Risk Averse Routing of Hazardous Materials with Scheduled Delays

Chiara BERSANI[1*], Riccardo MINCIARDI[1], Angela Maria TOMASONI[1,2], Roberto SACILE[1]
[1]*DIST, Department of Communication, Computer and System Sciences, University of Genova, Italy*
[2]*MINES Paris Tech – ARMINES, Ecole des Mines de Paris, CRC, Centre for Research on Risk and Crises, Sophia Antipolis, France*

Abstract The term "risk-averse" in the routing of hazardous material is used for problems whose objective is to find the best and safest routes to connect various origin-destination (OD) pairs, taking into account the objective of minimizing either the maximum risk or the maximum exposure. In recent works, it has been demonstrated that for repeated shipments, where the accident probabilities over the various links in the network are unknown, the safest strategy is generally based on the use of a multiple routes for each OD pair. In this work, it is shown that further improvements can be made through scheduling the deliveries, that is, spreading the risk both in space and in time. The scheduling is particularly relevant when the vulnerability of the network is time-dependent.

Keywords: Hazardous material transport, risk averse routing, link exposure, game theory, decision support system

Introduction

The increasing need for sustainable freight transportation taking into account economic, environmental, and risk aspects, requires models which enhance the overall transport planning process. As far as hazardous material (hazmat) transport is concerned, current decision making tools do not significantly differ from traditional planning tools for general freight, in that they compute and recommend the routes based mainly on the economical factors (distances covered and transport costs). However, from a sustainable transport viewpoint, the best route choice may also depend on risk and safety aspects which are often in conflict with economic efficiency. In addition, hazmat transport risk lacks a worldwide accepted definition. Even though several recent scientific papers discuss this issue [1–5], further work is required to agree a standard definition. It must be also noted that events with

* Corresponding Author: Chiara Bersani, DIST, Department of Communication Computer and System Sciences, University of Genova, Italy, University of Genova, via Opera Pia 13, 16145 Genova, Italy; E-mail: chiara.bersani@unige.it

DOI 10.1007/978-90-481-8563-4_2, © Springer Science + Business Media B.V. 2010

serious consequences have generally very low probabilities, thus making the hazmat transport risk very hard to be quantified from a probabilistic/statistical viewpoint.

In this context, risk averse routing for hazmat vehicles, taking into account the status of transportation infrastructures, the threats to security and safety, and the possible occurrence of hazmat and traffic incidents represents a meaningful contribution. Specifically, the term "risk-averse" in the routing of hazardous material is used to indicate approaches whose aim is to find the best and safest routes to connect the various origin-destination (OD) pairs of a transport network, with the objective of minimizing either the maximum risk on a link (over all links in the network), or – in case of lack of reliable statistical information – the maximum link exposure (again over all links). In this context, the term exposure is used to represent the loss in the event of an accident on the given link, times the probability of that link is selected by a network user [6].

From a practical viewpoint, distribution companies and common transport network users will be increasingly required to search for a trade-off between the travel cost (including e.g. distances, travel time, delay penalty) and the risk of using a specific path. In case of hazmat transportation, the serious consequences of an accident have been the subject of growing research interest [7–12], tackling the hazmat routing problem taking into account the probability of accidents, explosions, releases, along with an evaluation of population and environmental vulnerability. In [12], the authors developed a model that aims to achieve the lowest level of operational costs and the highest level of safety during hazmat transport. The optimization problem has been formalised as a bi-objective routing and scheduling problem: the minimization of operational costs and the minimization of the risk for the population. These bi-objective mathematical problems were solved using a new heuristic algorithm. For a thorough survey of the matter, the reader can refer to [13, 14].

Several studies have deepened the risk-averse approach to route choice. For example, the use of game theoretic approach in [15, 16] was based on the assumption that network users are pessimistic about the state of the road network, and they behave as if they were convinced that one accident will surely happen. This model of route choice behaviour seems to be suitable to describe events which threaten transport network reliability modelling the behaviour of two different agents. The first agent (network user) aims to minimize the expected cost by appropriate route choices. The second agent ("malicious demon"), aims to maximize the expected cost by choosing which (unique) link to fail. In particular, in [16], the authors introduce a risk-averse user equilibrium traffic assignment model, assuming that the number of users is fixed. Another approach is adopted in [17], where three ways of introducing risk aversion are presented: minimising the maximum consequence along a route; incorporating the variance of the losses along a route into route selection; and minimising the expected disutility of the losses when a convex utility function is used. It is shown that all these three approaches can be reduced to shortest path problems by appropriately defining link lengths. Finally, in [6], the author demonstrates that – for repeated shipments through a network, where the accident probabilities over the various links in the network are unknown, – the safest strategy is in general to use multiple routes for each OD pair. The same author also observes that, when there are multiple OD pairs, they may be considered separately. In fact, given that those travelling between different OD pairs do not exchange information, there is no reason for them to share expectations (or fears) related to the link costs.

Other models consider the hazmat routing problem defining paths with the aim to equalize the risk over the transport network [18–21]. Specifically the method presented in [21] requires complete information about the dominant (non-hazmat) traffic pattern (as a function of time) over each link in the network as an input. Moreover, it is assumed that information relevant to the hazmat traffic demand, for each OD pair, is available over an optimization horizon of suitable length. In this framework, the problem is that of managing the hazmat traffic with the objective of spreading and equalizing the risk over the network. The decision variables are the splitting coefficients at the various nodes in the network that determine the routing of hazmat vehicles.

Other approaches aim at finding an equitable risk distribution by determining a set of minimum risk alternative routes for each OD pair ([3, 22]). In [3], the model assigns a route to each hazmat delivery and schedules the deliveries over the assigned routes in order to minimize the total shipment delay, with the additional objectives of equalizing the spatial risk distribution and preventing the risk induced by hazmat vehicles travelling too close to each other. This hazmat shipment scheduling problem is modelled as a job-shop scheduling problem with alternative routes. In [22], a hazmat network design problem is considered as a linear bi-level model, where, at the higher level, the objective is that of minimizing the maximum population risk over links of the whole network, whereas at the lower level, the objective is that of minimizing the total risk over the network.

The approach proposed in this contribution, considers a model in which a decision maker (DM) has to plan each day several deliveries of hazardous material from depots (e.g. petroleum refineries) to several other destination (e.g. petrol service stations or other logistics nodes). It is assumed that the DM wishes to follow a risk-averse routing in the deliveries and that he takes into account the combined risk arising from the simultaneous presence of two or more vehicles on the same link at the same time. In addition, as normally happens in planning practice, the DM has a priori defined a small number of alternative paths for each OD pair. Two classes of decision variables are considered: the path selection probabilities, for each OD pair, and the schedule of departure times from the depots.

The main methodological contribution of this paper is allowing for deliveries to be spread over time, which, in general, provides additional improvement in minimising the overall maximum exposure. This possibility seems particularly interesting when the vulnerability of the link of the network is time dependent.

The Basic Problem Description

It is assumed that a DM plans deliveries of hazardous materials according to customer orders that must be satisfied within a given day but without any other specific temporal constraint. The hazmat vehicles leave from a given depot (the origin, for example a tank of a refinery) towards another depot (the destination, for example a petrol service station), according to a full drop (FD) delivery strategy. A FD delivery strategy means that the whole cargo carried by a vehicle is emptied at one destination, and afterwards the vehicle does not induce any danger for the territory and its population. The FD delivery model is quite frequent in the hazmat delivery, such as petrol products, as well as in general freight transportation. In the model considered, for each OD pair, the DM is assumed to have selected a priori a limited number of eligible paths, having minimum (or near-minimum) cost, found, for example, by means of a "k shortest paths" algorithm. The DM has also access to a reliable forecast of the hazmat incoming flows pattern for each OD pair, for the whole day considered.

The DM wishes to follow a risk-averse routing approach. In particular, he wishes to minimise the maximum exposure on a set of clearly identified critical infrastructures (for example tunnels) that are present on the different paths. Moreover, it is assumed that, in case of an accident on a critical infrastructure, the simultaneous presence of more than one hazmat vehicle can significantly amplify the number of persons injured, due to the nature of the accident or to other causes such as domino effects. So, the objective of a risk-averse DM is also to avoid the presence of several hazmat vehicles on critical infrastructures at the same time. Thus, the DM has to apply a control strategy defining for each delivery, the path and the scheduled delay, with respect to the beginning of the work time, so that he can obtain daily delivery plans that are in accordance with the adoption of a risk-averse criterion.

The Model and the Decision Problem

Network Model

- The roads network is supposed to be represented by a graph $G(N,L)$, where each link $l \in L$ represents a critical infrastructure with a time dependent loss $e(l,t)$, that is incurred in case of an accident (involving a single hazmat vehicle) on a link $l \in L$ in the time interval $(t, t + 1)$. Let the term *link exposure* be used to designate the quantity $e(l,t)$. In the adopted model, it is supposed that the road network is entirely made by critical infrastructures. In addition, each link is supposed to be characterized by a unitary travel time.[1]
- It is assumed that there is no availability of a significant historical data base of accidents on the road network, so that it is not possible, for any link, to define an objective value of the accident occurrence probability.
- Only direct FD deliveries are considered.
- If two or more vehicles, either related to the same or to different OD pairs, traverse the same link in the same time interval, the loss incurred in case of

[1] This modelling assumption should not represent a limitation, since if a longer time is required to traverse a critical infrastructure, then it may be modelled by several links.

an accident is additive. This means that, if an accident occurs on a link, all the hazmat vehicles present in that time interval on that link are assumed to be involved.

- Links are considered as isolated systems, so that an accident on one link does not induce any effect over other links, such as, for example, the adjacent ones.

Decision Making Framework

- It is assumed that one accident is expected to occur during the day, and that it will be inflicted with the intent to cause the maximum possible loss. Exactly one of such accidents will take place somewhere in the network during each day.
- The DM is risk-averse and expects that an accident will surely happen in the day, on some link, and within some time interval.

On this basis, two possible risk aversion approaches may be followed:

- *Minimising the maximum link loss over the whole time horizon*
- *Minimising the sum of the maximum link losses which may be caused at the various time intervals*

In the first case, the objective is expressed in accordance with the risk averse approach. Instead, in the second case, the objective is equivalent to the average maximum risk minimization over the time horizon.

It is worthwhile to underline that no risk definition is used in this work. In fact, in the present model, the probability of an accident is not a priori known and only the link loss is taken into account. Such a loss, as it will be clear later on, is evaluated as the product of the magnitude of the loss $e(l,t)$ incurred in case of an accident involving a single hazmat vehicle (for instance, the number of persons involved in the accident), times the number of hazmat vehicles passing on that link.

Set Definitions

- $l = 1, \ldots, L$: the network links
- $t = 0 \ldots T - 1$: the temporal working units of the day (for example, hours)
- $od = 1 \ldots OD$: the OD pairs considered
- P_{od}: the set of the predefined paths for pair od

Modelling Assumptions and Parameters

- $f(od, \bar{t})$, $\bar{t} = 0, \ldots, T-1$, $od = 1, \ldots, OD$, is the flow of hazmat vehicles that enter the network in the origin of the pair od and are directed to the destination of the pair od in the time interval $(\bar{t}, \bar{t}+1)$; such a value is normalised with respect to the value $\max_{\bar{t},od} f(od,\bar{t})$, so that $f(od, \bar{t}) \in [0,1]$ for all $\bar{t}$ and all od; all such values are all known a priori

- It is assumed that, in each time interval $(\bar{t}, \bar{t}+1)$, and for each *od* pair, the DM has to assign to each vehicle relevant to the flow $f(od,\bar{t})$ a path $p \in P_{od}$ and a (integer) delay $\tau \geq 0$ corresponding to a number of time intervals that the vehicle has to wait for, before starting its travel over the assigned path.
- It is assumed that the travel time for a hazmat vehicle on each link is equal to one time unit; on this basis, and on the basis of the knowledge of the selected path *p* and delay τ, it is possible to determine the position (i.e. the link over which it travels) in any time interval $(t, t+1)$, $t \geq \bar{t}+\tau$, of any hazmat vehicle arrived in time interval $(\bar{t}, \bar{t}+1)$, $\bar{t} \geq 0$; then it is possible to determine the value of the binary variable $tr(l,p,od,\bar{t},t,\tau)$, which is equal to 1 if a vehicle assigned to path $p \in P_{od}$, with a delay τ in time interval $(\bar{t}, \bar{t}+1)$, travels on link *l* (belonging to that path) in time interval $(t, t+1)$, and 0 otherwise

Decision Variables

- $h(p,od,\bar{t},\tau)$, that is the fraction of $f(od,\bar{t})$ that is routed (in time interval $(\bar{t}+\tau, \bar{t}+\tau+1)$) through path $p \in P_{od}$.

Other Variables

- *C,* which is the maximum link loss, for any choice of the link and of the time instant
- *c(t),* which is the maximum link loss, for any choice of the link, within a given time interval $(t,t+1)$

Decision Models

Then, two possible decision models can be considered. Another additional model can also be derived by the integration of such two models.

Decision model 1: minimising the maximum link loss over the whole time horizon

$$\min_{h(p,od,\bar{t},\tau)} Z_1 = C \tag{1}$$

$$\sum_{\bar{t}=0}^{T-1} \sum_{od=1}^{OD} \sum_{p \in P_{od}} \sum_{\tau} f(od,\bar{t}) h(p,od,\bar{t},\tau) tr(l,p,od,\bar{t},t,\tau) e(l,t) \leq C$$

$$l = 1,..,L \qquad t = 0,..,T-1 \tag{2}$$

s.t.

$$\sum_{p \in P_{od}} \sum_{\tau} h(p, od, \bar{t}, \tau) = 1 \qquad \begin{array}{l} od = 1,..,OD \\ \bar{t} = 0,...,T-1 \end{array} \tag{3}$$

Decision model 2: minimising the sum of the maximum link losses over the whole time horizon for given time intervals

$$\min_{h(p,od,\bar{t},\tau)} Z_2 = \sum_{t=0}^{T-1} c(t) \tag{1'}$$

$$\sum_{\bar{t}=0}^{T-1} \sum_{od=1}^{OD} \sum_{p \in P_{od}} \sum_{\tau} f(od,\bar{t}) h(p,od,\bar{t},\tau) tr(l,p,od,\bar{t},t,\tau) e(l,t) \le c(t)$$

$$\begin{array}{l} l = 1,..,L \\ t = 0,..,T-1 \end{array} \tag{2'}$$

s.t.

$$\sum_{p \in P_{od}} \sum_{\tau} h(p, od, \bar{t}, \tau) = 1 \qquad \begin{array}{l} od = 1,..,OD \\ \bar{t} = 0,...,T-1 \end{array} \tag{3'}$$

Decision model 3: integrating decision models 1 and 2.

It might be assumed that a risk averse DM wishes to follow an approach which is a mix of the two previous ones. This may accomplished by introducing a weighting parameter α; when $\alpha = 0$ the model corresponds to model 2, while for $\alpha \to \infty$ it tends to model 1.

$$\min_{h(p.od,\bar{t},\tau)} Z_3 = \sum_{t=0}^{T-1} c(t) + \alpha C \tag{1''}$$

s.t.

$$\sum_{\bar{t}=0}^{T-1} \sum_{od=1}^{OD} \sum_{p \in P_{od}} \sum_{\tau} f(od,\bar{t}) h(p,od,\bar{t},\tau) tr(l,p,od,\bar{t},t,\tau) e(l,t) \le C$$

$$\begin{array}{l} l = 1,..,L \\ t = 0,..,T-1 \end{array} \tag{2}$$

$$\sum_{\bar{t}=0}^{T-1}\sum_{od=1}^{OD}\sum_{p\in P_{od}}\sum_{\tau} f(od,\bar{t})h(p,od,\bar{t},\tau)tr(l,p,od,\bar{t},t,\tau)e(l,t) \le c(t) \qquad \begin{matrix} l=1,..,L \\ t=0,..,T-1 \end{matrix} \tag{2'}$$

$$\sum_{p\in P_{od}}\sum_{\tau} h(p,od,\bar{t},\tau)=1 \qquad \begin{matrix} od=1,..,OD \\ \bar{t}=0,...,T-1 \end{matrix} \tag{3}$$

Case Study: Description

Consider the transport network (with L = 12) shown in Figure 1.

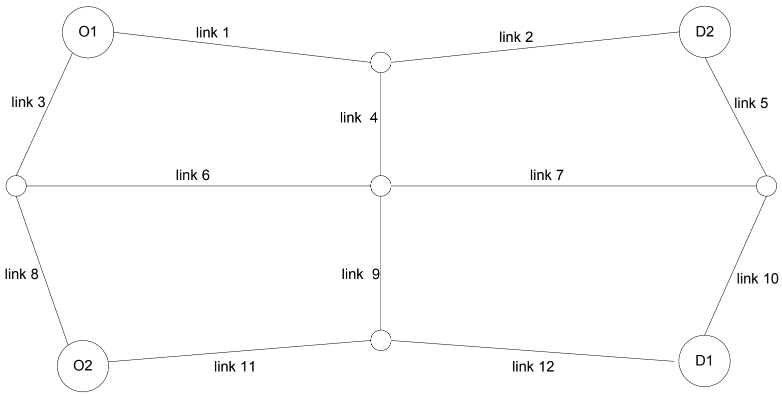

Figure 1. Transportation network used in this work (Adapted from [6])

In the network, there are two OD pairs (i.e. OD = 2), namely (*O1*, *D1*) and (*O2*, *D2*).

It is assumed that the overall flow is equally balanced on the two OD pairs and that it is different from 0 just in the first time interval, that is:

$$\begin{matrix} f(od,0)=1 & od=1,2 \\ f(od,\bar{t})=0 & \forall\bar{t}\ne 0 \quad od=1,2 \end{matrix}$$

For sake of simplicity, hereinafter, $\bar{t}$ will be omitted (e.g. $h(p,od,\bar{t},\tau)$ will be referred to as $h(p,od,\tau)$; similarly $f(od,t)$ will also be omitted).

This scenario corresponds to a fleet of vehicles that should leave at the beginning of the day from each origin. Time intervals are expressed in hours, and each day is made of eight working hours, that is t = 0…7 and T = 8. A hazmat vehicle spends 1 h to traverse each link.

There are two paths for each OD pair. The links for each path are:

od = 1; *p* = 1; links: 1, 4, 7, 10
od = 1; *p* = 2; links: 3, 6, 9, 12
od = 2; *p* = 1; links: 2, 4, 9, 11
od = 2; *p* = 2; links: 5, 6, 7, 8

The possible delays that are both feasible and allowed by the DM are the same for all the OD pair and the paths, specifically $\tau = 0\ldots3$. The link exposures $e(l,t)$ are assumed to vary during the day, in line with Table 1, where the maximum values for each link are indicated in bold.

Table 1. Exposures on each of the 12 links at each of eight time interval

Link\h	1	2	3	4	5	6	7	8
1	1,000	8,000	**11,000**	8,000	5,000	3,000	10,000	8,000
2	5,000	**6,000**	5,000	4,000	3,000	2,000	1,000	500
3	2,000	1,000	**2,000**	2,000	1,500	1,000	200	1,000
4	10,000	11,000	**15,000**	14,000	13,000	9,000	4,000	3,000
5	20,000	30,000	25,000	28,000	**31,000**	28,000	15,000	10,000
6	1,000	800	**1,000**	800	200	200	1,000	500
7	12,000	18,000	25,000	**32,000**	25,000	18,000	17,000	15,000
8	6,000	**7,000**	6,000	5,000	4,000	1,000	1,000	1,000
9	28,000	20,000	15,000	14,000	15,000	20,000	**28,000**	10,000
10	10,000	9,000	10,000	10,000	9,000	15,000	**17,000**	12,000
11	20,000	18,000	10,000	18,000	**22,000**	18,000	10,000	8,000
12	5,000	6,000	8,000	10,000	**14,000**	12,000	5,000	1,000

The values above have been used in the case study. When comparing the results with the approach in [6], which allows just one value of exposure for each link, two values have been taken into account: worst case loss (the maximum value of each row, in bold in Table 1) and average values, reported in Table 2.

Table 2. Worst and average exposures for each link used to compare the proposed model with Bell's approach [6]

Link	Worst	Average
1	11,000	6,750
2	6,000	3,312.5
3	2,000	1,337.5
4	15,000	9,875
5	31,000	23,375
6	1,000	687.5
7	32,000	20,250
8	7,000	3,875
9	28,000	18,750
10	17,000	11,500
11	22,000	15,500
12	14,000	7,625

Case Study: Results

The path probabilities that have been obtained according to Bell's approach [6] are reported in Table 3.

Table 3. Path probabilities obtained according to Bell's approach [6], computed on the basis on the link costs of Table 2

od	*p*	*h (worst)*	*h (average)*
1	1	0,466667	0,480769
1	2	0,533333	0,519231
2	1	0,533333	0,554896
2	2	0,466667	0,445104

Since Bell's approach [6] does not take into account delays, it is reasonable to suppose that a common risk-averse subjective strategy is to spread deliveries in time. In other words, the path probabilities that have been obtained in Table 3 have been shared in all the eligible time instants as shown in Table 4. The $h(p,od,\tau)$ values for $\tau=0,1,2,3$, which have been obtained, are reported in Tables 4 (worst) and 5 (average).

Table 4. Path probabilities obtained according to the Bell's approach [6] on worst link exposures, spread in time

OD	Path	$h(p,od,0)$	$h(p,od,1)$	$h(p,od,2)$	$h(p,od,3)$
1	1	0,116667	0,116667	0,116667	0,116667
1	2	0,133333	0,133333	0,133333	0,133333
2	1	0,133333	0,133333	0,133333	0,133333
2	2	0,116667	0,116667	0,116667	0,116667

Table 5. Path probabilities obtained according to the Bell's approach [6] on average link exposures, spread in time

OD	Path	$h(p,od,0)$	$h(p,od,1)$	$h(p,od,2)$	$h(p,od,3)$
1	1	0,120192	0,120192	0,120192	0,120192
1	2	0,129808	0,129808	0,129808	0,129808
2	1	0,138724	0,138724	0,138724	0,138724
2	2	0,111276	0,111276	0,111276	0,111276

Forcing the $h(p,od,\tau)$ values reported in Tables 4 and 5 in (1), (2), (1') and (2'), the Z1* and Z2* objectives have been computed and then compared with the optimal Z1 and Z2 values obtained solving the problems described in Section "Decision models".

Figure 2 shows the solution obtained in the case study for the three decision models defined in Section "Decision models". The solutions are reported in the space Z1, Z2. The exposures that have been used in Eqs. (2) and (2') are the ones showed in Table 1 for the case with variable losses (continuous line), and in the "worst" column of Table 2 for the case with constant losses.

Figure 2, showing the objectives values in the Z1 Z2 space, highlights that in case of both constant and variable arc exposures during the time horizon, the possibility to shift the departure time for some deliveries brings a significant improvement in the performance compared to the Bell's model with deliveries spread uniformly in time. In particular, the possibility to consider the varying exposure during the time horizon on each arc will have the favourable effect of reducing the use of the critical arc during the high level of exposure.

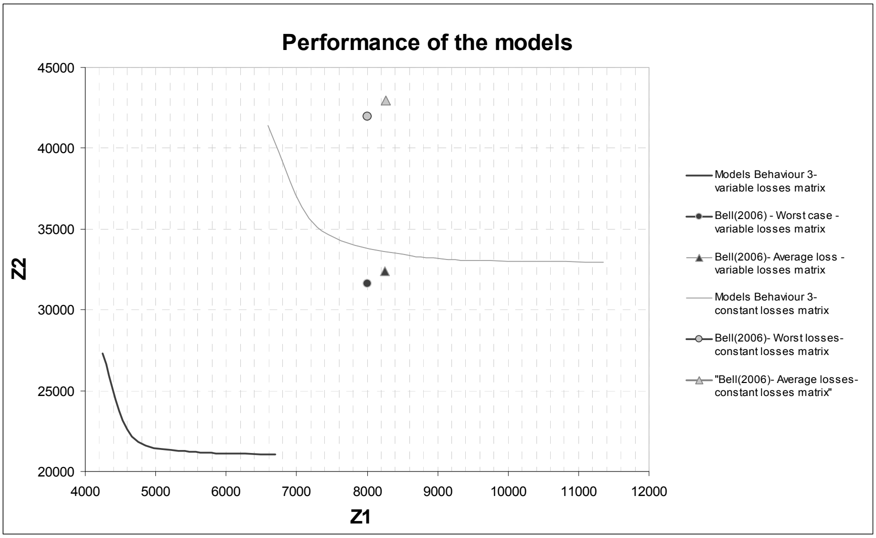

Figure 2. Pareto optimal results obtained for the proposed model (Behaviour 3 varying the parameter α)

As a next step, an optimal scheduling of a certain number of vehicles was undertaken, based on decision model 3 (Section "Decision models") defined as an integer programming problem, reported hereinafter with the simplifications related to the case study.

$$\min_{h(p.od,\bar{t},\tau)} Z_3 = Z_1 + \alpha Z_2 \tag{1*}$$

$$Z_1 = \frac{C}{nveh}$$

$$Z_2 = \frac{\sum_{t=0}^{T-1} c(t)}{nveh}$$

s.t.

$$\sum_{od=1}^{OD}\sum_{p=1}^{p_{od}}\sum_{\tau} h(p,od,\tau)tr(l,p,od,t,\tau)e(l,t) \le C \quad \begin{array}{l} l = 1,..,L \\ t = 0,..,T-1 \end{array} \tag{2*}$$

$$\sum_{od=1}^{OD}\sum_{p=1}^{p_{od}}\sum_{\tau} h(p,od,\tau)tr(l,p,od,t,\tau)e(l,t) \le c(t) \quad \begin{array}{l} l = 1,..,L \\ t = 0,..,T-1 \end{array} \tag{2**}$$

$$\sum_{p=1}^{P_{od}}\sum_{\tau} h(p,od,\tau) = nveh \quad \begin{array}{l} od = 1,..,OD \\ h(p,od,\tau) \in Z^{0,+} \end{array} \tag{3*}$$

Taking into account variable exposures, the model has been tested considering different number of available vehicles (*nveh*) for the scheduled deliveries. Figure 3 shows that increasing the number of vehicles brings the improvements of the performance of models, and that the models proposed in Section "Decision models" are equivalent to the integer problem described above for an infinite number of hazmat vehicles.

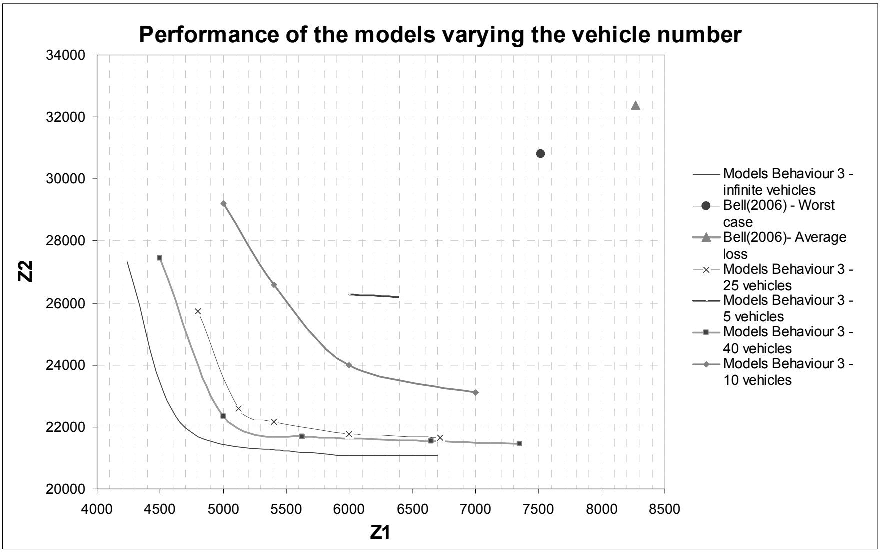

Figure 3. Results obtained varying the number of hazmat vehicles

Discussion

In this work, a risk averse decisional model for hazmat transport planning on road has been proposed, with the intent to show that spreading not only in space (i.e. on multiple paths) but also in time (i.e. adding delays in the departure of the deliveries) can decrease the overall maximum exposure.

The proposed model is formulated at planning level with one DM scheduling a relevant number of hazmat FD deliveries on several OD pairs. The DM can select a path from the set of predefined paths for each OD pair and decide whether a vehicle should depart immediately or later. Results on a simplified network demonstrate the reduction in overall exposure in comparison with the situation when the option to delay deliveries was not included. The benefit is more evident when vulnerability and exposure vary with time.

Future work will avoid adopting predefined paths for each OD pair. The method of successive averages will be adapted to the current formulation, to verify whether optimality conditions similar to [6] can be defined for the proposed formulation, and to verify whether the solution introduced in the current work can give additional insights on the integer programming problem introduced in Section "The model and the decision problem".

Acknowledgments

This work has been discussed in the NATO Advanced Research Workshop on "Security and Environmental Sustainability of Multimodal Transport", Imperial College, London, 2009. The participation to the Workshop has been supported by NATO Science for Peace and Security Programme.

References

[1] Akgün V., Parekhb A., Batta R., Rumpd C.M. (2007). Routing of a hazma truck in the presence of weather systems, *Computers & Operations Research* 34: 1351–1373.
[2] Brown D. F., Dunn W. E. (2007). Application of a quantitative risk assessment method to emergency response planning, *Computers & Operations Research* 34: 1243–1265.
[3] Carotenuto, P., Giordani, S., Ricciardelli, S. (2007). Finding minimum and equitable risk routes for hazmat shipments, *Computers & Operations Research* 34: 1304–1327.
[4] Fabiano B., Curro' F., Riverberi A.P., Pastorino R. (2005). Dangerous good transportation by road: from risk analysis to emergency planning, *Journal of Loss Prevention in the Process Industries* 18: 403–413.
[5] Verma M., Verter V. (2007). Railroad transportation of dangerous goods: Population exposure to airborne toxins, *Computers & Operations Research* 34: 1287–1303.
[6] Michael G. H. Bell (2006). Mixed Route Strategies for the Risk-Averse Shipment of Hazardous Materials, *Networks and Spatial Economics*, 6(3): 253–265.
[7] Bonvicini, S., Leonelli, P., Spadoni, G. (1998). Risk analysis of hazardous materials transportation: evaluating uncertainty by means of fuzzy logic, *Journal of Hazardous Materials* 62(1): 59–74.
[8] Frank, W., Thill, J., Batta, R. (2000). Spatial decision support system for hazardous material truck routing, *Transportation Research Part C - Emerging Technologies* 8(1-6): 337–359.
[9] Leonelli, P., Bonvicini, S., Spadoni, G. (2000). Hazardous materials transportation: a risk analysis-based routing methodology, *Journal of Hazardous Materials* 71(1): 283–300.
[10] Fabiano, B., Curro, F., Palazzi, E., Pastorino, R. (2002). A framework for risk assessment and decision-making strategies in dangerous good transportation. *Journal of Hazardous Materials* 93(1): 1–15.
[11] Erkut, E., Alp, O. (2007). Integrated routing and scheduling of hazmat trucks with stops en-route. *Transportation Science* 41(1): 107–122.

[12] Zografos, K., Androutsopoulos, K. (2004). A heuristic algorithm for solving hazardous materials distribution problems. *European Journal of Operational Research*, 152(2): 507–519.
[13] Erkut, E., Tjandra, S., Verter, V. (2007). Hazardous materials transportation. in C. Barnhart and G. Laporte (Eds.) Transportation, Handbook in OR & MS Vol. 14, Elsevier, 539–621.
[14] Centrone G., Pesenti R., Ukovich W., "Hazardous Materials Transportation: A Literature Review and an Annotated Bibliography" in "Advanced Technologies and Methodologies for Risk Management in the Global Transport of Dangerous Goods", Eds C. Bersani, A. Boulmakoul, E. Garbolino, R. Sacile, NATO Science for Peace and Security Series - E: Human and Societal Dynamics (ISSN 1874-6276) Volume 45, pag 261, ISBN 978-1-58603-899-1, IOS Press, 2008.
[15] Bell MGH (2000). A game theory approach to measuring the performance reliability of transport networks, *Transportation Research B*, 34B: 533–546.
[16] Bell MGH, Cassir C (2002). Risk-averse user equilibrium traffic assignment: an application of game theory, *Transportation Research B*, 36B: 671–681.
[17] Erkut, A. Ingolfsson (2000). Catastrophe avoidance models for hazardous materials route planning, *Transportation Science*, 34: 165–179.
[18] Gopalan, R., Kolluri, K., Batta, R., Karwan, M. (1990). Modeling equity of risk in the transportation of hazardous materials. *Operations Research* 38(6): 961–975.
[19] Current, J., Ratick, S. (1995). A model to assess risk, equity, and efficiency in facility location and transportation of hazardous materials. *Location Science* 3: 187–202.
[20] Akgün, V., Erkut, E., Batta, R. (2000). On finding dissimilar paths. *European Journal of Operations Research* 121: 232–246.
[21] Bersani C, Minciardi R, Sacile S., Tomasoni A.M. and Trasforini E., "An Integrated System for the Hazardous Materials Transport in a Sub-Regional Scale Area" in "Advanced Technologies and Methodologies for Risk Management in the Global Transport of Dangerous Goods", Eds C. Bersani, A. Boulmakoul, E. Garbolino, R. Sacile, NATO Science for Peace and Security Series - E: Human and Societal Dynamics (ISSN 1874-6276) Volume 45, pag 261, ISBN 978-1-58603-899-1, IOS Press, 2008.
[22] Bianco L., Caramia M., Giordani S. A bilevel flow model for hazmat transportation network design, *Transportation Research Part C: Emerging Technologies*, In Press.

Springer

http://www.springer.com/978-90-481-8561-0

Security and Environmental Sustainability of Multimodal Transport
Bell, M.; Hosseinloo, S.H.; Kanturska, U. (Eds.)
2010, XI, 260 p., Hardcover
ISBN: 978-90-481-8561-0