Hazmat Routing by Compulsory Checkpoints: a New Risk Mitigation Policy

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1 Introduction

Most of the services and amenities that we take for granted in our modern societies rely upon the continuous supply of large amounts of commodities, most of which imply the use of hazardous materials (hazmat). A crucial step in hazmat life cycle is transportation, since an accident on route may cause unintended release of toxic, poisonous, or even radioactive material that would severely affect human and environmental safety. For this reason, much research effort has been recently devoted to the development of risk mitigation policies.

In this study, we are concerned with hazmat transportation by truck on a road network, where several alternative itineraries from origin to destination are worthy of choice. Risk assessment studies provide the means to evaluate the risk associated with different itineraries. Usually, two stakeholders are involved in the decision making process: the local administrator and the carriers. Carriers face the problem of shipping hazmat from their origins to their destinations according to their own utility function, i.e., cost minimization. When there is no restriction on the carrier itineraries we speak of *unregulated scenario*. The administrator faces a global routing problem, where the global effect given by routing several shipments involving a few origin-destination pairs as well as several shipments for the same pair is considered. Issues like risk equity arise beside usual total risk minimization criterion. In a global routing problem itineraries are planned for the sake of the whole system and are imposed to individual carriers. In such a case we speak of *over regulated scenario*. When the administrator lacks the power of enforcing a specific itinerary for each shipment, it may indirectly influence the carrier routing decisions by imposing mandatory rules which carriers have to comply to. In this case we speak of *rule based scenario*. In this scenario, whatever the rules, a conflict arises between carriers and administrator, since the former are cost-oriented while the latter is risk-oriented. The hierarchical relationship between the rule-maker and the carriers is well captured by bilevel programming formulations. Examples include forbidding to traffic parts of the road network, i.e., individual links, which gives rise to network design problems as first studied in (Kara and Verter, 2004) and later in (Erkut and Gzara, 2008). Other options include toll pricing, a practice which discourages traversing certain links or entering specific areas by charging a toll at each usage (Marcotte et al., 2009).

In the rule based framework, we propose a new risk mitigation policy which consists of locating a set of gateways into the road transportation network, to be used like mandatory check points along the carriers itineraries. In this new system, the administrator will select the location of each check point and will decide which one has to be assigned to each carrier, so that carriers response will optimize the administrator objective function. We call such problem the *Gateway Location Problem* (GLP) for hazmat routing. To the best of our knowledge, GLP is a new problem in Combinatorial Optimization. In (Bruglieri et al., 2013) we provide a proof of NP-completeness. A previous study (Bruglieri et al., 2011) formalizes GLP by three mathematical models, discusses pros and cons, and provides computationally based evidence of its effectiveness as a risk mitigation strategy. In this work, we present the latest results of this study, concerning the impact of information guided policies for selecting potential locations for gateways installation. We show that on the data set used in our experimentation the same risk reduction that the GLP strategy reaches when selecting the gateway locations over the whole set of the network nodes can almost be achieved by considering only the 30% of the network nodes, if properly chosen. This feature may allow to tackle by exact approaches even much larger instances.

2 Solving the Gateway Location Problem

Given a set of vehicles $V = \{1 \ldots, n\}$, where each $v \in V$ carries a quantity φ_v from an origin o_v to a destination d_v, we are concerned with the problem of drifting them away from their minimum cost routes from origin to destination and routing them on less risky itineraries by assigning to each vehicle a compulsory crossing point, so called gateway, along the way from origin to destination. GLP consists of first selecting the location of k gateways among m candidate sites, whose set is denoted by N^{CS}, with $k < n$ and $k << m$. Then, each vehicle must be assigned to one gateway, so that the total risk of the new routes is minimized. A weighted directed graph $G = (N, A)$ models the network with $N^{CS} \cup \{o_v,\ v \in V\} \cup \{d_v,\ v \in V\} \subseteq N$. Cost and risk coefficients $c_{ij} > 0$, $r_{ij} \geq 0$ are given for each arc $(i,j) \in A$. Let $gtw(v)$ denote the gateway assigned to vehicle v. Once a gateway has been located at $h \in N^{CS}$ and gateway h has been assigned to v, then vehicle v will travel along the shortest gateway path with respect to h which is made by two paths, $\overline{p}_v^h$, i.e., the shortest path from o_v to h, and $\underline{p}_v^h$, i.e., the shortest path from h to d_v.

GLP can be formalized as the problem of selecting a subset N^{gtw} of size k out of N^{CS} and assigning to each vehicle v one gateway $h \in N^{gtw}$ so that the sum over each vehicle of the risks of the two paths $\underline{p}_v^h$ and $\overline{p}_v^h$ is minimized. More formally, we solve:

$$GLP : \min \Big\{ \sum_{v \in V} \sum_{\substack{h \in N^{gtw}: \\ h = gtw(v)}} \varphi_v \Big(\sum_{(i,j) \in \overline{p}_v^h} r_{ij} + \sum_{(i,j) \in \underline{p}_v^h} r_{ij} \Big) : N^{gtw} \subseteq N^{CS},\ |N^{gtw}| = k \Big\}.$$

Note that GLP is a hierarchical decision problem since expressions $\overline{p}_v^h$ and $\underline{p}_v^h$ hide a nested level of optimization. In fact, the minimum risk solution has to be searched for in the rational reaction set of the drivers.

The policy used to select the candidate site set N^{CS} consists in identifying a ground set and sampling it according to a probability distribution law until the desired number m of nodes is reached. Specifically, the ground set contains all those nodes that, vehicle by vehicle, belong to the safest path and do not belong to the shortest path. The probability distribution law assigns to each node in the ground set a weight that is proportional to the sum of the demands φ_v of all those vehicles containing that node in the safest path but not in the shortest one. This policy is referred to (C_2, Φ_3) in (Bruglieri et al., 2013).

3 Results and discussion

The experimental campaign was carried out on the same benchmark described in (Erkut and Gzara, 2008) regarding: *i*) the road network, being an undirected graph with 105 nodes and 134 arcs providing an abstraction of the road network of Ravenna (Italy); *ii*) three different risk functions, namely *on-arc*, *around-arc*, and *aggregate* risk, each one capturing different aspects of risk; *iii*) travel demand data, consisting of 35 origin-destination pairs together with their demand. These data provide three scenarios differing in the risk function. For each scenario, we build a sample of 10 instances of the GLP by generating 10 times the candidate site set N^{CS} according to policy (C_2, Φ_3). Each instance was solved by way of a MILP solver, namely Cplex 12.1, on a AMD Athlon (tm) 64x2 Dual Core Processor 4200+ (CPU MHz 2211.186). Running times are negligible, being in the order of few milliseconds for each run.

The GLP effectiveness has already been experimentally proved in (Bruglieri et al., 2011). However, it is worth providing additional information in order to rank GLP solutions in the range between the two extremes provided by the risk level achieved in the over regulated scenario and the one achieved in the unregulated scenario, denoted by R_o and R_u, respectively. Table 1 reports the average, minimum, and maximum risk of our reference solution $R(GLP)$ computed on the sample of 10 instances for each risk measure. In all cases, the coefficient of variability (standard deviation over the average) is around or even below 0.01%, which can be seen as a robusteness indicator since the solution quality is stable within each one of the three 10 instance samples. Our reference solutions are obtained by solving GLP with the following parameters: N^{CS} is the set returned by policy (C_2, Φ_3); its size m is thirty per cent of the number of nodes of the network ($|N^{CS}| = 30\%|N|$); the number of open gateways k is fixed to the value k^* for which the marginal risk mitigation level achievable by adding one more open gateway is negligible (these values are 5, 3 and 4 for the aggregate, around-arc, and on-arc risk measure, respectively).

Note that the relative percentage gap between the minimum and the maximum risk, i.e., $100(R_u - R_o)/R_o$, is 1669.14%, 257.13%, and 13.61% for the aggregate, around-arc, and on-arc risk measure, respectively. By making R_o equal to 0 and R_u equal to 100, our reference solution ranks on average at 13.02%, 1.07%, and 22.16% for the aggregate, around-arc, and on-arc risk measure, respectively. Table 1 shows that when the risk range $[R_u, R_o]$ is large and there is room for improvement the GLP based strategy achieves large risk reductions. However, when the unregulated solution is not very different from the over regulated one, our method is still able to reach almost 80% of the achievable risk reduction.

Another relevant fact is that the GLP based strategy provides an effective risk mitigation policy even when the number of open gateways is low ($k = k^*$). Furthermore, we will present data that show that, for the same value k^*, our reference solutions reach the same risk mitigation levels that are obtained when the candidate site set is the whole set of the network nodes, i.e., $N^{CS} = N$. This experimentally supports the idea that policy (C_2, Φ_3) allows to work with a reduced number of candidate sites at no detriment of solution quality. On the other side, we will show that if the size of $|N^{CS}|$ is lowered to $30\%|N|$ disregarding any information and the candidate site set is built by performing a pure blind random sampling over the network nodes, the solution obtained for the same value k^* ranks at 14.25%, 5.91% and 36.24% for the aggregate, around-arc, and on-arc risk measure, respectively. Solution quality deterioration is sensitive, but what is more remarkable is how much its robustness is affected. In fact, when going from an information guided policy to a pure blind random choice, the coefficient of variability of the 10 instance sample rises from 0.01% to 8.07% for the aggregate risk measure, from 0% to 11.13% for the around-arc one, and from 0.01% to 1.14% for the on-arc one.

Summarizing, the main highlights of the experimental campaign are the followings: *i*) it is possible to capture most of the risk mitigation potential of the whole gateway

Table 1: Risk range width and GLP efficacy

Risk Measure	R_u	avg $R(GLP)$	min $R(GLP)$	max $R(GLP)$	R_o
aggregate	2,208,839,655	396,203,056.8	396,152,220	396,224,844	124,854,028
around-arc	7,229,256,314	2,079,803,990.0	2,079,803,990	2,079,803,990	2,024,247,704
on-arc	567,773,424	514,839,597.5	514,788,176	514,993,511	499,767,899

based strategy by way of a limited number k^* of open gateways; *ii*) regarding the number of the candidate sites where gateways are potentially installed, for the fixed number k^* of open gateways, blindly decreasing the number of candidate sites may affect solution quality and most of all may affect robustness. At the same time, though, an information guided policy can select a lower number of candidate sites so that, on average, neither solution quality nor robustness are affected.

Reducing the number of candidate sites to be considered allows to reduce the size of the MILP model associated with the GLP. The size of the current instances is such that all models are solved very rapidly by a state of the art solver, and we did not notice any remarkable reduction of the running times when reducing the size of the candidate site set from $|N|$ to $30\%|N|$. Nevertheless, we believe that when tackling larger networks this feature will move forward the size of the largest exactly solvable instances.

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