IMPLICATIONS OF COST EQUITY CONSIDERATION IN HAZMAT NETWORK DESIGN

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ABSTRACT

The hazmat network design problem (HNDP) aims to reduce the risk of transporting hazmat in the network by enforcing regulation policies. The goal of reducing risk can increase cost for different hazmat carriers. Since HNDP involves multiple parties, it is essential to take the cost increase of all carriers into consideration for the implementation of the regulation policy. While we can consider cost by placing upper bounds on the total increase, the actual cost increase for various OD pairs can differ, which results in unfairness among carriers. Thus we propose to consider the cost equity issue as well in HNDP. Additionally, due to the existence of multiple solutions in current HNDP models and the possibility of unnecessarily closing road segments, we introduce a new objective considering the length of all the closed links. Our computational experience is based on a real network and we show results under different cost consideration cases.

INTRODUCTION

For hazmat transportation, the number of accidents is small compared to the number of shipments. However, the consequence is very severe in terms of fatalities, injuries, large-scale evacuations and environmental damage. Hence hazmat transportation usually remains part of a government's mandate. Government authority regulates hazmat transportation on the network under its jurisdiction by the following methods: banning or putting tolls on certain road segments, curfews (banning certain road segments for certain durations) and enforcing carriers to go through a set of chosen checkpoints.

Here we consider the *hazmat network design problem* (HNDP) with the regulation method of banning certain road segments. Kara and Verter (1) define the problem as follows: (1) given an existing road network, the hazmat network design problem involves selecting the road segments that should be closed so as to minimize total risk given that, (2) the carriers will then choose the minimum cost routes on the resulting network. Hence the government should consider the behaviours of the carriers when designing the road network.

Kara and Verter (1) formulate HNDP as a bilevel model with the government as a leader (upper level) and the carriers as followers (lower level). They transform the bilevel model into a single mixed integer problem by substituting the lower level problem with its KKT conditions and solve the single model with a standard optimization solver (CPLEX). Erkut and Alp (2) consider HNDP as a tree selection problem. In this way, the carriers have no alternative routes. They solve the problem using a commercial solver and develop a simple construction heuristic to expand the solution by adding road segments. This allows authorities to trade off risk and cost. Erkut and Gzara (3) generalize the problem considered by Kara and Verter (1) to the undirected case and propose a heuristic solution method. They also formulate the problem as a bi-objective bilevel model to include trade-offs between risk and cost. Alternatively, in consideration of a compromise between cost and risk, Verter and Kara (4) present a path-based formulation to identify paths that are mutually acceptable to the government and the carriers. Amaldi et al. (5) provide an exact formulation with fewer binary variables for HNDP. Gzara (6) proposes a family of valid cuts and incorporates them within an exact cutting plane algorithm to solve the HNDP. Xin et al. (7) consider a robust HNDP with risk interval data. Sun et al. (8) consider HNDP with risk uncertainty using robust optimization with a cardinality uncertainty set to allow for flexible decision making. Taslimi et al. (9) study HNDP by incorporating location of hazmat response teams and risk equity. Fan et al. (10) consider the regulation method of closing road segments for certain durations and present a path based model to mitigate risk.

Besides banning certain road segments, government can also set tolls to regulate hazmat transportation. Marcotte et al. (11) first propose the use of tolls in mitigating hazardous materials transport risk. Wang et al. (12) extend the approach to a dual toll pricing method to simultaneously control both regular and hazmat vehicles to reduce risk. Esfandeh et al. (13) enhance the dual toll pricing model by considering nonlinear delay time to more accurately measure the risk and model equilibrium. Bianco et al. (14) consider toll policies to regulate hazardous material transportation considering both total risk and risk spreading. Esfandeh et al. (15) propose and analyze a dual-toll setting policy for both hazmat and regular carriers to minimize total risk on the network while considering stochastic driver preferences in route selection. Bruglieri et al. (16) propose another risk mitigation regulation to select a set of gateways in the network and enforce carriers go through these checkpoints for their chosen routes.

Risk equity is also a major issue in hazmat transportation. In hazmat routing, models have been proposed for determining paths of minimum total risk while guaranteeing equitable risk spreading (17). Gopalan et al. (18) study a single hazmat trip and limit the risk difference between each pair of partitioned zones. Gopalan et al. (19) further develop the model into multiple O-D pairs of hazmat transportation. Carotenuto et al. (20) consider the risk equity issue by placing an upper limit on the total hazmat transportation risk over populated links. For HNDP, Bianco et al. (21) consider risk equity by assuming the regional authority aims to minimize the total transport risk induced over the entire region in which the transportation network is embedded, while local authorities want the risk over their local jurisdictions to be as low as possible. Bianco et al. (14) consider toll policies to regulate hazardous material transportation to not only minimize the total risk but also to spread the risk in an equitable way. Taslimi et al. (9) minimize the maximum risk among territory zones to address risk equity.

In HNDP, because government authority regulates different carriers likely leading to higher costs for the carriers, cost should be a consideration of the HNDP as well. Erkut and Gzara (3) extend the link based bilevel model to account for the cost/risk trade-off by including cost in the first-level objective weighting both total risk and cost. The same model is considered by Gzara (6) in analyzing a proposed cutting plane algorithm. Verter and Kara (4) consider a path based formulation with cost/risk trade-offs for government and carriers. Specifically, they consider a K-shortest path algorithm to generate all the paths. Alternatively, the paths with lengths that are within a certain percentage of the length of the shortest path can also be used. Cappanera and Nonato (22) study how to obtain the nondominated solutions considering risk and cost for gateway location risk mitigation strategies.

Cost, however, has not been fully systemically studied in the literature. Moreover, cost equity among different carriers is not considered in any of the current models. Closing certain road segments can result in higher cost for carriers. But the cost increase for carriers could be significantly different, resulting in unfairness of the regulation policy. In some extreme cases, for example, one carrier's cost could remain the same but another carrier could have its cost doubled. Thus we propose to consider cost equity in HNDP.

In this paper, we study different HNDP models with various cost considerations, particularly the cost equity issue, while addressing the existence of multiple optimal solutions. The remainder of the paper is organized as follows. The next section introduces the HNDP models in the literature. Then we provide different HNDP models with multiple cost consideration. Computational results are shown in the numerical experiments section. Finally, conclusions and suggestions are given.

HNDP DESCRIPTION

In this section, we first describe the leader-follower bilevel model for the HNDP. Due to the unimodularity of the lower level problem, it can be linearized and the bilevel model can be transformed into a single level model. We will then discuss the linearization methods.

Problem Description and Formulation

We consider the HNDP in which the government determines the available road segments to minimize total risk and carriers choose routes on the resulting network to minimize cost. Suppose we have a transportation network that is defined by a graph $G = (N, A)$, where N denotes the set of nodes (road intersections) and A denotes the set of arcs (road segments). HNDP involves transporting S shipments between different origins and destinations. For each shipment $s \in S$, n_s is the corresponding number of shipments, r_{ijs} and c_{ijs} are the risk and cost associated with arc $(i,j) \in A$. For simplicity, we assume the cost is independent of each shipment, resulting in $c_{ijs} = c_{ij}$ for any shipment $s \in S$. Let $x_{ijs} = 1$ if arc (i,j) is used to transport shipment s and $y_{ij} = 1$ if arc (i,j) is open to hazmat traffic. Then the problem can be formulated using a bilevel integer linear programming model (1) as

$$\min_{y_{ij}\in\{0,1\}} \sum_{(i,j)\in A} \sum_{s\in S} n_s r_{ijs} x_{ijs}, \tag{1}$$

where x_{ijs} is obtained by

$$\min_{x_{ijs}} \sum_{(i,j)\in A} \sum_{s\in S} c_{ijs} x_{ijs}, \tag{2}$$

subject to

$$\sum_{(i,k)\in A} x_{iks} - \sum_{(k,i)\in A} x_{kis} = \begin{cases} +1 & i = o(s) \\ -1 & i = d(s) \\ 0 & \text{otherwise} \end{cases} \qquad \forall i \in N, s \in S, \tag{3}$$

$$x_{ijs} \leqslant y_{ij} \quad \forall (i,j) \in A, s \in S, \tag{4}$$

$$x_{ijs} \in \{0,1\} \quad \forall (i,j) \in A, s \in S. \tag{5}$$

The objective in (1) is the total risk on the entire network, which should be minimized by the government by choosing y_{ij} values to decide open arcs. The lower level problem (2)–(5) decides the routes with corresponding arcs x_{ijs} based on open segments. Here we assume carriers choose the shortest (least cost) path. The objective for the lower level problem in (2) is the cost for the carriers. The number of shipments n_s is omitted since it has no effect on the routes chosen by carriers. Constraints (3) are the flow conservation requirements and constraints (4) restrict carriers from choosing arcs that are closed to hazmat transportation. Note this is a formulation for directed networks. For the undirected case, additional constraints $y_{ij} = y_{ji}$ for all $(i,j) \in A$ should be added to the upper level problem to ensure both arc (i,j) and (j,i) are open to use if either direction is used for hazmat traffic.

Erkut and Gzara (3) point out that the model introduced above can be ill-posed since there could be multiple minimum cost paths having different risk values under the same y_{ij}, which leads to an unstable solution. Amaldi et al. (5) propose an exact formulation to address this issue by modifying the lower level problem objective with

$$\min_{x_{ijs}} \sum_{s\in S} \left(\sum_{(i,j)\in A} c_{ijs} x_{ijs} - \frac{1}{R} \sum_{(i,j)\in A} r_{ijs} x_{ijs} \right), \tag{6}$$

where constant R is a large enough value, for example, the possible maximum risk path value for all OD pairs. The meaning of using objective (6) is that when multiple minimum cost paths exist, the government assumes carriers choose the one with the highest risk value.

Furthermore, the model can have multiple solutions since there are different ways of closing road segments to restrict carriers from transporting hazmat on a certain route. Thus we propose modifying the objective for the upper level problem by minimizing the total risk and the total length (cost) of the closed road segments. The objective for the government then becomes

$$\min_{y_{ij}\in\{0,1\}} \left(\sum_{(i,j)\in A} \sum_{s\in S} n_s r_{ijs} x_{ijs} \right) + \alpha \sum_{(i,j)\in A} (1 - y_{ij}) c_{ij}, \tag{7}$$

where a small value of α is used to weight the total length of the closed links while maintaining the risk value as the dominant part in the objective. The use of the second component of objective (7) is to provide a perturbation to choose among all minimum risk solutions so that the model accepts a solution without closing unnecessary links. While we use the total length here, other perturbations such as the total number of closed links can also be considered. Now that we have revised the model for HNDP, we will discuss the linearization method in order to solve it.

Linearization using KKT Conditions

For any given y, each lower level problem is totally unimodular. According to Kara and Verter (1), the lower level problem can be solved by the KKT conditions of its LP relaxation. The KKT conditions for the lower level problem are

$$c_{ijs} - \frac{1}{R} r_{ijs} - \pi_i^s + \pi_j^s - \phi_{ij}^s + \lambda_{ij}^s = 0 \qquad \forall (i,j) \in A, s \in S, \tag{8}$$

$$\phi_{ij}^s x_{ijs} = 0 \qquad \forall (i,j) \in A, s \in S, \tag{9}$$

$$\lambda_{ij}^s (x_{ijs} - y_{ij}) = 0 \qquad \forall (i,j) \in A, s \in S, \tag{10}$$

$$x_{ijs} \geqslant 0, \phi_{ij}^s \geqslant 0, \lambda_{ij}^s \geqslant 0, \pi_i^s \text{ free} \qquad \forall (i,j) \in A, s \in S, \tag{11}$$

where π, λ, ϕ are the dual variables for constraints (3), (4) and (5) respectively. Since constraints (9) and (10) are nonlinear, we linearize them using the Big-M method as

$$\phi_{ij}^s \leqslant M(1 - x_{ijs}) \qquad \forall (i,j) \in A, s \in S, \tag{12}$$

$$\lambda_{ij}^s \leqslant M[1 - (y_{ij} - x_{ijs})] \qquad \forall (i,j) \in A, s \in S, \tag{13}$$

$$x_{ijs}, y_{ij} \in \{0,1\} \qquad \forall (i,j) \in A, s \in S. \tag{14}$$

The above linearization is due to the binarity of x and y.

Linearization using Duality

Instead of using the KKT conditions of the lower level problem, Amaldi et al. (5) propose a different way using weak and strong duality theorems. With the totally unimodularity property, the relaxed linear problem can be replaced with the primal feasibility constraints, the dual feasibility constraints and reverse weak duality inequality. The constraints of linearization using duality are

$$\pi_j^s - \pi_i^s \leqslant c_{ijs} - \frac{1}{R} r_{ijs} + M(1 - y_{ij}) \quad \forall (i,j) \in A, s \in S, \tag{15}$$

$$\sum_{(i,j)\in A} c_{ijs} x_{ijs} - \frac{1}{R} \sum_{(i,j)\in A} r_{ijs} x_{ijs} \leqslant \pi_{d(s)}^s - \pi_{o(s)}^s \quad \forall s \in S, \tag{16}$$

$$0 \leqslant x_{ijs} \leqslant 1, \quad \forall (i,j) \in A, s \in S. \tag{17}$$

Constraints (15) are the dual feasibility constraints. Constraints (16) enforce the reverse weak duality. Constraints (17) relax the binary restriction of x to continuous variables. Marcotte et al. (11) also propose a linearization using duality by enforcing the equality of primal and dual, which can be shown to be the same as constraints (15) – (17).

Single Level Formulation

Above we have discussed how to linearize the lower level problem by using KKT conditions or duality. Now we can formulate the HNDP as a single level model using either linearization method. As shown by Amaldi et al. (5), the linearization using KKT conditions results in $(|S|+1)|A|$ number of binary variables while the linearization using duality only has $|A|$ number of binary variables. Thus we will illustrate the single level formulation using the duality linearization method as:

$$\min_{x,y,\pi}\Big(\sum_{(i,j)\in A}\sum_{s\in S} n_s r_{ijs} x_{ijs}\Big) + \alpha \sum_{(i,j)\in A}(1-y_{ij})c_{ij}, \tag{18}$$

subject to

$$\sum_{(i,k)\in A} x_{iks} - \sum_{(k,i)\in A} x_{kis} = \begin{cases} +1 & i=o(s) \\ -1 & i=d(s) \\ 0 & \text{otherwise} \end{cases} \quad \forall i\in N, s\in S, \tag{19}$$

$$x_{ijs} \leqslant y_{ij} \quad \forall (i,j)\in A, s\in S, \tag{20}$$

$$\pi_j^s - \pi_i^s \leqslant c_{ijs} - \frac{1}{R} r_{ijs} + M(1-y_{ij}) \quad \forall (i,j)\in A, s\in S, \tag{21}$$

$$\sum_{(i,j)\in A} c_{ijs}x_{ijs} - \frac{1}{R}\sum_{(i,j)\in A} r_{ijs}x_{ijs} \leqslant \pi_{d(s)}^s - \pi_{o(s)}^s \quad \forall s\in S, \tag{22}$$

$$0 \leqslant x_{ijs} \leqslant 1, \quad \forall (i,j)\in A, s\in S, \tag{23}$$

$$y_{ij}\in\{0,1\} \quad \forall (i,j)\in A. \tag{24}$$

HNDP WITH VARIOUS COST CONSIDERATIONS

Having formulated the HNDP problem, we now introduce HNDPs with multiple cost considerations. Particularly, we consider two categories: placing an upper bound on the cost increase or enforcing cost equity.

HNDP with Upper Bound Cost

The first model considered is to bound the cost for the whole hazmat transportation industry. The model can be formulated as

$$\text{(HNDP-W)} \quad \min\Big(\sum_{(i,j)\in A}\sum_{s\in S} n_s r_{ijs} x_{ijs}\Big) + \alpha \sum_{(i,j)\in A}(1-y_{ij})c_{ij},$$

subject to

$$\sum_{s\in S}\sum_{(i,j)\in A} n_s c_{ijs} x_{ijs} \leqslant \delta, \tag{25}$$

$$(19)-(24),$$

where δ is the maximum cost for all hazmat carriers. We can obtain δ by using a percentage (i.e. 120 %) of the total cost for all the carriers without regulations. This model is similar to the biobjective model in Verter and Kara (4), Gzara (6). Instead of weighting the total cost we put an upper bound on the total cost so that we know how much burden we are placing on the whole industry. We still can obtain multiple solutions by changing δ and compare the efficiency of the solutions.

Besides considering cost for the whole hazmat transportation industry, we can consider the cost for each OD pair. This model, referred to as HNDP-P-1, can be formulated by substituting constraint (25) with the following constraints:

$$\sum_{(i,j)\in A} c_{ijs}x_{ijs} \leqslant \eta^s \quad \forall s \in S, \tag{26}$$

where η^s can be obtained as a certain percentage (i.e. 120%) of the length of the shortest path for shipment $s \in S$. This model allows us to evaluate the cost burden for each OD pair and provides flexibility to analyze risk of each OD pair.

Another way is to consider cost by carriers. There could be many carriers in certain networks. By regulating hazmat transportation, the cost increase for various carriers might be quite different. Thus it is necessary to consider the cost among carriers. This model HNDP-C-1 can be formulated by replacing constraint (25) with

$$\sum_{s\in P^l}\sum_{(i,j)\in A} n_s c_{ijs}x_{ijs} \leqslant \varepsilon^l \quad \forall l \in L, \tag{27}$$

where L is the set of carriers and P^l is the set of OD pairs that carrier l covers. ε^l can be chosen as certain percentage (i.e. 120%) of the total cost for carrier l. This model regulates the hazmat transportation of carriers without putting too much burden on any of them.

HNDP with Cost Equity

The models above consider placing a bound on the cost. However, these models could still lead to different cost increases for different OD pairs, carriers or hazmat generating companies. In order to avoid unfairness of the regulation policies, the cost equity issue must be considered.

First, we can apply cost equity between OD pairs. This model HNDP-P-2 can be formulated as enforcing the difference of the cost increase ratio between all couples of OD pairs to be below a certain limit. It can be formulated by replacing constraint (25) with

$$-\beta \leqslant \frac{\sum_{(i,j)\in A} c_{ijs}x_{ijs}}{l^s} - \frac{\sum_{(i,j)\in A} c_{ijt}x_{ijt}}{l^t} \leqslant \beta \quad \forall s,t \in S, s \neq t \tag{28}$$

where β is a certain constant enforcing the ratio difference, l^s and l^t are the shortest path lengths for shipments s and t. However, the cost equity constraints with small β value might be too restrictive and could result in higher total risk value.

A more flexible way is to consider cost equity among carriers. We can apply constraints so that the difference of the cost increase ratio between various carriers is within a threshold value. This model HNDP-C-2 can be formulated by replacing constraint (25) with

$$-\gamma \leqslant \frac{\sum_{s\in P^l}\sum_{(i,j)\in A} n_s c_{ijs}x_{ijs}}{C^l} - \frac{\sum_{s\in P^k}\sum_{(i,j)\in A} n_s c_{ijs}x_{ijs}}{C^k} \leqslant \gamma \quad \forall l,k \in L, l \neq k, \tag{29}$$

where γ is a constant reflecting the ratio difference (i.e. 5%), C^l and C^k are the minimum costs for carriers l and k. This HNDP-C-2 model considers real cost equity among different carriers to avoid unfairness. By using a certain threshold, the model requires the cost increase between different carriers to be limited. At the same time, this model is flexible enough to allow some OD pairs to have a higher cost increase if some other OD pairs covered by the same carrier have a lower cost increase.

A concern for the HNDP-C-1 and HNDP-C-2 models is the uncertainty of the OD pairs covered by various carriers as they might change over time. One way to avoid this is to consider the HNDP-P-1 and HNDP-P-2 models on OD pairs. Alternatively, we can consider the hazmat generating companies which need the transportation of hazmat for certain OD pairs and are eventually responsible for the cost as they hire carriers to provide transportation. These companies usually have fixed locations over time. So instead of enforcing cost equity for various carriers, we can consider cost equity among companies that require the transportation of hazmat. From the modelling perspective, however, the only difference is to let L denote the set of hazmat generating companies instead of carriers. For brevity, we will not formulate this model as the analysis of the model would be the same as HNDP-C-1 and HNDP-C-2.

In modeling cost equity among carriers, we assume that longer path distances will proportionally increase the cost to carriers. This would be in addition to any fixed cost per shipment which would remain the same, e.g. pickup and discharge time/cost. The increased variable cost based on distance travelled would be eventually passed on to the companies hiring carriers. As we will see, different levels of equity result in different increase profiles among carriers.

NUMERICAL EXPERIMENTS

In this section, we illustrate results for the proposed models above. Since the HNDPs are formulated and transformed as mixed integer linear programming models, CPLEX is used to solve the models. The experiments are performed using C++ and CPLEX 12.6 on a computer with an Xeon processor and 32GB memory. The dataset we use is from the city of Ravenna, Italy (2, 23). The data consists of 105 nodes and 134 arcs. Risks are carefully measured as functions of both the accident frequency and its damage effects. 12 nodes of the entire network can be origin or destination nodes. 35 origin-destination (OD) pairs are formed to transport four kinds of hazmat, namely, chlorine, LPG, gasoline, and methanol. Demand is the number of shipments between each OD pair.

Upper Level Objective Effectiveness

First we examine the effectiveness of our proposed upper level objective function in (18). We consider two cases: (1) $\alpha = 0$, which is the same as the objective of the HNDP problem definition in Kara and Verter (1). (2) α is a sufficiently small number so that the total length of closed links is considered but will be dominated by the total risk value.

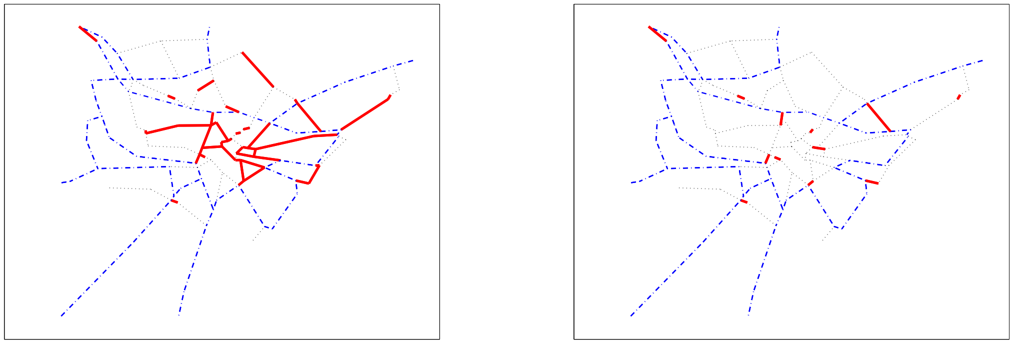
We test the model on the Ravenna network. The result for the two cases are shown in Figure 1. The dashed links are the ones used by carriers and the thicker solid links are the closed ones. Comparing the two cases, we can see that when $\alpha = 0$, we close many more links than necessary. It is possible to only close a subset of critical links and achieve the same risk mitigation objective.

HNDP with Various Cost Considerations

In order to analyze the effectiveness of the proposed models, we first study the results of HNDP without cost considerations. We show the cost and risk change with and without government regulations for each OD pair. The results are recorded in Table 1.

OD	MinCost	CostHNDP	RiskMinCost	RiskHNDP	MinRisk	CostIncrease	RiskChange	RiskGap
1	2.8044×10^7	2.8044×10^7	2337.38	2337.38	2337.38	0.00%	0.00%	0.00%
2	5.1892×10^7	5.9895×10^7	2799.79	3323.31	2799.79	15.42%	-18.70%	18.70%
3	1.7435×10^7	2.0268×10^7	2619.77	1922.13	1922.13	16.25%	26.63%	0.00%
4	5.7272×10^5	5.7272×10^5	17.02	17.02	17.02	0.00%	0.00%	0.00%
5	1.5853×10^7	2.2161×10^7	2161.84	2025.38	2025.38	39.79%	6.31%	0.00%
6	1.4009×10^7	1.6169×10^7	755.83	897.16	755.83	15.42%	-18.70%	18.70%
7	4.7093×10^7	5.1870×10^7	5674.24	4598.14	4598.14	10.14%	18.96%	0.00%
8	5.4379×10^6	5.4379×10^6	453.23	453.23	453.23	0.00%	0.00%	0.00%
9	2.0073×10^7	2.2219×10^7	3021.29	2428.84	2428.84	10.69%	19.61%	0.00%
10	1.4159×10^7	1.4159×10^7	1443.39	1443.39	1443.39	0.00%	0.00%	0.00%
11	1.6958×10^7	1.6958×10^7	1717.57	1717.57	1717.57	0.00%	0.00%	0.00%
12	1.5002×10^7	1.8334×10^7	2416.24	1643.56	1572.40	22.21%	31.98%	4.53%
13	5.5415×10^6	5.5415×10^6	461.87	461.87	461.87	0.00%	0.00%	0.00%
14	5.2879×10^6	5.2879×10^6	535.59	535.59	535.59	0.00%	0.00%	0.00%
15	2.1596×10^8	2.4926×10^8	31790.41	27664.53	27664.53	15.42%	12.98%	0.00%
16	8.3638×10^6	9.6538×10^6	1231.21	1071.42	1071.42	15.42%	12.98%	0.00%
17	3.5030×10^7	4.0722×10^7	10950.37	7913.62	7913.62	16.25%	27.73%	0.00%
18	1.2907×10^7	1.5005×10^7	4034.87	2915.93	2915.93	16.25%	27.73%	0.00%
19	3.6949×10^4	3.6949×10^4	2.33	2.33	2.33	0.00%	0.00%	0.00%
20	3.8335×10^5	3.8335×10^5	24.17	24.17	24.17	0.00%	0.00%	0.00%
21	7.3147×10^6	1.0225×10^7	2480.97	1866.20	1866.20	39.79%	24.78%	0.00%
22	3.6137×10^6	5.0515×10^6	1225.66	921.95	921.95	39.79%	24.78%	0.00%
23	1.5614×10^7	1.8022×10^7	2298.52	2000.21	2000.21	15.42%	12.98%	0.00%
24	1.6110×10^7	1.7744×10^7	4097.51	3158.71	3158.71	10.14%	22.91%	0.00%
25	1.8850×10^6	2.9647×10^6	444.42	407.71	394.14	57.28%	8.26%	3.44%
26	1.1646×10^7	1.8317×10^7	2745.88	2519.09	2435.21	57.28%	8.26%	3.44%
27	5.1788×10^5	5.9776×10^5	333.72	233.12	233.12	15.42%	30.15%	0.00%
28	4.9199×10^5	5.6787×10^5	11.93	11.96	11.93	15.42%	-0.24%	0.24%
29	1.4518×10^8	2.2833×10^8	7189.25	6093.71	6015.94	57.28%	15.24%	1.29%
30	7.6864×10^8	8.8719×10^8	18646.00	18691.42	18646.00	15.42%	-0.24%	0.24%
31	1.8892×10^8	2.1962×10^8	12001.95	8714.91	8647.30	16.25%	27.39%	0.78%
32	1.3794×10^7	1.3794×10^7	149.94	149.94	149.94	0.00%	0.00%	0.00%
33	2.4579×10^8	3.4358×10^8	14317.31	12441.50	12344.68	39.79%	13.10%	0.78%
34	1.3123×10^8	1.5147×10^8	3183.46	3191.22	3183.46	15.42%	-0.24%	0.24%
35	2.0189×10^8	2.2237×10^8	9763.56	7771.69	7694.80	10.14%	20.40%	1.00%
1-10	2.1457×10^8	2.4080×10^8	21283.8	19446.0	18781.1	12.22%	8.63%	3.54%
11-20	3.1547×10^8	3.6119×10^8	53164.6	43950.6	43879.4	14.49%	17.33%	0.16%
21-35	1.7526×10^9	2.1398×10^9	78890.1	68173.3	67703.6	22.09%	13.58%	0.69%
Total	2.2827×10^9	2.7418×10^9	153338.1	131569.9	130364.1	20.12%	14.20%	0.92%

TABLE 1 : Change of Cost and Risk



(a) $\alpha = 0$ (b) $\alpha = 0.00001$

FIGURE 1 : Resulting network of Ravenna dataset with different objectives

Without any regulation, carriers are assumed to choose the minimum cost routes. The cost and risk for this case are shown in columns labelled MinCost and RiskMinCost. With HNDP, the cost and risk could change. We record them in columns CostHNDP and RiskHNDP. We also record the minimum risk value for each OD pair to see the effectiveness of HNDP. We assume there are three carriers which cover OD pairs 1–10, 11–20 and 21–35 respectively. In order to analyze the results for each OD pair, as shown in the table, we calculate several statistics:

$$\text{CostIncrease} = \frac{\text{CostHNDP-MinCost}}{\text{MinCost}}, \tag{30}$$

$$\text{RiskChange} = \frac{\text{RiskMinCost-RiskHNDP}}{\text{RiskMinCost}}, \tag{31}$$

$$\text{RiskGap} = \frac{\text{RiskHNDP-MinRisk}}{\text{MinRisk}}. \tag{32}$$

CostIncrease is the increase in cost for each OD pair, carrier or the whole industry with regulation. From Table 1, we can see CostIncrease values differ among OD pairs, from 0% to as high as 57.28%. Thus without any cost consideration, government regulation can put different burdens on the OD pairs and carriers since they cover different sets of OD pairs. The average cost increase is 20.12%. RiskChange values give the risk reduction under government's regulation. There is a risk reduction if the value is positive and an increase in risk if the value is negative . Most OD pairs have risk reduction and this shows the effectiveness of HNDP. We can also observe that for some OD pairs (for example OD pair 25), even though the cost increase is very high, the risk reduction is limited. So we could consider other cost and risk effective paths for this OD pair. RiskGap records the risk gap between the minimum risk and that of HNDP. We can say the HNDP can be very effective for most OD pairs, and the risk gap average is only 0.92%.

Now we compare the results of different models considering cost. For choosing the parameters, since the cost increase for all the OD pairs is 20.12%, we set δ of model HNDP-W to be 1 : 0.0125 : 1.25 of the minimum total cost. Here 1 : 0.0125 : 1.25 means the lower bound value is 1, upper bound value is 1.25 and the increment is 0.0125. We use similar terms to denote other chosen parameters. For η values of model HNDP-P-1, the highest cost increase for any OD pair is 57.28%, so we set η to be 1 : 0.03 : 1.60 of the respective minimum cost path. The highest cost

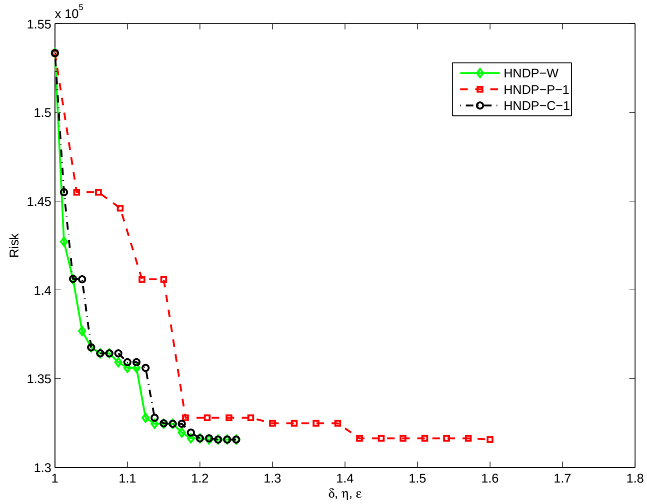


FIGURE 2 : Risk values considering different cost upper bounds (δ, η and ε)

increase ratio difference for any two OD pairs is also 57.28%, so we set β of model HNDP-P-2 to be $0:0.03:0.60$. For the three carriers we consider, the highest cost increase is 22.09%. We set ε of model HNDP-C-1 to be $1:0.0125:1.25$. The highest cost rise ratio difference among the carriers is 9.87%, so we consider γ of model HNDP-C-2 with $0:0.01:0.12$.

Then we record risk and cost values with different δ (HNDP-W), η (HNDP-P-1) and ε (HNDP-C-1) values in Tables 2 and 3. In the column labelled "Time(s)/Gap", we record the time of solving a certain model if it is solved optimally. If the solver fails to find the optimal solution within one hour, we record the optimality gap. We observe that most cases are solved optimally and the optimality gap is within 1%.

A visualization of the risk changes is shown in Figure 2. By looking at the trend of the risk changes, we can see the three models have a sharp risk reduction with small increase of cost at first. As the cost goes higher, the risk reduction benefit becomes smaller. For example, for model HNDP-W, if the cost of all OD pairs increases from 1 to 1.1375 of the minimum cost, the risk reduces from 153339 to 132459 (13.9% risk reduction). However, when δ increases from 1.1375 to 1.2125, the risk only reduces from 132459 to 131570 (0.6% risk reduction), which is 12.8 times slower. Thus a better decision for the government considering the whole cost burden on the industry could be making δ as 1.1375 instead of obtaining the maximal risk reduction.

If the government is much concerned with the cost, it could trade off the total risk and cost while maintaining a certain upper bound on cost. For instance, comparing HNDP-W using Table 2, a δ value of 1.0375 has a risk reduction of 10.21% and cost increase 3.40% while 13.63% and 13.70% for a δ value of 1.1375. Thus if the government is more aware of the cost burden of carriers, it could make a decision with $\delta = 1.0375$. Similarly, for HNDP-C-1 and HNDP-P-1, $\eta = 1.15$ and $\varepsilon = 1.0375$ could be chosen by observing Tables 3.

For the cost equity models, we show results with different β (HNDP-P-2) and γ (HNDP-C-2) values in Table 4. The same characteristics with the above upper bounds cases are recorded. From the "Time(s)/Gap" column, we observe HNDP-C-2 is harder to solve. When $\gamma = 0$, the gap is large. However, from solutions of other models, we can see the minimum cost routes with risk of

TABLE 2 : Risk and cost values considering different cost upper bounds for the whole industry (δ)

δ	Risk	RiskReduce	Cost	CostIncrease	Time(s)/Gap
1.0000	153339	0.00%	2.2827×10^9	0.00%	2.4
1.0125	142717	6.93%	2.3082×10^9	1.12%	13.8
1.0250	140595	8.31%	2.3391×10^9	2.47%	2792.1
1.0375	137687	10.21%	2.3603×10^9	3.40%	1165.6
1.0500	136763	10.81%	2.3794×10^9	4.24%	66.5
1.0625	136426	11.03%	2.4092×10^9	5.54%	24.8
1.0750	136426	11.03%	2.4092×10^9	5.54%	49.4
1.0875	135927	11.36%	2.4757×10^9	8.46%	114.4
1.1000	135606	11.56%	2.5087×10^9	9.90%	40.7
1.1125	135606	11.56%	2.5087×10^9	9.90%	115.4
1.1250	132796	13.40%	2.5655×10^9	12.39%	70.6
1.1375	132459	13.62%	2.5953×10^9	13.70%	25.4
1.1500	132459	13.62%	2.5953×10^9	13.70%	18.3
1.1625	132459	13.62%	2.5953×10^9	13.70%	159.6
1.1750	131961	13.94%	2.6618×10^9	16.61%	2152.8
1.1875	131639	14.15%	2.6948×10^9	18.05%	29.6
1.2000	131639	14.15%	2.6948×10^9	18.05%	72.4
1.2125	131570	14.20%	2.7418×10^9	20.12%	15
1.2250	131570	14.20%	2.7418×10^9	20.12%	16.3
1.2375	131570	14.20%	2.7418×10^9	20.12%	17.2
1.2500	131570	14.20%	2.7418×10^9	20.12%	17.1

153339 should be the optimal solution. So the solver has found the optimal solution value but fails to close the gap in the search process. The highest gap of the other cost equity models is 1.33%, which is acceptable.

The trend of risk reductions is displayed in Figure 3. We find a similar pattern as in Figure 2. There is a dramatic drop in risk at first and then the risk reductions grow at a much slower pace. For model HNDP-P-2, if no cost equity is considered among OD pairs, the largest cost increase for one OD pair is 58.7% while for some OD pairs the cost remains the same. By limiting the cost increase ratio difference while considering the total risk, we could reach a more equitable decision. For the study case, $\beta = 0.18$ could be a good choice for model HNDP-P-2 by observing the results in Table 4 and Figure 3 if focusing on risk reduction. The risk reduction when $\beta = 0.18$ is 14.61%, which is very close to the maximum 16.54%. If taking the total cost into consideration, there is a 12.39% cost increase for $\delta = 0.18$ and the risk reduction is 14.61%. A β value of 0.15 with risk reduction 9.06% and cost increase 2.47% could be better in terms of both risk reduction and cost increase.

We also record the cost distribution for all OD pairs in Figure 4 for the case $\beta = 0.18$. We can see there are large differences of cost increase percentages among OD pairs without equity. OD pairs 5, 12, 21, 22, 25, 26, 30 and 33 have much larger cost increases. While enforcing an 18% equity bound among difference, these OD pairs' cost increases are reduced to a reasonable percentage.

For model HNDP-C-2, the largest cost increase ratio among carriers is 9.87%. For one carrier, its cost increases 22.09% while another one only increases 12.22%. This large difference

TABLE 3 : Risk and cost values considering different cost upper bounds for each OD pair (η) and each carrier (ε)

Models	Values	Risk	RiskReduce	Cost	CostIncrease	Time(s)/Gap
	1.00	153339	0.00%	2.2827×10^9	0.00%	2.2
	1.03	145501	5.11%	2.3009×10^9	0.80%	7.3
	1.06	145501	5.11%	2.3009×10^9	0.80%	20.3
	1.09	144604	5.70%	2.3146×10^9	1.40%	46.3
	1.12	140595	8.31%	2.3391×10^9	2.47%	1789.2
	1.15	140595	8.31%	2.3391×10^9	2.47%	0.57%
	1.18	132796	13.40%	2.5655×10^9	12.39%	60
	1.21	132796	13.40%	2.5655×10^9	12.39%	84.9
	1.24	132796	13.40%	2.5655×10^9	12.39%	77.3
	1.27	132796	13.40%	2.5655×10^9	12.39%	0.18%
η	1.30	132485	13.60%	2.5936×10^9	13.62%	15.6
	1.33	132485	13.60%	2.5936×10^9	13.62%	48
	1.36	132485	13.60%	2.5936×10^9	13.62%	90.8
	1.39	132485	13.60%	2.5936×10^9	13.62%	0.57%
	1.42	131639	14.15%	2.6948×10^9	18.05%	24.8
	1.45	131639	14.15%	2.6948×10^9	18.05%	27.8
	1.48	131639	14.15%	2.6948×10^9	18.05%	25.5
	1.51	131639	14.15%	2.6948×10^9	18.05%	23.3
	1.54	131639	14.15%	2.6948×10^9	18.05%	40.3
	1.57	131639	14.15%	2.6948×10^9	18.05%	0.03%
	1.60	131570	14.20%	2.7418×10^9	20.12%	15.2
	1.0000	153339	0.00%	2.2827×10^9	0.00%	3.2
	1.0125	145501	5.11%	2.3009×10^9	0.80%	22.6
	1.0250	140622	8.29%	2.3339×10^9	2.24%	104.1
	1.0375	140595	8.31%	2.3391×10^9	2.47%	0.18%
	1.0500	136763	10.81%	2.3794×10^9	4.24%	63.5
	1.0625	136426	11.03%	2.4092×10^9	5.54%	11.9
	1.0750	136426	11.03%	2.4092×10^9	5.54%	29.7
	1.0875	136426	11.03%	2.4092×10^9	5.54%	29.6
	1.1000	135927	11.36%	2.4757×10^9	8.46%	137.9
ε	1.1125	135927	11.36%	2.4757×10^9	8.46%	0.20%
	1.1250	135606	11.56%	2.5087×10^9	9.90%	112.8
	1.1375	132796	13.40%	2.5655×10^9	12.39%	91.8
	1.1500	132485	13.60%	2.5936×10^9	13.62%	26.7
	1.1625	132459	13.62%	2.5953×10^9	13.70%	42.5
	1.1750	132459	13.62%	2.5953×10^9	13.70%	0.33%
	1.1875	131961	13.94%	2.6618×10^9	16.61%	2695.8
	1.2000	131639	14.15%	2.6948×10^9	18.05%	49.6
	1.2125	131639	14.15%	2.6948×10^9	18.05%	61.8
	1.2250	131570	14.20%	2.7418×10^9	20.12%	33.9
	1.2375	131570	14.20%	2.7418×10^9	20.12%	27.1
	1.2500	131570	14.20%	2.7418×10^9	20.12%	31.2

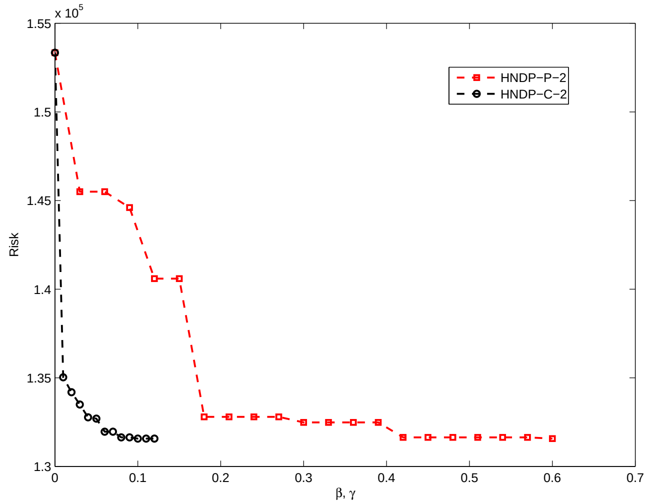


FIGURE 3 : Risk values considering different cost equity levels (β and γ)

leads to unfairness of the regulation policy and could harm the implementation of the policy. Thus it is essential to achieve a level of cost equity among carriers. In Figure 5, we record the cost percentage change under different equity levels among carriers. While enforcing a regulation policy could lead to risk reductions, there are cost increases for all carriers. Without considering cost equity among carriers ($\gamma = 0.12$), network design leads to carrier 3 having a much higher percentage cost increase. By incorporating equity, the difference in cost increases is much smaller. One interesting result from Figure 5 is that a more restrictive equity level ($\gamma = 0.01$) could lead to a higher cost increase for all carriers while the cost increase percentages are similar. The case $\gamma = 0.05$ has a lower cost increase for all carriers, however the difference of cost increase percentages is larger. If we only allow a 1% cost increase ratio difference among carriers, we still obtain a large reduction in risk (11.94%). Based on the decision maker's preference and negotiation with carriers, a 5% difference is also reasonable, especially since it leads to a smaller absolute cost in this case study. For some scenarios in which the differences are large, so that equity is not adequately addressed, the results can still show how the regulations affect the carriers, which could lead to other complementary regulations by the government.

CONCLUDING REMARKS

In this paper, we consider the hazmat network design problem (HNDP) with various cost considerations. Additionally, we propose a new objective considering the total length of closed road segments. We test the proposed objective on the Ravenna network and show the effectiveness of our proposed objective in avoiding closing unnecessary road segments. For cost considerations, we examine an upper bound burden on the total industry, each OD pair, hazmat carriers and generators. Since the cost increase for various OD pairs can be very different, we propose considering cost equity. We illustrate the results on the Ravenna network. By recording risks under different cost consideration parameters, we provide a more flexible framework for a government authority to design regulation policies in the hazmat transportation industry.

For designing regulation policy involving multiple parties, it is essential to consider the effects on all of them. Although HNDPs are formulated as leader-follower models where govern-

TABLE 4 : Risk and cost values considering different cost equity levels among OD pairs (β) and carriers (γ)

Models	Values	Risk	RiskReduce	Cost	CostIncrease	Time(s)/Gap
β	0.00	153339	0.00%	2.2827×10^9	0.00%	2.7
	0.03	145501	5.11%	2.3009×10^9	0.80%	10.1
	0.06	145501	5.39%	2.3009×10^9	0.80%	31.3
	0.09	144604	6.00%	2.3146×10^9	1.40%	68.3
	0.12	140595	8.81%	2.3391×10^9	2.47%	2450.7
	0.15	140595	9.06%	2.3391×10^9	2.47%	2988.8
	0.18	132796	14.61%	2.5655×10^9	12.39%	73.5
	0.21	132796	15.47%	2.5655×10^9	12.39%	85.3
	0.24	132796	15.47%	2.5655×10^9	12.39%	167.3
	0.27	132796	15.47%	2.5655×10^9	12.39%	0.12%
	0.30	132485	15.70%	2.5936×10^9	13.62%	29.2
	0.33	132485	15.74%	2.5936×10^9	13.62%	24.8
	0.36	132485	15.74%	2.5936×10^9	13.62%	110.8
	0.39	132485	15.74%	2.5936×10^9	13.62%	0.56%
	0.42	131639	16.38%	2.6948×10^9	18.05%	29.7
	0.45	131639	16.48%	2.6948×10^9	18.05%	33
	0.48	131639	16.48%	2.6948×10^9	18.05%	26.5
	0.51	131639	16.48%	2.6948×10^9	18.05%	28.5
	0.54	131639	16.48%	2.6948×10^9	18.05%	34.3
	0.57	131639	16.48%	2.6948×10^9	18.05%	0.03%
	0.60	131570	16.54%	2.7418×10^9	20.12%	29.5
γ	0.00	153339	0.00%	2.2827×10^9	0.00%	13.73%
	0.01	135029	11.94%	2.6406×10^9	15.68%	1.33%
	0.02	134187	12.49%	2.6252×10^9	15.00%	0.73%
	0.03	133493	12.94%	2.7168×10^9	19.02%	0.31%
	0.04	132772	13.41%	2.6670×10^9	16.83%	0.10%
	0.05	132696	13.46%	2.6069×10^9	14.20%	0.25%
	0.06	131961	13.94%	2.6618×10^9	16.61%	2522.8
	0.07	131961	13.94%	2.6618×10^9	16.61%	0.22%
	0.08	131639	14.15%	2.6948×10^9	18.05%	62.4
	0.09	131639	14.15%	2.6948×10^9	18.05%	61.4
	0.10	131570	14.20%	2.7418×10^9	20.12%	29.3
	0.11	131570	14.20%	2.7418×10^9	20.12%	12.6
	0.12	131570	14.20%	2.7418×10^9	20.12%	13.6

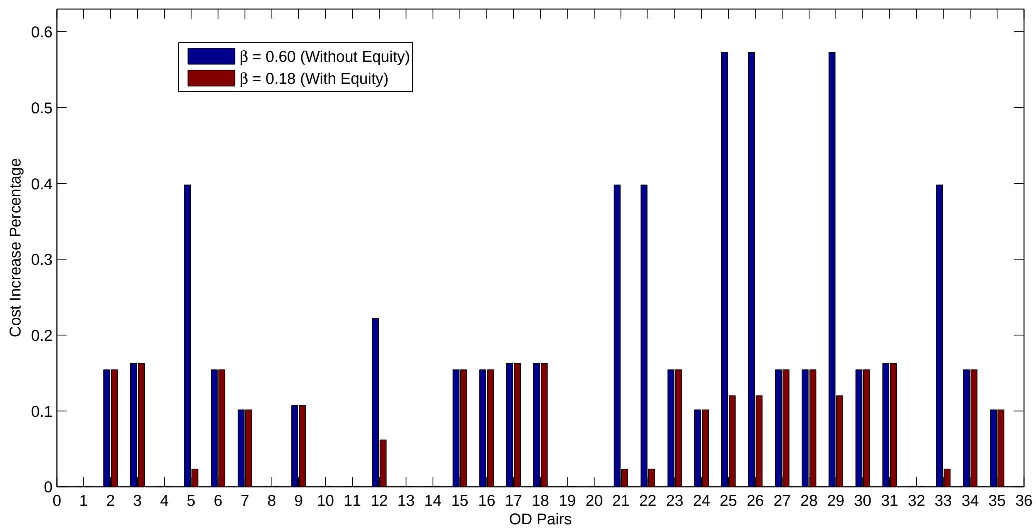


FIGURE 4 : Cost increase of the OD pairs with and without equity levels

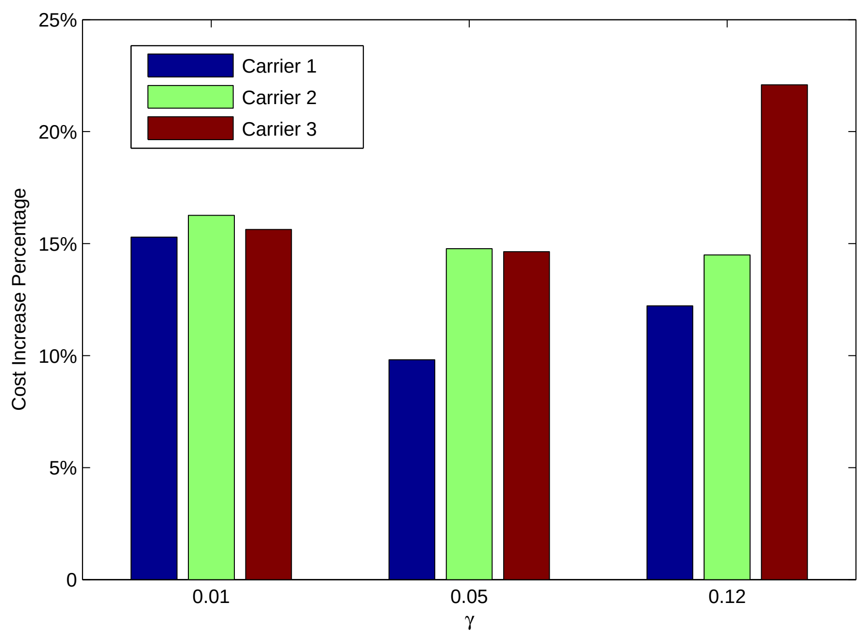


FIGURE 5 : Cost increase of the carriers for different equity levels

ment can make its decision first, it is in the government's interest to consider the cost on the carriers for the implementation of the policy. When considering cost in HNDP, it is natural to consider the total cost on all the carriers in the network. However it is easy to neglect the heterogeneity of the carriers. If we only bound the total cost, the effects on the carriers under a given governmental jurisdiction could be very different, leading to large difference in cost increases. Even when placing upper bounds on the carriers' cost and knowing the highest cost burden we possibly put on each carrier, the actual change could be different for each carrier. By limiting the cost increase between carriers, we are able to bound the unfairness. This is similar to the risk equity considered on territory zones, which has been well studied in the literature. However, the cost equity issue has lacked attention. A more restrictive way to consider cost and equity is based on OD pairs, which decomposes carriers into OD pairs. In this way, the model is flexible enough to analyze each OD pair. However, this approach could be too restrictive.

In conclusion, for HNDP, cost equity issues should be considered to avoid unfairness and will aid in the implementation of regulation policies. More generally, when designing policies, we should always keep in mind the heterogeneity issue and the effects on all parties.

For future research, to design regulation methods considering the trade-offs between risk, cost and equity issues, the potential preferences of government in choosing from the multiple optimal solutions could be considered. Currently we suggest the solution corresponding to the minimum length of all closed links from the multiple solutions. We can consider more complex issues of government's concerns in implementing the regulations and choose from the optimal and even sub-optimal solutions.

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