total weight on cost, and hence it is not surprising that the best possible solutions in all of the three cases were embedded on the minimum cost solution framework. But the above solution is different than the best-solution of the **base case**.

Best Possible Weighted Objective Value											
A: Cost (1.0) - Risk (0.0)=						*983703*					
B: Cost (0.9) - Risk (0.1)=						*892443*					
C: Cost (0.8) - Risk (0.2)=						*801170*					
D: Cost (0.7) - Risk (0.3)=						*709904*					
SL1	=	1	TTR1	=	1	CK1	=	1	SHS1	=	1
ST1	=	1	TSH1	=	1	CO4	=	1	SHL1	=	1
SK1	=	1	TQC1	=	1	CM1	=	1	SHT1	=	1
SO1	=	1	KS1	=	1	CTR2	=	1	SHK1	=	1
SC1	=	1	KL2	=	1	CSH2	=	1	SHO2	=	1
SM1	=	1	KT1	=	1	CQC2	=	1	SHC1	=	1
STR1	=	1	KO4	=	1	MS2	=	1	SHM1	=	1
SSH1	=	1	KC1	=	1	ML4	=	1	SHTR1	=	1
SQC1	=	1	KM1	=	1	MT1	=	1	SHQC1	=	1
LS1	=	1	KTR4	=	1	MK1	=	1	QCS1	=	1
LT1	=	1	KSH2	=	1	MO1	=	1	QCL1	=	1
LK1	=	1	KQC2	=	1	MC1	=	1	QCT1	=	1
LO1	=	1	OS1	=	1	MTR2	=	1	QCK1	=	1
LC1	=	1	OL1	=	1	MSH1	=	1	QCO1	=	1
LM1	=	1	OT1	=	1	MQC1	=	1	QCC1	=	1
LTR1	=	1	OK2	=	1	TRS2	=	1	QCM1	=	1
LSH1	=	1	OC2	=	1	TRL1	=	1	QCTR1	=	1
LQC1	=	1	OM2	=	1	TRT1	=	1	QCSH1	=	1
TS1	=	1	OTR1	=	1	TRK1	=	1	N(96)	=	3
TL1	=	1	OSH2	=	1	TRO1	=	1	N(80)	=	2
TK1	=	1	OQC2	=	1	TRC1	=	1	N(90)	=	2
TO1	=	1	CS1	=	1	TRM1	=	1	N(72)	=	2
TC1	=	1	CL2	=	1	TRSH1	=	1	N(82)	=	3
TM1	=	1	CT1	=	1	TRQC1	=	1	N(62)	=	2

Table A. 9: Best Solutions for *'A', 'B', 'C', and 'D'*

KO4: Pick-Up @ Kingston by train N(90) → Transfer @ Montreal → Connected to train N(62) → Delivered to Ottawa.

In Table A.9 itinerary '*KO4*' replaces '*KO2*', and has an impact in the network. The pick-up at Kingston yard by trains N(72) and N(90) will change. Now N(72) will pick-up 67 railcars and not 87 as in the **base case**, whereas N(90) will pick-up 90 railcars instead of the earlier 70. Although the population exposure at the Kingston yard remains unchanged, there is tangible impact at the Montreal and Toronto yards.

At Montreal, the total number of railcars to be transferred to train N(62) will go up by 20 railcars to a new value of 56, with 20 hazmat railcars. Hence the population exposure at the Montreal yard will go up. At the Toronto yard, a smaller number of railcars will need to be transferred to train N(80), since that traffic is not coming here anymore. Now 80 railcars will have to be transferred to train N(80), instead of the earlier 100. At the same time, the number of railcars with hazardous cargo goes down to 43 thereby reducing population exposure in Toronto.

'E': Cost is 0.6 & Risk is 0.4.

Under this weight combination, the first instance of '*best solution*' occurs in different generations for the two local search types.

Under the *Mask-based* local search, the first instance of '*best solution*' occurs in the 12th generation. There was no further improvement until the 14th generation, wherein each run took an average of 60 seconds and the '*best solution*' was in 25 of the 50 runs. Further iterations did not improve the solution, although 17th generation and beyond exhibited numerous instances of one solution convergence.

Under the *One-Bit* local search, the '*best-solution*' occurred in the 9th generation. The runs in this generation took an average of 54 seconds and returned the '*best-solution*' in 10% instances. This solution was not beaten in the next 5 generations, although in the 14th generation the frequency of occurrence went up to 40%. Once again there was no improvement in further generations and significant convergence was noticed, thereby implying algorithm termination.

Under this weight combination, the one-bit local search outperforms the mask local search. The former returned the '*best solution*' in earlier generations, although the total number of instances remained the same for the two.

Unlike the previous weight combinations, the best solution does not contain only the cheapest itineraries. This is perhaps the first indication that the effect of cost coefficients has been reduced enough to affect a set of itineraries different than the minimum cost solution result.

'F': Cost is 0.5 & Risk is 0.5.

With equal weights attached to the two objectives, the '*best solution*' was returned by the two local search types, on average, using similar CPU times.

Under the *Mask-based* local search, the '*best solution*' was returned in the 9th generation and it occurred in 5 of the 50 runs. This solution was not beaten in the subsequent generations, although the occurrence frequency went up to 20% in the 14th generation. No convergences were noticed and hence additional iterations were introduced. The '*best solution*' did not change for another 5 generations, but the two solution convergence was quite pronounced in the 19th generation.

The '*best solution*' was returned in the 9th generation under the *One-Bit* local search as well. It took about the same amount of CPU time, and contained 10% instances in the 50 runs for this generation. The 14th generation returned the '*best-solution*' more consistently, in 50% of the 50 runs. Unfortunately there was no solution improvement, and the generations after the 18th exhibited one solution convergence.

The performance of the two local searches is roughly equivalent for this weight combination. The itineraries returned in the '*best solution*' are distinct from the minimum cost solution, but similar to that for point '*E*'.

'G': Cost is 0.4 & Risk is 0.6.

This is the first instance with larger weight coefficient for the risk objective. The CPU times under the two local search types are similar, except for later generations when mask-based local search required more time than one-bit exchange local search.

Under the *Mask-based* local search, there were improvements until the 14th generation. The 14th generation runs, on average, took 60 seconds/run and contained the '*best solution*' in 40% instances. Further iteration did not result in any improvement, although the 19th and 20th generations returned 80% instances of '*best solution*'. Since the subsequent generations exhibited deterioration of solution and numerous instances of convergence, the algorithm was stopped.

The '*best solution*', under the *One-Bit* local search, did not occur till the 14th generation. Just like under mask-based local search, this generation took an average of 60 seconds per run and returned the '*best solution*' in 20 of the 50 instances. Unlike under the other local search type, the frequency of occurrence of the '*best solution*' went down to 20% in the 16th generation and to 10% in the 18th. Moreover there was noticeable convergence, implying algorithm termination.

This is perhaps the first instance when neither of the two local searches returned the '*best solution*' earlier than the 14th generation. Perhaps it is the higher weight attached to risk objective that warranted further iteration (generations) in order to reach the better solutions. The '*best solution*' has an itinerary different than the minimum cost solution and similar to the best-solutions in '*E*' and '*F*'.

'H': Cost is 0.3 & Risk is 0.7.

With a larger weight coefficient attached to the risk objective, the runs under this combination consumed similar CPU times as the points with higher weight on the risk coefficient.

Under the *Mask-based* local search, the '*best solution*' was reached in the 9th generation. It took an average time of 72 seconds per run and returned the '*best solution*' in 10% instances. Further iteration was introduced in an effort to beat the best solution. The 14th generation recorded the occurrence of the *'best solution'* in 30 of the 50 runs. Subsequent iterations did not improve the best solution, but the 19th and 20th generations clocked a higher occurrence frequency of the '*best solution.*'

The '*best solution*' was returned before the 14th generation under the *One-Bit* local search. The runs in the 14th generation took an average of 90 seconds, compared to 84 seconds under the mask-based local search, and returned the '*best solution*' in 40% instances. Further iterations did not improve the solution, but worse solutions were recorded after the 15th generation. Noticeable convergence occurred in the 19th and 20th generations.

Under this instance, the mask-based local search returned the '*best solution*' more regularly and at an earlier generation than the one-bit exchange local search. The latter does not contain the *'best solution'* before the 14th generation.

The itineraries in the '*best solution*' are similar to the best solutions of '*F*' and '*G*', implying no incremental effect of higher risk coefficient weights. It is important to point out that the routing options available to traffic-classes are rather limited, and hence it would be unreasonable to expect drastic changes with a ten-percent point change in risk and cost objectives. Moreover, some minimum cost itineraries can also be the ones with minimum risk and hence their presence in the weighted solutions should be considered good.

'I': Cost is 0.2 & Risk is 0.8.

This is the other instance which did not see the occurrence of the best solution before the 14th generation. The CPU times are rather similar for the two local search types.

Under *Mask-based* local search, the '*best solution*' is returned for the first time in the 14th generation. This generation took an average of 60 seconds per run and contained the '*best solution*' in 5 of the 50 runs. Further iterations were introduced in the hope of improvement, but the '*best solution*' was not beaten. The 19th generation runs took an average CPU time of 66 seconds and contained the '*best solution*' in 40% instances. Additional iterations produced solutions worse than the starting solutions, although convergence was noticed.

Under *One-Bit* local search, as well, the '*best solution*' did not occur before the 14th generation. The 14th generation runs took an average of 54 seconds and contained the '*best-solution*' in 20% instances. Although further iterations did not beat the *'best solution'*, they definitely increased the frequency of occurrence. The 17th generation runs took an average CPU time of 80 seconds, and returned the '*best solution*' in 40 of the 50 runs. Convergence was not regular until the 22nd generation, although the solution quality was considerably worse.

The itineraries in the '*best solution*' are similar to the ones with the three previous weight combinations, but distinct from the minimum cost solution.

Once again before moving on, let us evaluate the best possible solutions for the five points discussed since the last evaluation.

Table A.10 reports the weighted objective value and the best possible solutions for the next five points. Incidentally the itineraries here are exactly the same as the **base case** solution. With increasing weight coefficient for risk and decreasing one for cost, the best possible solutions moved towards the weighted (balanced) **base case** solution. Although this illustrates the diminishing effect of cost and increasing influence of risk, more importantly it tells us that the itineraries in the best possible solution in **base case** are **not** the minimum cost solution itineraries. However from an interpretational perspective, there is absolutely no difference between the five solutions in table 4.18 and the **base case** solution, except the weighted objective values. The cost numbers and risk exposures are exactly the same, of course adjusted with appropriate weight coefficients. The decoded results will be the same as in the **base case.**

Best Possible Weighted Objective Value											
E: Cost (0.6) - Risk (0.4)=						*618521*					
F: Cost (0.5) - Risk (0.5)=						*526639*					
G: Cost (0.4) - Risk (0.6)=						*434677*					
H: Cost (0.3) - Risk (0.7)=						*342754*					
I: Cost (0.2) - Risk (0.8)=						*250816*					
SL1	=	1	TTR1	=	1	CK1	=	1	SHS1	=	1
ST1	=	1	TSH1	=	1	CO4	=	1	SHL1	=	1
SK1	=	1	TQC1	=	1	CM1	=	1	SHT1	=	1
SO1	=	1	KS1	=	1	CTR2	=	1	SHK1	=	1
SC1	=	1	KL2	=	1	CSH2	=	1	SHO2	=	1
SM1	=	1	KT1	=	1	CQC2	=	1	SHC1	=	1
STR1	=	1	KO2	=	1	MS2	=	1	SHM1	=	1
SSH1	=	1	KC1	=	1	ML4	=	1	SHTR1	=	1
SQC1	=	1	KM1	=	1	MT1	=	1	SHQC1	=	1
LS1	=	1	KTR4	=	1	MK1	=	1	QCS1	=	1
LT1	=	1	KSH2	=	1	MO1	=	1	QCL1	=	1
LK1	=	1	KQC2	=	1	MC1	=	1	QCT1	=	1
LO1	=	1	OS1	=	1	MTR2	=	1	QCK1	=	1
LC1	=	1	OL1	=	1	MSH1	=	1	QCO1	=	1
LM1	=	1	OT1	=	1	MQC1	=	1	QCC1	=	1
LTR1	=	1	OK2	=	1	TRS2	=	1	QCM1	=	1
LSH1	=	1	OC2	=	1	TRL1	=	1	QCTR1	=	1
LQC1	=	1	OM2	=	1	TRT1	=	1	QCSH1	=	1
TS1	=	1	OTR1	=	1	TRK1	=	1	N(96)	=	3
TL1	=	1	OSH2	=	1	TRO1	=	1	N(80)	=	2
TK1	=	1	OQC2	=	1	TRC1	=	1	N(90)	=	2
TO1	=	1	CS1	=	1	TRM1	=	1	N(72)	=	2
TC1	=	1	CL2	=	1	TRSH1	=	1	N(82)	=	3
TM1	=	1	CT1	=	1	TRQC1	=	1	N(62)	=	2

Table A. 10: Best Solution for *'E', 'F', 'G', 'H', and 'I'*

'J': Cost is 0.1 & Risk is 0.9.

A very high 90% weight attachment to the risk objective returns the '*best solution*' distinct from the other best solutions seen so far.

Under the *Mask-based* local search, although the '*best solution*' is returned in the 14th generation there were instances in the 9th, 10th and 11th generations when the solutions returned were very close to the best. The 14th generation runs took an average of 58 seconds and contained the '*best solution*' in 5 of the 50 runs. Further iterations were introduced in an effort to beat the '*best solution'*. No improvement was noticed until the 19th generation, wherein the occurrence frequency for the '*best solution*' doubled to 20%. Although our first stopping condition was already met, further iterations were introduced to check for the other stopping condition. Starting in the 22nd generation there was substantial convergence, without any improvement in solution quality.

Under the *One-Bit* local search, the '*best solution*' occurred in the 9th generation. The 9th generation runs took an average of 42 seconds and contained the '*best solution*' 10% of the time. Further iterations did not improve the solution, although some convergence was noticeable. The 11th and 14th generation runs took an average CPU time of 54 seconds and 60 seconds, respectively, and did not contain any instance of the '*best solution*'. In fact the solution quality deteriorated rather sharply under this search type.

Best Possible Weighted Objective Value											
J: Cost (0.1) - Risk (0.9)=						*158877*					
SL1	=	1	TTR1	=	1	CK1	=	1	SHS1	=	1
ST1	=	1	TSH1	=	1	CO4	=	1	SHL1	=	1
SK1	=	1	TQC1	=	1	CM1	=	1	SHT1	=	1
SO1	=	1	KS1	=	1	CTR2	=	1	SHK1	=	1
SC1	=	1	KL2	=	1	CSH2	=	1	SHO1	=	1
SM1	=	1	KT1	=	1	CQC2	=	1	SHC1	=	1
STR1	=	1	KO2	=	1	MS2	=	1	SHM1	=	1
SSH1	=	1	KC1	=	1	ML4	=	1	SHTR1	=	1
SQC1	=	1	KM1	=	1	MT1	=	1	SHQC1	=	1
LS1	=	1	KTR4	=	1	MK1	=	1	QCS1	=	1
LT1	=	1	KSH2	=	1	MO1	=	1	QCL1	=	1
LK1	=	1	KQC2	=	1	MC1	=	1	QCT1	=	1
LO1	=	1	OS1	=	1	MTR2	=	1	QCK1	=	1
LC1	=	1	OL1	=	1	MSH1	=	1	QCO1	=	1
LM1	=	1	OT1	=	1	MQC1	=	1	QCC1	=	1
LTR1	=	1	OK2	=	1	TRS2	=	1	QCM1	=	1
LSH1	=	1	OC2	=	1	TRL1	=	1	QCTR1	=	1
LQC1	=	1	OM2	=	1	TRT1	=	1	QCSH1	=	1
TS1	=	1	OTR1	=	1	TRK1	=	1	N(96)	=	3
TL1	=	1	OSH2	=	1	TRO1	=	1	N(80)	=	2
TK1	=	1	OQC2	=	1	TRC1	=	1	N(90)	=	2
TO1	=	1	CS1	=	1	TRM1	=	1	N(72)	=	2
TC1	=	1	CL2	=	1	TRSH1	=	1	N(82)	=	3
TM1	=	1	CT1	=	1	TRQC1	=	1	N(62)	=	2

Table A. 11: Best Solution for '*J*'.

Under this weight combination, the *'best solution'* was reached under the *one-bit* exchange local search in the 9th generation but not returned after the 13th generation. On the other hand, it was reached in the 14th and sustained until the 19th generation under the *mask-based* local search. The itineraries in the *'best solution'* for this weight combination are distinct from the others indicating the effect of high value of risk coefficients.

The increased weight on risk objective has introduced further change in the solution in table A.11. Now that risk has a higher weight, the itineraries seem to be moving towards the minimum risk solution. In that effort '*SHO1*' replaces '*SHO2*', the only difference from the **base case**.

SHO1: Pick-Up @ Sherbrooke by train N(82) → Delivered to Ottawa.

This replacement affects only the origin yard viz. Sherbrooke. The new pick-up traffic for the two impacted trains, N(62) and N(82), changes. Now N(62) will pick-up 70 railcars instead of the 85 as in the base case, and N(82) will pick-up 66 railcars and not 51.

'K': The Minimum Risk Solution.

Point '*K*' is the second of the extreme points, '*A*' being the first. Interestingly enough, the '*best solution*' returned under each of the two local search type is different.

Best Possible Weighted Objective Value											
K: Cost (0) - Risk (1.0)=						*66985*					
SL1	=	1	TTR1	=	1	CK1	=	1	SHS1	=	1
ST1	=	1	TSH1	=	1	CO4	=	1	SHL1	=	1
SK1	=	1	TQC1	=	1	CM1	=	1	SHT1	=	1
SO1	=	1	KS1	=	1	CTR2	=	1	SHK1	=	1
SC1	=	1	KL2	=	1	CSH2	=	1	SHO1	=	1
SM1	=	1	KT1	=	1	CQC2	=	1	SHC1	=	1
STR1	=	1	KO4	=	1	MS2	=	1	SHM1	=	1
SSH1	=	1	KC1	=	1	ML4	=	1	SHTR1	=	1
SQC1	=	1	KM1	=	1	MT1	=	1	SHQC1	=	1
LS1	=	1	KTR4	=	1	MK1	=	1	QCS1	=	1
LT1	=	1	KSH2	=	1	MO1	=	1	QCL1	=	1
LK1	=	1	KQC2	=	1	MC1	=	1	QCT1	=	1
LO1	=	1	OS1	=	1	MTR2	=	1	QCK1	=	1
LC1	=	1	OL1	=	1	MSH1	=	1	QCO1	=	1
LM1	=	1	OT1	=	1	MQC1	=	1	QCC1	=	1
LTR1	=	1	OK2	=	1	TRS2	=	1	QCM1	=	1
LSH1	=	1	OC2	=	1	TRL1	=	1	QCTR1	=	1
LQC1	=	1	OM2	=	1	TRT1	=	1	QCSH1	=	1
TS1	=	1	OTR1	=	1	TRK1	=	1	N(96)	=	3
TL1	=	1	OSH2	=	1	TRO1	=	1	N(80)	=	2
TK1	=	1	OQC2	=	1	TRC1	=	1	N(90)	=	2
TO1	=	1	CS3	=	1	TRM1	=	1	N(72)	=	2
TC1	=	1	CL2	=	1	TRSH1	=	1	N(82)	=	3
TM1	=	1	CT1	=	1	TRQC1	=	1	N(62)	=	2

Table A. 12: Best Solution for *'K'*

Under the *Mask Local Search*, the '*best solution*' returned is different than the one obtained at point '*J*'. On the other hand, the '*best solution*' under the *One-*

Bit Local Search contains similar itineraries as in '*J*'. But since the former has a lower objective value, we will consider that to be the minimum risk solution.

Table A.12 contains the minimum risk solution. It is distinct, in the sense that it contains itineraries different from any we have seen so far. Three itineraries are different than the **base case**. '*KO4*', '*CS3*' and '*SHO1*' replaces '*KO2*', '*CS1*' and '*SHO2*', respectively in the **base case**.

KO4: Pick-Up @ Kingston by train N(90) → Transfer @ Montreal → Connected to train N(62) → Delivered to Ottawa.

The '*KO4*' replacement will have the following effect. The pick-up at Kingston yard by trains N(72) and N(90) will change. Now N(72) will pick-up 67 railcars and not 87 as in the base case, whereas N(90) will pick-up 90 railcars instead of the previous 70. Despite this the population exposure at the Kingston yard remains unchanged. But the Montreal and Toronto yards are affected as well. At Montreal, the total number of railcars to be transferred to train N(62) will go up by 20 railcars to have a new value of 56, with 20 containing hazardous cargo. Hence the population exposure at the Montreal yard will go up. At the Toronto yard, lesser number of railcars will need to be transferred to train N(80), since that traffic is not coming here anymore. Now 80 railcars will have to be transferred to train N(80), instead of the earlier 100. At the same time, the number of railcars with hazardous cargo goes down to 43 thereby reducing population exposure in Toronto.

CS3: Pick-Up @ Cornwall by train N(90) → Transfer @ Montreal → Connected to train N962) – Delivered to Sarnia.

The '*CS3*' replacement will have the following impact. At Cornwall (origin yard) there will be no change since train N(90) is the connection for both the itineraries to meet the Sarnia demand. But this affects the yard operations in both Montreal and Toronto. In Montreal, there is no longer any need to classify and block for Sarnia, hence that load will be eliminated. Now only 15 railcars (10 with hazmat cargo) will have to be classified / blocked for train N(62). In addition, the number of railcars to be picked-up by train N(62) goes down to 50 railcars, including 26 hazmat railcars. The corresponding number in **base case** is 65 railcars, of which 36 contains hazmat cargo. But the classification load in

Toronto will increase. Now, 30 railcars (16 with hazmat cargo) will have to be classified / blocked before being connected to train N(80). At the same time the number of railcars to be picked-up by train N(80) increases to 52, including 21 with hazardous cargo.

SHO1: Pick-Up @ Sherbrooke by train N(82) → Delivered to Ottawa.

As for the previous point *'J'*, '*SHO1*' replacement affects only the origin yard viz. Sherbrooke. The new pick-up traffic for the two impacted trains, N(62) and N(82), changes. Now N(62) will pick-up 70 railcars instead of the 85 as in the base case, and N(82) will pick-up 66 railcars and not 51.

4-A.7: <u>*Normalized Data Analysis*</u>

Once again using a gene pool size of 100, we ran the Memetic Algorithm under the two local search–stopping rule criteria, and the pertinent results are presented in table A.13.

	100 (Population Pool Size)				
Mask Local Search					
CPU Time:	54	78	96	100	108
Best Solution:	1268316	1267493	1276643	1267493	1267493
Generation # :	9	14	19	21	24
One-bit Local Search					
CPU Time:	72	90	94	96	
Best Solution:	1270382	1267493	1267493	1274448	
Generation # :	9	14	19	21	

Table A. 13: Algorithm Report with Normalized Data

Under the *Mask-based* local search, there was continuous improvement in the end solution value. The runs in the 9th generation took an average of 54 seconds and returned 1,268,316 ($ + People) as the objective value. This occurred in 10% of the 50 runs. Seeking improvement, further iterations were introduced. The 14th generation runs took an average CPU time of 78 seconds and returned 1,267,493 ($+People), which was an improvement over previous best solution. This new '*best yet*' solution occupied best spot in 5 of the 50 runs. In an effort to further improve solution, additional iterations were introduced. The 19th generation runs took an average of 96 seconds but did not return a better solution. The solution deteriorated and occurred in 10 of the 50 runs. Some instances of perfect one solution convergences were noticed in this generation, but without regularity. There was no improvement in the '*best yet*' till the 24th generation, and now the instances of perfect convergence became more frequent. Now that both stopping conditions were met under the mask-based local search, the algorithm was stopped.

Under the *One-Bit* local search, there was continuous improvement until the 14th generation. The 9th generation runs took an average time of 72 seconds and returned 1,270,382 ($+People) as the best solution in 20% of the 50 instances. Clearly it did not beat the '*best yet*' from above. Further iterations were introduced. In the 14th generation, the '*best yet*' solution was returned in 40% instances. The runs in this generation took an average time of 90 seconds. Additional iterations did not improve the solution, although the occurrence frequency was halved in the 19th generation, wherein the runs took an average of 94 seconds. Any further iteration resulted in worse off solutions. In addition, the 20th and 21st generations exhibited numerous instances of one and two solution convergence.

There were 55 instances of '*best solution*' from the 450 runs conducted for normalized values. Most importantly, the normalization of risk values does not change the itineraries contained in the best solution. The itineraries for railcars in the '*best solution*' are exactly the same as those in the '*best solution*' of the **base case**. It underlines the robustness of our results, and implies that results obtained with un-normalized data were not skewed towards either cost or risk. We end up with same set of itineraries in both instances, and hence this set of itineraries is indeed the '*best solution*' for problem **(P)**.

The itineraries contained in table A.14 are exactly the same as in the **base case**. The values of risk have been increased, but the cost numbers are the same. There is no difference between the solution in table 4.22 and one for the base case, except the weighted objective value coming from the normalization of risk numbers used in **(P)** coming from normalized risk data. There is no difference in the decoded result from that of the **base case**.

Best Possible Solution with Normalized Values Weighted Objective Value =1267493											
SL1	=	1	TTR1	=	1	CK1	=	1	SHS1	=	1
ST1	=	1	TSH1	=	1	CO4	=	1	SHL1	=	1
SK1	=	1	TQC1	=	1	CM1	=	1	SHT1	=	1
SO1	=	1	KS1	=	1	CTR2	=	1	SHK1	=	1
SC1	=	1	KL2	=	1	CSH2	=	1	SHO2	=	1
SM1	=	1	KT1	=	1	CQC2	=	1	SHC1	=	1
STR1	=	1	KO2	=	1	MS2	=	1	SHM1	=	1
SSH1	=	1	KC1	=	1	ML4	=	1	SHTR1	=	1
SQC1	=	1	KM1	=	1	MT1	=	1	SHQC1	=	1
LS1	=	1	KTR4	=	1	MK1	=	1	QCS1	=	1
LT1	=	1	KSH2	=	1	MO1	=	1	QCL1	=	1
LK1	=	1	KQC2	=	1	MC1	=	1	QCT1	=	1
LO1	=	1	OS1	=	1	MTR2	=	1	QCK1	=	1
LC1	=	1	OL1	=	1	MSH1	=	1	QCO1	=	1
LM1	=	1	OT1	=	1	MQC1	=	1	QCC1	=	1
LTR1	=	1	OK2	=	1	TRS2	=	1	QCM1	=	1
LSH1	=	1	OC2	=	1	TRL1	=	1	QCTR1	=	1
LQC1	=	1	OM2	=	1	TRT1	=	1	QCSH1	=	1
TS1	=	1	OTR1	=	1	TRK1	=	1	N(96)	=	3
TL1	=	1	OSH2	=	1	TRO1	=	1	N(80)	=	2
TK1	=	1	OQC2	=	1	TRC1	=	1	N(90)	=	2
TO1	=	1	CS1	=	1	TRM1	=	1	N(72)	=	2
TC1	=	1	CL2	=	1	TRSH1	=	1	N(82)	=	3
TM1	=	1	CT1	=	1	TRQC1	=	1	N(62)	=	2

Table A. 14: Best Solution with Normalized Data

4-A.8: *Evaluation with Chlorine:*

According to the NIOSH handbook, 14 to 21 ppm of chlorine for 0.5 to 1.0 hr can be dangerous; and, 34 to 51 ppm of chlorine for 1.0 to 1.5 hr can be lethal. Using the equivalent conversion, as for propane, we end up with 25,200 ppm and 122,400 ppm, for severe injury and fatality, respectively. Hence, a population center will be considered exposed if the aggregate concentration level, in this center, exceeds the injury threshold. Having generated the threshold distances for railcars containing chlorine, we entered the *GIS ArcView* environment. As before *Avenue Programming* was done on the railroad network and population centers to generate the exposure bands. These exposure bands, like in propane, were generated for all possible number of railcars with chlorine, passing through each of the twenty service legs and each the 10 yards in the physical railroad network of interest. Once again 10,400 population exposure bands had to be (avenue programmed and) generated in *ArcView* to account for all possible traffic-combinations on the 20 train service legs and the 10 yards. The above mentioned calculations result in new risk data values for Chlorine. The cost numbers are unchanged since the total demand has not changed from the **base case**.

Once again *Memetic Algorithm*, coded in ***Visual Basic 6.0***, was used with both types of local searches and the two stopping conditions. Each scenario was run 50 times, and the best solution returned for each scenario is reported. Just like in the **base case**, three different gene pool sizes are experimented with.

30 Pops

A total of 400 runs were conducted between the two local searches with the two stopping conditions as described earlier in this section.

Under *Mask-based* local search, the solutions improved consistently. The 4th generation runs took an average of 36 seconds, and returned a best-solution value of 1,081,918 ($+People). This solution occurred in 10% instances of the 50 runs conducted for this scenario. Additional iteration was introduced to further explore the search space. The 9th generation returned a better solution. It took an average CPU time of 42 seconds to return a new '*best yet*' solution in 5 out of 50 runs. Since there was improvement in the best-solution, further iterations were introduced. The solution improved until the 14th generation. The runs in this generation, on average, took 48 seconds per run and resulted in a better '*best yet*' solution. This solution occurred in 30% instances and had an objective value of 1,080,219 ($+People). In addition, there were some instances of convergence. Encouraged by improved solution, further iterations were introduced. But there was no further improvement in the solution. The 19th generation runs took an average of 54 seconds, but the '*best yet*' solution could not be topped. Although this solution was returned 30 out of 50 times, there were numerous instances of one solution convergence.

Under the *One-Bit* local search the '*best yet*' solution obtained above does not occur until later generations. There were continuous improvements. The 4th generation runs took an average time of 36 seconds, and returned a best-solution of 1,082,561 ($+People) in 10% instances of the 50 runs. Seeking further improvement, higher number of generations was introduced. The 9th generation runs took an average of 42 seconds and returned a better solution. This solution, 1,081,136 ($+People), was returned in 5 of the 50 runs. Further iterations were introduced, in an effort to find better solutions. A new best solution was present in 10% instances. This occurred in the 14th generation and took an average of 45 seconds, with an objective value of 1,080,509 ($+People). There have been improvements until now, hence further iterations were introduced. The 19th generation returned the '*best yet*' solution. It took an average of 48 seconds per run in this generation, and returned the '*best yet*' solution in 60% instances. The quality of solution starts deteriorating hereafter. In addition substantial convergence is noticeable.

With a gene pool size of 30, the mask-based local search returns the '*best yet*' solution at an earlier generation compared to the one-bit exchange local search, which starts returning it in the 19th generation. Although the one-bit local search returns the best-solution later, the number of instances are healthier than in the runs with mask-based local search. Between the two local search types, the '*best yet*' solution returned in 45 of the 400 runs done with the gene-pool size of 30.

<u>50 Pops</u>

As in the **base-case**, the gene pool size was increased to 50 chromosomes. Now between the two local search types, the program was run 500 times.

Under *Mask-based* local search, the solutions showed improvement. In the 4th generation, each run on average took 38 seconds and returned the best solution with an objective value of 1,083,881 ($+People). This solution occurred in 10% of the 50 instances. Further iterations were introduced. The 9th generation runs took an average CPU time of 42 seconds and beat the old best solution. The new '*best yet*' solution was returned in 10% of the 50 runs, and had an objective value of 1,080,828 ($+People). Since there was improvement, further iterations were introduced. The 14th generation yielded a new best solution, thereby beating the previous one. The runs in this generation, on average, took 48 seconds per run and contained the new '*best yet*' in 30 of the 50 runs. Once again further iterations were introduced. The '*best yet*' could not be beaten in the subsequent 10 generations. The 19th generation runs, on average, took 72 seconds per run and returned the '*best yet*' in 40% instances. Although our first stopping condition was met, we still wanted to evaluate the effect of the second one and hence introduced further iteration. The 24th generation runs took 81 seconds per run, and still contained the '*best yet*' in 40% instances. Substantial convergence, in this generation and the subsequent ones, imply algorithm termination.

Under the *One-Bit* local search, just like above, there were improvements. The 4th generation returned a best solution of 1,081,454 ($+People) in 10% of the 50 runs. Each run, on average, took 36 seconds. Further iterations were introduced. The 9th generation returned the '*best yet*' from the above search in 5 of the 50 instances. The runs in this generation took an average CPU time of 42 seconds. Further iterations returned the '*best yet*' solution with more regularity. In the 14th generation, the '*best yet*' solution was returned in 40% of the 50 runs. Any further iteration did not improve the solution. In the 19th generation, the frequency of occurrence of the '*best yet*' solution went up to 60%. The runs in this generation, on average, took 60 seconds. Any further iteration led to worse off solutions. The 24th and 25th generations also exhibited one and two solution convergences.

The performance of the two types of local searches is not that different in the gene pool with 50 chromosomes. The one-bit local search yielded maximum instances of '*best yet*' solution in the 19th generation, while the mask-based local search was more effective in the 14th generation. It is in line with our earlier observation that the one-bit local search seems more effective in later generations than in earlier ones, wherein mask-based local search performs more efficiently.

The comparison between the two population sizes is more straightforward in this case. Out of the 500 runs, conducted with a population pool size of 50, 125 returned what would be the '*best yet*' solution. This success rate of 25% is far healthier than 11.25% rate achieved with a population size of 30.

100 Pops

Once again the gene pool size was changed, this time to 100 chromosomes. With this population size, 500 runs were conducted under the two types of local searches and with the two stopping conditions.

Under *Mask-based* local search, there was continuous solution improvement. The 4th generation runs, on average, took 36 seconds per run and returned the best solution in 10% instances. Encouraged by improvement, further iterations were introduced. There were marginal improvements into the 9th generation. The runs in this generation, on average, took 48 seconds and returned a best solution of 1,080,826 ($+People). Further iterations were introduced. The 14th generation returned the '*best yet*' solutions, with the 30 and 50 Pops cases. The runs in this generation, on average, took 54 seconds and contained the '*best yet*' solution in 15 of the 50 runs. Although any further iteration did not improve the solution, the regularity of the occurrence of the '*best yet*' solution went up in subsequent generations. In the 19th generation, there were 40% instances of the '*best yet*' solution. In here some instances of convergence could be noticed as well. Ordinarily we could have stopped here, but we wanted to explore the effect of the second stopping condition. Although the solution did not improve, the occurrence frequency went up to 60% of the 50 instances in the 24th generation. The runs in the 19th and 24th generations, on average, took 96 and 108 second per run. Starting in the 23rd generation substantial convergence was noted, although the instances of one solution convergence became more pronounced.

With the *One-Bit* local search, just like with the other local search there was no instance of '*best yet*' until the 14th generation. The 4th generation runs took an average of 42 seconds and returned a best solution of 1,084,058 ($+People) in 10% instances. Further iterations were introduced to explore for better solutions. There were continual improvements. The 9th generation runs took an average CPU time of 48 seconds and returned 1,080,895 ($+People) as the best solution. This best solution occurred in 10% of the 50 cases for this generation. Further iterations were introduced. In the 14th generation the '*best yet*' solution was returned in 15 of the 50 runs, where each run on average took 72 seconds. Just like with the other local search, any further iteration did not yield a result better than the '*best yet*' solution. The 19^{th} generation runs on average, took 96 seconds and contained the '*best yet*' solution in 30 of the 50 runs. Although there was no improvement, further iterations were introduced, to implement the second stopping condition. The 24^{th} generation runs on average, took 98 seconds and returned the '*best yet*' solution in 40% instances. But now there were numerous instances of one and two solution convergence, and most of them were worse than the starting solutions.

Once again there is very little difference between the two local search types. Under both types of local searches, the '*best yet*' solution occurs in the 14^{th} generation. Although it takes longer for the one-bit local search to iterate in this generation than it did with the other type of local search. The best solutions until the 9^{th} generation were better from mask-based local search than from one-bit local search.

The 100 Pops instances definitely result in higher solution quality. Out of the 500 runs conducted with a pool size of 100, a very healthy 150 of them returned the '*best yet*' solution. This population size is definitely better than the other two, since the success rate is 30% while it is 25% and 12.5% respectively, for 50 Pops and 30 Pops gene pool sizes.

Best-Solution: Decoding

The **best solution** in instances with propane and chlorine contains the same itineraries. From an interpretational perspective, there is no change in traffic routing, blocking paths for traffic-classes, and number of trains of different types. The only difference between the two cases is the population exposure or risk-values. With chlorine the number of persons exposed with similar hazmat volume increases, since the IDLH levels are persistent at lower ppm levels compared to propane. This lower IDLH level implies a larger hazard area, since toxic levels of concern are present until a longer distance thereby increasing the threshold distances.

Best Possible Solution for Chlorine Weighted Objective Value =1080219											
SL1	=	1	TTR1	=	1	CK1	=	1	SHS1	=	1
ST1	=	1	TSH1	=	1	CO4	=	1	SHL1	=	1
SK1	=	1	TQC1	=	1	CM1	=	1	SHT1	=	1
SO1	=	1	KS1	=	1	CTR2	=	1	SHK1	=	1
SC1	=	1	KL2	=	1	CSH2	=	1	SHO2	=	1
SM1	=	1	KT1	=	1	CQC2	=	1	SHC1	=	1
STR1	=	1	KO2	=	1	MS2	=	1	SHM1	=	1
SSH1	=	1	KC1	=	1	ML4	=	1	SHTR1	=	1
SQC1	=	1	KM1	=	1	MT1	=	1	SHQC1	=	1
LS1	=	1	KTR4	=	1	MK1	=	1	QCS1	=	1
LT1	=	1	KSH2	=	1	MO1	=	1	QCL1	=	1
LK1	=	1	KQC2	=	1	MC1	=	1	QCT1	=	1
LO1	=	1	OS1	=	1	MTR2	=	1	QCK1	=	1
LC1	=	1	OL1	=	1	MSH1	=	1	QCO1	=	1
LM1	=	1	OT1	=	1	MQC1	=	1	QCC1	=	1
LTR1	=	1	OK2	=	1	TRS2	=	1	QCM1	=	1
LSH1	=	1	OC2	=	1	TRL1	=	1	QCTR1	=	1
LQC1	=	1	OM2	=	1	TRT1	=	1	QCSH1	=	1
TS1	=	1	OTR1	=	1	TRK1	=	1	N(96)	=	3
TL1	=	1	OSH2	=	1	TRO1	=	1	N(80)	=	2
TK1	=	1	OQC2	=	1	TRC1	=	1	N(90)	=	2
TO1	=	1	CS1	=	1	TRM1	=	1	N(72)	=	2
TC1	=	1	CL2	=	1	TRSH1	=	1	N(82)	=	3
TM1	=	1	CT1	=	1	TRQC1	=	1	N(62)	=	2

Table A. 15: Best Solution for Chlorine

Appendix B: Chapter 5

5-B.1: *OTHER NINE SHIPPERS*

FEASIBLE ROUTES: Boucherville to various Receivers																					
Regular Intermodal Service:		97	hrs.			Lachine Yard Loading:			1	hr.				Loading @ Shipper:			2	hrs.			
Edmonton Swap Stop:		6	hrs.			Vancouver Yard Unloading:			1	hr.				Unloading @ Receiver:			2	hrs.			
INBOUND Drayage		Path 1					Path 2					Path 3					Path 4				
Time in *HOURS*		1.84					1.792					2.28					2.5				
OUTBOUND Drayage (Paths)		1	2	3	4	5	1	2	3	4	5	1	2	3	4	5	1	2	3	4	5
	Kelowna	9.70	7.35	7.34	7.37	7.46	9.70	7.35	7.34	7.37	7.46	9.70	7.35	7.34	7.37	7.46	9.70	7.35	7.34	7.37	7.46
	Kamloops	7.88	6.96	7.23	7.20	7.09	7.88	6.96	7.23	7.20	7.09	7.88	6.96	7.23	7.20	7.09	7.88	6.96	7.23	7.20	7.09
	Burnaby	0.26	0.35	0.32	0.47		0.26	0.35	0.32	0.47		0.26	0.35	0.32	0.47		0.26	0.35	0.32	0.47	
	Surrey	0.70	0.96	1.20	0.76	0.77	0.70	0.96	1.20	0.76	0.77	0.70	0.96	1.20	0.76	0.77	0.70	0.96	1.20	0.76	0.77
	Richmond	0.27	0.28	0.58	0.36		0.27	0.28	0.58	0.36		0.27	0.28	0.58	0.36		0.27	0.28	0.58	0.36	
	Haney	0.86	0.83	0.80			0.86	0.83	0.80			0.86	0.83	0.80			0.86	0.83	0.80		
	Coquitlam	0.57	0.60	0.74			0.57	0.60	0.74			0.57	0.60	0.74			0.57	0.60	0.74		
	Forest Hills	0.28	0.48	0.47			0.28	0.48	0.47			0.28	0.48	0.47			0.28	0.48	0.47		
	Pr-George	13.22	18.27	18.40	18.33	18.34	13.22	18.27	18.40	18.33	18.34	13.22	18.27	18.40	18.33	18.34	13.22	18.27	18.40	18.33	18.34
	Pr-Rupert	25.66	27.50	27.49	30.53	30.52	25.66	27.50	27.49	30.53	30.52	25.66	27.50	27.49	30.53	30.52	25.66	27.50	27.49	30.53	30.52
Elapsed Time (in DAYS):		1	2	3	4	5	1	2	3	4	5	1	2	3	4	5	1	2	3	4	5
5.0 days	Kelowna	5.02	4.92	4.92	4.93	4.93	5.02	4.92	4.92	4.92	4.93	5.04	4.94	4.94	4.94	4.95	5.05	4.95	4.95	4.95	4.96
	Kamloops	4.95	4.91	4.92	4.92	4.91	4.94	4.91	4.92	4.92	4.91	4.96	4.93	4.94	4.94	4.93	4.97	4.94	4.95	4.95	4.94
4.5 days	Burnaby	4.63	4.63	4.63	4.64		4.63	4.63	4.63	4.64		4.65	4.65	4.65	4.66		4.66	4.66	4.66	4.67	
	Surrey	4.65	4.66	4.67	4.65	4.65	4.65	4.66	4.67	4.65	4.65	4.67	4.68	4.69	4.67	4.67	4.68	4.69	4.70	4.68	4.68
	Richmond	4.63	4.63	4.64	4.63		4.63	4.63	4.64	4.63		4.65	4.65	4.66	4.65		4.66	4.66	4.67	4.66	
4.0 days	Haney	4.65	4.65	4.65			4.65	4.65	4.65			4.67	4.67	4.67			4.68	4.68	4.68		
	Coquitlam	4.64	4.64	4.65			4.64	4.64	4.65			4.66	4.66	4.67			4.67	4.67	4.68		
	Forest Hills	4.63	4.64	4.64			4.63	4.64	4.64			4.65	4.66	4.66			4.66	4.67	4.67		
6.0 days	Pr-George	5.17	5.38	5.38	5.38	5.38	5.17	5.38	5.38	5.38	5.38	5.19	5.40	5.40	5.40	5.40	5.20	5.41	5.41	5.41	5.41
	Pr-Rupert	5.69	5.76	5.76	5.89	5.89	5.69	5.76	5.76	5.89	5.89	5.71	5.78	5.78	5.91	5.91	5.72	5.79	5.79	5.92	5.92
FEASIBLE ROUTES: Boucherville to various Receivers																					
Premium Intermodal Service: 73 hours																					
Elapsed Time (in DAYS):		1	2	3	4	5	1	2	3	4	5	1	2	3	4	5	1	2	3	4	5
5.0 days	Kelowna	4.02	3.92	3.92	3.93	3.93	4.02	3.92	3.92	3.92	3.93	4.04	3.94	3.94	3.94	3.95	4.05	3.95	3.95	3.95	3.96
	Kamloops	3.95	3.91	3.92	3.92	3.91	3.94	3.91	3.92	3.92	3.91	3.96	3.93	3.94	3.94	3.93	3.97	3.94	3.95	3.95	3.94
4.5 days	Burnaby	3.63	3.63	3.63	3.64		3.63	3.63	3.63	3.64		3.65	3.65	3.65	3.66		3.66	3.66	3.66	3.67	
	Surrey	3.65	3.66	3.67	3.65	3.65	3.65	3.66	3.67	3.65	3.65	3.67	3.68	3.69	3.67	3.67	3.68	3.69	3.70	3.68	3.68
	Richmond	3.63	3.63	3.64	3.63		3.63	3.63	3.64	3.63		3.65	3.65	3.66	3.65		3.66	3.66	3.67	3.66	
4.0 days	Haney	3.65	3.65	3.65			3.65	3.65	3.65			3.67	3.67	3.67			3.68	3.68	3.68		
	Coquitlam	3.64	3.64	3.65			3.64	3.64	3.65			3.66	3.66	3.67			3.67	3.67	3.68		
	Forest Hills	3.63	3.64	3.64			3.63	3.64	3.64			3.65	3.66	3.66			3.66	3.67	3.67		
6.0 days	Pr-George	4.17	4.38	4.38	4.38	4.38	4.17	4.38	4.38	4.38	4.38	4.19	4.40	4.40	4.40	4.40	4.20	4.41	4.41	4.41	4.41
	Pr-Rupert	4.69	4.76	4.76	4.89	4.89	4.69	4.76	4.76	4.89	4.89	4.71	4.78	4.78	4.91	4.91	4.72	4.79	4.79	4.92	4.92

Table B.1: For Shipper at *BOUCHERVILLE*

Table B.1 represents the feasible and infeasible intermodal options for the shipper at Boucherville. Just as before the shaded region implies infeasibility with the regular intermodal service. The shaded regions with the Premium intermodal service means that these routes are not being used, since they were already feasible with the regular service.

The shaded regions for premium intermodal service in each of the tables below also indicate that these particular routes are not being used, since they were feasible with the regular intermodal service.

FEASIBLE ROUTES: Saint Hubert to various Receivers.

Regular Intermodal Service:	97	hrs.	Lachine Yard Loading:	1	hr.	Loading @ Shipper:	2	hrs.
Edmonton Swap Stop:	6	hrs.	Vancouver Yard Unloading:	1	hr.	Unloading @ Receiver:	2	hrs.

INBOUND Drayage	Path 1					Path 2					Path 3					Path 4				
Time in *HOURS*	1.72					2.08					2					2.32				
OUTBOUND Drayage (Paths)	1	2	3	4	5	1	2	3	4	5	1	2	3	4	5	1	2	3	4	5
Kelowna	9.70	7.35	7.34	7.37	7.46	9.70	7.35	7.34	7.37	7.46	9.70	7.35	7.34	7.37	7.46	9.70	7.35	7.34	7.37	7.46
Kamloops	7.88	6.96	7.23	7.20	7.09	7.88	6.96	7.23	7.20	7.09	7.88	6.96	7.23	7.20	7.09	7.88	6.96	7.23	7.20	7.09
Burnaby	0.26	0.35	0.32	0.47		0.26	0.35	0.32	0.47		0.26	0.35	0.32	0.47		0.26	0.35	0.32	0.47	
Surrey	0.70	0.96	1.20	0.76	0.77	0.70	0.96	1.20	0.76	0.77	0.70	0.96	1.20	0.76	0.77	0.70	0.96	1.20	0.76	0.77
Richmond	0.27	0.28	0.58	0.36		0.27	0.28	0.58	0.36		0.27	0.28	0.58	0.36		0.27	0.28	0.58	0.36	
Haney	0.86	0.83	0.80			0.86	0.83	0.80			0.86	0.83	0.80			0.86	0.83	0.80		
Coquitlam	0.57	0.60	0.74			0.57	0.60	0.74			0.57	0.60	0.74			0.57	0.60	0.74		
Forest Hills	0.28	0.48	0.47			0.28	0.48	0.47			0.28	0.48	0.47			0.28	0.48	0.47		
Pr-George	13.22	18.27	18.40	18.33	18.34	13.22	18.27	18.40	18.33	18.34	13.22	18.27	18.40	18.33	18.34	13.22	18.27	18.40	18.33	18.34
Pr-Rupert	25.66	27.50	27.49	30.53	30.52	25.66	27.50	27.49	30.53	30.52	25.66	27.50	27.49	30.53	30.52	25.66	27.50	27.49	30.53	30.52

	Elapsed Time (in DAYS):	1	2	3	4	5	1	2	3	4	5	1	2	3	4	5	1	2	3	4	5
5.0 days	Kelowna	5.02	4.92	4.92	4.92	4.92	5.03	4.93	4.93	4.94	4.94	5.03	4.93	4.93	4.93	4.94	5.04	4.94	4.94	4.95	4.95
	Kamloops	4.94	4.90	4.91	4.91	4.91	4.96	4.92	4.93	4.93	4.92	4.95	4.92	4.93	4.93	4.92	4.97	4.93	4.94	4.94	4.93
4.5 days	Burnaby	4.62	4.63	4.63	4.63		4.64	4.64	4.64	4.65		4.64	4.64	4.64	4.64		4.65	4.65	4.65	4.66	
	Surrey	4.64	4.65	4.66	4.64	4.65	4.66	4.67	4.68	4.66	4.66	4.65	4.67	4.68	4.66	4.66	4.67	4.68	4.69	4.67	4.67
	Richmond	4.62	4.63	4.64	4.63		4.64	4.64	4.65	4.64		4.64	4.64	4.65	4.64		4.65	4.65	4.66	4.65	
4.0 days	Haney	4.65	4.65	4.65			4.66	4.66	4.66			4.66	4.66	4.66			4.67	4.67	4.67		
	Coquitlam	4.64	4.64	4.64			4.65	4.65	4.66			4.65	4.65	4.66			4.66	4.66	4.67		
	Forest Hills	4.63	4.63	4.63			4.64	4.65	4.65			4.64	4.65	4.64			4.65	4.66	4.66		
6.0 days	Pr-George	5.16	5.37	5.38	5.38	5.38	5.18	5.39	5.39	5.39	5.39	5.18	5.39	5.39	5.39	5.39	5.19	5.40	5.40	5.40	5.40
	Pr-Rupert	5.68	5.76	5.76	5.89	5.88	5.70	5.77	5.77	5.90	5.90	5.69	5.77	5.77	5.90	5.90	5.71	5.78	5.78	5.91	5.91

FEASIBLE ROUTES: Saint Hubert to various Receivers.

Premium Intermodal Service: 73 hours

	Elapsed Time (in DAYS):	1	2	3	4	5	1	2	3	4	5	1	2	3	4	5	1	2	3	4	5
5.0 days	Kelowna	4.02	3.92	3.92	3.92	3.92	4.03	3.93	3.93	3.94	3.94	4.03	3.93	3.93	3.93	3.94	4.04	3.94	3.94	3.95	3.95
	Kamloops	3.94	3.90	3.91	3.91	3.91	3.96	3.92	3.93	3.93	3.92	3.95	3.92	3.93	3.93	3.92	3.97	3.93	3.94	3.94	3.93
4.5 days	Burnaby	3.62	3.63	3.63	3.63		3.64	3.64	3.64	3.65		3.64	3.64	3.64	3.64		3.65	3.65	3.65	3.66	
	Surrey	3.64	3.65	3.66	3.64	3.65	3.66	3.67	3.68	3.66	3.66	3.65	3.67	3.68	3.66	3.66	3.67	3.68	3.69	3.67	3.67
	Richmond	3.62	3.63	3.64	3.63		3.64	3.64	3.65	3.64		3.64	3.64	3.65	3.64		3.65	3.65	3.66	3.65	
4.0 days	Haney	3.65	3.65	3.65			3.66	3.66	3.66			3.66	3.66	3.66			3.67	3.67	3.67		
	Coquitlam	3.64	3.64	3.64			3.65	3.65	3.66			3.65	3.65	3.66			3.66	3.66	3.67		
	Forest Hills	3.63	3.63	3.63			3.64	3.65	3.65			3.64	3.65	3.64			3.65	3.66	3.66		
6.0 days	Pr-George	4.16	4.37	4.38	4.38	4.38	4.18	4.39	4.39	4.39	4.39	4.18	4.39	4.39	4.39	4.39	4.19	4.40	4.40	4.40	4.40
	Pr-Rupert	4.68	4.76	4.76	4.89	4.88	4.70	4.77	4.77	4.90	4.90	4.69	4.77	4.77	4.90	4.90	4.71	4.78	4.78	4.91	4.91

Table B.2: For Shipper at *SAINT HUBERT*

Table B.2 presents the feasible routes (unshaded) for the shipper at *Saint Hubert*. Because of the time specification of the receivers at *Burnaby, Surrey, Richmond, Haney, Coquitlam* and *Forest Hills*, their shipments cannot take the regular service and arrive on time. Just like before these shipments would have to take premium service at a higher price in order to reach their destinations within specified time.

Table B.3 presents the viable options for the shipper at *Brossard*. Once again the shaded cells indicate infeasible options, while the normal ones are feasible ones. The six receivers (as above) cannot expect to receive their shipments within the desired time, if regular intermodal trains are used to move them from Montreal to Vancouver. These shipments need to be loaded onto the premium train service in order to reach their destinations on time.

Table B.4 depicts the feasible options for the shippers at *Chateauguay*. Once again the shaded and normal cells indicate violations and viability, respectively. The six locations in and around Vancouver cannot have their demands met using regular intermodal option, and the shippers have to use the premium service for these deliveries.

FEASIBLE ROUTES: Brossard to various Receivers.

Regular Intermodal Service: 97 hrs. | Edmonton Swap Stop: 6 hrs. | Lachine Yard Loading: 1 hr. | Vancouver Yard Unloading: 1 hr. | Loading @ Shipper: 2 hrs. | Unloading @ Receiver: 2 hrs.

INBOUND Drayage	Path 1					Path 2					Path 3				
Time in *HOURS*	1.59					1.85					2.06				
OUTBOUND Drayage (Paths)	1	2	3	4	5	1	2	3	4	5	1	2	3	4	5
Kelowna	9.70	7.35	7.34	7.37	7.46	9.70	7.35	7.34	7.37	7.46	9.70	7.35	7.34	7.37	7.46
Kamloops	7.88	6.96	7.23	7.20	7.09	7.88	6.96	7.23	7.20	7.09	7.88	6.96	7.23	7.20	7.09
Burnaby	0.26	0.35	0.32	0.47		0.26	0.35	0.32	0.47		0.26	0.35	0.32	0.47	
Surrey	0.70	0.96	1.20	0.76	0.77	0.70	0.96	1.20	0.76	0.77	0.70	0.96	1.20	0.76	0.77
Richmond	0.27	0.28	0.58	0.36		0.27	0.28	0.58	0.36		0.27	0.28	0.58	0.36	
Haney	0.86	0.83	0.80			0.86	0.83	0.80			0.86	0.83	0.80		
Coquitlam	0.57	0.60	0.74			0.57	0.60	0.74			0.57	0.60	0.74		
Forest Hills	0.28	0.48	0.47			0.28	0.48	0.47			0.28	0.48	0.47		
Pr-George	13.22	18.27	18.40	18.33	18.34	13.22	18.27	18.40	18.33	18.34	13.22	18.27	18.40	18.33	18.34
Pr-Rupert	25.66	27.50	27.49	30.53	30.52	25.66	27.50	27.49	30.53	30.52	25.66	27.50	27.49	30.53	30.52

Elapsed Time (in DAYS):	1	2	3	4	5	1	2	3	4	5	1	2	3	4	5
5.0 days — Kelowna	5.01	4.91	4.91	4.92	4.92	5.02	4.93	4.92	4.93	4.93	5.03	4.93	4.93	4.93	4.94
Kamloops	4.94	4.90	4.91	4.91	4.90	4.95	4.91	4.92	4.92	4.91	4.96	4.92	4.93	4.93	4.92
4.5 days — Burnaby	4.62	4.62	4.62	4.63		4.63	4.63	4.63	4.64		4.64	4.64	4.64	4.65	
Surrey	4.64	4.65	4.66	4.64	4.64	4.65	4.66	4.67	4.65	4.65	4.66	4.67	4.68	4.66	4.66
Richmond	4.62	4.62	4.63	4.62		4.63	4.63	4.64	4.63		4.64	4.64	4.65	4.64	
4.0 days — Haney	4.64	4.64	4.64			4.65	4.65	4.65			4.66	4.66	4.66		
Coquitlam	4.63	4.63	4.64			4.64	4.64	4.65			4.65	4.65	4.66		
Forest Hills	4.62	4.63	4.63			4.63	4.64	4.64			4.64	4.65	4.65		
6.0 days — Pr-George	5.16	5.37	5.37	5.37	5.37	5.17	5.38	5.39	5.38	5.38	5.18	5.39	5.39	5.39	5.39
Pr-Rupert	5.68	5.75	5.75	5.88	5.88	5.69	5.76	5.76	5.89	5.89	5.70	5.77	5.77	5.90	5.90

FEASIBLE ROUTES: Brossard to various Receivers.

Premium Intermodal Service: 73 hours

Elapsed Time (in DAYS):	1	2	3	4	5	1	2	3	4	5	1	2	3	4	5
5.0 days — Kelowna	4.01	3.91	3.91	3.92	3.92	4.02	3.93	3.92	3.93	3.93	4.03	3.93	3.93	3.93	3.94
Kamloops	3.94	3.90	3.91	3.91	3.90	3.95	3.91	3.92	3.92	3.91	3.96	3.92	3.93	3.93	3.92
4.5 days — Burnaby	3.62	3.62	3.62	3.63		3.63	3.63	3.63	3.64		3.64	3.64	3.64	3.65	
Surrey	3.64	3.65	3.66	3.64	3.64	3.65	3.66	3.67	3.65	3.65	3.66	3.67	3.68	3.66	3.66
Richmond	3.62	3.62	3.63	3.62		3.63	3.63	3.64	3.63		3.64	3.64	3.65	3.64	
4.0 days — Haney	3.64	3.64	3.64			3.65	3.65	3.65			3.66	3.66	3.66		
Coquitlam	3.63	3.63	3.64			3.64	3.64	3.65			3.65	3.65	3.66		
Forest Hills	3.62	3.63	3.63			3.63	3.64	3.64			3.64	3.65	3.65		
6.0 days — Pr-George	4.16	4.37	4.37	4.37	4.37	4.17	4.38	4.39	4.38	4.38	4.18	4.39	4.39	4.39	4.39
Pr-Rupert	4.68	4.75	4.75	4.88	4.88	4.69	4.76	4.76	4.89	4.89	4.70	4.77	4.77	4.90	4.90

Table B.3: For Shipper at *BROSSARD*

FEASIBLE ROUTES: Chateauguay to various Receivers.

Regular Intermodal Service: 97 hrs. | Edmonton Swap Stop: 6 hrs. | Lachine Yard Loading: 1 hr. | Vancouver Yard Unloading: 1 hr. | Loading @ Shipper: 2 hrs. | Unloading @ Receiver: 2 hrs.

INBOUND Drayage	Path 1					Path 2					Path 3					Path 4				
Time in *HOURS*	1.59					1.7					1.78					2.37				
OUTBOUND Drayage (Paths)	1	2	3	4	5	1	2	3	4	5	1	2	3	4	5	1	2	3	4	5
Kelowna	9.70	7.35	7.34	7.37	7.46	9.70	7.35	7.34	7.37	7.46	9.70	7.35	7.34	7.37	7.46	9.70	7.35	7.34	7.37	7.46
Kamloops	7.88	6.96	7.23	7.20	7.09	7.88	6.96	7.23	7.20	7.09	7.88	6.96	7.23	7.20	7.09	7.88	6.96	7.23	7.20	7.09
Burnaby	0.26	0.35	0.32	0.47		0.26	0.35	0.32	0.47		0.26	0.35	0.32	0.47		0.26	0.35	0.32	0.47	
Surrey	0.70	0.96	1.20	0.76	0.77	0.70	0.96	1.20	0.76	0.77	0.70	0.96	1.20	0.76	0.77	0.70	0.96	1.20	0.76	0.77
Richmond	0.27	0.28	0.58	0.36		0.27	0.28	0.58	0.36		0.27	0.28	0.58	0.36		0.27	0.28	0.58	0.36	
Haney	0.86	0.83	0.80			0.86	0.83	0.80			0.86	0.83	0.80			0.86	0.83	0.80		
Coquitlam	0.57	0.60	0.74			0.57	0.60	0.74			0.57	0.60	0.74			0.57	0.60	0.74		
Forest Hills	0.28	0.48	0.47			0.28	0.48	0.47			0.28	0.48	0.47			0.28	0.48	0.47		
Pr-George	13.22	18.27	18.40	18.33	18.34	13.22	18.27	18.40	18.33	18.34	13.22	18.27	18.40	18.33	18.34	13.22	18.27	18.40	18.33	18.34
Pr-Rupert	25.66	27.50	27.49	30.53	30.52	25.66	27.50	27.49	30.53	30.52	25.66	27.50	27.49	30.53	30.52	25.66	27.50	27.49	30.53	30.52

Elapsed Time (in DAYS):	1	2	3	4	5	1	2	3	4	5	1	2	3	4	5	1	2	3	4	5
5.0 days — Kelowna	5.01	4.91	4.91	4.92	4.92	5.02	4.92	4.92	4.92	4.92	5.02	4.92	4.92	4.92	4.93	5.04	4.95	4.95	4.95	4.95
Kamloops	4.94	4.90	4.91	4.91	4.90	4.94	4.90	4.91	4.91	4.91	4.94	4.91	4.92	4.92	4.91	4.97	4.93	4.94	4.94	4.94
4.5 days — Burnaby	4.62	4.62	4.62	4.63		4.62	4.63	4.63	4.63		4.63	4.63	4.63	4.64		4.65	4.66	4.65	4.66	
Surrey	4.64	4.65	4.66	4.64	4.64	4.64	4.65	4.66	4.64	4.64	4.65	4.66	4.67	4.65	4.65	4.67	4.68	4.69	4.67	4.67
Richmond	4.62	4.62	4.63	4.62		4.62	4.62	4.64	4.63		4.63	4.63	4.64	4.63		4.65	4.65	4.66	4.66	
4.0 days — Haney	4.64	4.64	4.64			4.65	4.65	4.65			4.65	4.65	4.65			4.68	4.67	4.67		
Coquitlam	4.63	4.63	4.64			4.64	4.64	4.64			4.64	4.64	4.65			4.66	4.67	4.67		
Forest Hills	4.62	4.63	4.63			4.62	4.63	4.63			4.63	4.64	4.64			4.65	4.66	4.66		
6.0 days — Pr-George	5.16	5.37	5.37	5.37	5.37	5.16	5.37	5.38	5.38	5.38	5.17	5.38	5.38	5.38	5.38	5.19	5.40	5.41	5.40	5.40
Pr-Rupert	5.68	5.75	5.75	5.88	5.88	5.68	5.76	5.76	5.88	5.88	5.69	5.76	5.76	5.89	5.89	5.71	5.79	5.79	5.91	5.91

FEASIBLE ROUTES: Chateauguay to various Receivers.

Premium Intermodal Service: 73 hours

Elapsed Time (in DAYS):	1	2	3	4	5	1	2	3	4	5	1	2	3	4	5	1	2	3	4	5
5.0 days — Kelowna	4.01	3.91	3.91	3.92	3.92	4.02	3.92	3.92	3.92	3.92	4.02	3.92	3.92	3.92	3.93	4.04	3.95	3.95	3.95	3.95
Kamloops	3.94	3.90	3.91	3.91	3.90	3.94	3.90	3.91	3.91	3.91	3.94	3.91	3.92	3.92	3.91	3.97	3.93	3.94	3.94	3.94
4.5 days — Burnaby	3.62	3.62	3.62	3.63		3.62	3.63	3.63	3.63		3.63	3.63	3.63	3.64		3.65	3.66	3.65	3.66	
Surrey	3.64	3.65	3.66	3.64	3.64	3.64	3.65	3.66	3.64	3.64	3.65	3.66	3.67	3.65	3.65	3.67	3.68	3.69	3.67	3.67
Richmond	3.62	3.62	3.63	3.62		3.62	3.62	3.64	3.63		3.63	3.63	3.64	3.63		3.65	3.65	3.66	3.66	
4.0 days — Haney	3.64	3.64	3.64			3.65	3.65	3.65			3.65	3.65	3.65			3.68	3.67	3.67		
Coquitlam	3.63	3.63	3.64			3.64	3.64	3.64			3.64	3.64	3.65			3.66	3.67	3.67		
Forest Hills	3.62	3.63	3.63			3.62	3.63	3.63			3.63	3.64	3.64			3.65	3.66	3.66		
6.0 days — Pr-George	4.16	4.37	4.37	4.37	4.37	4.16	4.37	4.38	4.38	4.38	4.17	4.38	4.38	4.38	4.38	4.19	4.40	4.41	4.40	4.40
Pr-Rupert	4.68	4.75	4.75	4.88	4.88	4.68	4.76	4.76	4.88	4.88	4.69	4.76	4.76	4.89	4.89	4.71	4.79	4.79	4.91	4.91

Table B.4: For Shipper at *CHATEAUGUAY*

Elapsed Time (Days)			5.0 days		4.5 days			4.0 days			6.0 days	
Path	hrs.	Paths	Kelowna	Kamloops	Burnaby	Surrey	Richmond	Haney	Coquitlam	Forest Hills	Pr-George	Pr-Rupert
		1	5.00	4.93	4.61	4.63	4.61	4.64	4.62	4.61	5.15	5.67
		2	4.91	4.89	4.61	4.64	4.61	4.63	4.62	4.62	5.36	5.75
		3	4.91	4.90	4.61	4.65	4.62	4.63	4.63	4.62	5.37	5.74
		4	4.91	4.90	4.62	4.63	4.61				5.36	5.87
1	1.39	5	4.91	4.89		4.63					5.36	5.87
		1	5.05	4.97	4.66	4.67	4.66	4.68	4.67	4.66	5.20	5.71
		2	4.95	4.93	4.66	4.68	4.66	4.68	4.67	4.66	5.41	5.79
		3	4.95	4.95	4.66	4.69	4.67	4.68	4.67	4.66	5.41	5.79
		4	4.95	4.94	4.66	4.68	4.66				5.41	5.92
2	2.46	5	4.95	4.94		4.68					5.41	5.92
		1	5.04	4.97	4.65	4.67	4.65	4.68	4.66	4.65	5.19	5.71
		2	4.95	4.93	4.65	4.68	4.66	4.67	4.67	4.66	5.40	5.79
		3	4.95	4.94	4.65	4.69	4.66	4.67	4.67	4.66	5.41	5.79
		4	4.95	4.94	4.66	4.67	4.65				5.40	5.91
3	2.36	5	4.95	4.94		4.67					5.40	5.91
		1	5.06	4.98	4.67	4.68	4.67	4.69	4.68	4.67	5.21	5.72
		2	4.96	4.94	4.67	4.69	4.67	4.69	4.68	4.67	5.42	5.80
		3	4.96	4.96	4.67	4.70	4.68	4.69	4.68	4.67	5.42	5.80
		4	4.96	4.95	4.67	4.69	4.67				5.42	5.93
4	2.7	5	4.96	4.95		4.69					5.42	5.93
		1	5.06	4.98	4.67	4.68	4.67	4.69	4.68	4.67	5.21	5.72
		2	4.96	4.94	4.67	4.69	4.67	4.69	4.68	4.67	5.42	5.80
		3	4.96	4.96	4.67	4.70	4.68	4.69	4.68	4.67	5.42	5.80
		4	4.96	4.95	4.67	4.69	4.67				5.42	5.93
5	2.76	5	4.96	4.95		4.69					5.42	5.93

FEASIBLE ROUTES: Using Premium Intermodal Service												
Elapsed Time (Days)			5.0 days		4.5 days			4.0 days			6.0 days	
Path	hrs.	Paths	Kelowna	Kamloops	Burnaby	Surrey	Richmond	Haney	Coquitlam	Forest Hills	Pr-George	Pr-Rupert
		1	4.00	3.93	3.61	3.63	3.61	3.64	3.62	3.61	4.15	4.67
		2	3.91	3.89	3.61	3.64	3.61	3.63	3.62	3.62	4.36	4.75
		3	3.91	3.90	3.61	3.65	3.62	3.63	3.63	3.62	4.37	4.74
		4	3.91	3.90	3.62	3.63	3.61				4.36	4.87
1	1.39	5	3.91	3.89		3.63					4.36	4.87
		1	4.05	3.97	3.66	3.67	3.66	3.68	3.67	3.66	4.20	4.71
		2	3.95	3.93	3.66	3.68	3.66	3.68	3.67	3.66	4.41	4.79
		3	3.95	3.95	3.66	3.69	3.67	3.68	3.67	3.66	4.41	4.79
		4	3.95	3.94	3.66	3.68	3.66				4.41	4.92
2	2.46	5	3.95	3.94		3.68					4.41	4.92
		1	4.04	3.97	3.65	3.67	3.65	3.68	3.66	3.65	4.19	4.71
		2	3.95	3.93	3.65	3.68	3.65	3.67	3.67	3.66	4.40	4.79
		3	3.95	3.94	3.65	3.69	3.66	3.67	3.67	3.66	4.41	4.79
		4	3.95	3.94	3.66	3.67	3.65				4.40	4.91
3	2.36	5	3.95	3.94		3.67					4.40	4.91
		1	4.06	3.98	3.67	3.68	3.67	3.69	3.68	3.67	4.21	4.72
		2	3.96	3.94	3.67	3.69	3.67	3.69	3.68	3.67	4.42	4.80
		3	3.96	3.96	3.67	3.70	3.68	3.69	3.68	3.67	4.42	4.80
		4	3.96	3.95	3.67	3.69	3.67				4.42	4.93
4	2.7	5	3.96	3.95		3.69					4.42	4.93
		1	4.06	3.98	3.67	3.68	3.67	3.69	3.68	3.67	4.21	4.72
		2	3.96	3.94	3.67	3.69	3.67	3.69	3.68	3.67	4.42	4.80
		3	3.96	3.96	3.67	3.70	3.68	3.69	3.68	3.67	4.42	4.80
		4	3.96	3.95	3.67	3.69	3.67				4.42	4.93
5	2.76	5	3.96	3.95		3.69					4.42	4.93

FEASIBLE ROUTES: Beaconsfield to various Receivers												
		Regular Intermodal Servivce:		97 hrs.		Lachine Yard Loading: 1 hr.			Loading @ Shipper: 2 hrs.			
		Edmonton Swap Stop:		6 hrs.		Vancouver Yard Unloading: 1 hr.			Unloading @ Receiver: 2 hrs.			
Inbound Drayage		Outbound Drayage										
Path	hrs.	Paths	Kelowna	Kamloops	Burnaby	Surrey	Richmond	Haney	Coquitlam	Forest Hills	Pr-George	Pr-Rupert
		1	9.70	7.88	0.26	0.70	0.27	0.86	0.57	0.28	13.22	25.66
		2	7.35	6.96	0.35	0.96	0.28	0.83	0.60	0.48	18.27	27.50
		3	7.34	7.23	0.32	1.20	0.58	0.80	0.74	0.47	18.40	27.49
		4	7.37	7.20	0.47	0.76	0.36				18.33	30.53
1	1.39	5	7.46	7.09		0.77					18.34	30.52
		1	9.70	7.88	0.26	0.70	0.27	0.86	0.57	0.28	13.22	25.66
		2	7.35	6.96	0.35	0.96	0.28	0.83	0.60	0.48	18.27	27.50
		3	7.34	7.23	0.32	1.20	0.58	0.80	0.74	0.47	18.40	27.49
		4	7.37	7.20	0.47	0.76	0.36				18.33	30.53
2	2.46	5	7.46	7.09		0.77					18.34	30.52
		1	9.70	7.88	0.26	0.70	0.27	0.86	0.57	0.28	13.22	25.66
		2	7.35	6.96	0.35	0.96	0.28	0.83	0.60	0.48	18.27	27.50
		3	7.34	7.23	0.32	1.20	0.58	0.80	0.74	0.47	18.40	27.49
		4	7.37	7.20	0.47	0.76	0.36				18.33	30.53
3	2.36	5	7.46	7.09		0.77					18.34	30.52
		1	9.70	7.88	0.26	0.70	0.27	0.86	0.57	0.28	13.22	25.66
		2	7.35	6.96	0.35	0.96	0.28	0.83	0.60	0.48	18.27	27.50
		3	7.34	7.23	0.32	1.20	0.58	0.80	0.74	0.47	18.40	27.49
		4	7.37	7.20	0.47	0.76	0.36				18.33	30.53
4	2.7	5	7.46	7.09		0.77					18.34	30.52
		1	9.70	7.88	0.26	0.70	0.27	0.86	0.57	0.28	13.22	25.66
		2	7.35	6.96	0.35	0.96	0.28	0.83	0.60	0.48	18.27	27.50
		3	7.34	7.23	0.32	1.20	0.58	0.80	0.74	0.47	18.40	27.49
		4	7.37	7.20	0.47	0.76	0.36				18.33	30.53
5	2.76	5	7.46	7.09		0.77					18.34	30.52

Table B.5: For Shipper at *BEACONSFIELD*

Table B.5 represents the viable options for the shipper at *Beaconsfield*. The number of possible paths on the inward drayage is five, and to be able to visually reprsesent all the possibilities a new template has been created as above. Once again the interpretations are identical.

FEASIBLE ROUTES: Kirkland to various Receivers

Regular Intermodal Servivce: 97 hrs. Lachine Yard Loading: 1 hr. Loading @ Shipper: 2 hrs.
Edmonton Swap Stop: 6 hrs. Vancouver Yard Unloading: 1 hr. Unloading @ Receiver: 2 hrs.

Inbound Drayage		Outbound Drayage										
Path	hrs.	Paths	*Kelowna*	*Kamloops*	*Burnaby*	*Surrey*	*Richmond*	*Haney*	*Coquitlam*	*Forest Hills*	*Pr-George*	*Pr-Rupert*
		1	9.70	7.88	0.26	0.70	0.27	0.86	0.57	0.28	13.22	25.66
		2	7.35	6.96	0.35	0.96	0.28	0.83	0.60	0.48	18.27	27.50
		3	7.34	7.23	0.32	1.20	0.58	0.80	0.74	0.47	18.40	27.49
		4	7.37	7.20	0.47	0.76	0.36				18.33	30.53
1	1.46	5	7.46	7.09		0.77					18.34	30.52
		1	9.70	7.88	0.26	0.70	0.27	0.86	0.57	0.28	13.22	25.66
		2	7.35	6.96	0.35	0.96	0.28	0.83	0.60	0.48	18.27	27.50
		3	7.34	7.23	0.32	1.20	0.58	0.80	0.74	0.47	18.40	27.49
		4	7.37	7.20	0.47	0.76	0.36				18.33	30.53
2	1.56	5	7.46	7.09		0.77					18.34	30.52
		1	9.70	7.88	0.26	0.70	0.27	0.86	0.57	0.28	13.22	25.66
		2	7.35	6.96	0.35	0.96	0.28	0.83	0.60	0.48	18.27	27.50
		3	7.34	7.23	0.32	1.20	0.58	0.80	0.74	0.47	18.40	27.49
		4	7.37	7.20	0.47	0.76	0.36				18.33	30.53
3	1.58	5	7.46	7.09		0.77					18.34	30.52
		1	9.70	7.88	0.26	0.70	0.27	0.86	0.57	0.28	13.22	25.66
		2	7.35	6.96	0.35	0.96	0.28	0.83	0.60	0.48	18.27	27.50
		3	7.34	7.23	0.32	1.20	0.58	0.80	0.74	0.47	18.40	27.49
		4	7.37	7.20	0.47	0.76	0.36				18.33	30.53
4	1.82	5	7.46	7.09		0.77					18.34	30.52
		1	9.70	7.88	0.26	0.70	0.27	0.86	0.57	0.28	13.22	25.66
		2	7.35	6.96	0.35	0.96	0.28	0.83	0.60	0.48	18.27	27.50
		3	7.34	7.23	0.32	1.20	0.58	0.80	0.74	0.47	18.40	27.49
		4	7.37	7.20	0.47	0.76	0.36				18.33	30.53
5	1.84	5	7.46	7.09		0.77					18.34	30.52

Elapsed Time (Days)			5.0 days		4.5 days			4.0 days			6.0 days	
Path	hrs.	Paths	*Kelowna*	*Kamloops*	*Burnaby*	*Surrey*	*Richmond*	*Haney*	*Coquitlam*	*Forest Hills*	*Pr-George*	*Pr-Rupert*
		1	5.01	4.93	4.61	4.63	4.61	4.64	4.63	4.61	5.15	5.67
		2	4.91	4.89	4.62	4.64	4.61	4.64	4.63	4.62	5.36	5.75
		3	4.91	4.90	4.62	4.65	4.63	4.64	4.63	4.62	5.37	5.75
		4	4.91	4.90	4.62	4.63	4.62				5.37	5.87
1	1.46	5	4.91	4.90		4.63					5.37	5.87
		1	5.01	4.93	4.62	4.64	4.62	4.64	4.63	4.62	5.16	5.68
		2	4.91	4.90	4.62	4.65	4.62	4.64	4.63	4.63	5.37	5.75
		3	4.91	4.91	4.62	4.66	4.63	4.64	4.64	4.63	5.37	5.75
		4	4.91	4.91	4.63	4.64	4.62				5.37	5.88
2	1.56	5	4.92	4.90		4.64					5.37	5.88
		1	5.01	4.94	4.62	4.64	4.62	4.64	4.63	4.62	5.16	5.68
		2	4.91	4.90	4.62	4.65	4.62	4.64	4.63	4.63	5.37	5.75
		3	4.91	4.91	4.62	4.66	4.63	4.64	4.64	4.63	5.37	5.75
		4	4.91	4.91	4.63	4.64	4.62				5.37	5.88
3	1.58	5	4.92	4.90		4.64					5.37	5.88
		1	5.02	4.95	4.63	4.65	4.63	4.65	4.64	4.63	5.17	5.69
		2	4.92	4.91	4.63	4.66	4.63	4.65	4.64	4.64	5.38	5.76
		3	4.92	4.92	4.63	4.67	4.64	4.65	4.65	4.64	5.38	5.76
		4	4.92	4.92	4.64	4.65	4.63				5.38	5.89
4	1.82	5	4.93	4.91		4.65					5.38	5.89
		1	5.02	4.95	4.63	4.65	4.63	4.65	4.64	4.63	5.17	5.69
		2	4.92	4.91	4.63	4.66	4.63	4.65	4.64	4.64	5.38	5.76
		3	4.92	4.92	4.63	4.67	4.64	4.65	4.65	4.64	5.38	5.76
		4	4.93	4.92	4.64	4.65	4.63				5.38	5.89
5	1.84	5	4.93	4.91		4.65					5.38	5.89

FEASIBLE ROUTES: Using Premium Intermodal Service												
Elapsed Time (Days)			5.0 days		4.5 days			4.0 days			6.0 days	
Path	hrs.	Paths	Kelowna	Kamloops	Burnaby	Surrey	Richmond	Haney	Coquitlam	Forest Hills	Pr-George	Pr-Rupert
		1	4.01	3.93	3.61	3.63	3.61	3.64	3.63	3.61	4.16	4.67
		2	3.91	3.89	3.62	3.64	3.61	3.64	3.63	3.62	4.38	4.75
		3	3.91	3.90	3.62	3.65	3.63	3.64	3.63	3.62	4.37	4.75
		4	3.91	3.90	3.62	3.63	3.62				4.37	4.87
1	1.46	5	3.91	3.90		3.63					4.37	4.87
		1	4.01	3.93	3.62	3.64	3.62	3.64	3.63	3.62	4.16	4.68
		2	3.91	3.90	3.62	3.65	3.62	3.64	3.63	3.63	4.37	4.75
		3	3.91	3.91	3.62	3.66	3.63	3.64	3.64	3.63	4.37	4.75
		4	3.91	3.91	3.63	3.64	3.62				4.37	4.88
2	1.56	5	3.92	3.90		3.64					4.37	4.88
		1	4.01	3.94	3.62	3.64	3.62	3.64	3.63	3.62	4.16	4.68
		2	3.91	3.90	3.62	3.65	3.62	3.64	3.63	3.63	4.37	4.75
		3	3.91	3.91	3.62	3.66	3.63	3.64	3.64	3.63	4.37	4.75
		4	3.91	3.91	3.63	3.64	3.62				4.37	4.88
3	1.58	5	3.92	3.90		3.64					4.37	4.88
		1	4.02	3.95	3.63	3.65	3.63	3.65	3.64	3.63	4.17	4.69
		2	3.92	3.91	3.63	3.66	3.63	3.65	3.64	3.64	4.38	4.76
		3	3.92	3.92	3.63	3.67	3.64	3.65	3.65	3.64	4.38	4.76
		4	3.92	3.92	3.64	3.65	3.63				4.38	4.89
4	1.82	5	3.93	3.91		3.65					4.38	4.89
		1	4.02	3.96	3.63	3.65	3.63	3.65	3.64	3.63	4.17	4.69
		2	3.92	3.91	3.63	3.66	3.63	3.65	3.64	3.64	4.38	4.76
		3	3.92	3.92	3.63	3.67	3.64	3.65	3.65	3.64	4.38	4.76
		4	3.93	3.92	3.64	3.65	3.63				4.38	4.89
5	1.84	5	3.93	3.91		3.65					4.38	4.89

Table B.6: For Shipper at *KIRKLAND*

Table B.6 presents the routing options for the shipper at *Kirkland*. The interpretation of the values in cells, and the representation of cells are as before.

FEASIBLE ROUTES: Saint Eustache to various Receivers												
		Regular Intermodal Servivce:	97 hrs.		Lachine Yard Loading: 1 hr.			Loading @ Shipper: 2 hrs.				
		Edmonton Swap Stop:	6 hrs.		Vancouver Yard Unloading: 1 hr.			Unloading @ Receiver: 2 hrs.				
Inbound Drayage						Outbound Drayage						
Path	hrs.	Paths	Kelowna	Kamloops	Burnaby	Surrey	Richmond	Haney	Coquitlam	Forest Hills	Pr-George	Pr-Rupert
		1	9.70	7.88	0.26	0.70	0.27	0.86	0.57	0.28	13.22	25.66
		2	7.35	6.96	0.35	0.96	0.28	0.83	0.60	0.48	18.27	27.50
		3	7.34	7.23	0.32	1.20	0.58	0.80	0.74	0.47	18.40	27.49
		4	7.37	7.20	0.47	0.76	0.36				18.33	30.53
1	1.83	5	7.46	7.09		0.77					18.34	30.52
		1	9.70	7.88	0.26	0.70	0.27	0.86	0.57	0.28	13.22	25.66
		2	7.35	6.96	0.35	0.96	0.28	0.83	0.60	0.48	18.27	27.50
		3	7.34	7.23	0.32	1.20	0.58	0.80	0.74	0.47	18.40	27.49
		4	7.37	7.20	0.47	0.76	0.36				18.33	30.53
2	1.8	5	7.46	7.09		0.77					18.34	30.52
		1	9.70	7.88	0.26	0.70	0.27	0.86	0.57	0.28	13.22	25.66
		2	7.35	6.96	0.35	0.96	0.28	0.83	0.60	0.48	18.27	27.50
		3	7.34	7.23	0.32	1.20	0.58	0.80	0.74	0.47	18.40	27.49
		4	7.37	7.20	0.47	0.76	0.36				18.33	30.53
3	1.77	5	7.46	7.09		0.77					18.34	30.52
		1	9.70	7.88	0.26	0.70	0.27	0.86	0.57	0.28	13.22	25.66
		2	7.35	6.96	0.35	0.96	0.28	0.83	0.60	0.48	18.27	27.50
		3	7.34	7.23	0.32	1.20	0.58	0.80	0.74	0.47	18.40	27.49
		4	7.37	7.20	0.47	0.76	0.36				18.33	30.53
4	2.11	5	7.46	7.09		0.77					18.34	30.52
		1	9.70	7.88	0.26	0.70	0.27	0.86	0.57	0.28	13.22	25.66
		2	7.35	6.96	0.35	0.96	0.28	0.83	0.60	0.48	18.27	27.50
		3	7.34	7.23	0.32	1.20	0.58	0.80	0.74	0.47	18.40	27.49
		4	7.37	7.20	0.47	0.76	0.36				18.33	30.53
5	2.3	5	7.46	7.09		0.77					18.34	30.52

Elapsed Time (Days)			5.0 days		4.5 days			4.0 days			6.0 days	
Path	hrs.	Paths	Kelowna	Kamloops	Burnaby	Surrey	Richmond	Haney	Coquitlam	Forest Hills	Pr-George	Pr-Rupert
		1	5.02	4.95	4.63	4.65	4.63	4.65	4.64	4.63	5.17	5.69
		2	4.92	4.91	4.63	4.66	4.63	4.65	4.64	4.64	5.38	5.76
		3	4.92	4.92	4.63	4.67	4.64	4.65	4.65	4.64	5.38	5.76
		4	4.93	4.92	4.64	4.65	4.63				5.38	5.89
1	1.83	5	4.93	4.91		4.65					5.38	5.89
		1	5.02	4.94	4.63	4.65	4.63	4.66	4.64	4.63	5.17	5.69
		2	4.92	4.91	4.63	4.66	4.63	4.65	4.64	4.64	5.38	5.76
		3	4.92	4.92	4.63	4.67	4.64	4.65	4.65	4.64	5.38	5.76
		4	4.92	4.92	4.64	4.65	4.63				5.38	5.89
2	1.8	5	4.93	4.91		4.65					5.38	5.89
		1	5.02	4.94	4.63	4.64	4.63	4.65	4.64	4.63	5.17	5.68
		2	4.92	4.91	4.63	4.66	4.63	4.65	4.64	4.64	5.38	5.76
		3	4.92	4.92	4.63	4.67	4.64	4.65	4.65	4.64	5.38	5.76
		4	4.92	4.92	4.63	4.65	4.63				5.38	5.89
3	1.77	5	4.93	4.91		4.65					5.38	5.89
		1	5.03	4.96	4.64	4.66	4.64	4.67	4.65	4.64	5.18	5.70
		2	4.94	4.92	4.64	4.67	4.64	4.66	4.65	4.65	5.39	5.78
		3	4.94	4.93	4.64	4.68	4.65	4.66	4.66	4.65	5.40	5.77
		4	4.94	4.93	4.65	4.66	4.64				5.39	5.90
4	2.11	5	4.94	4.92		4.66					5.39	5.90
		1	5.04	4.97	4.65	4.67	4.65	4.67	4.66	4.65	5.19	5.71
		2	4.94	4.93	4.65	4.68	4.65	4.67	4.66	4.66	5.40	5.78
		3	4.94	4.94	4.65	4.69	4.66	4.67	4.67	4.66	5.40	5.78
		4	4.94	4.94	4.66	4.67	4.66				5.40	5.91
5	2.3	5	4.95	4.93		4.67					5.40	5.91

FEASIBLE ROUTES: Using Premium Intermodal Service

Elapsed Time (Days)			5.0 days		4.5 days			4.0 days			6.0 days	
Path	hrs.	Paths	Kelowna	Kamloops	Burnaby	Surrey	Richmond	Haney	Coquitlam	Forest Hills	Pr-George	Pr-Rupert
		1	4.02	3.95	3.63	3.65	3.63	3.65	3.64	3.63	4.17	4.69
		2	3.92	3.91	3.63	3.66	3.63	3.65	3.64	3.64	4.38	4.76
		3	3.92	3.92	3.63	3.67	3.64	3.65	3.65	3.64	4.38	4.76
		4	3.93	3.92	3.64	3.65	3.63				4.38	4.89
1	1.83	5	3.93	3.91		3.65					4.38	4.89
		1	4.02	3.94	3.63	3.65	3.63	3.65	3.64	3.63	4.17	4.69
		2	3.92	3.91	3.63	3.66	3.63	3.65	3.64	3.64	4.38	4.76
		3	3.92	3.92	3.63	3.67	3.64	3.65	3.65	3.64	4.38	4.76
		4	3.92	3.92	3.64	3.65	3.63				4.38	4.89
2	1.8	5	3.93	3.91		3.65					4.38	4.89
		1	4.02	3.94	3.63	3.64	3.63	3.65	3.64	3.63	4.17	4.68
		2	3.92	3.91	3.63	3.66	3.63	3.65	3.64	3.64	4.38	4.76
		3	3.92	3.92	3.63	3.67	3.64	3.65	3.65	3.64	4.38	4.76
		4	3.92	3.92	3.63	3.65	3.63				4.39	4.89
3	1.77	5	3.93	3.91		3.65					4.38	4.89
		1	4.03	3.96	3.64	3.66	3.64	3.67	3.65	3.64	4.18	4.70
		2	3.94	3.92	3.64	3.67	3.64	3.66	3.65	3.65	4.39	4.78
		3	3.94	3.93	3.64	3.68	3.65	3.66	3.66	3.65	4.40	4.77
		4	3.94	3.93	3.65	3.66	3.64				4.39	4.90
4	2.11	5	3.94	3.92		3.66					4.39	4.90
		1	4.04	3.97	3.65	3.67	3.65	3.67	3.66	3.65	4.19	4.71
		2	3.94	3.93	3.65	3.68	3.65	3.67	3.66	3.66	4.40	4.78
		3	3.94	3.94	3.65	3.69	3.66	3.67	3.67	3.66	4.40	4.78
		4	3.94	3.94	3.66	3.67	3.65				4.40	4.91
5	2.3	5	3.95	3.93		3.67					4.40	4.91

Table B.7: For Shipper at *SAINT EUSTACHE*

Table B.7 is the possibilities for the shippers at *Saint Eustache*. As before the interpretation and data characteristics are the same.

Similar explanations are in order for tables B.8 and B.9, which are for the shippers at *Sainte Therese* and *Laval* respectively. Once again the data interpretation, cell representation and other characteristics are as before.

FEASIBLE ROUTES: Saint Therese to various Receivers

Regular Intermodal Servivce: 97 hrs. | Lachine Yard Loading: 1 hr. | Loading @ Shipper: 2 hrs.
Edmonton Swap Stop: 6 hrs. | Vancouver Yard Unloading: 1 hr. | Unloading @ Receiver: 2 hrs.

Inbound Drayage		Outbound Drayage										
Path	hrs.	Paths	Kelowna	Kamloops	Burnaby	Surrey	Richmond	Haney	Coquitlam	Forest Hills	Pr-George	Pr-Rupert
		1	9.70	7.88	0.26	0.70	0.27	0.86	0.57	0.28	13.22	25.66
		2	7.35	6.96	0.35	0.96	0.28	0.83	0.60	0.48	18.27	27.50
		3	7.34	7.23	0.32	1.20	0.58	0.80	0.74	0.47	18.40	27.49
		4	7.37	7.20	0.47	0.76	0.36				18.33	30.53
1	1.69	5	7.46	7.09		0.77					18.34	30.52
		1	9.70	7.88	0.26	0.70	0.27	0.86	0.57	0.28	13.22	25.66
		2	7.35	6.96	0.35	0.96	0.28	0.83	0.60	0.48	18.27	27.50
		3	7.34	7.23	0.32	1.20	0.58	0.80	0.74	0.47	18.40	27.49
		4	7.37	7.20	0.47	0.76	0.36				18.33	30.53
2	1.81	5	7.46	7.09		0.77					18.34	30.52
		1	9.70	7.88	0.26	0.70	0.27	0.86	0.57	0.28	13.22	25.66
		2	7.35	6.96	0.35	0.96	0.28	0.83	0.60	0.48	18.27	27.50
		3	7.34	7.23	0.32	1.20	0.58	0.80	0.74	0.47	18.40	27.49
		4	7.37	7.20	0.47	0.76	0.36				18.33	30.53
3	1.82	5	7.46	7.09		0.77					18.34	30.52
		1	9.70	7.88	0.26	0.70	0.27	0.86	0.57	0.28	13.22	25.66
		2	7.35	6.96	0.35	0.96	0.28	0.83	0.60	0.48	18.27	27.50
		3	7.34	7.23	0.32	1.20	0.58	0.80	0.74	0.47	18.40	27.49
		4	7.37	7.20	0.47	0.76	0.36				18.33	30.53
4	1.84	5	7.46	7.09		0.77					18.34	30.52
		1	9.70	7.88	0.26	0.70	0.27	0.86	0.57	0.28	13.22	25.66
		2	7.35	6.96	0.35	0.96	0.28	0.83	0.60	0.48	18.27	27.50
		3	7.34	7.23	0.32	1.20	0.58	0.80	0.74	0.47	18.40	27.49
		4	7.37	7.20	0.47	0.76	0.36				18.33	30.53
5	2.23	5	7.46	7.09		0.77					18.34	30.52
		1	9.70	7.88	0.26	0.70	0.27	0.86	0.57	0.28	13.22	25.66
		2	7.35	6.96	0.35	0.96	0.28	0.83	0.60	0.48	18.27	27.50
		3	7.34	7.23	0.32	1.20	0.58	0.80	0.74	0.47	18.40	27.49
		4	7.37	7.20	0.47	0.76	0.36				18.33	30.53
6	2.02	5	7.46	7.09		0.77					18.34	30.52

Elapsed Time (Days)			5.0 days		4.5 days			4.0 days			6.0 days	
Path	hrs.	Paths	Kelowna	Kamloops	Burnaby	Surrey	Richmond	Haney	Coquitlam	Forest Hills	Pr-George	Pr-Rupert
		1	5.02	4.94	4.62	4.64	4.62	4.65	4.64	4.62	5.16	5.68
		2	4.92	4.90	4.63	4.65	4.62	4.66	4.64	4.63	5.37	5.76
		3	4.92	4.91	4.63	4.66	4.64	4.65	4.64	4.63	5.38	5.76
		4	4.92	4.91	4.63	4.64	4.63				5.38	5.88
1	1.69	5	4.92	4.91		4.64					5.38	5.88
		1	5.02	4.95	4.63	4.65	4.63	4.65	4.64	4.63	5.17	5.69
		2	4.92	4.91	4.63	4.66	4.63	4.65	4.64	4.64	5.38	5.76
		3	4.92	4.92	4.63	4.67	4.64	4.65	4.65	4.64	5.38	5.76
		4	4.92	4.92	4.64	4.65	4.63				5.38	5.89
2	1.81	5	4.93	4.91		4.66					5.38	5.89
		1	5.02	4.95	4.63	4.65	4.63	4.65	4.64	4.63	5.17	5.69
		2	4.92	4.91	4.63	4.66	4.63	4.65	4.64	4.64	5.38	5.76
		3	4.92	4.92	4.63	4.67	4.64	4.65	4.65	4.64	5.38	5.76
		4	4.92	4.92	4.64	4.65	4.63				5.38	5.89
3	1.82	5	4.93	4.91		4.65					5.38	5.89
		1	5.02	4.95	4.63	4.65	4.63	4.65	4.64	4.63	5.17	5.69
		2	4.92	4.91	4.63	4.66	4.63	4.65	4.64	4.64	5.38	5.76
		3	4.92	4.92	4.63	4.67	4.64	4.65	4.65	4.64	5.38	5.76
		4	4.93	4.92	4.64	4.65	4.63				5.38	5.89
4	1.84	5	4.93	4.91		4.65					5.38	5.89
		1	5.04	4.96	4.65	4.66	4.65	4.67	4.66	4.65	5.19	5.70
		2	4.94	4.92	4.65	4.67	4.65	4.67	4.66	4.65	5.40	5.78
		3	4.94	4.94	4.65	4.68	4.66	4.67	4.67	4.65	5.40	5.78
		4	4.94	4.93	4.65	4.67	4.65				5.40	5.91
5	2.23	5	4.95	4.93		4.67					5.40	5.91
		1	5.03	4.95	4.64	4.66	4.64	4.66	4.65	4.64	5.18	5.70
		2	4.93	4.92	4.64	4.67	4.64	4.66	4.65	4.65	5.39	5.77
		3	4.93	4.93	4.64	4.68	4.65	4.66	4.66	4.65	5.39	5.77
		4	4.93	4.93	4.65	4.66	4.64				5.39	5.90
6	2.02	5	4.94	4.92		4.66					5.39	5.90

FEASIBLE ROUTES: Using Premium Intermodal Service												
Elapsed Time (Days):			5.0 days		4.5 days			4.0 days			6.0 days	
Path	hrs.	Paths	Kelowna	Kamloops	Burnaby	Surrey	Richmond	Haney	Coquitlam	Forest Hills	Pr-George	Pr-Rupert
		1	4.02	3.94	3.62	3.64	3.62	3.65	3.64	3.62	4.16	4.68
		2	3.92	3.90	3.63	3.65	3.62	3.65	3.64	3.63	4.37	4.76
		3	3.92	3.91	3.63	3.66	3.64	3.65	3.64	3.63	4.38	4.76
		4	3.92	3.91	3.63	3.64	3.63				4.38	4.88
1	1.69	5	3.92	3.91		3.64					4.38	4.88
		1	4.02	3.95	3.63	3.65	3.63	3.65	3.64	3.63	4.17	4.69
		2	3.92	3.91	3.63	3.66	3.63	3.65	3.64	3.64	4.38	4.76
		3	3.92	3.92	3.63	3.67	3.64	3.65	3.65	3.64	4.38	4.76
		4	3.92	3.92	3.64	3.65	3.63				4.38	4.89
2	1.81	5	3.93	3.91		3.65					4.38	4.89
		1	4.02	3.95	3.63	3.65	3.63	3.65	3.64	3.63	4.17	4.69
		2	3.92	3.91	3.63	3.66	3.63	3.65	3.64	3.64	4.38	4.76
		3	3.92	3.92	3.63	3.67	3.64	3.65	3.65	3.64	4.38	4.76
		4	3.92	3.92	3.64	3.65	3.63				4.38	4.89
3	1.82	5	3.93	3.91		3.65					4.39	4.89
		1	4.02	3.95	3.63	3.65	3.63	3.65	3.64	3.63	4.17	4.69
		2	3.92	3.91	3.63	3.66	3.63	3.65	3.64	3.64	4.38	4.76
		3	3.92	3.92	3.63	3.67	3.64	3.65	3.65	3.64	4.38	4.76
		4	3.93	3.92	3.64	3.65	3.63				4.38	4.89
4	1.84	5	3.93	3.91		3.65					4.38	4.89
		1	4.04	3.96	3.65	3.66	3.65	3.67	3.66	3.65	4.19	4.70
		2	3.94	3.92	3.65	3.67	3.65	3.67	3.66	3.65	4.40	4.78
		3	3.94	3.94	3.65	3.68	3.66	3.67	3.67	3.65	4.40	4.78
		4	3.94	3.93	3.65	3.67	3.65				4.40	4.91
5	2.23	5	3.95	3.93		3.67					4.40	4.91
		1	4.03	3.95	3.64	3.66	3.64	3.66	3.65	3.64	4.18	4.70
		2	3.93	3.92	3.64	3.67	3.64	3.66	3.65	3.65	4.39	4.77
		3	3.93	3.93	3.64	3.68	3.65	3.66	3.66	3.65	4.39	4.77
		4	3.93	3.93	3.65	3.66	3.64				4.39	4.90
6	2.02	5	3.94	3.92		3.66					4.39	4.90

Table B.8: For Shipper at *SAINT THERESE*

FEASIBLE ROUTES: Laval to various Receivers

Regular Intermodal Servivce: 97 hrs. Lachine Yard Loading: 1 hr. Loading @ Shipper: 2 hrs.
Edmonton Swap Stop: 6 hrs. Vancouver Yard Unloading: 1 hr. Unloading @ Receiver: 2 hrs.

		Path 1					Path 2					Path 3					Path 4				
	INBOUND Drayage Time in *HOURS*	1.47					1.7					1.65					1.67				
	OUTBOUND Drayage (Paths)	1	2	3	4	5	1	2	3	4	5	1	2	3	4	5	1	2	3	4	5
	Kelowna	9.70	7.35	7.34	7.37	7.46	9.70	7.35	7.34	7.37	7.46	9.70	7.35	7.34	7.37	7.46	9.70	7.35	7.34	7.37	7.46
	Kamloops	7.88	6.96	7.23	7.20	7.09	7.88	6.96	7.23	7.20	7.09	7.88	6.96	7.23	7.20	7.09	7.88	6.96	7.23	7.20	7.09
	Burnaby	0.26	0.35	0.32	0.47		0.26	0.35	0.32	0.47		0.26	0.35	0.32	0.47		0.26	0.35	0.32	0.47	
	Surrey	0.70	0.96	1.20	0.76	0.77	0.70	0.96	1.20	0.76	0.77	0.70	0.96	1.20	0.76	0.77	0.70	0.96	1.20	0.76	0.77
	Richmond	0.27	0.28	0.58	0.36		0.27	0.28	0.58	0.36		0.27	0.28	0.58	0.36		0.27	0.28	0.58	0.36	
	Haney	0.86	0.83	0.80			0.86	0.83	0.80			0.86	0.83	0.80			0.86	0.83	0.80		
	Coquitlam	0.57	0.60	0.74			0.57	0.60	0.74			0.57	0.60	0.74			0.57	0.60	0.74		
	Forest Hills	0.28	0.48	0.47			0.28	0.48	0.47			0.28	0.48	0.47			0.28	0.48	0.47		
	Pr-George	13.22	18.27	18.40	18.33	18.34	13.22	18.27	18.40	18.33	18.34	13.22	18.27	18.40	18.33	18.34	13.22	18.27	18.40	18.33	18.34
	Pr-Rupert	25.66	27.50	27.49	30.53	30.52	25.66	27.50	27.49	30.53	30.52	25.66	27.50	27.49	30.53	30.52	25.66	27.50	27.49	30.53	30.52
	Elapsed Time (in DAYS):	1	2	3	4	5	1	2	3	4	5	1	2	3	4	5	1	2	3	4	5
5.0 days	Kelowna	5.01	4.91	4.91	4.91	4.91	5.02	4.92	4.92	4.92	4.92	5.01	4.92	4.92	4.92	4.92	5.02	4.92	4.92	4.92	4.92
	Kamloops	4.93	4.89	4.90	4.90	4.90	4.94	4.90	4.91	4.91	4.91	4.94	4.90	4.91	4.91	4.91	4.94	4.90	4.91	4.91	4.91
4.5 days	Burnaby	4.61	4.62	4.62	4.62		4.62	4.63	4.63	4.63		4.62	4.63	4.62	4.63		4.62	4.63	4.62	4.63	
	Surrey	4.63	4.64	4.65	4.63	4.63	4.64	4.65	4.66	4.64	4.64	4.64	4.65	4.66	4.64	4.64	4.64	4.65	4.66	4.64	4.64
	Richmond	4.61	4.61	4.63	4.62		4.62	4.62	4.64	4.63		4.62	4.62	4.63	4.63		4.62	4.62	4.64	4.63	
4.0 days	Haney	4.64	4.64	4.64			4.65	4.65	4.65			4.65	4.64	4.64			4.65	4.65	4.64		
	Coquitlam	4.63	4.63	4.63			4.64	4.64	4.64			4.63	4.64	4.64			4.63	4.64	4.64		
	Forest Hills	4.61	4.62	4.62			4.62	4.63	4.63			4.62	4.63	4.63			4.62	4.63	4.63		
6.0 days	Pr-George	5.15	5.36	5.37	5.37	5.37	5.16	5.37	5.38	5.38	5.38	5.16	5.37	5.38	5.37	5.37	5.16	5.37	5.38	5.38	5.38
	Pr-Rupert	5.67	5.75	5.75	5.88	5.87	5.68	5.76	5.76	5.88	5.88	5.68	5.76	5.76	5.88	5.88	5.68	5.76	5.76	5.88	5.88

FEASIBLE ROUTES: Chateauguay to various Receivers

Premium Intermodal Service: 73 hours

	Elapsed Time (in DAYS):	1	2	3	4	5	1	2	3	4	5	1	2	3	4	5	1	2	3	4	5
5.0 days	Kelowna	4.01	3.91	3.91	3.91	3.91	4.02	3.92	3.92	3.92	3.92	4.01	3.92	3.92	3.92	3.92	4.02	3.92	3.92	3.92	3.92
	Kamloops	3.93	3.89	3.90	3.90	3.90	3.94	3.90	3.91	3.91	3.91	3.94	3.90	3.91	3.91	3.91	3.94	3.90	3.91	3.91	3.91
4.5 days	Burnaby	3.61	3.62	3.62	3.62		3.62	3.63	3.63	3.63		3.62	3.63	3.62	3.63		3.62	3.63	3.62	3.63	
	Surrey	3.63	3.64	3.65	3.63	3.63	3.64	3.65	3.66	3.64	3.64	3.64	3.65	3.66	3.64	3.64	3.64	3.65	3.66	3.64	3.64
	Richmond	3.61	3.61	3.63	3.62		3.62	3.62	3.64	3.63		3.62	3.62	3.63	3.63		3.62	3.62	3.64	3.63	
4.0 days	Haney	3.64	3.64	3.64			3.65	3.65	3.65			3.65	3.64	3.64			3.65	3.65	3.64		
	Coquitlam	3.63	3.63	3.63			3.64	3.64	3.64			3.63	3.64	3.64			3.63	3.64	3.64		
	Forest Hills	3.61	3.62	3.62			3.62	3.63	3.63			3.62	3.63	3.63			3.62	3.63	3.63		
6.0 days	Pr-George	4.15	4.36	4.37	4.37	4.37	4.16	4.37	4.38	4.38	4.38	4.16	4.37	4.38	4.37	4.37	4.16	4.37	4.38	4.38	4.38
	Pr-Rupert	4.67	4.75	4.75	4.88	4.87	4.68	4.76	4.76	4.88	4.88	4.68	4.76	4.76	4.88	4.88	4.68	4.76	4.76	4.88	4.88

Table B.9: For Shipper at *LAVAL*

5-B.2: *Shippers & Southern Route*

FEASIBLE ROUTES: Boucherville to various Receivers

	INBOUND Drayage	Path 1					Path 2					Path 3					Path 4				
	Time in *HOURS*	1.84					1.79					2.28					2.5				
	Elapsed Time (in DAYS):	1	2	3	4	5	1	2	3	4	5	1	2	3	4	5	1	2	3	4	5
5.0 days	Kelowna	4.73	4.63	4.63	4.63	4.64	4.73	4.63	4.63	4.63	4.64	4.75	4.65	4.65	4.65	4.66	4.76	4.66	4.66	4.66	4.66
	Kamloops	4.65	4.62	4.63	4.63	4.62	4.65	4.61	4.63	4.62	4.62	4.67	4.64	4.65	4.65	4.64	4.68	4.64	4.66	4.65	4.65
4.5 days	Burnaby	4.34	4.34	4.34	4.35		4.34	4.34	4.34	4.34		4.36	4.36	4.36	4.36		4.37	4.37	4.37	4.37	
	Surrey	4.36	4.37	4.38	4.36	4.36	4.35	4.36	4.37	4.36	4.36	4.37	4.39	4.40	4.38	4.38	4.38	4.39	4.40	4.39	4.39
	Richmond	4.34	4.34	4.35	4.34		4.34	4.34	4.35	4.34		4.36	4.36	4.37	4.36		4.37	4.37	4.38	4.37	
4.0 days	Haney	4.36	4.36	4.36			4.36	4.36	4.36			4.38	4.38	4.38			4.39	4.39	4.39		
	Coquitlam	4.35	4.35	4.36			4.35	4.35	4.36			4.37	4.37	4.38			4.38	4.38	4.38		
	Forest Hills	4.34	4.35	4.35			4.34	4.34	4.34			4.36	4.37	4.36			4.37	4.37	4.37		
6.0 days	Pr-George	4.88	5.09	5.09	5.09	5.09	4.88	5.09	5.09	5.09	5.09	4.90	5.11	5.11	5.11	5.11	4.91	5.12	5.12	5.12	5.12
	Pr-Rupert	5.40	5.47	5.47	5.60	5.60	5.39	5.47	5.47	5.60	5.60	5.41	5.49	5.49	5.62	5.62	5.42	5.50	5.50	5.63	5.63

FEASIBLE ROUTES: Saint Hubert to various Receivers

	INBOUND Drayage	Path 1					Path 2					Path 3					Path 4				
	Time in *HOURS*	1.72					2.08					2					2.32				
	Elapsed Time (in DAYS):	1	2	3	4	5	1	2	3	4	5	1	2	3	4	5	1	2	3	4	5
5.0 days	Kelowna	4.73	4.63	4.63	4.63	4.63	4.74	4.64	4.64	4.64	4.65	4.74	4.64	4.64	4.64	4.64	4.75	4.65	4.65	4.65	4.66
	Kamloops	4.65	4.61	4.62	4.62	4.62	4.66	4.63	4.64	4.64	4.63	4.66	4.62	4.63	4.63	4.63	4.67	4.64	4.65	4.65	4.64
4.5 days	Burnaby	4.33	4.34	4.34	4.34		4.35	4.35	4.35	4.36		4.34	4.35	4.35	4.35		4.36	4.36	4.36	4.37	
	Surrey	4.35	4.36	4.37	4.35	4.35	4.37	4.38	4.39	4.37	4.37	4.36	4.37	4.38	4.36	4.37	4.38	4.39	4.40	4.38	4.38
	Richmond	4.33	4.33	4.35	4.34		4.35	4.35	4.36	4.35		4.34	4.35	4.36	4.35		4.36	4.36	4.37	4.36	
4.0 days	Haney	4.36	4.36	4.36			4.37	4.37	4.37			4.37	4.37	4.37			4.38	4.38	4.38		
	Coquitlam	4.35	4.35	4.35			4.36	4.36	4.37			4.36	4.36	4.36			4.37	4.37	4.38		
	Forest Hills	4.33	4.34	4.34			4.35	4.36	4.36			4.35	4.35	4.35			4.36	4.37	4.37		
6.0 days	Pr-George	4.87	5.08	5.09	5.09	5.09	4.89	5.10	5.10	5.10	5.10	4.88	5.09	5.10	5.10	5.10	4.90	5.11	5.11	5.11	5.11
	Pr-Rupert	5.39	5.47	5.47	5.59	5.59	5.41	5.48	5.48	5.61	5.61	5.40	5.48	5.48	5.61	5.60	5.42	5.49	5.49	5.62	5.62

FEASIBLE ROUTES: Brossard to various Receivers

	INBOUND Drayage	Path 1					Path 2					Path 3				
	Time in *HOURS*	1.59					1.85					2.06				
	Elapsed Time (in DAYS):	1	2	3	4	5	1	2	3	4	5	1	2	3	4	5
5.0 days	Kelowna	4.72	4.62	4.62	4.62	4.63	4.73	4.63	4.63	4.63	4.64	4.74	4.64	4.64	4.64	4.65
	Kamloops	4.64	4.61	4.62	4.62	4.61	4.66	4.62	4.63	4.63	4.62	4.66	4.63	4.64	4.64	4.63
4.5 days	Burnaby	4.33	4.33	4.33	4.34		4.34	4.34	4.34	4.35		4.35	4.35	4.35	4.36	
	Surrey	4.35	4.36	4.37	4.35	4.35	4.36	4.37	4.38	4.36	4.36	4.37	4.38	4.39	4.37	4.37
	Richmond	4.33	4.33	4.34	4.33		4.34	4.34	4.35	4.34		4.35	4.35	4.36	4.35	
4.0 days	Haney	4.35	4.35	4.35			4.36	4.36	4.36			4.37	4.37	4.37		
	Coquitlam	4.34	4.34	4.35			4.35	4.35	4.36			4.36	4.36	4.37		
	Forest Hills	4.33	4.34	4.34			4.34	4.35	4.35			4.35	4.36	4.36		
6.0 days	Pr-George	4.87	5.08	5.08	5.08	5.08	4.88	5.09	5.09	5.09	5.09	4.89	5.10	5.10	5.10	5.10
	Pr-Rupert	5.39	5.46	5.46	5.59	5.59	5.40	5.47	5.47	5.60	5.60	5.41	5.48	5.48	5.61	5.61

FEASIBLE ROUTES: Chateauguay to various Receivers.

	INBOUND Drayage	Path 1					Path 2					Path 3					Path 4				
	Time in *HOURS*	1.59					1.7					1.78					2.37				
	Elapsed Time (in DAYS):	1	2	3	4	5	1	2	3	4	5	1	2	3	4	5	1	2	3	4	5
5.0 days	Kelowna	4.72	4.62	4.62	4.62	4.63	4.72	4.63	4.63	4.63	4.63	4.73	4.63	4.63	4.63	4.63	4.75	4.66	4.65	4.66	4.66
	Kamloops	4.64	4.61	4.62	4.62	4.61	4.65	4.61	4.62	4.62	4.62	4.65	4.61	4.63	4.62	4.62	4.68	4.64	4.65	4.65	4.64
4.5 days	Burnaby	4.33	4.33	4.33	4.34		4.33	4.34	4.33	4.34		4.34	4.34	4.34	4.34		4.36	4.36	4.36	4.37	
	Surrey	4.35	4.36	4.37	4.35	4.35	4.35	4.36	4.37	4.35	4.35	4.35	4.36	4.37	4.36	4.36	4.38	4.39	4.40	4.38	4.38
	Richmond	4.33	4.33	4.34	4.33		4.33	4.33	4.34	4.34		4.34	4.34	4.35	4.34		4.36	4.36	4.37	4.36	
4.0 days	Haney	4.35	4.35	4.35			4.36	4.36	4.35			4.36	4.36	4.36			4.38	4.38	4.38		
	Coquitlam	4.34	4.34	4.35			4.34	4.35	4.35			4.35	4.35	4.35			4.37	4.37	4.38		
	Forest Hills	4.33	4.34	4.34			4.33	4.34	4.34			4.34	4.34	4.34			4.36	4.37	4.37		
6.0 days	Pr-George	4.87	5.08	5.08	5.08	5.08	4.87	5.08	5.09	5.08	5.09	4.88	5.09	5.09	5.09	5.09	4.90	5.11	5.12	5.11	5.11
	Pr-Rupert	5.39	5.46	5.46	5.59	5.59	5.39	5.47	5.47	5.59	5.59	5.39	5.47	5.47	5.60	5.60	5.42	5.49	5.49	5.62	5.62

FEASIBLE ROUTES: Beaconsfield to various Receivers.

	INBOUND Drayage	Path 1					Path 2					Path 3					Path 4					Path 5				
	Time in *HOURS*	1.39					2.46					2.36					2.7					2.76				
	Elapsed Time (in DAYS):	1	2	3	4	5	1	2	3	4	5	1	2	3	4	5	1	2	3	4	5	1	2	3	4	5
5.0 days	Kelowna	4.71	4.61	4.61	4.62	4.62	4.76	4.66	4.66	4.66	4.66	4.75	4.65	4.65	4.66	4.66	4.77	4.67	4.67	4.67	4.67	4.77	4.67	4.67	4.67	4.68
	Kamloops	4.64	4.60	4.61	4.61	4.60	4.68	4.64	4.65	4.65	4.65	4.68	4.64	4.65	4.65	4.64	4.69	4.65	4.66	4.66	4.66	4.69	4.66	4.67	4.67	4.66
4.5 days	Burnaby	4.32	4.32	4.32	4.33		4.36	4.37	4.37	4.37		4.36	4.36	4.36	4.37		4.37	4.38	4.38	4.38		4.38	4.38	4.38	4.38	
	Surrey	4.34	4.35	4.36	4.34	4.34	4.38	4.39	4.40	4.38	4.38	4.38	4.39	4.40	4.38	4.38	4.39	4.40	4.41	4.39	4.39	4.39	4.41	4.42	4.40	4.40
	Richmond	4.32	4.32	4.33	4.32		4.36	4.36	4.38	4.37		4.36	4.36	4.37	4.36		4.37	4.37	4.39	4.38		4.38	4.38	4.39	4.38	
4.0 days	Haney	4.34	4.34	4.34			4.39	4.39	4.39			4.38	4.38	4.38			4.40	4.40	4.40			4.40	4.40	4.40		
	Coquitlam	4.33	4.33	4.34			4.38	4.38	4.38			4.37	4.37	4.38			4.39	4.39	4.39			4.39	4.39	4.40		
	Forest Hills	4.32	4.33	4.33			4.36	4.37	4.37			4.36	4.37	4.37			4.37	4.38	4.38			4.38	4.39	4.38		
6.0 days	Pr-George	4.86	5.07	5.07	5.07	5.07	4.90	5.11	5.12	5.12	5.12	4.90	5.11	5.11	5.11	5.11	4.91	5.12	5.13	5.13	5.13	4.92	5.13	5.13	5.13	5.13
	Pr-Rupert	5.38	5.45	5.45	5.58	5.58	5.42	5.50	5.50	5.62	5.62	5.42	5.49	5.49	5.62	5.62	5.43	5.51	5.51	5.63	5.63	5.43	5.51	5.51	5.64	5.64

FEASIBLE ROUTES: Kirkland to various Receivers.

	INBOUND Drayage	Path 1					Path 2					Path 3					Path 4					Path 5				
	Time in *HOURS*	1.46					1.56					1.58					1.82					1.84				
	Elapsed Time (in DAYS):	1	2	3	4	5	1	2	3	4	5	1	2	3	4	5	1	2	3	4	5	1	2	3	4	5
5.0 days	Kelowna	4.71	4.62	4.62	4.62	4.62	4.72	4.62	4.62	4.62	4.63	4.72	4.62	4.62	4.62	4.63	4.73	4.63	4.63	4.63	4.64	4.73	4.63	4.63	4.63	4.64
	Kamloops	4.64	4.60	4.61	4.61	4.61	4.64	4.61	4.62	4.62	4.61	4.64	4.61	4.62	4.62	4.61	4.65	4.62	4.63	4.63	4.62	4.65	4.62	4.63	4.63	4.62
4.5 days	Burnaby	4.32	4.33	4.32	4.33		4.33	4.33	4.33	4.33		4.33	4.33	4.33	4.34		4.34	4.34	4.34	4.35		4.34	4.34	4.34	4.35	
	Surrey	4.34	4.35	4.36	4.34	4.34	4.34	4.36	4.37	4.35	4.35	4.35	4.36	4.37	4.35	4.35	4.36	4.37	4.38	4.36	4.36	4.36	4.37	4.38	4.36	4.36
	Richmond	4.32	4.32	4.33	4.33		4.33	4.33	4.34	4.33		4.33	4.33	4.34	4.33		4.34	4.34	4.35	4.34		4.34	4.34	4.35	4.34	
4.0 days	Haney	4.35	4.35	4.34			4.35	4.35	4.35			4.35	4.35	4.35			4.36	4.36	4.36			4.36	4.36	4.36		
	Coquitlam	4.33	4.34	4.34			4.34	4.34	4.35			4.34	4.34	4.35			4.35	4.35	4.36			4.35	4.35	4.36		
	Forest Hills	4.32	4.33	4.33			4.33	4.34	4.33			4.33	4.34	4.34			4.34	4.35	4.35			4.34	4.35	4.35		
6.0 days	Pr-George	4.86	5.07	5.08	5.07	5.08	4.87	5.08	5.08	5.08	5.08	4.87	5.08	5.08	5.08	5.08	4.88	5.09	5.09	5.09	5.09	4.88	5.09	5.09	5.09	5.09
	Pr-Rupert	5.38	5.46	5.46	5.58	5.58	5.38	5.46	5.46	5.59	5.59	5.39	5.46	5.46	5.59	5.59	5.40	5.47	5.47	5.60	5.60	5.40	5.47	5.47	5.60	5.60

FEASIBLE ROUTES: Saint Eustache to various Receivers.

	INBOUND Drayage	Path 1					Path 2					Path 3				
	Time in *HOURS*	1.83					1.8					1.77				
	Elapsed Time (in DAYS):	1	2	3	4	5	1	2	3	4	5	1	2	3	4	5
5.0 days	Kelowna	4.73	4.63	4.63	4.63	4.64	4.73	4.63	4.63	4.63	4.64	4.73	4.63	4.63	4.63	4.63
	Kamloops	4.65	4.62	4.63	4.63	4.62	4.65	4.62	4.63	4.63	4.62	4.65	4.61	4.62	4.62	4.62
4.5 days	Burnaby	4.34	4.34	4.34	4.35		4.34	4.34	4.34	4.34		4.33	4.34	4.34	4.34	
	Surrey	4.36	4.37	4.38	4.36	4.36	4.35	4.37	4.38	4.36	4.36	4.35	4.36	4.37	4.36	4.36
	Richmond	4.34	4.34	4.35	4.34		4.34	4.34	4.35	4.34		4.33	4.34	4.35	4.34	
4.0 days	Haney	4.36	4.36	4.36			4.36	4.36	4.36			4.36	4.36	4.36		
	Coquitlam	4.35	4.35	4.36			4.35	4.35	4.36			4.35	4.35	4.35		
	Forest Hills	4.34	4.35	4.35			4.34	4.35	4.34			4.34	4.34	4.34		
6.0 days	Pr-George	4.88	5.09	5.09	5.09	5.09	4.88	5.09	5.09	5.09	5.09	4.87	5.09	5.09	5.09	5.09
	Pr-Rupert	5.40	5.47	5.47	5.60	5.60	5.39	5.47	5.47	5.60	5.60	5.39	5.47	5.47	5.60	5.60

INBOUND Drayage	Path 4					Path 5				
Time in *HOURS*	2.11					2.3				
Elapsed Time (in DAYS):	1	2	3	4	5	1	2	3	4	5
Kelowna	4.74	4.64	4.64	4.65	4.65	4.75	4.65	4.65	4.65	4.66
Kamloops	4.67	4.63	4.64	4.64	4.63	4.67	4.64	4.65	4.65	4.64
Burnaby	4.35	4.35	4.35	4.36		4.36	4.36	4.36	4.37	
Surrey	4.37	4.38	4.39	4.37	4.37	4.38	4.39	4.40	4.38	4.38
Richmond	4.35	4.35	4.36	4.35		4.36	4.36	4.37	4.36	
Haney	4.37	4.37	4.37			4.38	4.38	4.38		
Coquitlam	4.36	4.36	4.37			4.37	4.37	4.38		
Forest Hills	4.35	4.36	4.36			4.36	4.37	4.37		
Pr-George	4.89	5.10	5.10	5.10	5.10	4.90	5.11	5.11	5.11	5.11
Pr-Rupert	5.41	5.48	5.48	5.61	5.61	5.42	5.49	5.49	5.62	5.62

FEASIBLE ROUTES: Sainte Therese to various Receivers.

	INBOUND Drayage	Path 1					Path 2					Path 3				
	Time in *HOURS*	1.69					1.81					1.82				
	Elapsed Time (in DAYS):	1	2	3	4	5	1	2	3	4	5	1	2	3	4	5
5.0 days	Kelowna	4.72	4.63	4.63	4.63	4.63	4.73	4.63	4.63	4.63	4.64	4.73	4.63	4.63	4.63	4.64
	Kamloops	4.65	4.61	4.62	4.62	4.62	4.65	4.62	4.63	4.63	4.62	4.65	4.62	4.63	4.63	4.62
4.5 days	Burnaby	4.33	4.34	4.33	4.34		4.34	4.34	4.34	4.34		4.34	4.34	4.34	4.35	
	Surrey	4.35	4.36	4.37	4.35	4.35	4.35	4.37	4.38	4.36	4.36	4.36	4.37	4.38	4.36	4.36
	Richmond	4.33	4.33	4.34	4.34		4.34	4.34	4.35	4.34		4.34	4.34	4.35	4.34	
4.0 days	Haney	4.36	4.35	4.35			4.36	4.36	4.36			4.36	4.36	4.36		
	Coquitlam	4.34	4.35	4.35			4.35	4.35	4.36			4.35	4.35	4.36		
	Forest Hills	4.33	4.34	4.34			4.34	4.35	4.35			4.34	4.35	4.35		
6.0 days	Pr-George	4.87	5.08	5.09	5.08	5.08	4.88	5.09	5.09	5.09	5.09	4.88	5.09	5.09	5.09	5.09
	Pr-Rupert	5.39	5.47	5.47	5.59	5.59	5.39	5.47	5.47	5.60	5.60	5.40	5.47	5.47	5.60	5.60

INBOUND Drayage	Path 4					Path 5					Path 6				
Time in *HOURS*	1.84					2.23					2.02				
Elapsed Time (in DAYS):	1	2	3	4	5	1	2	3	4	5	1	2	3	4	5
Kelowna	4.73	4.63	4.63	4.63	4.64	4.75	4.65	4.65	4.65	4.65	4.74	4.64	4.64	4.64	4.64
Kamloops	4.65	4.62	4.63	4.63	4.62	4.67	4.63	4.64	4.64	4.64	4.66	4.62	4.64	4.63	4.63
Burnaby	4.34	4.34	4.34	4.35		4.35	4.36	4.36	4.36		4.35	4.35	4.35	4.35	4.33
Surrey	4.36	4.37	4.38	4.36	4.36	4.37	4.38	4.39	4.37	4.37	4.36	4.37	4.38	4.37	4.37
Richmond	4.34	4.34	4.35	4.34		4.35	4.35	4.37	4.36		4.35	4.35	4.36	4.35	4.33
Haney	4.36	4.36	4.36			4.38	4.38	4.38			4.37	4.37	4.37	4.33	4.33
Coquitlam	4.35	4.35	4.36			4.37	4.37	4.37			4.36	4.36	4.36	4.33	4.33
Forest Hills	4.34	4.35	4.35			4.35	4.36	4.36			4.35	4.35	4.35	4.33	4.33
Pr-George	4.88	5.09	5.09	5.09	5.09	4.89	5.10	5.11	5.11	5.11	4.89	5.10	5.10	5.10	5.10
Pr-Rupert	5.40	5.47	5.47	5.60	5.60	5.41	5.49	5.49	5.62	5.61	5.40	5.48	5.48	5.61	5.61

FEASIBLE ROUTES: Laval to various Receivers.

	INBOUND Drayage	Path 1					Path 2				
	Time in *HOURS*	1.47					1.7				
	Elapsed Time (in DAYS):	1	2	3	4	5	1	2	3	4	5
5.0 days	Kelowna	4.72	4.62	4.62	4.62	4.62	4.72	4.63	4.63	4.63	4.63
	Kamloops	4.64	4.60	4.61	4.61	4.61	4.65	4.61	4.62	4.62	4.62
4.5 days	Burnaby	4.32	4.33	4.32	4.33		4.33	4.34	4.33	4.34	
	Surrey	4.34	4.35	4.36	4.34	4.34	4.35	4.36	4.37	4.35	4.35
	Richmond	4.32	4.32	4.34	4.33		4.33	4.33	4.34	4.34	
4.0 days	Haney	4.35	4.35	4.34			4.36	4.36	4.35		
	Coquitlam	4.33	4.34	4.34			4.34	4.35	4.35		
	Forest Hills	4.32	4.33	4.33			4.33	4.34	4.34		
6.0 days	Pr-George	4.86	5.07	5.08	5.08	5.08	4.87	5.08	5.09	5.08	5.09
	Pr-Rupert	5.38	5.46	5.46	5.58	5.58	5.39	5.47	5.47	5.59	5.59

INBOUND Drayage	Path 3					Path 4				
Time in *HOURS*	1.65					1.67				
Elapsed Time (in DAYS):	1	2	3	4	5	1	2	3	4	5
Kelowna	4.72	4.63	4.62	4.63	4.63	4.72	4.63	4.63	4.63	4.63
Kamloops	4.65	4.61	4.62	4.62	4.61	4.65	4.61	4.62	4.62	4.61
Burnaby	4.33	4.33	4.33	4.34		4.33	4.33	4.33	4.34	
Surrey	4.35	4.36	4.37	4.35	4.35	4.35	4.36	4.37	4.35	4.35
Richmond	4.33	4.33	4.34	4.33		4.33	4.33	4.34	4.33	
Haney	4.35	4.35	4.35			4.36	4.35	4.35		
Coquitlam	4.34	4.34	4.35			4.34	4.34	4.35		
Forest Hills	4.33	4.34	4.34			4.33	4.34	4.34		
Pr-George	4.87	5.08	5.09	5.08	5.08	4.87	5.08	5.09	5.08	5.08
Pr-Rupert	5.39	5.46	5.46	5.59	5.59	5.39	5.47	5.46	5.59	5.59

Table B.10: Time Elapsed, Shippers and Southern IM Route

Table B.10 provides the details of the inbound and outbound drayage when used in conjunction with the Southern IM Route, the one going through Calgary. As may be evident that all the intermodal combinations are feasible with ***R-IM*** on this route, and hence there is no need to move any traffic on the more expensive ***P-IM*** train service.

5-B.3: <u>*INTERMODAL MODEL DEVELOPMENT*</u>

This section develops the two special cases for ***(IMM)***.

<u>*Special Case#1:*</u>

Figure B.1 is intended to aid the development of a mathematical model for time-based rail-truck intermodal transportation system. There are two shippers and two receivers, wherein each of the former has to supply to each of the latter. There is only one IM train service between the two terminals. This service takes 80 hours to cover its journey.

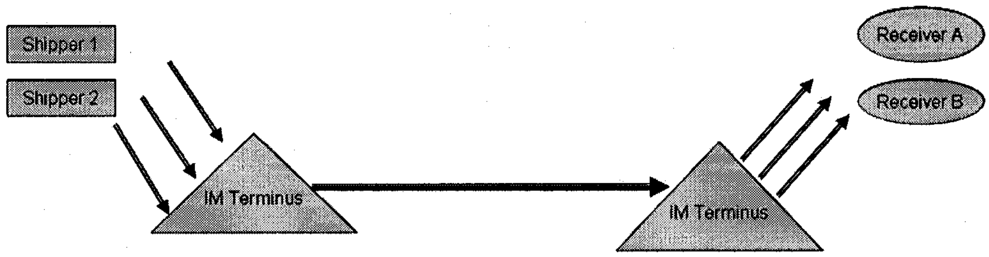

Figure B.1: Available Network for illustrative example

The demand from each receiver consists of both *hazardous* cargo and *regular* freight, to be moved in intermodal units (IMUs). For our purposes, demand is expressed in terms of IMUs with hazardous cargo and IMUs with regular freight. Each of the two shippers specifies a delivery time of 4 days (96 hours), after placing an order on Monday @ 10:00 am.

	Hazmat	Regular	Total
1 to A	2	5	7
1 to B	1	8	9
2 to A	1	8	9
2 to B	2	6	8

IM terminus -Shipper 1 - IM terminus			
	1	2	3
Time (hrs.)	2.08	2.28	2.12
Cost ($)	254	264	256
P.E. (people)	2959	2787	2557

IM terminus -Receiver A - IM terminus			
	1	2	3
Time (hrs.)	0.26	0.35	0.32
Cost ($)	33	38	36
P.E. (people)	447	528	499

IM terminus -Shipper 2 - IM terminus			
	1	2	3
Time (hrs.)	1.84	1.79	2.28
Cost ($)	242	240	264
P.E. (people)	2902	2609	1174

IM terminus -Receiver B - IM terminus			
	1	2	3
Time (hrs.)	0.7	0.96	1.2
Cost ($)	88	104	119
P.E. (people)	625	738	846

Table B.11: Time, Cost and Risk for Drayage

There are three paths from each of the two shippers to the IM terminus and also three paths from the IM terminus (at the end of journey) to each of the two receivers (Table B.11). The time to complete the inbound/ outbound drayage, cost and associated population exposure (risk) of each path are produced. The figures corresponding to unit weight on both objectives are produced below in Table B.12.

Weighted Cost + Risk ($ + people)							
	1	2	3		1	2	3
Shipper 1	3213	3051	2813	Receiver A	480	566	535
Shipper 2	3144	2849	1438	Receiver B	713	842	965

Table B.12: Drayage with unit weights

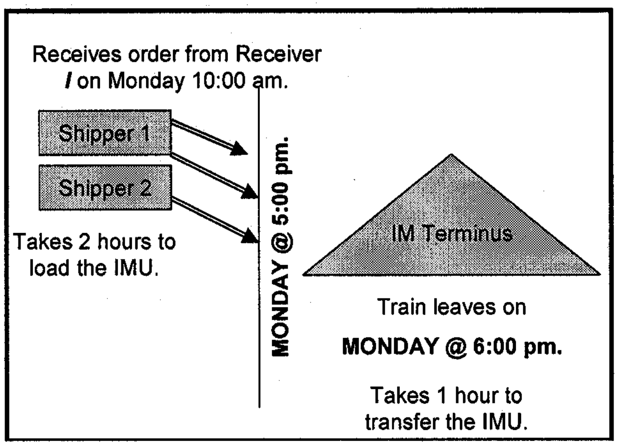

Figure B.2: Inbound Drayage & Cut-Off Time

The two shippers receive the demand orders from the two receivers on Monday 10:00 am for delivery by Friday 10:00 am. The IM train, needed to meet the specified deadline, departs at 6:00 pm from the nearest terminus, and it takes a total of three hours /IMU (two hours at the shipper and one hour at the IM yard) to complete the loading and transfer operations at the two sites (Figure B.2). Moreover, there is a cut-off time after which an IMU will not be able to make to this train. The cut-off time is Monday 5:00 pm and hence the *inbound drayage* must be completed by then to make to the Monday evening train.

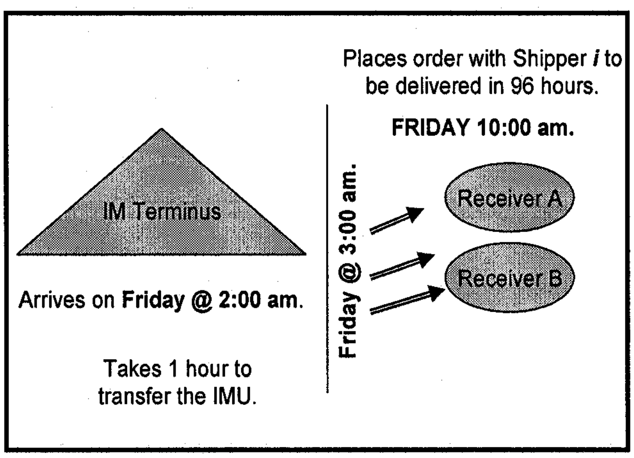

Figure B.3: Earliest Outbound Drayage

The IM train will arrive at its' destination on Friday morning @ 2:00 am. It will take an hour to transfer the IMUs to the waiting trucks, and hence the *outbound drayage* can start at 3:00 am on Friday (Figure B.3).

It is convenient to visualize the entire intermodal chain as a series of just-in-time activities, which may never be delayed. After factoring in an hour each for loading and unloading the IMUs from the IM train, we will assume a total rail-haul time of 82 hours (80+1+1).

A mathematical model of the above system will involve the following.

Constraints:

- Two sets of *transshipment constraints* corresponding to the two IM terminals.
- *Demand constraints* at each receiver from each shipper.
- *Capacity constraint* for the IM train between the two IM terminals.
- *Lead-time constraints* to ensure that delivery takes place by the specified deadline. These constraints would evaluate, based on travel times, the feasibility of the three transport links of the intermodal chain viz. *inbound drayage–IM train–outbound drayage*, and keep the solution confined to the combinations of feasible transport links.
- *Forcing constraints* for indicator variables. These constraints will enable the above feasibility evaluation, and would be activated by the flow variables. If flow variable moves on path 1, then the indicator variable corresponding to path 1 will be activated to evaluate feasibility for the complete intermodal route, given that path 1 has been chosen.
- *Sign Restrictions* constraints.

Variables:

- Flow variables for hazmat IMUs and regular IMUs.
- Number of IM trains.
- Indicator variables for time-feasibility constraints. Are binary in form, and would be activated by the flow variables (both hazmat IMUs and regular IMUs).

Sets:

I:	Set of shippers = {1, 2}.
L:	Set of receivers = {A, B}.
P_1:	Set of paths between shipper *1* and originating IM terminal = {1, 2, 3}.
P_2:	Set of paths between shipper *2* and originating IM terminal = {1, 2, 3}.
Q_A:	Set of paths between terminating IM terminal and receiver *A* = {a, b, c}.
Q_B:	Set of paths between terminating IM terminal and receiver *B* = {a, b, c}.
IM :	IM train service between the IM terminals = {1}.

Variables:

For Inbound Drayage:

$X(h)^p_{1A}$: number of hazmat IMUs demanded by receiver *A* from shipper *1* using paths = {1, 2, 3} for inbound drayage.

$X(nh)^p_{1A}$: number of regular IMUs demanded by receiver *A* from shipper *1* using paths = {1, 2, 3} for inbound drayage.

$X(h)^p_{1B}$: number of hazmat IMUs demanded by receiver *B* from shipper *1* using paths = {1, 2, 3} for inbound drayage.

$X(nh)^p_{1B}$: number of regular IMUs demanded by receiver *B* from shipper *1* using paths = {1, 2, 3} for inbound drayage.

➔ 12 variables.

$X(h)^p_{2A}$: number of hazmat IMUs demanded by receiver *A* from shipper *2* using paths = {a, b, c} for inbound drayage.

$X(nh)^p_{2A}$: number of regular IMUs demanded by receiver *A* from shipper *2* using paths = {a, b, c} for inbound drayage.

$X(h)^{p}_{2B}$: number of hazmat IMUs demanded by receiver B from shipper 2 using paths = {a, b, c} for inbound drayage.

$X(nh)^{p}_{2B}$: number of regular IMUs demanded by receiver B from shipper 2 using paths = {a, b, c} for inbound drayage.

➔ 12 variables.

<u>For IM train service:</u>

Since there is only one IM train service, hence all the IMUs from the two shippers to the two receivers will be loaded on this train to be moved to the terminating IM yard.

$X(h)_{1A}$: number of hazmat IMUs demanded by receiver A from shipper 1 using IM train service.

$X(nh)_{1A}$: number of regular IMUs demanded by receiver A from shipper 1 using IM train service.

$X(h)_{1B}$: number of hazmat IMUs demanded by receiver B from shipper 1 using IM train service.

$X(nh)_{1B}$: number of regular IMUs demanded by receiver B from shipper 1 using IM train service.

➔ 4 variables.

$X(h)_{2A}$: number of hazmat IMUs demanded by receiver A from shipper 2 using IM train service.

$X(nh)_{2A}$: number of regular IMUs demanded by receiver A from shipper 2 using IM train service.

$X(h)_{2B}$: number of hazmat IMUs demanded by receiver B from shipper 2 using IM train service.

$X(nh)_{2B}$: number of regular IMUs demanded by receiver B from shipper 2 using IM train service.

➔ 4 variables.

For Outbound Drayage:

$X(h)_{1A}^{q}$: number of hazmat IMUs demanded by receiver *A* from shipper *1* using paths = {a, b, c} for outbound drayage.

$X(nh)_{1A}^{q}$: number of regular IMUs demanded by receiver *A* from shipper *1* using paths = {a, b, c} for outbound drayage.

$X(h)_{1B}^{q}$: number of hazmat IMUs demanded by receiver *B* from shipper *1* using paths = {a, b, c} for outbound drayage.

$X(nh)_{1B}^{q}$: number of regular IMUs demanded by receiver *B* from shipper *1* using paths = {a, b, c} for outbound drayage.

➔ 12 variables.

$X(h)_{2A}^{q}$: number of hazmat IMUs demanded by receiver *A* from shipper *2* using paths = {a, b, c} for outbound drayage.

$X(nh)_{2A}^{q}$: number of regular IMUs demanded by receiver *A* from shipper *2* using paths = {a, b, c} for outbound drayage.

$X(h)_{2B}^{q}$: number of hazmat IMUs demanded by receiver *B* from shipper *2* using paths = {a, b, c} for outbound drayage.

$X(nh)_{2B}^{q}$: number of regular IMUs demanded by receiver *B* from shipper *2* using paths = {a, b, c} for outbound drayage.

➔ 12 variables.

As indicated earlier, corresponding to each variable for inbound and outbound drayage, there will be an indicator variable. These variables would be presented in the constraints, and that is where these are going to be operationalized.

Constraints:

Transshipment Constraints:

First Set: The total number of hazmat or regular IMUs coming into the origin IM yard (O) using the three specified paths, with unique *shipper-receiver-*

commodity type identifier, is equal to the number of IMUs departing on the **only** IM train service *SL*.

$$X(h)_{1A}^{1} + X(h)_{1A}^{2} + X(h)_{1A}^{3} = X(h)_{1A}$$

$$X(nh)_{1A}^{1} + X(nh)_{1A}^{2} + X(nh)_{1A}^{3} = X(nh)_{1A}$$

$$X(h)_{1B}^{1} + X(h)_{1B}^{2} + X(h)_{1B}^{3} = X(h)_{1B}$$

$$X(nh)_{1B}^{1} + X(nh)_{1B}^{2} + X(nh)_{1B}^{3} = X(nh)_{1B}$$

$$X(h)_{2A}^{1} + X(h)_{2A}^{2} + X(h)_{2A}^{3} = X(h)_{2A}$$

$$X(nh)_{2A}^{1} + X(nh)_{2A}^{2} + X(nh)_{2A}^{3} = X(nh)_{2A}$$

$$X(h)_{2B}^{1} + X(h)_{2B}^{2} + X(h)_{2B}^{3} = X(h)_{2B}$$

$$X(nh)_{2B}^{1} + X(nh)_{2B}^{2} + X(nh)_{2B}^{3} = X(nh)_{2B}$$

The above block of constraints is equivalent to the following:

➔ $\sum_{p=1,2,3} X(h)_{il}^{p} = X(h)_{il} \quad \forall i = \{1,2\},\ l = \{1,2\}.$

➔ $\sum_{p=1,2,3} X(nh)_{il}^{p} = X(nh)_{il} \quad \forall i = \{1,2\},\ l = \{1,2\}.$

Second Set: The total number of hazmat or regular IMUs coming into destination yard *D* from origin yard *O* using the **only** IM train service *SL*, with unique *shipper-receiver-commodity type* identifier, is equal to the number of IMUs leaving *D* for receivers using the three specified paths.

$$X(h)_{1A} = X(h)_{1A}^{a} + X(h)_{1A}^{b} + X(h)_{1A}^{c}$$

$$X(nh)_{1A} = X(nh)_{1A}^{a} + X(nh)_{1A}^{b} + X(nh)_{1A}^{c}$$

$$X(h)_{1B} = X(h)_{1B}^{a} + X(h)_{1B}^{b} + X(h)_{1B}^{c}$$

$$X(nh)_{1B} = X(nh)_{1B}^{a} + X(nh)_{1B}^{b} + X(nh)_{1B}^{c}$$

$$X(h)_{2A} = X(h)_{2A}^{a} + X(h)_{2A}^{b} + X(h)_{2A}^{c}$$

$$X(nh)_{2A} = X(nh)_{2A}^{a} + X(nh)_{2A}^{b} + X(nh)_{2A}^{c}$$

$$X(h)_{2B} = X(h)_{2B}^{a} + X(h)_{2B}^{b} + X(h)_{2B}^{c}$$

$$X(nh)_{2B} = X(nh)_{2B}^{a} + X(nh)_{2B}^{b} + X(nh)_{2B}^{c}$$

The above block of constraints is equivalent to the following:

$\rightarrow X(h)_{il} = \sum_{q=a,b,c} X(h)_{il}^{q} \quad \forall i = \{1,2\}, l = \{1,2\}$

$\rightarrow X(nh)_{il} = \sum_{q=a,b,c} X(nh)_{il}^{q} \quad \forall i = \{1,2\}, l = \{1,2\}$

Demand Constraints: The demand (hazmat and non-hazmat) at each receiver is fulfilled using one and/or more paths available for outbound drayage. The demand for hazmat and non-hazmat cannot be combined since they have different moving cost(s). The hazmat movement will also result in societal cost in the form of population exposure, while the regular freight incurs only the dollar cost. If the two are combined to meet the total demand in the same constraint, this distinction is blurred, and the regular shipments may take the minimum risk route or the hazmat shipments may take the minimum cost route, and not the intentioned weighted cost-risk route.

$X(h)_{1A}^{a} + X(h)_{1A}^{b} + X(h)_{1A}^{c} = 2$

$X(nh)_{1A}^{a} + X(nh)_{1A}^{b} + X(nh)_{1A}^{c} = 5$

$X(h)_{1B}^{a} + X(h)_{1B}^{b} + X(h)_{1B}^{c} = 1$

$X(nh)_{1B}^{a} + X(nh)_{1B}^{b} + X(nh)_{1B}^{c} = 8$

$X(h)_{2A}^{a} + X(h)_{2A}^{b} + X(h)_{2A}^{c} = 1$

$X(nh)_{2A}^{a} + X(nh)_{2A}^{b} + X(nh)_{2A}^{c} = 8$

$X(h)_{2B}^{a} + X(h)_{2B}^{b} + X(h)_{2B}^{c} = 2$

$X(nh)_{2B}^{a} + X(nh)_{2B}^{b} + X(nh)_{2B}^{c} = 6$

The above block of constraints is equivalent to the following:

$\rightarrow \sum_{q=a,b,c} X(h)_{il}^{q} = D(h)_{li} \quad \forall\, i = \{1,2\},\ l = \{1,2\}$

$\rightarrow \sum_{q=a,b,c} X(nh)_{il}^{q} = D(nh)_{li} \quad \forall\, i = \{1,2\},\ l = \{1,2\}$

Capacity Constraint: There is only one train service between the two IM yards, and hence only one capacity constraint will be required.

$$X(h)_{1A} + X(nh)_{1A} + X(h)_{1B} + X(nh)_{1B}$$
$$+ X(h)_{2A} + X(nh)_{2A} + X(h)_{2B} + X(nh)_{2B} \leq 120(N\ )$$

The above constraint is equivalent to the following:

$$\rightarrow \quad \sum_i \sum_l [X(h)_{il} + X(nh)_{il}] \leq U\ N \qquad \forall\ IM\ .$$

<u>Lead-Time Constraints:</u> The total intermodal journey has to be completed in 96 hours so as to be feasible. This implies that the sequence of activities forming an intermodal chain should be completed by the specified deadline. The three components of the chain are *inbound drayage*, *rail haul service*, and *outbound drayage*. Since there is only one rail haul service and each IMU container has to take this IM service, there is no need for indices for distinguishing IM train services.

This is one of the two sets of constraints using indicator (binary) variables. So depending on the paths chosen for inbound and outbound drayage, the two together will be evaluated with the train service time for feasible-routing possibilities. It also implies that only the feasible sequence of combinations will be chosen, irrespective of the cost or risk factors.

So we introduce Y variables corresponding to each inbound and outbound drayage paths, and the intermodal train service. Three Y variables will be used to build an intermodal chain, and all the possible chains have to be enumerated. The variables corresponding to inbound drayage will be defined as follows:

$$Y_{il}^{p} = \begin{cases} 1 \text{ if } X(h)_{il}^{p} > 0 \text{ OR } X(nh)_{il}^{p} > 0 \\ 0 \text{ otherwise} \end{cases}$$

There is no need to develop separate indicator variables for hazardous and regular IMUs, since a complete path and hence adhering to lead-time constraints is independent of the commodity type. In other words, travel time on an intermodal path (drayage or rail haul) is not influenced by the content of the intermodal units, and hence a common indicator variable could be used for the lead-time evaluation for the intermodal movement of both hazardous and regular IMUs.

There will be similar representations for the outbound drayage. There is only one type of intermodal train to which all the IMUs will be connected, and hence we need only one Y variable for train.

Shipper 1:

This block of 9-constraints, denotes the different transport leg combinations for the regular and hazardous IMU containers from shipper 1 to receiver A.

$$2.08Y_{1A}^{1} + 82Y + 0.26Y_{1A}^{a} \leq 96$$
$$2.08Y_{1A}^{1} + 82Y + 0.35Y_{1A}^{b} \leq 96$$
$$2.08Y_{1A}^{1} + 82Y + 0.32Y_{1A}^{c} \leq 96$$

$$2.28Y_{1A}^{2} + 82Y + 0.26Y_{1A}^{a} \leq 96$$
$$2.28Y_{1A}^{2} + 82Y + 0.35Y_{1A}^{b} \leq 96$$
$$2.28Y_{1A}^{2} + 82Y + 0.32Y_{1A}^{c} \leq 96$$

$$2.12Y_{1A}^{3} + 82Y + 0.26Y_{1A}^{a} \leq 96$$
$$2.12Y_{1A}^{3} + 82Y + 0.35Y_{1A}^{b} \leq 96$$
$$2.12Y_{1A}^{3} + 82Y + 0.32Y_{1A}^{c} \leq 96$$

This block of 9-constraints evaluates the feasibility of regular and hazardous IMU traffic from shipper 1 to receiver B.

$$2.08Y_{1B}^{1} + 82Y + 0.70Y_{1B}^{a} \leq 96$$
$$2.08Y_{1B}^{1} + 82Y + 0.96Y_{1B}^{b} \leq 96$$
$$2.08Y_{1B}^{1} + 82Y + 1.20Y_{1B}^{c} \leq 96$$

$$2.28Y_{1B}^{2} + 82Y + 0.70Y_{1B}^{a} \leq 96$$
$$2.28Y_{1B}^{2} + 82Y + 0.96Y_{1B}^{b} \leq 96$$
$$2.28Y_{1B}^{2} + 82Y + 1.20Y_{1B}^{c} \leq 96$$

$$2.12Y_{1B}^{3} + 82Y + 0.70Y_{1B}^{a} \leq 96$$
$$2.12Y_{1B}^{3} + 82Y + 0.96Y_{1B}^{b} \leq 96$$
$$2.12Y_{1B}^{3} + 82Y + 1.20Y_{1B}^{c} \leq 96$$

Shipper 2:

The next 18-constraints serve the same purpose for shipper 2, as the above 18-constraints for shipper 1.

$$1.84Y_{2A}^{1} + 82Y + 0.26Y_{2A}^{a} \leq 96$$
$$1.84Y_{2A}^{1} + 82Y + 0.35Y_{2A}^{b} \leq 96$$
$$1.84Y_{2A}^{1} + 82Y + 0.32Y_{2A}^{c} \leq 96$$

$$1.79Y_{2A}^{2} + 82Y + 0.26Y_{2A}^{a} \leq 96$$
$$1.79Y_{2A}^{2} + 82Y + 0.35Y_{2A}^{b} \leq 96$$
$$1.79Y_{2A}^{2} + 82Y + 0.32Y_{2A}^{c} \leq 96$$

$$2.28Y_{2A}^{3} + 82Y + 0.26Y_{2A}^{a} \leq 96$$
$$2.28Y_{2A}^{3} + 82Y + 0.35Y_{2A}^{b} \leq 96$$
$$2.28Y_{2A}^{3} + 82Y + 0.32Y_{2A}^{c} \leq 96$$

$$1.84Y_{2B}^{1} + 82Y + 0.70Y_{2B}^{a} \leq 96$$
$$1.84Y_{2B}^{1} + 82Y + 0.96Y_{2B}^{b} \leq 96$$
$$1.84Y_{2B}^{1} + 82Y + 1.20Y_{2B}^{c} \leq 96$$

$$1.79Y_{2B}^{2} + 82Y + 0.70Y_{2B}^{a} \leq 96$$
$$1.79Y_{2B}^{2} + 82Y + 0.96Y_{2B}^{b} \leq 96$$
$$1.79Y_{2B}^{2} + 82Y + 1.20Y_{2B}^{c} \leq 96$$

$$2.28Y_{2B}^{3} + 82Y + 0.70Y_{2B}^{a} \leq 96$$
$$2.28Y_{2B}^{3} + 82Y + 0.96Y_{2B}^{b} \leq 96$$
$$2.28Y_{2B}^{3} + 82Y + 1.20Y_{2B}^{c} \leq 96$$

The above block of constraints is equivalent to the following:

➔ $t(in)_{il}^{p} Y_{il}^{p} + t(IM)_{il} Y + t(out)_{il}^{q} Y_{il}^{q} \leq 96 \quad \forall\, p, i, IM, l, q.$

Forcing Constraints: The ***Y*** variables in the feasible time constraints are indicator variables, activated by the flow variables ***X***. The activation of ***Y*** variables and consequent feasibility evaluation of an intermodal route stems from the movement of IMU containers on paths for inbound and outbound drayage, and IM train service.

There will be 24 forcing constraints for *inbound drayage*, one corresponding to each of the 24 inbound drayage variables. These constraints will be of the form:

$$MY_{1A}^{1} \geq X(h)_{1A}^{1}$$

This says that if IMUs, destined for receiver *A* from shipper *1*, follow path *1* for inbound drayage then the associated indicator variable for path *1* will assume a value of *1*. '*M*' can be large number, in here it is 35 (total demand for the two receivers is 33).

These 24 constraints can be compactly represented as follows:

➔ $MY_{il}^{p} \geq X(h)_{il}^{p} \quad \forall\ p = \{1,2,3\}, i = \{1,2\},\ l = \{1,2\}.$

➔ $MY_{il}^{p} \geq X(nh)_{il}^{p} \quad \forall\ p = \{1,2,3\}, i = \{1,2\},\ l = \{1,2\}.$

There will be 24 forcing constraints for *outbound drayage*, one corresponding to each of the 24 outbound drayage variables. These constraints will be of the form:

$$MY_{1A}^{a} \geq X(h)_{1A}^{a}$$

This says that if IMUs, destined for receiver *A* from shipper *1*, follow path *a* for outbound drayage then the associated indicator variable for path a will assume *a* value of *1*. '*M*' is a large number, in here it is 35 (total demand for the two receivers is 33). These 24 constraints can be represented in compact form as follows:

➔ $MY_{il}^{q} \geq X(h)_{il}^{q} \quad \forall\ q = \{1,2,3\}, i = \{1,2\},\ l = \{1,2\}.$

➔ $MY_{il}^{q} \geq X(nh)_{il}^{q} \quad \forall\ q = \{1,2,3\}, i = \{1,2\},\ l = \{1,2\}.$

Since there is only one *IM train service*, which all IMUs are going to be connected to, the value of ***Y*** in the feasible-time constraints will be *1*. But if we had choices of train services then we can insert indices to the ***Y*** variable, as was done for inbound and outbound drayage.

Sign Restrictions: The ***X*** variables are non-negative integer variables, while the ***Y*** variables are binary indicator variables.

Objectives: It is a multi-criteria problem, with *risk* and *cost* as the two objectives. The demand fulfillment is driven by the element of time, and hence just minimizing the cost and/or risk may not be a feasible option. The compact expression for our instance is below. There is only one origin terminal (*J={1}*), only one destination terminal ($K=\{1\}$), and only one IM train service ($IM = \{1\}$), which simplifies the illustrative problem.

Min

$$\sum_i \sum_p \sum_l \left[C(h)_{il}^p X(h)_{il}^p + C(nh)_{il}^p X(nh)_{il}^p\right]$$
$$+ \sum_i \sum_l \left[C(h)_{il} X(h)_{il} + C(nh)_{il} X(nh)_{il}\right]$$
$$+ \sum_i \sum_q \sum_l \left[C(h)_{il}^q X(h)_{il}^q + C(nh)_{il}^q X(nh)_{il}^q\right]$$
$$+ C(IM)N$$

$$\sum_i \sum_p \sum_l CE(h)_{il}^p X(h)_{il}^p$$
$$+ CE(h)_{il}\left(\sum_i \sum_l X(h)_{il}\right)$$
$$+ \sum_i \sum_q \sum_l CE(h)_{il}^q X(h)_{il}^q$$

Once again, just like in the Tactical Planning instance in Chapter 4, the *population exposure* risk stemming from the rail-transport of IMUs with hazardous cargo is due to multiple sources of release, and hence the aggregate concentration curves will be non-linear. Typically these two also imply absence of any closed form expression for risk, and the consequent inability to use a commercial solver.

But in here, there is only one train between the two terminals and hence we could solve the example using a commercial solver. One train implies that all the IMUs moving from the two shippers to the two receivers have to be loaded on this very train, and hence we know the exact number of IMU with hazardous cargo. Earlier this was precisely the reason for the absence of any closed form expression, but now since we know the exact number of IMUs with hazardous cargo, we can calculate the corresponding *population exposure* risk.

The above problem was solved (in LINDO) without the '*risk*' expression for IM train-loading, thereafter the exact amount of risk accruing from train movement of these hazardous IMUs was added to the answer to result in a weighted solution. This solution is optimum since we know that all IMUs are loaded on this very train, and hence adding the risk value consequent to the solution returned by a solver is not inappropriate.

Clearly this cannot be done when the number of IM trains is more than one. *First*, as we saw in Chapter 4, enumerating all possibilities is both inefficient and computationally prohibitive. *Second*, adopting the above approach will not longer provide us with the optimum solution since it is impossible to ascertain a priori the best possible routes and combinations without generating all possible traffic combinations.

We next present Special Case #2, wherein there is still only one set of origin-destination intermodal terminals, but there are a range of train service options between these terminals. The variables appearing in Table 5.15 imply the following:

Inbound Drayage

$X1 \rightarrow X(h)^1_{1A}$
$X3 \rightarrow X(h)^3_{1A}$
$X5 \rightarrow X(nh)^1_{1A}$
$X6 \rightarrow X(nh)^2_{1A}$
$X7 \rightarrow X(nh)^3_{1A}$

$X9 \rightarrow X(h)^1_{1B}$
$X11 \rightarrow X(h)^3_{1B}$
$X13 \rightarrow X(nh)^1_{1B}$
$X15 \rightarrow X(nh)^3_{1B}$

$X18 \rightarrow X(h)^2_{2A}$
$X19 \rightarrow X(h)^3_{2A}$
$X21 \rightarrow X(nh)^1_{2A}$
$X22 \rightarrow X(nh)^2_{2A}$
$X23 \rightarrow X(nh)^3_{2A}$

$X26 \rightarrow X(h)^2_{2B}$
$X27 \rightarrow X(h)^3_{2B}$
$X30 \rightarrow X(nh)^3_{2B}$
$X31 \rightarrow X(nh)^3_{2B}$

Outbound Drayage

$X41 \rightarrow X(h)^{a}_{1A}$ $X49 \rightarrow X(h)^{a}_{1B}$ $X59 \rightarrow X(h)^{a}_{2A}$

$X45 \rightarrow X(nh)^{a}_{1A}$ $X54 \rightarrow X(nh)^{a}_{1B}$ $X63 \rightarrow X(nh)^{a}_{2A}$

$X46 \rightarrow X(nh)^{b}_{1A}$ $X55 \rightarrow X(nh)^{b}_{1B}$ $X64 \rightarrow X(nh)^{b}_{2A}$

$X67 \rightarrow X(h)^{a}_{2B}$

$X68 \rightarrow X(h)^{a}_{2B}$

$X72 \rightarrow X(nh)^{a}_{2B}$

$X73 \rightarrow X(nh)^{b}_{2B}$

It should be noted that while having only one intermodal train makes the problem solvable by a commercial package, it also makes it less interesting since we already know the train make-up plan. Analogously, we know that the remaining X variables in table 5.15 refer to the only rail-haul part of their journey and does not present any interesting analysis.

Special Case #2:

Using the example illustrated in Figure A.1 and Tables A.26 and A.27, we set up this case. The only difference between this case and the one above is the number of intermodal train services available in this instance. Since there is only one originating and terminating intermodal terminal, hence we can continue to leave out subscripts *'j'* and *'k'*, but the subscript indicating different train services will have to be retained. We will only point out the incremental changes (or differences) between these two cases.

Sets:

IM^{SL} : IM train services between the IM terminals.

Variables:

For IM train service:

Since there are a number of IM train services, hence the IMU loading decision is known a priori.

$X(h)^{SL}_{1A}$: number of hazmat IMUs demanded by receiver *A* from shipper *1* using IM train service *SL*.

$X(nh)_{1A}^{SL}$: number of regular IMUs demanded by receiver A from shipper 1 using IM train service SL.

$X(h)_{1B}^{SL}$: number of hazmat IMUs demanded by receiver B from shipper 1 using IM train service SL.

$X(nh)_{1B}^{SL}$: number of regular IMUs demanded by receiver B from shipper 1 using IM train service SL.

➔ 4 variables.

$X(h)_{2A}^{SL}$: number of hazmat IMUs demanded by receiver A from shipper 2 using IM train service SL.

$X(nh)_{2A}^{SL}$: number of regular IMUs demanded by receiver A from shipper 2 using IM train service SL.

$X(h)_{2B}^{SL}$: number of hazmat IMUs demanded by receiver B from shipper 2 using IM train service SL.

$X(nh)_{2B}^{SL}$: number of regular IMUs demanded by receiver B from shipper 2 using IM train service SL.

➔ 4 variables.

Constraints:

Transshipment Constraints:

First Set: The total number of hazmat or regular IMUs coming into the origin IM yard using the three specified paths, with unique *shipper-receiver-commodity type* identifier, is equal to the number of IMUs departing on all the IM train services indexed SL.

$$X(h)_{1A}^{1} + X(h)_{1A}^{2} + X(h)_{1A}^{3} = X(h)_{1A}^{SL}$$

$$X(nh)_{1A}^{1} + X(nh)_{1A}^{2} + X(nh)_{1A}^{3} = X(nh)_{1A}^{SL}$$

$$X(h)_{1B}^{1} + X(h)_{1B}^{2} + X(h)_{1B}^{3} = X(h)_{1B}^{SL}$$

$$X(nh)_{1B}^{1} + X(nh)_{1B}^{2} + X(nh)_{1B}^{3} = X(nh)_{1B}^{SL}$$

$$X(h)_{2A}^{1} + X(h)_{2A}^{2} + X(h)_{2A}^{3} = X(h)_{2A}^{SL}$$

$$X(nh)_{2A}^{1} + X(nh)_{2A}^{2} + X(nh)_{2A}^{3} = X(nh)_{2A}^{SL}$$

$$X(h)_{2B}^{1} + X(h)_{2B}^{2} + X(h)_{2B}^{3} = X(h)_{2B}^{SL}$$

$$X(nh)_{2B}^{1} + X(nh)_{2B}^{2} + X(nh)_{2B}^{3} = X(nh)_{2B}^{SL}$$

The above block of constraints is equivalent to the following:

$$\rightarrow \sum_{p=1,2,3} X(h)_{il}^{p} = \sum_{SL} X(h)_{il}^{SL} \quad \forall i = \{1,2\},\ l = \{1,2\}.$$

$$\rightarrow \sum_{p=1,2,3} X(nh)_{il}^{p} = \sum_{SL} X(nh)_{il}^{SL} \quad \forall i = \{1,2\},\ l = \{1,2\}.$$

Second Set: The total number of hazmat or regular IMUs coming into destination yard from origin yard using a number of IM train services, with unique *shipper-receiver-commodity type* identifier, is equal to the number of IMUs leaving the terminating yard for receivers using the three specified paths.

$$\sum_{SL} X(h)_{1A}^{SL} = X(h)_{1A}^{a} + X(h)_{1A}^{b} + X(h)_{1A}^{c}$$

$$\sum_{SL} X(nh)_{1A}^{SL} = X(nh)_{1A}^{a} + X(nh)_{1A}^{b} + X(nh)_{1A}^{c}$$

$$\sum_{SL} X(h)_{1B}^{SL} = X(h)_{1B}^{a} + X(h)_{1B}^{b} + X(h)_{1B}^{c}$$

$$\sum_{SL} X(nh)_{1B}^{SL} = X(nh)_{1B}^{a} + X(nh)_{1B}^{b} + X(nh)_{1B}^{c}$$

$$\sum_{SL} X(h)_{2A}^{SL} = X(h)_{2A}^{a} + X(h)_{2A}^{b} + X(h)_{2A}^{c}$$

$$\sum_{SL} X(nh)_{2A}^{SL} = X(nh)_{2A}^{a} + X(nh)_{2A}^{b} + X(nh)_{2A}^{c}$$

$$\sum_{SL} X(h)_{2B}^{SL} = X(h)_{2B}^{a} + X(h)_{2B}^{b} + X(h)_{2B}^{c}$$

$$\sum_{SL} X(nh)_{2B}^{SL} = X(nh)_{2B}^{a} + X(nh)_{2B}^{b} + X(nh)_{2B}^{c}$$

The above block of constraints is equivalent to the following:

$$\rightarrow \sum_{SL} X(h)_{il}^{SL} = \sum_{q=a,b,c} X(h)_{il}^{q} \quad \forall i = \{1,2\}, l = \{1,2\}$$

$$\rightarrow \sum_{SL} X(nh)_{il}^{SL} = \sum_{q=a,b,c} X(nh)_{il}^{q} \quad \forall i = \{1,2\}, l = \{1,2\}$$

Demand Constraints: The demand (hazmat and non-hazmat) at each receiver is fulfilled using one and/or more paths available for outbound drayage. The demand for hazmat and non-hazmat cannot be combined since they have different moving cost(s). The hazmat movement will also result in societal cost in the form of population exposure, while the regular freight incurs only the dollar cost. If the two are combined to meet the total demand in the same constraint, this distinction is blurred, and the regular shipments may take the minimum risk route or the hazmat shipments may take the minimum cost route, and not the intentioned weighted cost-risk route.

$$X(h)_{1A}^{a} + X(h)_{1A}^{b} + X(h)_{1A}^{c} = 5$$

$$X(nh)_{1A}^{a} + X(nh)_{1A}^{b} + X(nh)_{1A}^{c} = 2$$

$$X(h)_{1B}^{a} + X(h)_{1B}^{b} + X(h)_{1B}^{c} = 8$$

$$X(nh)_{1B}^{a} + X(nh)_{1B}^{b} + X(nh)_{1B}^{c} = 1$$

$$X(h)_{2A}^{a} + X(h)_{2A}^{b} + X(h)_{2A}^{c} = 8$$

$$X(nh)_{2A}^{a} + X(nh)_{2A}^{b} + X(nh)_{2A}^{c} = 1$$

$$X(h)_{2B}^{a} + X(h)_{2B}^{b} + X(h)_{2B}^{c} = 6$$

$$X(nh)_{2B}^{a} + X(nh)_{2B}^{b} + X(nh)_{2B}^{c} = 2$$

The above block of constraints is equivalent to the following:

$$\rightarrow \sum_{q=a,b,c} X(h)_{il}^{q} = D(h)_{l_i} \quad \forall\, i = \{1,2\},\ l = \{1,2\}$$

$$\rightarrow \sum_{q=a,b,c} X(nh)_{il}^{q} = D(nh)_{l_i} \quad \forall\, i = \{1,2\},\ l = \{1,2\}$$

Capacity Constraint: There is only one train service between the two IM yards, and hence only one capacity constraint will be required.

$$X(h)_{1A}^{SL} + X(nh)_{1A}^{SL} + X(h)_{1B}^{SL} + X(nh)_{1B}^{SL} + X(h)_{2A}^{SL} + X(nh)_{2A}^{SL} + X(h)_{2B}^{SL} + X(nh)_{2B}^{SL} \le 120(N^{SL}) \qquad \forall \quad IM^{SL}$$

The above constraint is equivalent to the following:

$$\rightarrow \quad \sum_{i}\sum_{l}[X(h)_{il}^{SL} + X(nh)_{il}^{SL}] \le U_{SL}N^{SL} \quad \forall\ IM^{SL}.$$

Lead-Time Constraints: Since there are more than one rail haul service there is a need for indices for distinguishing IM train services. The indicator variable will take a subscript *'SL'* to denote the specific IM train service. The time taken to traverse by this service will be denoted by $t(IM)^{SL}$.

This is one of the two sets of constraints using indicator (binary) variables. So depending on the paths chosen for inbound and outbound drayage, the two together will be evaluated with the train service time for feasible-routing possibilities. It also implies that only the feasible sequence of combinations will be chosen, irrespective of the cost or risk factors.

Shipper 1:

This block of 9-constraints, denotes the different transport leg combinations for the regular and hazardous IMU containers from shipper 1 to receiver A.

$$2.08Y_{1A}^{1} + t(IM)^{SL}Y^{SL} + 0.26Y_{1A}^{a} \leq 96$$
$$2.08Y_{1A}^{1} + t(IM)^{SL}Y^{SL} + 0.35Y_{1A}^{b} \leq 96$$
$$2.08Y_{1A}^{1} + t(IM)^{SL}Y^{SL} + 0.32Y_{1A}^{c} \leq 96$$

$$2.28Y_{1A}^{2} + t(IM)^{SL}Y^{SL} + 0.26Y_{1A}^{a} \leq 96$$
$$2.28Y_{1A}^{2} + t(IM)^{SL}Y^{SL} + 0.35Y_{1A}^{b} \leq 96$$
$$2.28Y_{1A}^{2} + t(IM)^{SL}Y^{SL} + 0.32Y_{1A}^{c} \leq 96$$

$$2.12Y_{1A}^{3} + t(IM)^{SL}Y^{SL} + 0.26Y_{1A}^{a} \leq 96$$
$$2.12Y_{1A}^{3} + t(IM)^{SL}Y^{SL} + 0.35Y_{1A}^{b} \leq 96$$
$$2.12Y_{1A}^{3} + t(IM)^{SL}Y^{SL} + 0.32Y_{1A}^{c} \leq 96$$

This block of 9-constraints evaluates the feasibility of regular and hazardous IMU traffic from shipper 1 to receiver B.

$$2.08Y_{1B}^{1} + t(IM)^{SL}Y^{SL} + 0.70Y_{1B}^{a} \leq 96$$
$$2.08Y_{1B}^{1} + t(IM)^{SL}Y^{SL} + 0.96Y_{1B}^{b} \leq 96$$
$$2.08Y_{1B}^{1} + t(IM)^{SL}Y^{SL} + 1.20Y_{1B}^{c} \leq 96$$

$$2.28Y_{1B}^{2}+t(IM)^{SL}Y^{SL}+0.70Y_{1B}^{a}\leq 96$$
$$2.28Y_{1B}^{2}+t(IM)^{SL}Y^{SL}+0.96Y_{1B}^{b}\leq 96$$
$$2.28Y_{1B}^{2}+t(IM)^{SL}Y^{SL}+1.20Y_{1B}^{c}\leq 96$$

$$2.12Y_{1B}^{3}+t(IM)^{SL}Y^{SL}+0.70Y_{1B}^{a}\leq 96$$
$$2.12Y_{1B}^{3}+t(IM)^{SL}Y^{SL}+0.96Y_{1B}^{b}\leq 96$$
$$2.12Y_{1B}^{3}+t(IM)^{SL}Y^{SL}+1.20Y_{1B}^{c}\leq 96$$

Shipper 2:

The next 18-constraints serve the same purpose for shipper 2, as the above 18-constraints for shipper 1.

$$1.84Y_{2A}^{1}+t(IM)^{SL}Y^{SL}+0.26Y_{2A}^{a}\leq 96$$
$$1.84Y_{2A}^{1}+t(IM)^{SL}Y^{SL}+0.35Y_{2A}^{b}\leq 96$$
$$1.84Y_{2A}^{1}+t(IM)^{SL}Y^{SL}+0.32Y_{2A}^{c}\leq 96$$

$$1.79Y_{2A}^{2}+t(IM)^{SL}Y^{SL}+0.26Y_{2A}^{a}\leq 96$$
$$1.79Y_{2A}^{2}+t(IM)^{SL}Y^{SL}+0.35Y_{2A}^{b}\leq 96$$
$$1.79Y_{2A}^{2}+t(IM)^{SL}Y^{SL}+0.32Y_{2A}^{c}\leq 96$$

$$2.28Y_{2A}^{3}+t(IM)^{SL}Y^{SL}+0.26Y_{2A}^{a}\leq 96$$
$$2.28Y_{2A}^{3}+t(IM)^{SL}Y^{SL}+0.35Y_{2A}^{b}\leq 96$$
$$2.28Y_{2A}^{3}+t(IM)^{SL}Y^{SL}+0.32Y_{2A}^{c}\leq 96$$

$$1.84Y_{2B}^{1}+t(IM)^{SL}Y^{SL}+0.70Y_{2B}^{a}\leq 96$$
$$1.84Y_{2B}^{1}+t(IM)^{SL}Y^{SL}+0.96Y_{2B}^{b}\leq 96$$
$$1.84Y_{2B}^{1}+t(IM)^{SL}Y^{SL}+1.20Y_{2B}^{c}\leq 96$$

$$1.79Y_{2B}^{2}+t(IM)^{SL}Y^{SL}+0.70Y_{2B}^{a}\leq 96$$
$$1.79Y_{2B}^{2}+t(IM)^{SL}Y^{SL}+0.96Y_{2B}^{b}\leq 96$$
$$1.79Y_{2B}^{2}+t(IM)^{SL}Y^{SL}+1.20Y_{2B}^{c}\leq 96$$

$$2.28Y_{2B}^{3}+t(IM)^{SL}Y^{SL}+0.70Y_{2B}^{a}\leq 96$$
$$2.28Y_{2B}^{3}+t(IM)^{SL}Y^{SL}+0.96Y_{2B}^{b}\leq 96$$
$$2.28Y_{2B}^{3}+t(IM)^{SL}Y^{SL}+1.20Y_{2B}^{c}\leq 96$$

The above block of constraints is equivalent to the following:

$\rightarrow\; t(in)_{il}^{p}Y_{il}^{p} + t(IM)^{SL}Y^{SL} + t(out)_{il}^{q}Y_{il}^{q} \le 96 \qquad \forall\, p,i,IM^{SL},l,q.$

Forcing Constraints: Does not change for the drayage part of the intermodal chain, but now there is more than one IM train service and we need to account for that. So we will separate indicator variables for each train type, subscripted by *SL*.

$$MY^{SL} \ge X(h)_{il}^{SL}$$

$$MY^{SL} \ge X(nh)_{il}^{SL}$$

Objectives: It is a multi-criteria problem, with *risk* and *cost* as the two objectives. The demand fulfillment is driven by the element of time, and hence just minimizing the cost and/or risk may not be a feasible option. The compact expression for our instance is below. There is only one origin terminal (*J={1}*), only one destination terminal (*K={1}*), and only one IM train service ($IM = \{1\}$), which simplifies the illustrative problem.

Min

$$\sum_i\sum_p\sum_l\left[C(h)_{il}^{p}X(h)_{il}^{p} + C(nh)_{il}^{p}X(nh)_{il}^{p}\right]$$
$$+\sum_{SL}\sum_i\sum_l\left[C(h)_{il}^{SL}X(h)_{il}^{SL} + C(nh)_{il}^{SL}X(nh)_{il}^{SL}\right]$$
$$+\sum_i\sum_q\sum_l\left[C(h)_{il}^{q}X(h)_{il}^{q} + C(nh)_{il}^{q}X(nh)_{il}^{q}\right]$$
$$+\sum_{SL}C(IM)^{SL}N^{SL}$$

$$\sum_i\sum_p\sum_l CE(h)_{il}^{p}X(h)_{il}^{p}$$
$$+\sum_{SL}CE(h)_{il}^{SL}\left(\sum_i\sum_l X(h)_{il}^{SL}\right)$$
$$+\sum_i\sum_q\sum_l CE(h)_{il}^{q}X(h)_{il}^{q}$$

Here just like in the tactical planning instance in chapter 4 and general case of intermodal transportation in chapter 5, the *population exposure* risk is without a closed form expression, and hence cannot be solved using a commercial solver.

Moreover because there is more than one type of intermodal train service between the terminals, it is rather impossible to know the train make-up a priori.

Hence, we would have to resort to some kind of heuristic solution development perhaps on the lines of intelligent enumeration. This solution development will be done along with the solution methodology development for the general case model ***(IMM)***.

x------x------x