Subsidy Policy for Risk Equity in the Rail Hazmat Transportation Network: A Risk Mitigation Strategy

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Railroad transportation is one of the crucial means of transportation for hazardous material (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 the risk in the railroad network. We propose the subsidy policy to be considered by government to induce favorable routing of the hazmat shipments by carriers. The government's objective is to achieve risk equity in the network, whereas, the carriers' 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 and solve it for realistic mid-west United States rail infrastructure using state-of-the art solver cplex 12.8.0 in reasonable time.

Key words: railroad hazmat transportation; risk mitigation; bilevel programming

1. Motivation

Hazardous materials (hazmat), though dangerous, 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. Railroad is one of the primary and most reliable mode for transporting hazmat shipments. 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 Veter, 2013). However, given the catastrophic nature of rail hazmat accidents, every 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. Given the aforementioned, we explore a new tool to bring about a more equitable distribution of risk across the railroad network.

2. Problem Statement

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 shipments. 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 shippers to consider alternative routes for shipments such that more equitable distribution of rail hazmat risk could be achieved in the railroad network. According to this policy, the government may offer a subsidy to the hazmat transfer 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 hazmat risk while the carrier would seek to minimize cost to transport shipments, the former offers subsidy to the latter, who would decide to re-route the shipments taking into consideration the subsidy. To ensure judicious utilization of the budget allocated towards subsidy, it is pertinent for government to consider rational response from the carrier while offering subsidy. Thus, we are dealing with a bi-level program.

3. Approach

Let us consider a rail hazmat transportation network G = (N,A); where N is the set of rail yards and A is the set of bi-directed service-legs. let C_{ij}, R^m_{ij} and $\mathcal{B}$ express the cost of travelling on service-leg (i,j), unitary population exposure due to hazmat of type m on service-leg (i,j) and budget allocated by government for subsidy, respectively. And, D_{cm} is the number of the rail-cars of hazmat type m in shipment c traversing between origin O(c) and destination D(c). With this, we formulate the bi-level mixed integer programming (MIP) formulation as below:

Variables:

X^c_{ij} : 1 if service-leg (i,j) is used to transfer shipment 'c', 0 otherwise

T^m_{ij} : Subsidy provided by the government if hazmat type 'm' is transferred on service-leg (i,j)

θ : The maximum risk among service-legs across the network; A risk equity measure

Mathematical formulation:

$$\underset{T^m_{ij}}{\text{Minimize}} \quad \theta \tag{1}$$

$$\textbf{Subject to:} \quad \sum_c \sum_m D_{cm}\, R^m_{ij}(\hat{X}^c_{ij} + \hat{X}^c_{ji}) \leq \theta \qquad \forall (i,j) \in E,\ i<j \tag{2}$$

$$\sum_{(i,j)}\sum_{c}\sum_{m} D_{cm}\, C_{ij}\, T_{ij}^{m}\, \hat{X}_{ij}^{c} \leq \mathcal{B} \tag{3}$$

$$0 \leq T_{ij}^{m} \leq 1 \qquad \forall (i,j) \in E,\ \forall m \in M \tag{4}$$

$$\theta \geq 0 \tag{5}$$

Where, $\hat{X}_{ij}^{c}$ solves following routing problem for carriers for proposed subsidy $\hat{T}_{ij}^{m}$:

$$\text{Minimize} \quad \sum_{(i,j)}\sum_{c}\sum_{m} D_{cm}\, C_{ij}\, (1-\hat{T}_{ij}^{m})\, X_{ij}^{c} \tag{6}$$

$$\textbf{Subject to:} \quad \sum_{j:(i,j)\in E} X_{ij}^{c} - \sum_{j:(j,i)\in E} X_{ji}^{c} = \begin{cases} 1, & \text{if } i = O(c) \\ -1, & \text{if } i = D(c) \\ 0 & \text{otherwise} \end{cases} \qquad \forall i \in N,\ c \in C \tag{7}$$

$$X_{ij}^{c} \in \{0,1\} \qquad \forall\, (i,j) \in E,\ \forall\, c \in C \tag{8}$$

Taking advantage of the unimodularity characteristic(Wolsey, 1998) of the multi-commodity network flow problem at lower-level, we consider continuous relaxation of binary variable X_{ij}^{c} and replace the lower-level problem with its Karush-Kuhn-Tucker (KKT) conditions. We make use of primal-dual objective function equality constraint to ensure optimality condition(Marcotte et al., 2009). We obtain the linear model by restoring the binary characteristic of the X_{ij}^{c} variable. We solve the resulting mixed integer linear program (MILP) through MIP solver cplex 12.8.0.

4. Results

We test the MILP model by solving the problem instances generated using the realistic infrastructure of a Class 1 railroad operator, in mid-west United States, that was introduced in (Verma,Verter and Gendreau, 2011). It consists of 25 rail-yards and 53 service legs, operable in both directions. On this network, we solve the problem for up-to 25 shipments, each comprises a combination of randomly generated demand of two hazmat types, class 2 and class 3. For expositional reason, we show the results for the problem instances with 20 shipments and different budget proposed by the government. 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 show that, by utilization of merely 132 units of subsidy offered, the maximum risk (max-risk) among the service-legs across the network reduces by 46%. And, the maximum reduction, of around 70% compared to no-subsidy scenario, in max-risk can be ascertained by offering 5055 units of subsidy. It provides significant managerial insight for government that it is sufficient to allocate only 5055 units of budget for subsidy for this instance that is just around 15% of the minimum transportation cost (the carriers' total cost, when the subsidy is not offered) of 33299 units. It is interesting to note that addressing the risk equity concern in the network also results in reducing the total population exposure to the risk. i.e., With 6000 units allocated for subsidy, the total population exposure to the risk reduces to 307455, which is the reduction of around 13.5% compared to no-subsidy scenario.

Table 1 Results for instance with 20 shipments and two hazmat types

SN	Budget	Subsidy Utilized (a)	Total Cost (without Subsidy) (b)	Effective Cost (b-a)	Max Risk (Objective)	Total Risk	Time(s)
1	0	0	33299	33299	62080	355543	0.33
2	132	132	33431	33299	32978	310935	4.19
3	418	418	33717	33299	29064	298373	6.45
4	567.5	567.5	33866.5	33299	26976	311177	4.11
5	1786	1786	35029.5	33243.5	26598	333833	16.83
6	2035	2034.1	35227.5	33193.4	24180	327961	25.48
7	2054	2054	35246.5	33192.5	23716	335293	20.49
8	2180	2180	35372.5	33192.5	22568	335821	22.96
9	2325	2324.1	35514.5	33190.4	21798	321705	21.81
10	2566	2566	35755.5	33189.5	20956	336429	23.66
11	2619	2619	35862.5	33243.5	20448	326193	12.58
12	3980	3979.3	37101.5	33122.2	19404	320821	28.99
13	4347	4337	37468.5	33131.5	19344	328729	35.59
14	4355	4355	37429.5	33074.5	19108	325141	42.92
15	4654	4654	37728.5	33074.5	18684	314329	56.47
16	5055	5054.05	38100.5	33046.45	18112	329515	41.45
17	6000	6000	38627	32627	18112	307455	17.61
18	10000	10000	41876.5	31876.5	18112	321789	22.23

5. Conclusions

In this article, we propose the subsidy policy that can be considered by the government as a risk mitigation strategy for rail hazmat transportation. It is aimed to achieve risk equity in the network while taking carriers' interest and budget constraint into consideration. We formulate the bi-level MIP model for rail hazmat transportation framework. We apply KKT conditions to lower level problem, and solve reduced single-level MILP through the state-of-the art optimizer cplex 12.8.0. The results attest the proposed subsidy policy as efficient risk mitigation strategy for rail hazmat transportation framework.

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