A Subsidy Policy to Ensuring Risk-Equity in Railroad Hazmat Transportation Network

A SUBSIDY POLICY TO ENSURING RISK-EQUITY IN RAILROAD HAZMAT TRANSPORTATION NETWORK: A RISK MITIGATION STRATEGY

BY

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A THESIS

SUBMITTED TO THE SCHOOL OF COMPUTATIONAL SCIENCE & ENGINEERING

AND THE SCHOOL OF GRADUATE STUDIES

OF MCMASTER UNIVERSITY

IN PARTIAL FULFILMENT OF THE REQUIREMENTS

FOR THE DEGREE OF

MASTER OF SCIENCE

Master of Science (2020) McMaster University
(School of Computational Science & Engineering) Hamilton, Ontario, Canada

TITLE: A Subsidy Policy to Ensuring Risk-Equity in Railroad Hazmat Transportation Network: A Risk Mitigation Strategy

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NUMBER OF PAGES: x, 64

Abstract

Railroad is one of the primary modes for transporting hazardous materials (hazmat). Given the dangerous nature of the hazmat, risk mitigation in the railroad transportation is the need of the hour. Hence, we explore the idea of equitable distribution of risk in the railroad network. We propose the subsidy policy to be considered by government to induce favourable routings of the hazmat shipments. The government's objective is to achieve risk equity in the network, whereas, the carrier's cost effective approach leads to increased risk in low-cost service-legs. To model this, we formulate the problem as a bi-level mixed integer program. We derive the single level mixed integer linear program (MILP) and test it on the rail infrastructure in midwest United States using state-of-the-art solver CPLEX 12.8.0. The instances with upto 25 shipments on the network are solved efficiently on a local machine. We use high performance computing resource available at Graham cluster of Compute Canada facility to solve the large instances with 50 shipments on the network. We show the effectiveness of the subsidy policy as a risk mitigation tool for the railroad hazmat transportation, and review the efficiency of the solution methodology to solve the MILP for the network. Moreover, the results demonstrate the economic feasibility for the government to allocate the budget for the subsidy.

Acknowledgements

I would like to express my deep sense of gratitude to my supervisor, Dr. Manish Verma, for his continuous support, motivation and valuable guidance throughout my Master's study at School of Computational Science and Engineering, McMaster University. His expertise in the area, prompt feedbacks and advice helped me maintain momentum in my research. He has always been there to provide moral and social support. I, truly, admire his kind nature.

I am thankful to Dr. Elkafi Hassini for his valuable insights and academic guidance about my future course of action. I wish to extend my gratitude to Dr. Sharon McNicholas, Dr. Ned Nedialkov, Dr. Mihai Albu and Dr. Ben Bolker for providing their excellent learning during my study. I acknowledge kind cooperation of Dr. Behrouz Bakhtiari, Dr. Yun Zhou, Dr. John Milternburg and colleagues while working with them for my TA assignments. I am grateful to Dr. Sachin Jayaswal, who played a vital role in moulding my skills in the area that helped me to get the opportunity of studying at McMaster University.

I feel blessed to have unconditional love and constant support from my parents during every phase of my life. Despite the challenges in their life, they have made many sacrifices to provide me appropriate environment to follow my dreams. I am thankful to my siblings for sharing my social and moral responsibilities while I was away from home. Special thanks to my wife for her care, compassion, encouragement and eternal love during my journey of life. I am grateful to my extended family members and friends for all the joyful moments I had with them.

Most importantly, I bow down to the Almighty God for empowering and offering me strength through out my life.

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Chapter 1

Introduction

Hazardous materials (hazmat) are vastly consumed commodities since they are integral to fulfilling the needs of the industrialized society. In general, the sourcing and consumption locations are different, and necessitate frequent movement between the two. In North America, railroad network is a predominant mode to transport hazmat shipments. The commodity flow survey for 2012 reports that 111 million tons of hazmat were moved via railraod in the United States (USDOT, 2015), whereas, in Canada, the number was 48.38 million tons in 2014 (Jabbarzadeh, Azad and Verma, 2020). Generally, railroad is largely preferred for long-distance hazmat shipments (Bagheri, Verma and Verter, 2014). There are mainly two reasons to expect that the statistics of rail hazmat movements are going to increase: first, the surge in intermodal transportation to move chemicals (Verma, Verter and Zufferey, 2012); and second, the increased amount of crude oil extraction from the Bakken Shale formation region in the United States and Canada, and the subsequent need to transport to the refineries across the North America (AAR (2014); CAPP (2014)). Moreover, continual growth in rail hazmat shipments since 2009 also promotes this expectation.

It is important to note that, according to U.S Department of Transportation (USDOT), the substance classified as hazmat is capable of posing an unreasonable risk to health, safety and property when transported in commerce. As per Transport Canada, hazardous materials are categorized into nine classes (Government of Canada, 2014). We focus on class 2, 3 and 8 that include gasses, flammable liquids and corrosives respectively, and constitute 80 % of hazmat shipments in Canada (Vaezi and Verma, 2017). Though railroad is one of the primary and most reliable modes for transporting hazmat shipments, the inherent risk could be devastating. Fortunately, a number of efforts have been made to improve the safety of rail hazmat shipments, some of which entailed the formation of inter-industry task force, and the focus on tank-car design and content release following an accident (Verma and Verter, 2013). Nevertheless, the tragic incident happened in Lac-Megantic, Quebec (Canada) in 2013, which not only costed economic and environmental destruction, but also took human lives following derailment and explosion of several crude oil railcars, is alarming. In Canada, between 2008 to 2018 every year, an average of 127 railroad accidents involved dangerous goods, and an average of 4 accidents resulted in release of dangerous goods (Transportation Safety Board, 2018). Given the catastrophic nature of rail hazmat accidents, such statistics necessitate more scrutiny of rail hazmat transportation. Hence, every possible effort should be made to mitigate the inherent risk.

One of the strategies towards risk mitigation could involve routing rail hazmat shipments over the given network. There are two pertinent facts in this regard: first, the carrier's natural tendency to follow cost effective solution often leads to overloading of low-cost service legs; and second, rail transportation system is intentioned to connect population centers, and overloading of low-cost service legs might result in increased risk around population centers. Therefore, the issue of risk aggregation over certain service-legs requires attention. Given the aforementioned, we explore a new tool to bring about a more equitable distribution of risk across the railroad network. For this, we use population exposure (PE) to assess the risk. PE is the maximum number of people that might be affected in the event of complete release of hazmat from a tank-car following a rail accident.

Railroad transportation infrastructure is distinct from road transportation in that it is relatively sparse and is normally owned and managed by private entity, i.e., railroad companies. Hence, typical network design policies such as closing links and imposing tolls would be impractical for railroad network. Furthermore, given the dynamic nature of supply/demand volumes, infrastructural investments with the intention to add service-legs might not provide long-term risk mitigation from rail hazmat transportation. It should be evident that any effort at risk mitigation should be able to circumvent the aforementioned issues. Consequently, we propose a subsidy policy that could be considered by the government to encourage carriers to consider alternative routes for shipments such that more equitable distribution of risk could be achieved in the railroad network. According to this policy, the government may offer a subsidy to the hazmat movement over the service-legs in the railroad network to induce carriers to carry shipments over service-legs with lower risk. Since the government's objective is to ensure more equitable distribution of risk while the carriers would seek to minimize the cost of transporting shipments, the former offers subsidy to the latter, who would decide to re-route the shipments taking into consideration the subsidy. The government has restriction over budget to be used for subsidy. To ensure judicious utilization of the budget allocated for subsidy, it is pertinent for government to consider rational response from the carriers while offering subsidy. Subsequently, carriers react by choosing the cheapest routes for their shipments. To incorporate this, we formulate bi-level mixed integer programming problem. We develop a mixed integer linear program (MILP) and use the state-of-the-art solver CPLEX 12.8.0 to solve the problem. This technique is applied to the problem instances generated using the realistic infrastructure of a Class 1 railroad operator, in midwest United States, that was introduced in Verma, Verter and Gendreau (2011).

The remainder of the thesis is organized as follows. Chapter 2 explores the literature in the relevant areas followed by problem description and mathematical formulation in chapter 3. Chapter 4 details the methodology developed to perform computational experiments in chapter 5. Finally, chapter 6 presents the concluding remarks.

Chapter 2

Literature Review

Because of the importance of hazmat transportation and its intrinsic disastrous nature, it has been studied widely by researchers over the past four decades. According to its main contribution, the research in hazmat transportation domain can be broadly classified into following categories: Risk assessment, Routing, Combined location and routing, Network design and Toll setting (Holeczek (2019); Erkut, Tjandra and Verter (2007); Bianco et al. (2013)). Also, the contributions are applicable to various modes of transportation, which include road (highway), rail, marine, air and intermodal transportation. Our focus is to consider suitable risk assessment technique and develop risk mitigation strategy for railroad transportation while routing hazmat shipments. We present the literature review for two important aspects of hazmat transportation relevant to our work: 1) Risk assessment in railroad hazmat transportation, 2) Risk mitigation in hazmat transportation. Having reviewed the relevant literature, we identify the need for research to develop a risk mitigation strategy, which addresses the special concerns pertaining to rail hazmat transportation.

2.1 Risk Assessment in Railroad Hazmat Transportation

In North America, hazmat transportation has been used widely to meet the demands of the industrialized society. Its inseparable risk makes it more sensitive than a regular freight transportation. Therefore, risk assessment is essential in hazmat transportation. Moreover, railroad transportation largely accounts for bulk and long distance hazmat movements that requires considering more suitable risk assessment methodology while conducting a research in this area. The general definition of risk comprises of the probability and the consequence of an undesirable event; the product of both is referred as Traditional Risk. It was used by Bubbico, Cave and Mazzarotta (2004a,b) in their studies of hazmat transportation. The assessment of traditional risk requires reliable data about the possibility of catastrophic events, tank-car derailments, consequences and other characteristics of hazmat accidents that poses some limitations in its usage as a risk measure.

To overcome the requirement of data, researchers explored the idea of considering either probability or consequence of the hazmat incidents as a measure of risk. As a result, they proposed two distinct measures of risk: 1) Incident Probability (IP), 2) Population Exposure (PE). IP does not include consequence that makes it more applicable to the rail network with relatively low risk. Certainly, low probability - high consequence incidents are most likely to be in the blind spot of this measure. The other measure, PE, takes into account the total number of population exposed to risk following the rail accident. Verma and Verter (2007) adapted this measure for rail hazmat transportation, however, it was developed for road hazmat transportation in

Batta and Chiu (1988) and ReVelle, Cohon and Shobrys (1991). Though it is useful to address low probability - high consequence characteristics of rail shipments, its use may result in overloading low-risk service-legs while minimizing the total risk. In contrast to these efforts, Vaezi and Verma (2017) recently developed an analytics based approach to estimate hazmat traffic data at rail yards and on rail-links that may help to overcome the challenge of data unavailability.

Verma (2011) considered train length and train accidents characteristics to propose comprehensive risk assessment methodology. This methodology offers precise assessment of risk based on causal factors of train accidents, train decile position of hazmat railcar in train-consist, likelihood of release from multiple sources and events following hazmat release. Subsequently, Bagheri, Verma and Verter (2014) and Cheng, Verma and Verter (2017) considered position-specific derailment probabilities while determining hazmat risk. Hosseini and Verma (2017) came up with a Value-at-Risk (VaR) approach to obtain optimal routing of rail hazmat shipment that minimized transportation risk. VaR takes into account the risk preference of the decision maker to provide different routes between a given origin-destination pair. It is useful to obtain balanced distribution of the risk in the rail-network. However, it is important to note that the approach incorporates risk preference of the decision maker, and does not consider the transportation cost involved that is the prevailing factor that may induce a decision maker, a carrier in case of railroad transportation, to be risk neutral. Further in this direction, Hosseini and Verma (2018) proposed Conditional Value-at-Risk (CVaR) based risk assessment methodology for rail hazmat transportation to obtain optimal train configuration and routing of rail hazmat shipments.

Our aim is to capture the conflicting concerns of the government and carriers, pertaining to risk and cost respectively, as the redressal of both is important to ensure sustainability of a risk mitigation strategy. To better incorporate risk concern, following a conservative approach, we consider PE as a measure of risk.

2.2 Risk Mitigation in Hazmat Transportation

Though railroad is one of the safest modes of transportation, because of the catastrophic nature of hazmat shipments that can't be overlooked, risk mitigation is necessary for its acceptability in public and government domain. Therefore, in the efforts to make it more reliable, the rail industry has implemented different strategies to mitigate the risk in railroad hazmat transportation. These strategies can be broadly categorized as: 1) reduce the number of tank-car accidents, 2) lower the likelihood of release in case of an accident, and 3) minimize the consequences in case of release following an accident.

Reducing the number of tank-car accidents is important as it is in the interest of all the stakeholders. Significant investment in the railroad infrastructure has led to improvement in quality and reliability of the railroad network, and resulted in fewer track related derailments (Gallamore (1999) and Dennis (2002)). Further in this direction, the studies by Verma (2011) and Cheng, Verma and Verter (2017) showed the effect of appropriate train make up in reducing the chances of tank-car derailment.

In the event of tank-car derailment, the catastrophic consequences could be avoided, if the possibility of hazmat release from the tank-cars could be contained. To lower the likelihood of release, rail operators follow improved tank-car safety design standards and regulations maintained by Association of American Railroad (AAR). In addition to this, several researchers explored the ways to enhance tank-car safety design. Barkan, Ukkusuri and waller (2007), Barkan (2008), and Saat and Barkan (2011) analysed trade-off between increased weight of tank-car for more resistance to damage and transportation efficiency to help make decision about most efficient tank-car design.

Having made efforts to reduce tank-car accidents and the possibility of hazmat release, the focus is to minimize consequences in case of the catastrophic events. To this end, Glickman, Erkut and Zschocke (2007) modelled the trade-off between risk and cost as a weighted combination to reroute the hazmat shipments on railroad network to reduce risk. Though weighing risk factor produced low-risk routes with modest increment of cost for the rail network they used, this may not be the case all the time, as such routes may not always cost effective. Verma (2009) and Verma, Verter and Gendreau (2011) developed a tactical planning model comprising the bi-objective terms of cost and risk. The analysis of cost - expected consequence trade-off shows that risk reduction is achieved at the expense of increased transportation cost. Therefore, carriers having economic concerns may not agree with the alternate routings.

Other risk mitigation strategies that have been widely implemented, mostly in highway hazmat transportation, are Network Design (ND) and Toll Setting (TS). Kara and Verter (2004), firstly, developed a bi-level integer programming model, and captured the relationship between regulators and carriers. According to this research, to regulate the hazmat shipments with the aim to reduce risk, the authority makes available a network to carriers for hazmat transportation by closing certain road segments. It is important to design the network in such a way that carriers' cost effective routing decisions also minimize the risk in the network. They reduced the problem into single level, and solved it to design a separate network for each hazmat type. Erkut and Gzara (2008) considered the similar bi-level model, but with a single network for all the hazmat types, and developed a heuristic solution technique to address the possibility of unstable solution in the single level problem, that is a possibility of multiple minimum cost solutions with different risk values in the worst case scenario. However, the results show that solving bi-level model produces reduced risk but high cost solutions, which may not be acceptable to carriers. Therefore, they proposed a bi objective-bilevel model by including cost term along with risk term that can generate good decisions for the network design problem. Gzara (2013) solved this problem more efficiently using a cutting plane algorithm. With the purpose to offer better compromise between regulator's risk concern and carriers' cost concern, Verter and Kara (2008) came up with an alternative path-based formulation for hazmat transportation network design problem.

Marcotte et al. (2009) proposed an alternative risk mitigation tool of setting tolls on certain road segments. According to Toll Setting (TS) policy, the regulator levies tolls on road segments instead of completely closing them that enables to differentiate between shipments carrying different hazmat types. This feature of TS makes it more flexible and effective in risk mitigation. They solved the bilevel formulation for larger shipments through inverse optimization in reasonable time. Fontaine and Minner (2018) extended the hazmat transportation network design model to address issue of unstable solutions using a way suggested by Amaldi, Bruglieri and Fortz

(2011), and solved it efficiently through benders decomposition. Taslimi, Batta and Kwon (2017) consider comprehensive risk mitigation scheme comprising of hazmat network design and response team location to obtain risk equity in the network, and propose a greedy heuristic approach to solve for large instances. Assadipour, Ke and Verma (2016) developed a bi-objective bi-level integer programming problem for rail-truck intermodal hazmat transportation that identify and impose tolls on intermodal terminals to minimize risk and tolling cost. The bi-level problem, which takes into account perspectives of the government and carriers, was solved using a particle swarm algorithm. The risk-cost results show that the reduction of risk requires imposing large tolls, which in turn incurs high cost for carriers. This creates an obstacle in settling mutually agreeable deal between government and carriers. Jabbarzadeh, Azad and Verma (2020) formulated a bi-objective two-stage stochastic problem to propose a novel approach of tackling random disruption while planning rail hazmat shipments.

2.3 Research Gap

We review the literature of risk assessment in rail hazmat transportation and risk mitigation in hazmat transportation. Through the review, we obtain useful insights, as discussed in next paragraph, that help us to identify the research gap to develop risk mitigation strategy for rail hazmat transportation.

The infrastructure investment to enhance quality of railroad network is a strategic decision, whereas, the evolution of tank-car design technology is a continuous process. Developing railroad infrastructure and meeting safety standards including of tank-car require huge capital investments (Barkan, 2008) that poses economic hurdle in implementing them unless the return is significant. Hence, there is a need of tactical planning to route the hazmat shipments; risk mitigation while routing hazmat shipments is a part of comprehensive measure. However, to make it more viable, it is important to take into consideration carriers' economic concern. Also, efforts should be made to maintain public posture and ascertain government's co-operation. As discussed in the literature review, ND and TS policies are effective in incorporating the conflicting concerns of the stakeholders. Unlike road transportation network, railroad networks are sparse and generally owned by private entities. Therefore, despite their efficacy in mitigating risk for road hazmat transportation, ND and TS schemes face challenges to be applied to railroad network due to its unique characteristics.

To offer a solution, suitable for rail hazmat transportation, we propose the subsidy policy as a risk mitigation strategy while routing hazmat shipments over a railroad network. We address the problem of risk congestion around large population centers by inducing alternative routing plans to obtain the equitable distribution of risk over entire railroad network. To be conservative in incorporating risk concern, we consider population exposure as a measure of risk. In our best knowledge, this is the first attempt to develop risk mitigation strategy for railroad hazmat transportation that takes into account underlying challenges in railroad network due to its unique characteristics while addressing conflicting concerns of the stakeholders.

Chapter 3

Mathematical Formulation : Subsidy Policy for Railroad Hazmat Transportation

We focus on risk mitigation for rail hazmat transportation while routing hazmat shipments over a railroad network. As described in previous chapters, due to its unique characteristics, the railroad transportation poses different challenges that make classical risk mitigation strategies such as Infrastructure Investment, Network Design and Toll Setting less implementable. To address underlying challenges in rail hazmat transportation, we propose the subsidy policy as a risk mitigation tool while routing hazmat shipments over a railroad network. Observing a fact that the high population centres, because of the economic importance they hold, have increased risk exposure around them, our focus is to obtain risk equity in the railroad network. As mentioned earlier, population exposure is considered as a measure of risk. The main idea of the subsidy policy is that the government incentivize carriers to induce alternative routing plans in order to achieve substantially fair distribution of risk over a railroad network. To do this, it offers carriers subsidy for utilising certain service-legs (rail links) for routing their hazmat shipments. Each carrier has to transport a shipment comprising of a number of tank-cars containing different hazmat types between origin and destination. It is important to note that, unlike road hazmat transportation, a shipment in rail hazmat transportation can consist multiple hazmat types. The subsidy is realized as a percentage of discount on travelling cost for a tank-car containing hazmat of particular type on a service-leg in the corresponding direction. The subsidy decisions are subject to the hazmat type, the service-leg and its direction of travel on the service-leg. We allow the subsidy decisions to be different for a hazmat type travelling on a service-leg in opposite directions. Hence, it is possible that subsidies for a tank-car containing particular hazmat may be different for its travel in opposite directions. The government always has the limitation on the budget to be allocated for the subsidy. Therefore, we incorporate the budget as a parametric variable in the budget constraint.

We make some reasonable assumptions while formulating the problem. We consider the cost of travelling on a service-leg as a linear proportion to the distance required to travel on the service-leg. In this work, we do not consider the handling cost at the rail-yards. It is reasonable to do so, as we assume that carriers would use a single train service between a pair of origin-destination to transport different hazmat types along with regular freights. Also, the proposed subsidy policy tool does not consider to offer cost benefit over rail-yard usage. To derive the closed form expression of risk following a conservative approach, it is assumed that a threshold radius covered due to spill from multiple tank-cars is directly proportional to a threshold radius covered due to spill from a single tank-car. So, the total population exposed is the number of tank-cars of particular type times the population that might be exposed due to release from a single tank-car of the hazmat type. We use following sign convention for service-legs. The notation '(i,j)' represents the service-leg with its respective direction (from i to j), whereas, the notation '(i-j)' represents the service-leg irrespective of direction. We consider hazmat class 2, 3 and 8 that constitute a large amount (80 %) of hazmat moved in Canada (Vaezi and Verma, 2017). We formulate the problem for the single time-frame for which the demands of different hazmat types, in terms of number of tank-cars, and their respective OD pairs are known. With these arrangements, we pose the problem as a tactical planning problem.

For a given railroad network, corresponding risk and cost, demands of different hazmat types between respective OD pairs and the budget, the subsidy policy for railroad hazmat transportation can be formulated as a bi-level problem. The government's objective in the upper level problem is to minimize maximum risk among the service-legs across the railroad network by providing subsidy using the limited budget available, whereas the carriers' objective in the lower level problem is to minimize the transportation cost after utilising the subsidy offered by the government. The subsidy Policy can be represented as the Stackelberg game where the government is a leader and the carrier is a follower. The structure of the bi-level problem describing sequential decisions, objectives of the leader and followers, and variable types is shown in figure 3.1 followed by parameters, variables and the mathematical formulation of bi-level mixed integer programming (Bi-MIP).

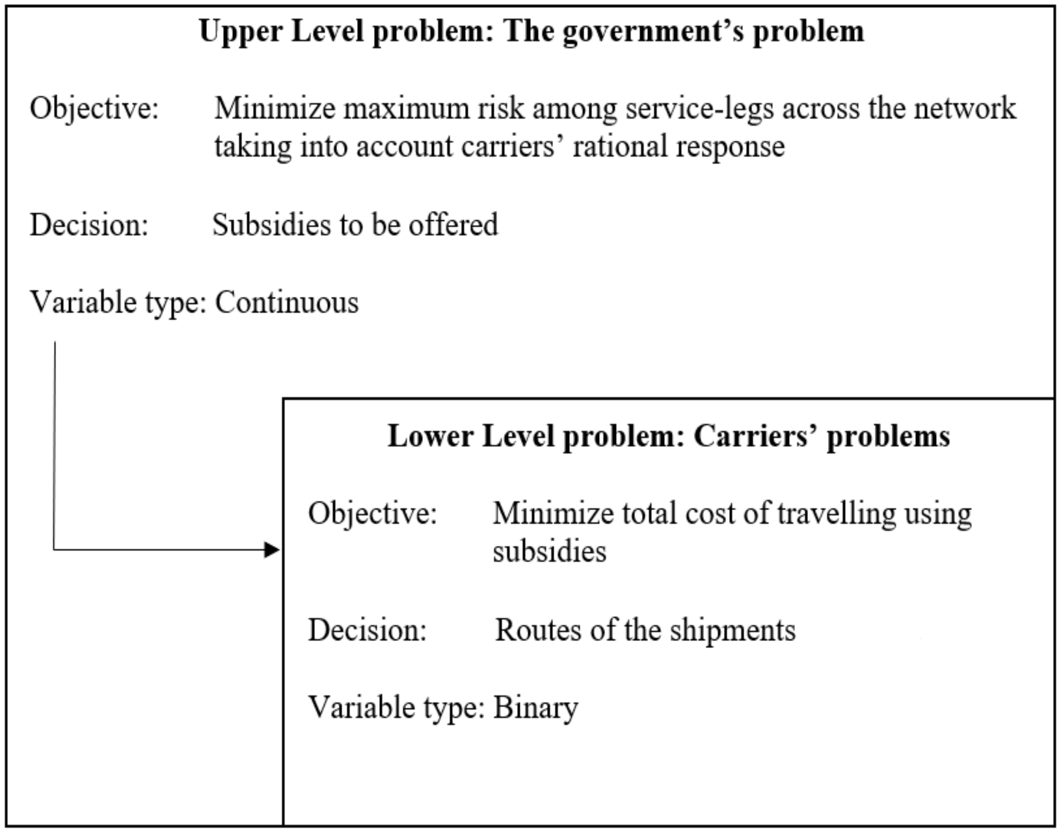

Figure 3.1: Bi-level Structure - Subsidy policy for railroad hazmat transportation

Bi-level Formulation

Sets and indices:

N: Set of rail-yards indexed by 'i' and 'j'.

M: Set of hazmat types indexed by 'm'.

C: Set of shipments indexed by 'c'.

E: Set of service-legs (bi-directed) in the network indexed by '(i,j)' for corresponding direction and '(i-j)' irrespective of direction.

Parameters:

O(c): Origin of shipment c $\in$ C, O(c) $\in$ N.

D(c): Destination of shipment c $\in$ C, D(c) $\in$ N.

$\mathcal{B}$: Budget considered by the government to provide subsidy/incentive/discount.

$\mathcal{D}^{mc}$: Demand (in terms of no. of tank-cars) for hazmat type 'm' in shipment 'c'.

C_{ij}: Cost of travelling on service-leg (i,j) for a single tank-car or length of service-leg (i,j); $C_{ij} = C_{ji}$.

R_{ij}^m: Population exposed due to complete release from a single tank-car containing hazmat type 'm' on service-leg (i,j); $R_{ij}^m = R_{ji}^m$.

Risk parameter R_{ij}^m can be defined using parameters ρ^m and p_{ij} as below:

ρ^m: Threshold radius of the area exposed due to complete release from a single tank-car containing hazmat of type 'm'.

p_{ij}: Population within ρ^m radius around service-leg (i,j).

With this, R_{ij}^m can be expressed as below:

$$R_{ij}^m = \rho^m \times p_{ij}$$

Variables:

X_{ij}^c: 1 if service-leg (i,j) is used to transport shipment 'c', 0 otherwise.

T_{ij}^m: Subsidy, which is a percentage of discount, offered by the government to a tank-car containing hazmat of type 'm' travelling on service-leg (i,j) in that direction; $0 \leq T_{ij}^m \leq 1$

θ: The maximum risk among all the service-legs across the network; a risk equity measure.

Bi-MIP:

$$\underset{T_{ij}^m}{\text{Minimize}} \quad \theta \tag{3.1}$$

Subject to:

$$\sum_{c \in C} \sum_{m \in M} \mathcal{D}^{mc} \, R_{ij}^m \left(\hat{X}_{ij}^c + \hat{X}_{ji}^c \right) \leq \theta \qquad \forall \, (i,j) \in E, \; i < j \tag{3.2}$$

$$\sum_{(i,j) \in E} \sum_{c \in C} \sum_{m \in M} \mathcal{D}^{mc} \, C_{ij} \, T_{ij}^m \, \hat{X}_{ij}^c \leq \mathcal{B} \tag{3.3}$$

$$0 \leq T_{ij}^m \leq 1 \qquad \forall (i,j) \in E, \; \forall m \in M \tag{3.4}$$

Where $\hat{X}_{ij}^c$ solves following routing problem of shipments given subsidy offered $\hat{T}_{ij}^m$:

$$\underset{X_{ij}^c}{\text{Minimize}} \sum_{(i,j) \in E} \sum_{c \in C} \sum_{m \in M} \mathcal{D}^{mc} \, C_{ij} \, (1 - \hat{T}_{ij}^m) \, X_{ij}^c \tag{3.5}$$

Subject to:

$$\sum_{j:(i,j) \in E} X_{ij}^c - \sum_{j:(j,i) \in E} X_{ji}^c = \begin{cases} 1, & \text{if } i = O(c) \\ -1, & \text{if } i = D(c) \\ 0 & \text{otherwise} \end{cases} \qquad \forall i \in N, \; \forall c \in C \tag{3.6}$$

$$X_{ij}^{c} \in \{0,1\} \qquad \forall\,(i,j) \in E,\ \forall c \in C \tag{3.7}$$

The objective (3.1) of the upper level problem is to minimize maximum risk among the service-legs across the railroad network. The constraint set (3.2) is intended to ensure equity in the network. Note that total risk on service-leg (i-j) is cumulative of risk in both (opposite) directions. The constraint (3.3) limits the total subsidy amount being utilized to the government's budget '$\mathcal{B}$', whereas the constraint set (3.4) is bound on the subsidy variable. Considering the subsidy ($\hat{T}_{ij}^{m}$) offered by the government, the lower level problem solves the routing problem between the respective origins and destinations of the shipments to minimize the transportation cost after utilizing subsidy offered that is the objective (3.5) of the lower level problem. The constraints (3.6) are flow conservation equations for each rail-yard and each shipment. The constraints (3.7) are the binary requirement of the routing variables. In next chapter, we describe the solution methodology to solve the Bi-MIP problem.

Chapter 4

Solution Methodology

In this chapter, we present the solution methodology we used to solve the Bi-MIP problem formulated in the previous chapter. Bi-MIP contains $|M||E|$ continuous (subsidy) variables corresponding to the upper level problem and $|C||E|$ binary (routing) variables corresponding to the lower level problem. Amaldi, Bruglieri and Fortz (2011) showed that the hazmat transportation network design problem to minimize the total risk in the network with the upper level problem deciding roads to be closed and the lower level problem being minimum cost network flow problem is NP-Hard even for single commodity. Compared to the network design problem discussed in Amaldi, Bruglieri and Fortz (2011), Bi-MIP comprises the additional upper-level constraints (3.2 and 3.3) and multiple hazmat types in each shipment. However, the subsidy variables are continuous compared to the network design variables, which are binary.

We exploit the special property of the lower level problem to solve Bi-MIP. Given the subsidy decisions obtained from the upper level problem, the lower level problem is the minimum cost network flow (MCNF) problems for all the shipments. Notice the fact that the shipments in the lower level problem do not share any resource.

Therefore, the lower level problem does not contain any linking constraint that makes the MCNF corresponding to each shipment independent to MCNFs corresponding to others. It is important to note that the coefficient matrix of the constraints of MCNF (for a single shipment) is totally unimodular (Wolsey, 1998). Taking advantage of the integrality property of the totally unimodular matrix, we relax the binary requirement of X_{ij}^c with $X_{ij}^c \geq 0$. The resulting linear relaxation of the lower level problem can be solved to optimality using its Karush-Kuhn-Tucker (KKT) conditions. Bi-MIP is transformed into a single level problem, that is non-linear, by replacing the linear relaxation of the lower level problem by its KKT conditions. We linearise the non-linear single level problem to obtain mixed integer linear programming (MILP) problem. Then, we present the alternative MILP formulation that is used to solve the instances of realistic railroad network in the computational experiments. Next, we show the development of the MILP, its alternative formulation and the reason for the alternative formulation.

4.1 Dual to the lower level problem

We present the dual of linear relaxation of the lower level problem. First, let us consider the primal problem. Given the subsidy, $\hat{T}_{ij}^m$, obtained from the upper level problem, the lower level problem with continuous relaxation of the binary variable X_{ij}^c is as follows:

Primal:

$$\text{Minimize} \sum_{(i,j)} \sum_{c} \sum_{m} \mathcal{D}^{mc}\, C_{ij}\, (1 - \hat{T}_{ij}^{m})\, X_{ij}^{c} \tag{3.5}$$

Subject to:

$$\sum_{j:(i,j)\in E} X_{ij}^{c} - \sum_{j:(j,i)\in E} X_{ji}^{c} = \begin{cases} 1, & \text{if } i = O(c) \\ -1, & \text{if } i = D(c) \\ 0 & \text{otherwise} \end{cases} \qquad \forall i \in N,\ \forall c \in C \tag{3.6}$$

$$X_{ij}^{c} \geq 0 \qquad \forall\, (i,j) \in E,\ \forall c \in C \tag{4.1}$$

Notice that, as right hand side of the constraint matrix is $\{-1, 0, 1\}$ vector, the minimization objective makes $X_{ij}^{c} \leq 1$ constraints (arising due to continuous relaxation of its binary requirement) redundant. Let w_{ci} be the dual variable corresponding to the flow conservation constraints (3.6) that represents the worth of utilizing node 'i' to route a shipment 'c'. With this, the dual corresponds to the primal problem is as below:

Dual:

$$\text{Maximize } \sum_{c} w_{c,O(c)} - \sum_{c} w_{c,D(c)} \tag{4.2}$$

Subject to:

$$w_{ci} - w_{cj} \leq \sum_{m} \mathcal{D}^{mc}\, C_{ij}\, (1 - \hat{T}_{ij}^{m}) \qquad \forall (i,j) \in E,\ \forall c \in C \tag{4.3}$$

$$w_{ci} \ \text{ free} \qquad \forall i \in N,\ \forall c \in C \tag{4.4}$$

The constraint set (4.3) is dual feasibility constraints. The objective is to maximize the total worth of sending flows from origin to destination satisfying the dual feasibility constraints. Next, the problem is reduced to a single level problem using the dual problem.

4.2 Single level reduction

The bi-level problem is reduced to the single level problem by replacing the lower level problem with its KKT conditions. The single level problem comprises the decisions of both upper and lower level problems as variables, which are supposed to solve simultaneously. The single level problem is presented below:

$$\underset{X_{ij}^c,\ T_{ij}^m}{\text{Minimize}}\ \theta \tag{3.1}$$

Subject to:

$$\sum_c \sum_m \mathcal{D}^{mc}\, R_{ij}^m \left(X_{ij}^c + X_{ji}^c\right) \leq \theta \qquad \forall\,(i,j)\,, i < j \tag{3.2}$$

$$\sum_{(i,j)} \sum_c \sum_m \mathcal{D}^{mc}\, C_{ij}\, T_{ij}^m\, X_{ij}^c \leq \mathcal{B} \tag{3.3}$$

$$0 \leq T_{ij}^m \leq 1 \qquad \forall (i,j) \in E,\ \forall m \in M \tag{3.4}$$

$$\sum_{j:(i,j)\in E} X_{ij}^c - \sum_{j:(j,i)\in E} X_{ji}^c = \begin{cases} 1, & \text{if } i = O(c) \\ -1, & \text{if } i = D(c) \\ 0 & \text{otherwise} \end{cases} \qquad \forall i \in N,\ \forall c \in C \tag{3.6}$$

$$w_{ci} - w_{cj} \ \leq \sum_m \mathcal{D}^{mc}\, C_{ij}\, (1 - T_{ij}^m) \qquad \forall (i,j) \in E,\ \forall c \in C \tag{4.3}$$

$$X_{ij}^{c}\left(w_{ci} - w_{cj} - \sum_{m} \mathcal{D}^{mc}\, C_{ij}\,(1 - T_{ij}^{m})\right) = 0 \qquad \forall (i,j) \in E,\ \forall c \in C \tag{4.5}$$

$$w_{ci} \ \text{free} \qquad \forall i \in N,\ \forall c \in C \tag{4.4}$$

$$X_{ij}^{c} \geq 0 \qquad \forall\,(i,j) \in E,\ \forall c \in C \tag{4.1}$$

The constraints (3.1)-(3.4) represent the upper level problem. The equations (3.6,4.1) and (4.3, 4.4) are primal and dual constraints of the linear relaxation of the lower level problem respectively. The equation (4.5) is complementary slackness condition corresponding to dual inequality constraint (4.3). The single level problem is non-linear, primarily, because both the variables (subsidy and routing) are being solved simultaneously.

4.3 Linearization

As mentioned, the resulting single level, mixed integer programming problem is non-linear because of the non-linear term $T_{ij}^{m} X_{ij}^{c}$ in the budget constraint (3.3) and the complementary slackness condition (4.5). These constraints can be linearised by restoring binary property of the X_{ij}^{c} variable. To linearise budget constraint (3.3), we introduce the auxiliary variable μ_{ij}^{mc} to represent the non-linear term $T_{ij}^{m} X_{ij}^{c}$ in the formulation. Given the binary nature of X_{ij}^{c}, the auxiliary variable μ_{ij}^{mc} is the subsidy being offered for the transport of hazmat type 'm' of shipment 'c' on service-leg (i,j) in that direction when the service-leg (i,j) is considered to be in the route of shipment 'c'. μ_{ij}^{mc} is zero, if the service-leg (i,j) is not in the route of shipment 'c'. Thus, μ_{ij}^{mc} must satisfy following conditions:

$$\mu_{ij}^{mc} = \begin{cases} T_{ij}^{m}, & \text{if } X_{ij}^{c} = 1 \\ 0, & \text{if } X_{ij}^{c} = 0 \end{cases}$$

To satisfy these conditions, we add the following constraints:

$$\mu_{ij}^{mc} \geq T_{ij}^{m} - \mathcal{M}_1(1 - X_{ij}^{c}) \qquad \forall (i,j) \in E,\ \forall m \in M,\ \forall c \in C \tag{4.6}$$

$$\mu_{ij}^{mc} \leq T_{ij}^{m} \qquad \forall (i,j) \in E,\ \forall m \in M,\ \forall c \in C \tag{4.7}$$

$$\mu_{ij}^{mc} \leq X_{ij}^{c} \qquad \forall (i,j) \in E,\ \forall m \in M,\ \forall c \in C \tag{4.8}$$

$$\mu_{ij}^{mc} \geq 0 \qquad \forall (i,j) \in E,\ \forall m \in M,\ \forall c \in C \tag{4.9}$$

The constraint sets (4.6) and (4.7) ensure that μ_{ij}^{mc} is equal to T_{ij}^{m} when X_{ij}^{c} is 1. The constraint set (4.8) ensures μ_{ij}^{mc} is zero if X_{ij}^{c} is zero. The constraint set (4.9) is the non-negativity constraint. We add the constraint (4.10) to ensure that the subsidy should be offered to move hazmat type 'm' over service-leg (i,j), only if atleast a single shipment with hazmat type 'm' travels on service-leg (i,j). Similarly, the complementary slackness condition (4.5) is linearised by replacing it with the constraint set (4.11). $\mathcal{M}_1$ and $\mathcal{M}_2$ are the big-M values for constraints (4.6) and (4.11) respectively.

$$T_{ij}^{m} \leq \sum_{c \in C(m)} X_{ij}^{c} \qquad \forall (i,j) \in E,\ \forall m \in M \tag{4.10}$$

$$w_{ci} - w_{cj} \geq \sum_{m} \mathcal{D}^{mc}\, C_{ij}\, (1 - T_{ij}^{m}) - \mathcal{M}_2\, (1 - X_{ij}^{c}) \qquad \forall (i,j) \in E,\ \forall c \in C \tag{4.11}$$

4.4 Single level reduction - linear model

Considering the above linearisation, the resulting single level, mixed integer linear programming (MILP) problem is as below:

$$\underset{X_{ij}^{c},\, T_{ij}^{m}}{\text{Minimize}} \quad \theta \tag{3.1}$$

Subject to:

$$\sum_{c} \sum_{m} \mathcal{D}^{mc}\, R_{ij}^{m} \left(X_{ij}^{c} + X_{ji}^{c}\right) \leq \theta \qquad \forall\, (i,j) \in E, i < j \tag{3.2}$$

$$\sum_{(i,j)} \sum_{c} \sum_{m} \mathcal{D}^{mc}\, C_{ij}\, \mu_{ij}^{mc} \leq \mathcal{B} \tag{3.3}$$

$$\mu_{ij}^{mc} \geq T_{ij}^{m} - \mathcal{M}_1(1 - X_{ij}^{c}) \qquad \forall (i,j) \in E,\ \forall m \in M,\ \forall c \in C \tag{4.6}$$

$$\mu_{ij}^{mc} \leq T_{ij}^{m} \qquad \forall (i,j) \in E,\ \forall m \in M,\ \forall c \in C \tag{4.7}$$

$$\mu_{ij}^{mc} \leq X_{ij}^{c} \qquad \forall (i,j) \in E,\ \forall m \in M,\ \forall c \in C \tag{4.8}$$

$$\mu_{ij}^{mc} \geq 0 \qquad \forall (i,j) \in E,\ \forall m \in M,\ \forall c \in C \tag{4.9}$$

$$T_{ij}^{m} \leq \sum_{c \in C(m)} X_{ij}^{c} \qquad \forall (i,j) \in E,\ \forall m \in M \tag{4.10}$$

$$0 \leq T_{ij}^{m} \leq 1 \qquad \forall (i,j) \in E,\ \forall m \in M \tag{3.4}$$

$$\sum_{j:(i,j)\in E} X_{ij}^c - \sum_{j:(j,i)\in E} X_{ji}^c = \begin{cases} 1, & \text{if } i = O(c) \\ -1, & \text{if } i = D(c) \\ 0 & \text{otherwise} \end{cases} \qquad \forall i \in N,\ \forall c \in C \tag{3.6}$$

$$w_{ci} - w_{cj} \leq \sum_m \mathcal{D}^{mc}\, C_{ij}\, (1 - T_{ij}^m) \qquad \forall (i,j) \in E,\ \forall c \in C \tag{4.3}$$

$$w_{ci} - w_{cj} \geq \sum_m \mathcal{D}^{mc}\, C_{ij}\, (1 - T_{ij}^m) - \mathcal{M}_2\, (1 - X_{ij}^c) \quad \forall (i,j) \in E,\ \forall c \in C \tag{4.11}$$

$$w_{ci} \text{ free} \qquad \forall i \in N,\ \forall c \in C \tag{4.4}$$

$$X_{ij}^c \in \{0,1\} \qquad \forall\, (i,j) \in E,\ \forall c \in C \tag{3.7}$$

4.5 Big-M Values

In order to efficiently solve the MILP, it is important to use the tighter values of Big-Ms. We present the explanation for the appropriate big-M values.

Big-M $\mathcal{M}_1$:

$\mathcal{M}_1$ has relevance when X_{ij}^c is zero. In that case, the constraints (4.8) and (4.9) make μ_{ij}^{mc} zero, and the constraint (4.6), which is as follows, should become redundant.

$$\mu_{ij}^{mc} \geq T_{ij}^m - \mathcal{M}_1 \qquad \forall (i,j) \in E,\ \forall m \in M,\ \forall c \in C$$

It is possible that the subsidy for hazmat 'm' on service-leg (i,j) (T_{ij}^m) is positive even if X_{ij}^c is zero; T_{ij}^m can take maximum value of 1. So, for $\mathcal{M}_1 < 1$, the lower bound to μ_{ij}^{mc} might set to some positive value that is contradicting as μ_{ij}^{mc} is already zero. Therefore, $\mathcal{M}_1 \geq 1$ is feasible region to make constraint (4.6) redundant. We set $\mathcal{M}_1$ to 1.

Big-M $\mathcal{M}_2$:

For a given shipment 'c' and a service-leg (i,j), from the constraint (4.11), we can write:

If $X_{ij}^c = 0$ then $\mathcal{M}_2 \;\geq\; \sum_m \mathcal{D}^{mc}\, C_{ij}\, (1 - T_{ij}^m) - (w_{ci} - w_{cj})$

It is pertinent to note that the valid $\mathcal{M}_2$ depends on the subsidy T_{ij}^m and the worth of service-leg (i,j) for the given subsidy decisions across the network. As the subsidy variables (T_{ij}^m) are solved simultaneously and, hence, unknown, it poses a significant challenge in obtaining the tighter value of $\mathcal{M}_2$. To circumvent the challenge, we consider an alternative formulation that is described in the next section.

4.6 The alternative formulation

Marcotte et al. (2009) proposed that when the lower level problem is linear, the single level reduction of the bi-level problem can be obtained by enforcing the equality of its primal and dual objectives instead of using complementary slackness condition (4.5). To overcome the challenge of obtaining the tighter value of $\mathcal{M}_2$, we apply the same idea to obtain the alternative formulation. The complementary slackness condition (4.5) is replaced by the equality of primal and dual objectives of the lower level problem that is expressed as in equation (4.12). It is linearised using the auxiliary variable μ_{ij}^{mc} as in equation (4.13).

$$\sum_c w_{c,O(c)} - \sum_c w_{c,D(c)} = \sum_{(i,j)} \sum_c \sum_m \mathcal{D}^{mc}\, C_{ij}\, (1 - T_{ij}^m)\, X_{ij}^c \tag{4.12}$$

$$\sum_c w_{c,O(c)} - \sum_c w_{c,D(c)} = \sum_{(i,j)} \sum_c \sum_m \mathcal{D}^{mc}\, C_{ij}\, (X_{ij}^c - \mu_{ij}^{mc}) \tag{4.13}$$

The alternative formulation is presented below by replacing the constraint (4.11) by the equation (4.13) in the single level linear model presented in section 4.4.

$$\underset{X_{ij}^{c},\, T_{ij}^{m}}{\text{Minimize}} \ \theta \tag{3.1}$$

Subject to:

$$\sum_{c} \sum_{m} \mathcal{D}^{mc} \, R_{ij}^{m} \, \left(X_{ij}^{c} + X_{ji}^{c}\right) \leq \theta \qquad \forall \,(i,j)\,, i < j \tag{3.2}$$

$$\sum_{(i,j)} \sum_{c} \sum_{m} \mathcal{D}^{mc} \, C_{ij} \, \mu_{ij}^{mc} \leq \mathcal{B} \tag{3.3}$$

$$\mu_{ij}^{mc} \geq T_{ij}^{m} - \mathcal{M}_1(1 - X_{ij}^{c}) \qquad \forall (i,j) \in E,\ \forall m \in M,\ \forall c \in C \tag{4.6}$$

$$\mu_{ij}^{mc} \leq T_{ij}^{m} \qquad \forall (i,j) \in E,\ \forall m \in M,\ \forall c \in C \tag{4.7}$$

$$\mu_{ij}^{mc} \leq X_{ij}^{c} \qquad \forall (i,j) \in E,\ \forall m \in M,\ \forall c \in C \tag{4.8}$$

$$\mu_{ij}^{mc} \geq 0 \qquad \forall (i,j) \in E,\ \forall m \in M,\ \forall c \in C \tag{4.9}$$

$$T_{ij}^{m} \leq \sum_{c \in C(m)} X_{ij}^{c} \qquad \forall (i,j) \in E,\ \forall m \in M \tag{4.10}$$

$$0 \leq T_{ij}^{m} \leq 1 \qquad \forall (i,j) \in E,\ \forall m \in M \tag{3.4}$$

$$\sum_{j:(i,j)\in E} X_{ij}^c - \sum_{j:(j,i)\in E} X_{ji}^c = \begin{cases} 1, & \text{if } i = O(c) \\ -1, & \text{if } i = D(c) \\ 0 & \text{otherwise} \end{cases} \qquad \forall i \in N,\ c \in C \tag{3.6}$$

$$w_{ci} - w_{cj} \leq \sum_{m} \mathcal{D}^{mc}\, C_{ij}\, (1 - T_{ij}^m) \qquad \forall (i,j) \in E,\ \forall c \in C \tag{4.3}$$

$$\sum_{c} w_{c,O(c)} - \sum_{c} w_{c,D(c)} = \sum_{(i,j)} \sum_{c} \sum_{m} \mathcal{D}^{mc}\, C_{ij}\, (X_{ij}^c - \mu_{ij}^{mc}) \tag{4.13}$$

$$w_{ci} \text{ free} \qquad \forall i \in N,\ \forall c \in C \tag{4.4}$$

$$X_{ij}^c \in \{0,1\} \qquad \forall\, (i,j) \in E,\ \forall c \in C \tag{3.7}$$

In our computational experiments, we solve the alternative formulation using the state-of-the-art solver CPLEX 12.8.0. We describe the settings of the computational experiments and results in the next chapter.

Chapter 5

Computational Experiments

The proposed subsidy policy is analysed using the methodology described in previous chapter to assess both the effectiveness of the proposed risk mitigation tool and the efficiency of the methodology. The solution methodology is applied to solve the problem instances generated using the realistic railroad network in midwest United States. The problem setting is discussed in detail in section 5.1. In section 5.2, we present the test results, and discuss the effectiveness of the proposed subsidy policy as a risk mitigation tool for railroad hazmat transportation. We study the results for the realistic infrastructure in section 5.3. Finally, in section 5.4, we comment on the efficiency of the solution methodology.

5.1 Problem Setting

We use the realistic infrastructure of a Class 1 railroad operator, in midwest United States, that was introduced in Verma, Verter and Gendreau (2011). Figure 5.2 shows the midwest United States railroad network, which is the replication of the service

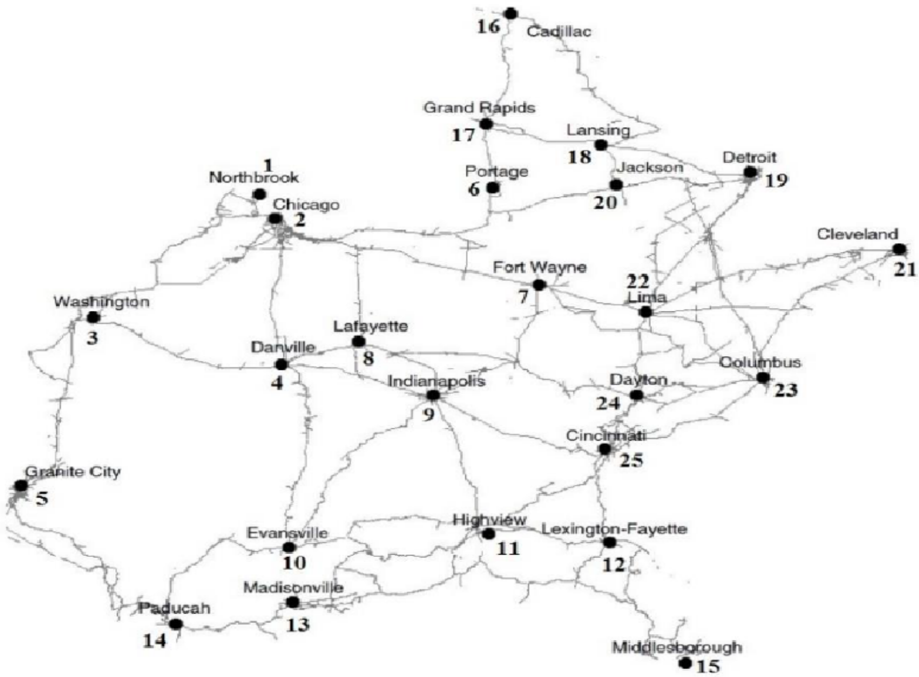

Figure 5.2: Railroad Network in the Midwest United States,
Source: Hosseini and Verma (2017)

network of Norfolk Southern (NS), a Class 1 railroad operator. It consists of 25 rail-yards, each of which can be an origin and destination for others. There are 53 service-legs in the railroad network that are operable in both directions. The rail-yards are ordered as shown in the figure 5.2, and, accordingly, the symmetric arc matrix is created to identify service-legs in the network. The cost associated with a service-leg is directly proportional to the distance required to travel on the service-leg. A symmetric cost matrix is created using the information about the travel distances on service-legs that are given in miles, and car-mile cost of \$ 0.5. Following a conservative approach, we consider population exposure as a measure of risk. We consider hazmat class 2, 3 and 8 that constitute a large amount (80 %) of hazmat moved in Canada (Vaezi and Verma, 2017). However, due to similar spilling characteristics of hazmat classes 3 and 8 that result in equivalent population exposure by both, their total tank-cars can be combined as a single hazmat type. With this, symmetric risk matrices for hazmat type 2 and 3 are created using the information about population exposure due to complete release from a single tank-car containing respective hazmat type. We randomly generate the demands in terms of a number of tank-cars for each hazmat type between the origin and destination. The shipment is associated with the corresponding OD pair, which is obtained randomly, and transports upto 30 hazmat tank-cars of different hazmat types. For our computational experiments on this network, we solve the problem for upto 50 shipments, each comprises a combination of randomly generated demands of two hazmat types, 2 and 3.

5.2 Solution of the problem

We solve the resulting MILP problem using the off-the-shelf solver IBM ILOG CPLEX 12.8.0. The problem is coded in C++ language in CPLEX concert technology environment on Visual Studio platform. We use CPLEX software available through IBM Academic Initiative program and Visual Studio, 2017. The problem instances are tested on a local machine with 1.60 GHz, intel core i5 CPU having 8 GB memory. The problem instances with 50 shipments are solved using high power computing resource available at Graham cluster of Compute Canada facility.

Using aforementioned computational infrastructure and problem setting, we study the rational response of carriers to government's offer of subsidy, and review the efficacy of this tool in achieving equitable distribution of risk across the railroad network. For this purpose, we generate the problem instances with the number of shipments varying from 5 to 50, and cost and risk corresponding to the given network. Each shipment 'c' comprises of demands for two hazmat types in terms of number of tank-cars '$\mathcal{D}^{mc}$' travelling between origin 'O(c)' and destination 'D(c)'. To conduct the parametric analysis of the impact of various budget allocation by the government, we supply different budget '$\mathcal{B}$' values congruent with the generated problem instances. For each instance and its corresponding budget, we record the total subsidy utilized out of the budget allocated and subsidy offered for each hazmat type on each service-leg 'T_{ij}^{m}'. We obtain the routes chosen for all shipments, and record the total cost of routing after utilizing the subsidy that is the lower level objective and resulting total risk in the network. The objective value of the MILP (θ) is the lowest maximum risk among all the service-legs across the network that is a measure of risk equity in the network. Before presenting the results for the midwest United States railroad network, next, we show the essence of applying subsidy policy for achieving risk equity in the network through an illustration of a small hypothetical railroad network.

5.2.1 Illustrative Example

Let us consider a hypothetical railroad network with 8 rail-yards and 13 service-legs operable in both directions. The network topology, in figure 5.3, shows the associated risk and cost in the same sequence over each service-leg. There are three shipments with origins and destinations {O,D} {2,8}, {1,6} and {3,7}, and demands of 10, 8 and 7 tank-cars respectively. For expositional reasons, it is considered that all demands consist of a single hazmat type. It is important to note that nodes '4' and '5' are dense population centers as the corresponding service-legs (as highlighted in figure

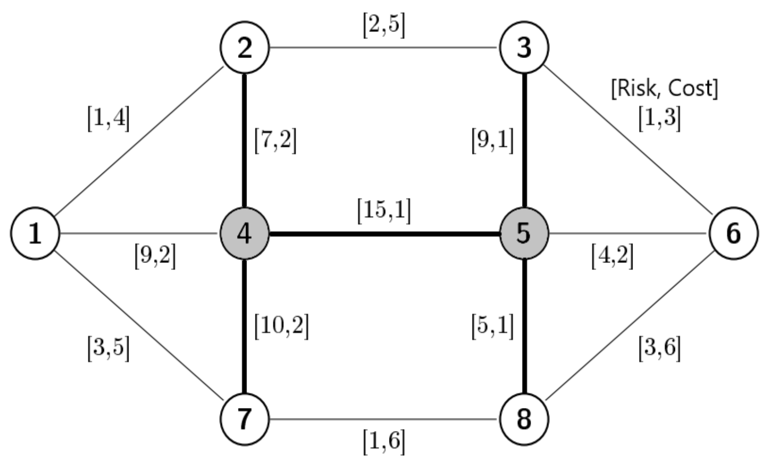

Figure 5.3: Hypothetical Railroad Network

5.3) are riskier, but they are cheaper to travel. Whereas, the peripheral service-legs are safer, but costlier.

We solve MILP for subsidy policy for this network with no budget allocated first, and, then, with 243 units of budget allocated for subsidy. Table 5.1 reports the results to review the changes in cost and risk in the network due to alternative routings of the shipments. With the budget of 243 units allocated for subsidy, maximum risk among the service-legs across the network reduces to 30 units from 375 units, when no budget is allocated. It is because utilizing the subsidy enables the carriers to route shipments through less riskier routes that is through peripheral service-legs in

Table 5.1: Results for hypothetical railroad network

SN	**{O,D}**	**Demand**	**Budget = 0**			**Budget = 243**		
			Route	**Cost**	**Risk**	**Route**	**Cost**	**Risk**
1	{2,8}	10	2-4-5-8	40	270	2-1-7-8	150	50
2	{1,6}	8	1-4-5-6	40	224	1-2-3-6	96	32
3	{3,7}	7	3-5-4-7	28	238	3-6-8-7	105	35
		Total		108	732		351	117
		Max-Risk Service-leg	(4-5)			(1-7)		
		Max-Risk	375			30		

this case. This results in equitable redistribution of risk, with Max-Risk on service-leg (1-7), compared to risk congestion on service-leg (4-5) earlier. The change in the routings of shipments are demonstrated in figure 5.4. Such alternative routes selection also results in reduction of total risk in the network from 732 units to 117 units. It is clear from the results that offering subsidy is a good incentive for carriers to choose less riskier though costlier routes for hazmat movements. For example, after offering subsidy, the first shipment is routed through costlier (150 units) but safer (50 units) path '2-1-7-8' compared to cheaper (40 units) but riskier (270 units) path '2-4-5-8' earlier. Table 5.2 shows the subsidy offered (T_{ij}^m) and the total discount out of 243 units on a service-leg for the movement of hazmat to achieve the purpose. It can be observed that the service-legs with low risk level have been offered more subsidy. Mostly, all the peripheral service-legs, which are safer in this network, have

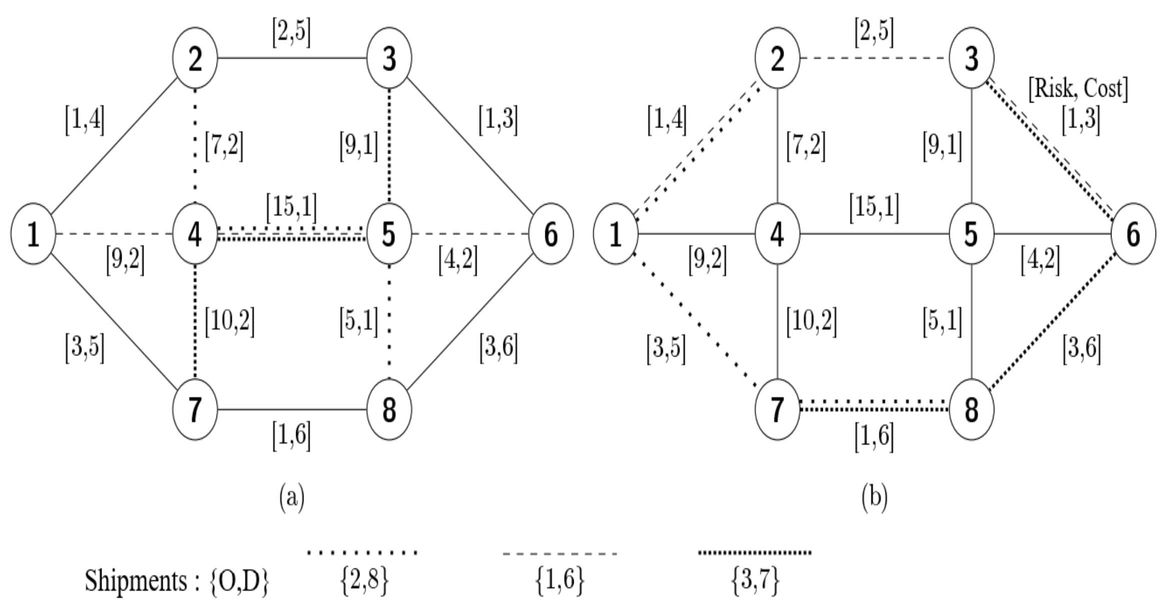

Figure 5.4: comparison between (a) without subsidy and (b) with subsidy routings

been offered subsidy for hazmat movements. Travel on service-legs (1-2) (in both directions) and (6,8) is made completely free for hazmat movement, whereas, the service-leg (7-8) (in both directions) are offered 67% discount on travel cost for hazmat movement.

Table 5.2: Subsidy offered over service-legs, hypothetical railroad network

SN	Hazmat type	Service-Leg	T_{ij}^m	Total Discount
1	1	(1,2)	1.00	32
2	1	(1,7)	0.60	30
3	1	(2,1)	1.00	40
4	1	(2,3)	0.40	16
5	1	(3,6)	0.33	15
6	1	(6,8)	1.00	42
7	1	(7,8)	0.67	40
8	1	(8,7)	0.67	28
Total Subsidy Utilized				243

Please note that 243 units is the amount, with which the most equitable distribution of risk in the network is obtained. Increasing the budget beyond it adds no value to the purpose. Through the example of hypothetical network, we attempt to show the usefulness of subsidy policy as a risk mitigation tool for railroad hazmat transportation network. Next, we report the results for the realistic midwest United States railroad network.

5.2.2 The Midwest United States Railroad Network

Table 5.3 shows the results of the midwest United States railroad network for upto 25 shipments. As mentioned in section 5.1, the demands, in terms of number of tank-cars for different hazmat types, and respective OD pairs for all shipments are randomly generated. To analyse the effect of budget, we start with no-budget allocated for subsidy for all shipments, and record the results for the budget amounts, for which the risk equity measure, that is the objective of MILP (θ), improves. It means that, for each considered value of budget, the objective value 'θ' (reported as 'Max-Risk' in table 5.3) decreases and between two consecutive values of budget, it remains same as one with the lower budget. In table 5.3, for expositional reason, we, only, report the results for the budgets that improve the objective significantly. To study the economic impact following carriers' rational response, we report the total subsidy utilized by the carriers (column 'a'), the total cost of alternative routings of the shipments without using subsidy (column 'b') and effective cost to carriers (column 'b-a') after utilising subsidy. Total risk is reported to study the change in cumulative risk over the network. The last column reports the computational time in seconds it took to solve on the machine.

Studying the results provides some significant insights about the effectiveness of the subsidy policy. First, it is evident from the results that the risk equity in the network is quite sensitive to the budget allocated by the government for subsidy. The results for 25 shipments instances show that, by utilization of $ 637 as subsidy that is around 1.5 % of the minimum transportation cost ($ 48,111.5, the total transportation cost, when subsidy is not offered), the maximum risk (Max-Risk) among the service-legs across the network reduces by 33%. It is, infact, the minimum budget required to allocate for subsidy to reduce Max-Risk across the network. The average for minimum budget for all the considered shipments is around 1% of the minimum transportation cost. The minimum budget brings down Max-Risk in the network by around 30% on average for all the shipments.

Table 5.3: Results for the midwest railroad network

SN	No. of Shipments	Budget	Subsidy Utilized (a)	Total Cost (without Subsidy) (b)	Effective Cost (b-a)	Max-Risk ($\boldsymbol{\theta}$)	Total Risk	Time(s)
1		0.0	0.0	8,004.0	8,004.0	15,314.0	55,544.0	0.21
2	5	19.0	19.0	8,023.0	8,004.0	13,702.0	62,876.0	0.26
3		504.0	504.0	8,508.0	8,004.0	9,106.0	47,316.0	0.16
4		0.0	0.0	18,275.5	18,275.5	32,978.0	158,822.0	0.17
5	10	286.0	286.0	18,561.5	18,275.5	21,726.0	146,260.0	1.43
6		622.0	622.0	18,897.5	18,275.5	15,314.0	151,168.0	3.31
7		641.0	641.0	18,916.5	18,275.5	15,048.0	158,500.0	1.80
8		0.0	0.0	27,578.5	27,578.5	32,978.0	245,915.0	0.38
9		435.5	435.5	28,014.0	27,578.5	23,716.0	246,157.0	3.74
10	15	783.5	783.5	28,362.0	27,578.5	21,726.0	254,077.0	4.65
11		1,119.5	1,119.5	28,698.0	27,578.5	19,404.0	258,985.0	3.91
12		1,911.5	1,911.5	29,490.0	27,578.5	17,898.0	255,979.0	11.82
13		0.0	0.0	33,299.0	33,299.0	62,080.0	355,543.0	0.33
14		132.0	132.0	33,431.0	33,299.0	32,978.0	310,935.0	4.19
15		567.5	567.5	33,866.5	33,299.0	26,976.0	311,177.0	4.11
16		1,786.0	1,786	35,029.5	33,243.5	26,598.0	333,833.0	16.83
17		2,180.0	2,180.0	35,372.5	33,192.5	22,568.0	335,821.0	22.96
18	20	2,325.0	2,324.1	35,514.5	33,190.4	21,798.0	321,705.0	21.81
19		2,566.0	2,566.0	35,755.5	33,189.5	20,956.0	336,429.0	23.66
20		2,619.0	2,619.0	35,862.5	33,243.5	20,448.0	326,193.0	12.58
21		3,980.0	3,979.3	37,101.5	33,122.2	19,404.0	320,821.0	28.99
22		4,654.0	4,654.0	37,728.5	33,074.5	18,684.0	314,329.0	56.47
23		0.0	0.0	48,111.5	48,111.5	116,676.0	694,080.0	0.41
24		637.0	637.0	48,594.5	47,957.5	77,784.0	658,944.0	15.31
25		1,473.0	1,473.0	49,584.5	48,111.5	58,344.0	545,648.0	4.64
26		2,859.0	2,859.0	50,970.5	48,111.5	42,772.0	533,888.0	17.08
27		2,991.0	2,991.0	51,102.5	48,111.5	40,392.0	504,843.0	42.05
28	25	3,172.5	3,172.5	51,284.0	48,111.5	38,892.0	520,939.0	24.06
29		3,809.0	3,809.0	51,767.0	47,958.0	37,400.0	485,803.0	54.66
30		3,985.0	3,985.0	51,844.0	47,859.0	35,976.0	489,771.0	111.19
31		5,500.0	5,500.0	53,302.0	47,802.0	32,978.0	490,835.0	191.33
32		6,000.0	6,000.0	53,635.0	47,635.0	29,202.0	493,517.0	36.51

Second, the maximum reduction, of more than 74% compared to no-subsidy scenario, in Max-Risk (from population exposure of 116,676 to 29,202) can be ascertained by offering $ 6,000 as subsidy for 25-shipments instance. It provides significant managerial insight for the government that it is sufficient to allocate only $ 6,000 budget for subsidy for this instance that is just around 12% of the minimum transportation cost; we refer the amount as cut-off budget. The average cut-off budget for all the shipments is around 8% of the minimum transportation cost that could achieve maximum reduction of around 57% in the risk equity measure on average.

Third, it is interesting to note that addressing the risk equity concern in the network also results in reducing the total population exposure risk, though it is not guaranteed. Excluding 15-shipments instances, in almost all instances, selection of alternative paths also reduce total risk in the network. For some instances, such reduction is significant. i.e., For 25-shipments instance with $ 6,000 allocated for subsidy, the total population exposure risk reduces to 493,517 that is the reduction of around 29% compared to no-subsidy scenario. Average reduction in total population exposure for these instances is around 25% compared to no-subsidy scenario.

5.3 Result Analysis

In this section, we study the results for the midwest United States network to review the effect of subsidy policy on the realistic infrastructure. As mentioned, we record the results corresponding to the budgets that improve the objective (Max-Risk). However, in table 5.3, we reported the results only for the budgets that significantly improve the objective. Figure 5.5 provides overview of the improvement in Max-Risk for all the values of budget that have been recorded. As alluded, between two consecutive values of budgets, the Max-Risk remains same as one with the lower budget. The deeper steps at the beginning, with respect to the scale, reflect the sensitive relationship between the subsidy and the risk equity in the network. Please note that, beyond the cut-off budget, there is no improvement in maximum risk.

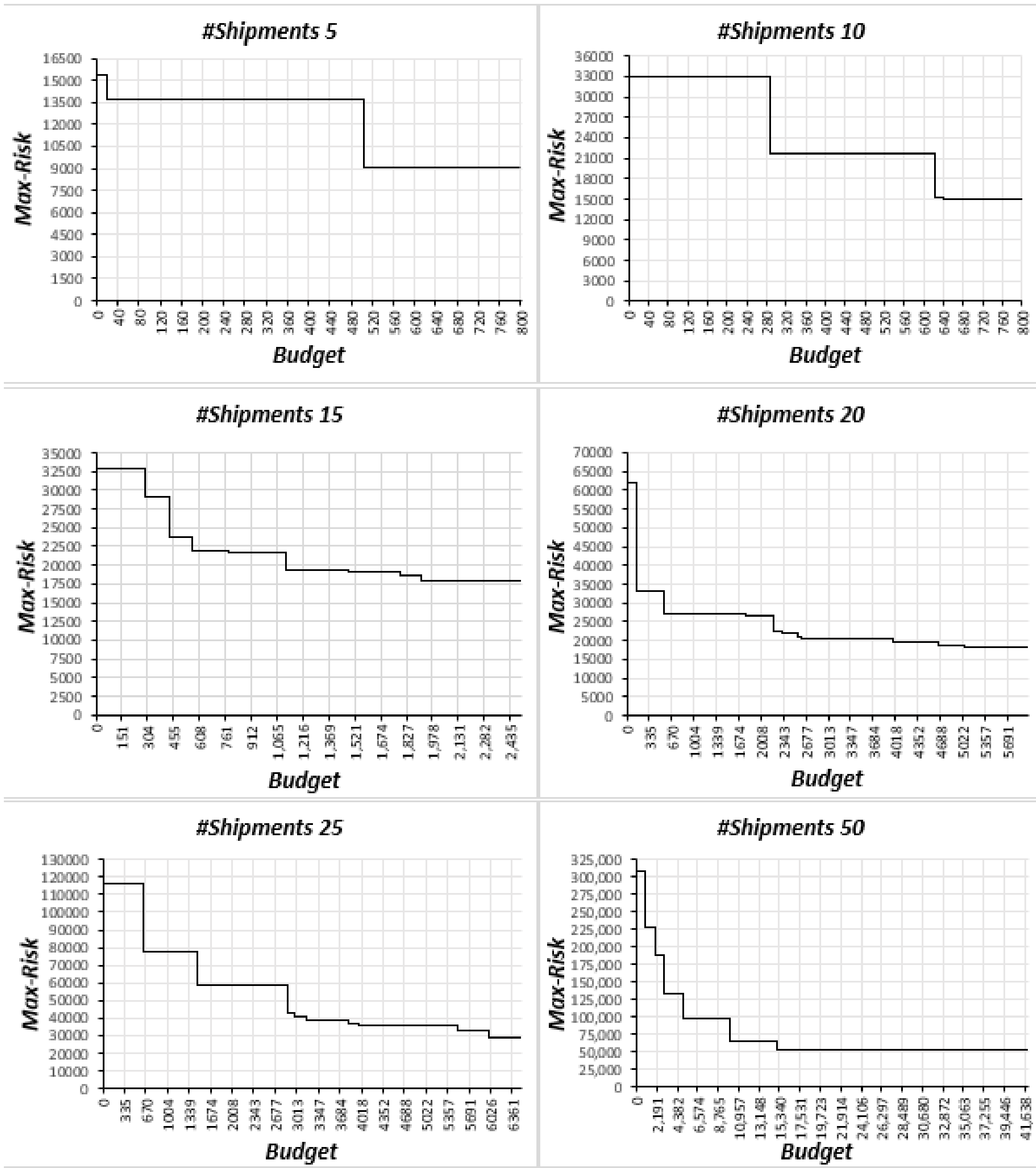

Figure 5.5: Max-Risk Vs Budget for the midwest US network

5.3.1 Study of the changes in routes

To study the changes in routings following the government's various budget allocations, we record the routes of the shipments for each budget considered. For expositional reasons, the routes of 25 shipments, along with their OD pairs and demands, are presented in table 5.4 for selected values of budget; the corresponding risk and cost numbers are also reported. In table 5.4, the results are reported for the budgets

Table 5.4: Routes for 25-shipments instances of the midwest railroad network

SN	(O,D)	Demand	Routes				
		[Type 2, Type 3]	No-budget	Budget = $ 1,473	Budget = $ 2,859	Budget = $ 5,500	Budget = $ 6,000
1	{7,10}	[10, 14]	7 - 9 - 10	7 - 9 - 10	7 - 9 - 10	7 - 9 - 10	7 - 9 - 10
2	{8,21}	[7, 2]	8 - 7 - 22 - 21	8 - 7 - 22 - 21	8 - 7 - 22 - 21	8 - 7 - 22 - 21	8 - 7 - 22 - 21
3	{14,5}	[7, 15]	14 - 5	14 - 5	14 - 5	14 - 5	14 - 5
4	{16,11}	[2, 0]	16 - 17 - 7- 9 - 11	16 - 17 - 7 - 9 - 11	16 - 17 - 7 - 9 - 11	16 - 17 - 7 - 9 - 11	16 - 17 - 7 - 9 - 11
5	{22,25}	[2, 10]	22 - 24 - 25	22 - 24 - 25	22 - 24 - 25	22 - 24 - 25	22 - 24 - 25
6	{2,25}	[11, 0]	2- 4 - 9 - 25	2 - 4 - 9 - 25	2 - 4 - 9 - 25	2 - 4 - 9 - 25	**2 - 6 - 8 - 9 - 25**
7	{3,18}	[5, 6]	3 - 4 - 8 - 6 - 20 - 18	3 - 4 - 8 - 6 - 20 - 18	3 - 4 - 8 - 6 - 20 - 18	**3 - 2 - 6 - 20 - 18**	3 - 2 - 6 - 20 - 18
8	{19,4}	[0, 12]	19 - 20 - 6 - 8 - 4	19 - 20 - 6 - 8 - 4	19 - 20 - 6 - 8 - 4	19 - 20 - 6 - 8 - 4	19 - 20 - 6 - 8 - 4
9	{10,19}	[4, 14]	10 - 4 - 8 - 6 - 20 - 19	10 - 4 - 8 - 6 - 20 - 19	10 - 4 - 8 - 6 - 20 - 19	10 - 4 - 8 - 6 - 20 - 19	10 - 4 - 8 - 6 - 20 - 19
10	{15,22}	[2, 4]	15 - 12 - 25 - 24 - 22	15 - 12 - 25 - 24 - 22	15 - 12 - 25 - 24 - 22	15 - 12 - 25 - 24 - 22	15 - 12 - 25 - 24 - 22
11	{12,21}	[9, 4]	12 - 25 - 23 - 21	12 - 25 - 23 - 21	12 - 25 - 23 - 21	12 - 25 - 23 - 21	12 - 25 - 23 - 21
12	{5,11}	[10, 8]	5 - 14 - 10 - 11	5 - 14 - 10 - 11	5 - 14 - 10 - 11	**5 - 14 - 13 - 10 - 11**	**5 - 14 - 10 - 11**
13	{13,8}	[0, 3]	13 - 10 - 4 - 8	13 - 10 - 4 - 8	13 - 10 - 4 - 8	13 - 10 - 4 - 8	13 - 10 - 4 - 8
14	{17,20}	[2, 0]	17 - 18 - 20	17 - 18 - 20	17 - 18 - 20	17 - 18 - 20	17 - 18 - 20
15	{21,25}	[11, 12]	21 - 23 - 25	21 - 23 - 25	21 - 23 - 25	21 - 23 - 25	21 - 23 - 25
16	{16,19}	[10, 12]	16 - 18 - 19	**16 - 17 - 18 - 19**	16 - 17 - 18 - 19	16 - 17 - 18 - 19	16 - 17 - 18 - 19
17	{12,25}	[7, 15]	12 - 25	12 - 25	12 - 25	12 - 25	12 - 25
18	{3,10}	[1, 0]	3 - 4 - 10	3 - 4 - 10	3 - 4 - 10	3 - 4 - 10	**3 - 2 - 4 - 10**
19	{6,14}	[0, 4]	6 - 8 - 4 - 10 - 14	6 - 8 - 4 - 10 - 14	6 - 8 - 4 - 10 - 14	6 - 8 - 4 - 10 - 14	6 - 8 - 4 - 10 - 14
20	{10,22}	[3, 4]	10 - 9 - 7 - 22	10 - 9 - 7 - 22	10 - 9 - 7 - 22	10 - 9 - 7 - 22	10 - 9 - 7 - 22
21	{1,15}	[6, 12]	1 - 2 - 4 - 9 - - 11 - 15	**1 - 3 - 4 - 9 -** **- 25 - 12 - 15**	**1 - 3 - 5 - 14 -** **- 13 - 15**	1 - 3 - 5 - 14 - - 13 - 15	1 - 3 - 5 - 14 - - 13 - 15
22	{9,24}	[6, 4]	9 - 25 - 24	9 - 25 - 24	9 - 25 - 24	9 - 25 - 24	9 - 25 - 24
23	{23,3}	[14, 8]	23 - 24 - 8 - 4 - 3	23 - 24 - 8 - 4 - 3	23 - 24 - 8 - 4 - 3	23 - 24 - 8 - 4 - 3	23 - 24 - 8 - 4 - 3
24	{24,1}	[5, 2]	24 - 22 - 7 - - 6 - 2 - 1	24 - 22 - 7 - - 6 - 2 - 1	24 - 22 - 7 - - 6 - 2 - 1	**24 - 25 - 12 - 13-** **- 14 - 5 - 3 - 1**	**24 - 25 - 11 - 10 -** **- 14 - 5 - 3 - 1**
25	{15,9}	[15, 7]	15 - 11 - 9	15 - 11 - 9	15 - 11 - 9	**15 - 12 - 25 - 9**	15 - 12 - 25 - 9
Max-Risk Service-leg			1-2	3-4	11-15	2-4	5-14
Max-Risk			116,676.0	58,344.0	42,772.0	32,978.0	29,202.0
Total Risk			694,080.0	545,648.0	533,888.0	490,835.0	493,517.0
Total cost before subsidy			48,111.5	49,584.5	50,970.5	53,302.0	53,635.0
Effective cost after subsidy			48,111.5	48,111.5	48,111.5	47,802.0	47,635.0

that could reroute the shipments such that service-leg with maximum risk is altered. The routes for all the budgets considered for 25-shipments instances are presented in table A.2 for the reader's reference. The shipments that are rerouted are shown in bold text. For these results, we discuss the major change in routings in context of maximum risk in the network.

With \$ 1,473 allocated for subsidy, maximum risk among service-legs reduces from population exposure of 116,676 to 58,344 by shifting it on service-leg (3-4) from (1-2). To achieve this, shipment no. '21' is directed away from service-leg (1,2) to service-leg (1,3) by offering discounts (T_{ij}^m) of 55% and 94% for travelling of hazmat type '2' and '3', respectively, on service-leg (1,3) (refer table A.4). The subsidy results (T_{ij}^m) corresponding to all the budgets are presented in the appendix for the reader's reference. It is important to note that the travelling cost on service-leg (1-3) is seven times higher than it is on service-leg (1-2), and service-leg (1-2) is the riskiest in the network (refer table A.1); shipment no. '21' transports 6 and 12 tank-cars of hazmat type '2' and '3' respectively. Improvement of around 50% in the risk-equity measure by allocating \$ 1,473 for subsidy, that is just 3% of the minimum transportation cost (\$ 48,111.5), is the essence of the subsidy policy as a risk mitigation tool.

When the budget is increased to \$ 2,859, the model offers incentives to transport hazmat through service-legs in the viscinity of (3-4) and other connected service-legs in the network; it makes the travel of hazmat type '3' on service-leg (3,5) completely free (refer table A.5). This brings down maximum risk in the network to population exposure of 42,772 by shifting it on service-leg (11-15). By (almost) doubling the budget to \$ 5,500, the model is able to offer subsidy on many service-legs simultaneously (refer table A.10) that could obtain comprehensive change in routings to improve the risk-equity measure. Further increment of the budget to \$ 6,000, the cut-off value, brings down maximum risk to the lowest. Increasing the budget beyond the cut-off value adds no benefit to the objective, as the shipments have already been routed through the longest path available for this topology following allocation of the cut-off budget for subsidy. However, it could reduce the effective transportation cost of the shipments by providing larger discounts on the service-legs.

5.3.2 Study of the changes in risk on service-legs

To study the changes in risk at the service-leg level, we record risk on all 53 service-legs corresponding to each budget considered. We select service-legs such as (1-2), (2-4), (3-4), (5-14) and (11-15), the usage of which in routings is observed to be, primarily, responsible for change in the risk-equity measure for this network topology. The associated risk and cost for these service-legs are shown in table 5.5 in the decreasing order of their risk. Sevice-leg (1-2) is the riskiest but cheapest, service-legs (2-4), and (11-15) are moderately riskier and costlier and service-legs (5-14) and (3-4) are comparatively safer and moderately costlier. From figure 5.6, it is observed that the utilization of subsidy enables the re-routing of shipments that significantly decreases

Table 5.5: Selected service-legs, the midwest US network

SN	**Service-leg**	**Cost per tank-car (C_{ij})**	**Risk per tank-car (R_{ij}^m)**	
			Type '2'	**Type '3'**
1	1-2	12	6482	3241
2	2-4	63	2998	1499
3	11-15	92.5	2312	1156
4	3-4	59	1496	748
5	5-14	84	628	314

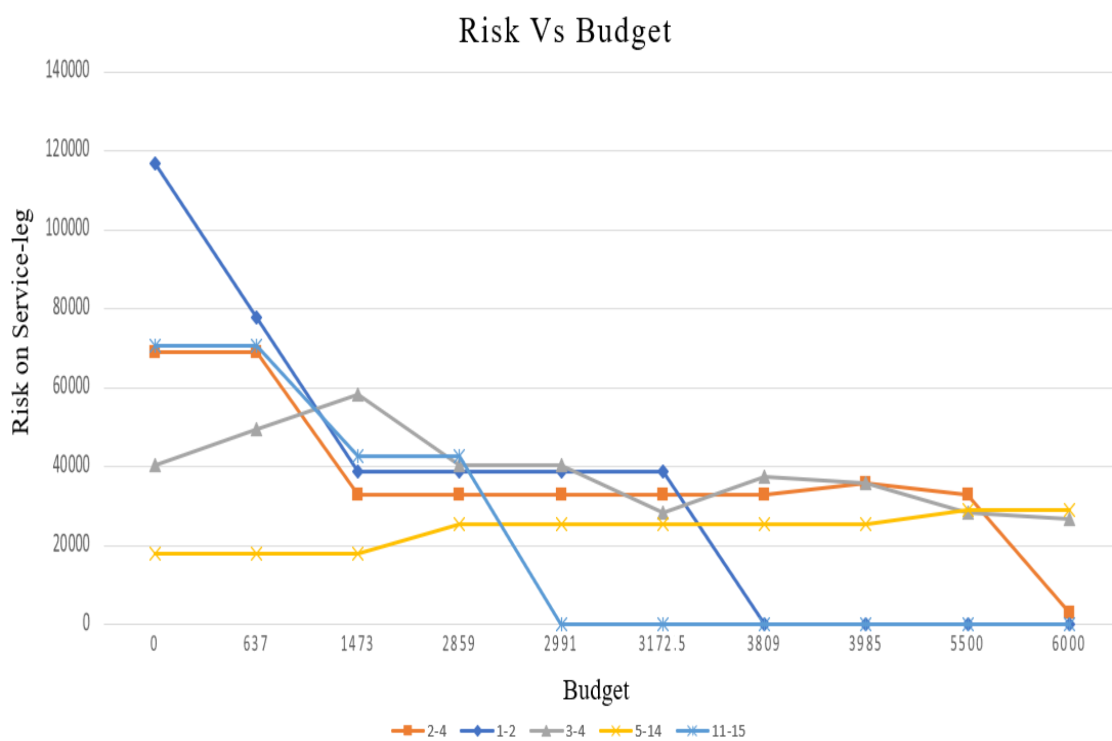

Figure 5.6: Risk Vs Budget on selected service-legs of the midwest US network for 25-shipments instances

risk on service-leg (1-2) and, eventually, makes it zero. Similar trends are observed for service-legs (2-4) and (11-15). The shipments travelling on high risk service-legs before subsidy are diverted to safer service-legs that include service-legs (5-14) and (3-4). Because of the re-routings, the (5-14) becomes the service-leg with maximum population exposure of 29,202 at the cut-off budget.

5.4 Efficiency of the solution methodology

We review the efficiency of the methodology in terms of computational time it takes to solve the problem instances and quality of the solution. The problem instances with upto 25-shipments are solved efficiently using the local machine having specification as described in section 5.1. All the instances with upto 15 shipments are solved within 15 seconds. Similar trends are observed for 20-shipments instances; other than the cut-off budget instance, which takes around 60 seconds, all the instances are solved within 30 seconds. 25-shipments instances generally take less than 60 seconds and 200 seconds at maximum for few budget values. CPLEX 12.8.0 is promptly

Table 5.6: Results for mid-west railroad network with 50 shipments using HPC resource

SN	No. of Shipments	Budget	Subsidy Utilized (a)	Total Cost (without Subsidy) (b)	Effective Cost (b-a)	Max Risk (Objective)	Total Risk	Time(s)
1	50	0	0	107,820	107,820	307,895	1,497,390	1.81
2		1,000	1,000	108,710	107,710	226,870	1,408,870	32.00
3		2,000	2,000	109,297	107,297	187,978	1,364,100	517.00
4		3,000	3,000	110,262	107,262	133,144	1,322,270	363.00
5		5,000	5,000	112,718	107,718	98,736	1,335,320	3,597.00
6		10,000	10,000	115,914	105,914	65,076	1,184,730	59,291.00
7		15,000	15,000	119,710	104,710	54,008	1,110,870	2,695.00
8		20,000	20,000	121,488	101,488	54,008	1,118,370	>172,800.00
9		30,000	30,000	126,180	96,180	52,668	1,171,650	>172,800.00
10		40,000	40,000	125,917	85,917	52,465	1,158,570	10,709.00

able to solve the instances upto 25 shipments to optimality. However, on the local machine, it takes hours to solve 50-shipments instances to optimality, and days for some budget instances without guaranteeing good quality solution. Therefore, we attempt to solve 50-shipments instances using high power computing (HPC) resource available at Graham cluster of Compute Canada facility. A node at Graham cluster consists of multiple 2.1 GHz Intel E5, E7 or Xeon CPUs, also referred as threads, with memory varying 124G to 3022G (Graham, Compute Canada, 2017). The problem instances are solved on a node with 32 such threads and 30G to 100G memory. Table 5.6 reports the results of 50-shipments instances solved to optimality using HPC resource. It is noticed that, except three instances that take longer, almost all instances are solved to optimality within an hour; the \$ 40,000 budget instance is solved within 3 hours. The instances with budgets \$ 20,000 and \$ 30,000 could not solve to optimality even in two days. However, it is observed that HPC resource produces good quality solutions in reasonable time. Hence, in our computation for 50-shipments instances using the HPC resource, we set the time limit of 7200 seconds and relative optimality gap of 2%. In table 5.7, we report the results for 50-shipments instances along with quality of the solutions in terms of the relative optimality gap.

Table 5.7: Results for the midwest US network with 50 shipments using HPC resource;
Time Limit = 7200 s, Optimality Gap = 2%

SN	No. of Shipments	Budget	Subsidy Utilized (a)	Total Cost (without Subsidy) (b)	Effective Cost (b-a)	Max Risk (Objective)	Total Risk	Time(s)	Gap (%)
1	50	0	0	107,820	107,820	307,895	1,497,390	2	0.00
2		1,000	1,000	108,710	107,710	226,870	1,408,870	32	0.00
3		2,000	2,000	109,297	107,297	187,978	1,364,100	517	0.00
4		3,000	3,000	110,262	107,262	133,144	1,322,270	363	0.00
5		5,000	5,000	112,178	107,178	98,736	1,335,320	864	1.99
6		10,000	10,000	115,896	105,896	65,076	1,191,400	863	1.99
7		15,000	15,000	118,791	103,791	54,008	1,102,000	2,623	1.99
8		20,000	20,000	120,236	100,236	54,008	1,083,090	7,200	3.05
9		30,000	30,000	127,949	97,949	53,380	1,177,420	3,302	1.97
10		40,000	40,000	130,386	90,386	52,752	1,215,920	1,904	0.74

The results of the 50-shipments instances attest the effectiveness of the subsidy policy as a risk mitigation tool for railroad hazmat transportation. A subsidy of \$ 1,000, which is less than 1% of the minimum transportation cost (\$ 107,820), is able to improve risk equity measure by around 26% to population exposure of 226,870 from 307,895. Moreover, the improvement of upto around 82% in risk equity measure is ascertained by utilizing \$ 40,000, that is 37% of the minimum transportation cost. The results affirm the fact that the carriers' reaction, that is to consider alternative routes for distributed risk in the network, is quite sensitive to subsidy. Also, it is pertinent to note that, though, the proposed methodology requires longer computational time on HPC resource to solve large instances optimally, it can produce good quality solutions in reasonable time.

Table 5.8 shows the overview of the reduction in Max-Risk (the objective) and Total Risk for the minimum and cut-off budget values for all the shipments. $\Delta\mathcal{B}$ is the percentage of the minimum and cut-off budgets with respect to the corresponding minimum transportation cost. $\Delta\theta$ and ΔTR are the percentage reduction in Max-Risk and Total Risk, respectively, for the minimum and cut-off budgets with respect to their values during no-subsidy scenario. It is clear that, by offering the minimum budget as subsidy, the Max-Risk in the network is reduced by minimum of 10.53% to maximum of 46.88%. It is the average reduction of Max-Risk by around 30% by offering the

Table 5.8: Max-Risk and Total Risk compared to no-budget scenario for minimum and cut-off budgets

SN	**#Shipments**	**(%) change from no-subsidy scenario**	**Minimum budget**	**Cut-off budget**
1		$\Delta\mathcal{B}$	0.24 %	6.30 %
2	5	$\Delta\theta$	10.53 %	40.54 %
3		ΔTR	-13.20 %	14.81 %
4		$\Delta\mathcal{B}$	1.56 %	3.51 %
5	10	$\Delta\theta$	34.12 %	54.37 %
6		ΔTR	7.91 %	0.20 %
7		$\Delta\mathcal{B}$	1.58 %	6.93 %
8	15	$\Delta\theta$	28.09 %	45.73 %
9		ΔTR	-0.10 %	-4.09 %
10		$\Delta\mathcal{B}$	0.40 %	13.98 %
11	20	$\Delta\theta$	46.88 %	69.90 %
12		ΔTR	12.55 %	11.59 %
13		$\Delta\mathcal{B}$	1.32 %	12.47 %
14	25	$\Delta\theta$	33.33 %	74.97 %
15		ΔTR	5.06 %	28.90 %
16		$\Delta\mathcal{B}$	0.93 %	37.10 %
17	50	$\Delta\theta$	26.32 %	82.87 %
18		ΔTR	5.91 %	18.80 %

minimum budget that is around 1% of the respective minimum transportation cost in average. Similarly, by offering the cut-off budget as the subsidy, the Max-Risk in the network is reduced by minimum of 40.54% to maximum of 82.87%. It is the average reduction of around 61% by offering the average cut-off budget that is around 13% of the respective minimum transportation cost in average. The sensitive relation of Max-Risk (the objective) with the subsidy is the essence of the subsidy policy as the risk mitigation strategy. Moreover, it is observed that except 15-shipments instances, in almost all the instances, there is ultimate reduction in Total Risk, that is the complementary benefit of implementing subsidy policy in rail hazmat transportation.

Chapter 6

Conclusion

Realizing the underlying challenges in a railroad transportation network due to its unique characteristics, we propose the subsidy policy as a risk mitigation strategy for railroad hazmat transportation. We formulate the bi-level mixed integer problem to address the government's risk averse concern and the carriers' cost effective concern. We exploit the special structure of the lower level problem and reduce it to MILP using its KKT conditions. We present the alternative formulation of the MILP, which is solved for the instances of the realistic midwest United States railroad network. The instances of upto 25 shipments over the midwest railroad network are efficiently solved by the state-of-the-art solver CPLEX 12.8.0. Also, we solve the 50-shipments instances using the HPC resource at Graham cluster at Compute Canada facility with good quality solutions in reasonable time. The results show the effectiveness of the subsidy policy in achieving the most equitable distribution of the risk across the network. The important insight of the results is that the carriers' reaction to consider alternative routing plans are quite sensitive to the subsidy being offered. This makes the risk mitigation strategy more practical and economically feasible.

This work appends significant developments for risk mitigation in railroad hazmat transportation to the literature. First, the idea of the subsidy policy is absolutely worth to achieve risk equity in a railroad network. In our best knowledge, it is the first of its kind approach in railroad hazmat transportation that ascertain the government's objective of risk averse railroad hazmat transportation, which is not assured otherwise due to carriers' cost effective nature, by appropriately compensating them. Second, we propose the mathematical formulation that enclose contrasting objectives and requirements of both the government and carriers, and relevant restrictions in railroad transportation. Third, the proposed solution methodology is capable of obtaining optimal solution for upto 25-shipments instances efficiently and good quality solution for 50-shipments instances in reasonable time through off-the-self solver. Finally, the analysis of results draws important managerial insights to make informed decisions pertaining to future planning.

This work can be advanced to include assumptions made. It does not take into account the usage of different train service types for a shipment, that may be helpful for economies of scale and offer operational convenience, and the subsequent handling cost arising at rail-yards . This work can be extended to include such attributes of railroad transportation. We make use of population exposure as risk measure with a conservative approach. The subsidy policy can be further analysed considering more precise risk assessment techniques described in the literature. Finally, these extensions of work may require development of the efficient algorithm, which can solve large size instances with more than two hazmat types over a larger railroad network.

Appendix A

Appendix

Table A.1: Cost and Risk, the midwest US railroad network

SN	Service-leg	C_{ij}	R^m_{ij}		SN	Service-leg	C_{ij}	R^m_{ij}	
			Type '2'	**Type '3'**				**Type '2'**	**Type '3'**
1	1-2	12.0	6482	3241	**28**	10-14	64.0	1088	544
2	1-3	84.5	902	451	**29**	11-12	40.0	476	238
3	2-3	73.0	2466	1233	**30**	11-13	92.0	368	184
4	2-4	63.0	2998	1499	**31**	11-15	92.5	2312	1156
5	2-6	64.0	1368	684	**32**	11-25	63.0	514	257
6	3-4	59.0	1496	748	**33**	12-13	112.0	320	160
7	3-5	83.0	990	495	**34**	12-15	64.0	424	212
8	4-8	25.0	276	138	**35**	12-25	40.5	492	246
9	4-9	45.5	462	231	**36**	13-14	37.0	458	229
10	4-10	78.0	208	104	**37**	13-15	133.5	390	195
11	5-14	84.0	628	314	**38**	16-17	54.5	514	257
12	6-7	32.5	120	60	**39**	16-18	80.5	3880	1940
13	6-8	36.5	50	25	**40**	17-18	32.0	578	289
14	6-20	34.0	74	37	**41**	18-19	42.5	1686	843
15	7-8	55.0	198	99	**42**	18-20	25.0	410	205
16	7-9	58.0	806	403	**43**	19-20	39.5	1278	639
17	7-17	88.0	328	164	**44**	19-22	63.5	1132	566
18	7-20	85.5	154	77	**45**	20-22	78.5	218	109
19	7-22	30.5	532	266	**46**	20-23	100.0	1270	635
20	7-23	81.0	420	210	**47**	21-22	74.5	686	343
21	8-9	34.0	900	450	**48**	21-23	70.0	620	310
22	8-24	85.0	394	197	**49**	22-23	41.0	594	297
23	9-10	79.0	360	180	**50**	22-24	45.5	422	211
24	9-11	57.5	746	373	**51**	23-24	37.0	1124	562
25	9-25	51.5	572	286	**52**	23-25	56.0	1038	519
26	10-11	59.5	586	293	**53**	24-25	30.5	1078	539
27	10-13	27.5	218	109					

Table A.2: Routes for 25-shipments instances of the midwest railroad network, all budgets

SN	(O,D)	Demand	Routes									
		[Type 2, Type 3]	No-budget	Budget = $ 637	Budget = $ 1,473	Budget = $ 2,859	Budget = $ 2,991	Budget = $ 3,172.5	Budget = $ 3,809	Budget = $ 3,985	Budget = $ 5,500	Budget = $ 6,000
1	{7,10}	[10, 14]	7 - 9 - 10	7 - 9 - 10	7 - 9 - 10	7 - 9 - 10	7 - 9 - 10	7 - 9 - 10	7 - 9 - 10	7 - 9 - 10	7 - 9 - 10	7 - 9 - 10
2	{8,21}	[7, 2]	8 - 7 - 22 - 21	8 - 7 - 22 - 21	8 - 7 - 22 - 21	8 - 7 - 22 - 21	8 - 7 - 22 - 21	8 - 7 - 22 - 21	8 - 7 - 22 - 21	8 - 7 - 22 - 21	8 - 7 - 22 - 21	8 - 7 - 22 - 21
3	{14,5}	[7, 15]	14 - 5	14 - 5	14 - 5	14 - 5	14 - 5	14 - 5	14 - 5	14 - 5	14 - 5	14 - 5
4	{16,11}	[2, 0]	16 - 17 - 7 - 9 - 11	16 - 17 - 7 - 9 - 11	16 - 17 - 7 - 9 - 11	16 - 17 - 7 - 9 - 11	16 - 17 - 7 - 9 - 11	16 - 17 - 7 - 9 - 11	16 - 17 - 7 - 9 - 11	16 - 17 - 7 - 9 - 11	16 - 17 - 7 - 9 - 11	16 - 17 - 7 - 9 - 11
5	{22,25}	[2, 10]	22 - 24 - 25	22 - 24 - 25	22 - 24 - 25	22 - 24 - 25	22 - 24 - 25	22 - 24 - 25	22 - 24 - 25	22 - 24 - 25	22 - 24 - 25	22 - 24 - 25
6	{2,25}	[11, 0]	2 - 4 - 9 - 25	2 - 4 - 9 - 25	2 - 4 - 9 - 25	2 - 4 - 9 - 25	2 - 4 - 9 - 25	2 - 4 - 9 - 25	2 - 4 - 9 - 25	2 - 4 - 9 - 25	2 - 4 - 9 - 25	**2 - 6 - 8 - 9 - 25**
7	{3,18}	[5, 6]	3 - 4 - 8 - 6 - 20 - 18	3 - 4 - 8 - 6 - 20 - 18	3 - 4 - 8 - 6 - 20 - 18	3 - 4 - 8 - 6 - 20 - 18	3 - 4 - 8 - 6 - 20 - 18	**3 - 2 - 6 - 20 - 18**	3 - 2 - 6 - 20 - 18	3 - 2 - 6 - 20 - 18	3 - 2 - 6 - 20 - 18	3 - 2 - 6 - 20 - 18
8	{19,4}	[0, 12]	19 - 20 - 6 - 8 - 4	19 - 20 - 6 - 8 - 4	19 - 20 - 6 - 8 - 4	19 - 20 - 6 - 8 - 4	19 - 20 - 6 - 8 - 4	19 - 20 - 6 - 8 - 4	19 - 20 - 6 - 8 - 4	19 - 20 - 6 - 8 - 4	19 - 20 - 6 - 8 - 4	19 - 20 - 6 - 8 - 4
9	{10,19}	[4, 14]	10 - 4 - 8 - 6 - 20 - 19	10 - 4 - 8 - 6 - 20 - 19	10 - 4 - 8 - 6 - 20 - 19	10 - 4 - 8 - 6 - 20 - 19	10 - 4 - 8 - 6 - 20 - 19	10 - 4 - 8 - 6 - 20 - 19	10 - 4 - 8 - 6 - 20 - 19	10 - 4 - 8 - 6 - 20 - 19	10 - 4 - 8 - 6 - 20 - 19	10 - 4 - 8 - 6 - 20 - 19
10	{15,22}	[2, 4]	15 - 12 - 25 - 24 - 22	15 - 12 - 25 - 24 - 22	15 - 12 - 25 - 24 - 22	15 - 12 - 25 - 24 - 22	15 - 12 - 25 - 24 - 22	15 - 12 - 25 - 24 - 22	15 - 12 - 25 - 24 - 22	15 - 12 - 25 - 24 - 22	15 - 12 - 25 - 24 - 22	15 - 12 - 25 - 24 - 22
11	{12,21}	[9, 4]	12 - 25 - 23 - 21	12 - 25 - 23 - 21	12 - 25 - 23 - 21	12 - 25 - 23 - 21	12 - 25 - 23 - 21	12 - 25 - 23 - 21	12 - 25 - 23 - 21	12 - 25 - 23 - 21	12 - 25 - 23 - 21	12 - 25 - 23 - 21
12	{5,11}	[10, 8]	5 - 14 - 10 - 11	5 - 14 - 10 - 11	5 - 14 - 10 - 11	5 - 14 - 10 - 11	5 - 14 - 10 - 11	5 - 14 - 10 - 11	5 - 14 - 10 - 11	5 - 14 - 10 - 11	**5 - 14 - 13 - 10 - 11**	**5 - 14 - 10 - 11**
13	{13,8}	[0, 3]	13 - 10 - 4 - 8	13 - 10 - 4 - 8	13 - 10 - 4 - 8	13 - 10 - 4 - 8	13 - 10 - 4 - 8	13 - 10 - 4 - 8	13 - 10 - 4 - 8	13 - 10 - 4 - 8	13 - 10 - 4 - 8	13 - 10 - 4 - 8
14	{17,20}	[2, 0]	17 - 18 - 20	17 - 18 - 20	17 - 18 - 20	17 - 18 - 20	17 - 18 - 20	17 - 18 - 20	17 - 18 - 20	17 - 18 - 20	17 - 18 - 20	17 - 18 - 20
15	{21,25}	[11, 12]	21 - 23 - 25	21 - 23 - 25	21 - 23 - 25	21 - 23 - 25	21 - 23 - 25	21 - 23 - 25	21 - 23 - 25	21 - 23 - 25	21 - 23 - 25	21 - 23 - 25
16	{16,19}	[10, 12]	16 - 18 - 19	16 - 18 - 19	**16 - 17 - 18 - 19**	16 - 17 - 18 - 19	16 - 17 - 18 - 19	16 - 17 - 18 - 19	16 - 17 - 18 - 19	16 - 17 - 18 - 19	16 - 17 - 18 - 19	16 - 17 - 18 - 19
17	{12,25}	[7, 15]	12 - 25	12 - 25	12 - 25	12 - 25	12 - 25	12 - 25	12 - 25	12 - 25	12 - 25	12 - 25
18	{3,10}	[1, 0]	3 - 4 - 10	3 - 4 - 10	3 - 4 - 10	3 - 4 - 10	3 - 4 - 10	3 - 4 - 10	3 - 4 - 10	**3 - 2 - 4 - 10**	**3 - 4 - 10**	**3 - 2 - 4 - 10**
19	{6,14}	[0, 4]	6 - 8 - 4 - 10 - 14	6 - 8 - 4 - 10 - 14	6 - 8 - 4 - 10 - 14	6 - 8 - 4 - 10 - 14	6 - 8 - 4 - 10 - 14	6 - 8 - 4 - 10 - 14	6 - 8 - 4 - 10 - 14	6 - 8 - 4 - 10 - 14	6 - 8 - 4 - 10 - 14	6 - 8 - 4 - 10 - 14
20	{10,22}	[3, 4]	10 - 9 - 7 - 22	10 - 9 - 7 - 22	10 - 9 - 7 - 22	10 - 9 - 7 - 22	10 - 9 - 7 - 22	10 - 9 - 7 - 22	10 - 9 - 7 - 22	10 - 9 - 7 - 22	10 - 9 - 7 - 22	10 - 9 - 7 - 22
21	{1,15}	[6, 12]	1 - 2 - 4 - 9 - - 11 - 15	1 - 2 - 4 - 9 - - 11 - 15	**1 - 3 - 4 - 9 - - 25 - 12 - 15**	**1 - 3 - 5 - 14 - - 13 - 15**	1 - 3 - 5 - 14 - - 13 - 15	1 - 3 - 5 - 14 - - 13 - 15	1 - 3 - 5 - 14 - - 13 - 15	1 - 3 - 5 - 14 - - 13 - 15	1 - 3 - 5 - 14 - - 13 - 15	1 - 3 - 5 - 14 - - 13 - 15
22	{9,24}	[6, 4]	9 - 25 - 24	9 - 25 - 24	9 - 25 - 24	9 - 25 - 24	9 - 25 - 24	9 - 25 - 24	9 - 25 - 24	9 - 25 - 24	9 - 25 - 24	9 - 25 - 24
23	{23,3}	[14, 8]	23 - 24 - 8 - 4 - 3	23 - 24 - 8 - 4 - 3	23 - 24 - 8 - 4 - 3	23 - 24 - 8 - 4 - 3	23 - 24 - 8 - 4 - 3	23 - 24 - 8 - 4 - 3	23 - 24 - 8 - 4 - 3	23 - 24 - 8 - 4 - 3	23 - 24 - 8 - 4 - 3	23 - 24 - 8 - 4 - 3
24	{24,1}	[5, 2]	24 - 22 - 7 - 6 - - 2 - 1	**24 - 8 - 4 - 3 - 1**	**24 - 22 - 7 - 6 - - 2 - 1**	24 - 22 - 7 - 6 - - 2 - 1	24 - 22 - 7 - 6 - - 2 - 1	24 - 22 - 7 - 6 - - 2 - 1	**24 - 8 - 4 - 3 - 1**	24 - 8 - 4 - 3 - 1	**24 - 25 - 12 - 13 - - 14 - 5 - 3 - 1**	**24 - 25 - 11 - 10 - - 14 - 5 - 3 - 1**
25	{15,9}	[15, 7]	15 - 11 - 9	15 - 11 - 9	15 - 11 - 9	15 - 11 - 9	**15 - 12 - 25 - 9**	15 - 12 - 25 - 9	15 - 12 - 25 - 9	15 - 12 - 25 - 9	15 - 12 - 25 - 9	15 - 12 - 25 - 9
Max-Risk Service-leg			1-2	1-2	3-4	11-15	3-4	1-2	3-4	2-4	2-4	5-14
Max-Risk			116,676.0	77,784.0	58,344.0	42,772.0	40,392.0	38,892.0	37,400.0	35,976.0	32,978.0	29,202.0
Total Risk			694,080.0	658,944.0	545,648.0	533,888.0	504,843.0	520,939.0	485,803.0	489,771.0	490,835.0	493,517.0
Total cost before subsidy			48,111.5	48,594.5	49,584.5	50,970.5	51,102.5	51,284.0	51,767.0	51,844.0	53,302.0	53,635.0
Effective cost after subsidy			48,111.5	47,957.5	48,111.5	48,111.5	48,111.5	48,111.5	47,958.0	47,859.0	47,802.0	47,635.0

Table A.3: Subsidy results for the midwest US network : Budget = \$ 637, No. of shipments = 25

Subsidy results : Budget = 637, Shipments = 25				
SN	**Hazmat type**	**Service-Leg**	T_{ij}^{m}	**Total-discount**
1	2	(3,1)	1.00	422.50
2	2	(4,3)	0.16	176.70
3	2	(8,4)	0.03	13.30
4	3	(3,1)	0.06	10.50
5	3	(3,4)	0.04	14.00

Table A.4: Subsidy results for the midwest US network : Budget = \$ 1,473, No. of shipments = 25

SN	**Hazmat type**	**Service-Leg**	T_{ij}^{m}	**Total-discount (\$)**
1	2	(1,3)	0.55	279.00
2	3	(1,3)	0.94	954.00
3	3	(12,15)	0.14	108.00
4	3	(16,17)	0.20	132.00

Table A.5: Subsidy results for the midwest US network : Budget = \$ 2,859, No. of shipments = 25

SN	**Hazmat type**	**Service-Leg**	T_{ij}^{m}	**Total-discount (\$)**
1	2	(1,3)	0.81	411.00
2	2	(3,5)	0.08	39.60
3	2	(14,13)	0.02	5.40
4	3	(1,3)	0.49	492.00
5	3	(3,5)	1.00	996.00
6	3	(13,15)	0.49	783.00
7	3	(17,18)	0.34	132.00

Table A.6: Subsidy results for the midwest US network : Budget = \$ 2,991, No. of shipments = 25

SN	Hazmat type	Service-Leg	T_{ij}^{m}	Total-discount
1	2	(1,3)	0.55	279.00
2	2	(3,5)	0.91	451.50
3	2	(13,15)	0.98	783.00
4	2	(25,9)	0.17	132.00
5	3	(1,3)	0.94	954.00
6	3	(3,5)	0.25	246.00
7	3	(14,13)	0.03	13.50
8	3	(17,18)	0.34	132.00

Table A.7: Subsidy results for the midwest US network : Budget = \$ 3,172.5, No. of shipments = 25

SN	Hazmat type	Service-Leg	T_{ij}^{m}	Total-discount
1	2	(1,3)	0.72	362.51
2	2	(3,5)	1.00	498.00
3	2	(25,9)	0.12	90.00
4	3	(1,3)	0.65	661.71
5	3	(3,2)	0.41	181.50
6	3	(3,5)	0.83	826.29
7	3	(13,15)	0.23	364.99
8	3	(14,13)	0.03	13.50
9	3	(17,18)	0.34	132.00
10	3	(25,9)	0.12	42.00

Table A.8: Subsidy results for the midwest US network : Budget = \$ 3,809, No. of shipments = 25

SN	Hazmat type	Service-Leg	T_{ij}^{m}	Total-discount
1	2	(3,1)	1.00	422.27
2	2	(3,2)	0.50	181.50
3	2	(3,5)	1.00	498.00
4	2	(4,3)	0.19	208.32
5	2	(13,15)	0.92	735.60
6	2	(14,13)	0.02	5.40
7	2	(25,9)	0.17	132.00
8	3	(1,3)	0.49	492.00
9	3	(3,1)	0.04	5.91
10	3	(3,5)	1.00	996.00
11	3	(16,17)	0.20	132.00

Table A.9: Subsidy results for the midwest US network : Budget = \$ 3,985, No. of shipments = 25

SN	Hazmat type	Service-Leg	T_{ij}^{m}	Total-discount
1	2	(1,3)	1.00	507.00
2	2	(2,4)	0.06	48.00
3	2	(3,1)	1.00	422.50
4	2	(3,2)	1.00	438.00
5	2	(3,5)	1.00	498.00
6	2	(14,13)	0.02	5.40
7	2	(24,8)	0.0008	1.36
8	2	(25,9)	0.17	132.00
9	3	(3,1)	0.36	60.14
10	3	(3,5)	1.00	996.00
11	3	(13,15)	0.46	744.60
12	3	(17,18)	0.34	132.00

Table A.10: Subsidy results for the midwest US network : Budget = \$ 5,500, No. of shipments = 25

SN	Hazmat type	Service-Leg	T_{ij}^{m}	Total-discount (\$)
1	2	(1,3)	0.81	411.00
2	2	(3,1)	1.00	422.50
3	2	(3,5)	1.00	498.00
4	2	(5,3)	0.81	337.50
5	2	(12,13)	1.00	560.00
6	2	(13,14)	1.00	185.00
7	2	(14,5)	0.42	422.58
8	2	(14,13)	0.01	8.00
9	2	(15,12)	0.12	126.70
10	2	(24,25)	0.79	168.32
11	2	(25,12)	0.44	90.00
12	3	(1,3)	0.49	492.00
13	3	(3,1)	0.04	5.83
14	3	(3,2)	0.41	181.50
15	3	(3,5)	1.00	996.00
16	3	(12,13)	0.49	110.87
17	3	(13,14)	0.01	1.00
18	3	(13,15)	0.20	321.00
19	3	(14,13)	0.01	10.00
20	3	(16,17)	0.20	132.00
21	3	(25,9)	0.06	20.20

Table A.11: Subsidy results for the midwest US network : Budget = $ 6,000, No. of shipments = 25

SN	**Hazmat type**	**Service-Leg**	T_{ij}^{m}	**Total-discount ($)**
1	2	(1,3)	0.48	243.00
2	2	(2,4)	0.06	4.00
3	2	(2,6)	0.03	35.20
4	2	(3,1)	1.00	422.50
5	2	(3,2)	1.00	438.00
6	2	(3,5)	1.00	498.00
7	2	(5,3)	0.81	337.50
8	2	(6,8)	0.39	157.30
9	2	(8,9)	0.40	148.50
10	2	(10,14)	1.00	320.00
11	2	(11,10)	1.00	297.50
12	2	(13,15)	0.98	783.00
13	2	(14,5)	0.30	304.11
14	2	(14,13)	0.02	5.40
15	2	(16,17)	0.11	72.00
16	2	(17,7)	0.14	24.60
17	2	(25,9)	0.17	132.00
18	2	(25,11)	0.86	270.00
19	3	(1,3)	1.00	1014.00
20	3	(3,1)	0.36	60.50
21	3	(3,5)	0.21	207.60
22	3	(11,10)	0.30	36.29
23	3	(16,17)	0.11	72.00
24	3	(25,11)	0.93	117.00

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