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Hazardous materials transportation: a risk-analysis-based routing methodology

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Abstract

This paper introduces a new methodology based on risk analysis for the selection of the best route for the transport of a hazardous substance. In order to perform this optimisation, the network is considered as a graph composed by nodes and arcs; each arc is assigned a cost per unit vehicle travelling on it and a vehicle capacity. After short discussion about risk measures suitable for linear risk sources, the arc capacities are introduced by comparison between the societal and individual risk measures of each arc with hazardous materials transportation risk criteria; then arc costs are defined in order to take into account both transportation out-of-pocket expenses and risk-related costs. The optimisation problem can thus be formulated as a 'minimum cost flow problem', which consists of determining for a specific hazardous substance the cheapest flow distribution, honouring the arc capacities, from the origin nodes to the destination nodes. The main features of the optimisation procedure, implemented on the computer code OptiPath, are presented. Test results about shipments of ammonia are discussed and finally further research developments are proposed.

Keywords: Hazardous materials; Individual risk; Min cost flow problem; Optimisation; OptiPath; Risk analysis; Routing; Societal risk; Transportation

1. Introduction

The transportation of hazardous materials (HazMats) is a growing problem worldwide due to the increasing transported volumes. In fact, as a consequence of industrial development, huge quantities of HazMats are yearly produced and obviously the production of them goes together with their transportation.

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Both historical evidence and previsional calculations have shown that the risks arising from the transportation of HAZMATS are often of the same magnitude of those ones due to fixed installations, and thus need to be taken into account with the same attention in order to keep them under control and to reduce them. One way to achieve this objective is through appropriate routing decisions, which can lead to the determination of alternative routes with respect to that usually chosen by truck drivers. In order to identify these alternative routes, an optimal routing problem has to be solved; suppose that there is a road network, which can be viewed as a graph $G=(M,A)$ formed by the node set M and arc set A, and that a certain amount of shipments of some hazardous substance have to be made yearly from node O to node D: a question arises spontaneously, that is, which is the route the truck tankers should drive in order to take into account risk minimisation?

Due to these reasons HAZMATS routing has become a very active area of research, having attracted the attention of many academic scientists, as confirmed by the great number of papers and by some special issues published on this topic. A review of the most important publications provided by Refs. [1–3] are presented and discussed.

In this paper a new routing methodology, implemented on the computer code OPTIPATH, is presented. The most important features of this new procedure and the contents of the paper are the following. First of all risk indexes suitable for linear risk sources are introduced (Section 2). Then the fact that, as in the case of fixed installations, also in HAZMATS transportation risk criteria have to be taken into account, leads to the definition of a maximum tanker capacity for each network arc (Section 3). Furthermore, each arc is assigned a cost function, which contains both transportation out-of-pocket expenses and the monetary evaluation of the impact on population of an accident (Section 4). The routing problem can thus be formulated as the well known 'minimum cost flow problem', which is a major topic in network optimisation problems (Section 5). Finally test results are presented (Section 6) for the case of a road network and future research developments are suggested (Section 7); conclusions are reported in Section 8.

2. Risk measures for linear risk sources

2.1. Traditional risk indexes

In risk analysis of fixed installations, several risk indexes have been developed; among these the 'individual risk' and the 'societal risk' represented by means of $F(N)$ curves have been especially successful. The individual risk represents the yearly death frequency of an average individual permanently staying without protective devices at a fixed point of the impact area. The $F(N)$ curve, which is a measure of the societal risk, represents the cumulated frequency F of having an accident with N or more fatalities.

These risk indexes can also be extended to linear risk sources with some major computational effort, since the route has to be considered as a sequence of a great number of point risk sources, and the contribution of each of these sources to the total risk has to be evaluated. In Ref. [4], two very efficient procedures, implemented on the computer codes TRANSIN and TRANSOC, for evaluating individual risk and $F(N)$ curves for linear risk sources are presented; these codes can take into account at the same time more transport modalities (truck, rail, pipeline and inland waterways) and more hazardous substances travelling on the same area; the area can be described specifying the meteorological conditions and the wind probability density distribution which characterize it, and very accurately mapping the outdoor and indoor population, both off-route and on-route; furthermore, in each HazMat shipment various sizes of accidental holes and final accident outcomes (each with its probability of occurrence) can be assigned to, and in each network arc a different incident frequency can be given.

In our view, when routing HazMats shipments, a real risk-analysis-based methodology has to be applied; that is, carefully evaluated risk measures, like individual risk and $F(N)$ curves, should be considered due to their powerful and unambiguous meaning. In particular, through the TranSoc code, $F(N)$ curves can be calculated for each network arc; we refer to these curves as the *arc* $F(N)$ curves.

2.2. The 'arc point F′(N) curves'

When considering $F(N)$ curves for linear risk sources some further considerations have to be made, which point out the necessity of introducing risk indexes specific for this risk source tipology.

Suppose that there are two arcs, A and B, going from O to D, with different lengths, B being much longer than A, with identical HazMats shipments, identical release frequencies and passing through areas with identical population densities. The *arc* $F(N)$ curve of B will be higher than the *arc* $F(N)$ curve of A because B is longer than A, meaning, the longer the arc is, the more probable the occurrence of a release will be. As anyone would claim and as confirmed by the *arc* $F(N)$ curves, in order to minimise risk, arc A has to be preferred than arc B. In fact, as it will be explained in Section 4, it is just a function of the *arc* $F(N)$ curve that appears in the arc cost definition and thus contributes to the determination of the optimal route. But if the problem is to travel a fixed distance on the two arcs, it seems rather obvious that travelling this distance on arc A will be as risky as travelling it on arc B.

To voice this concept, an additional risk measure has to be introduced; that is, a measure of the societal risk per unit length, which for definition, will be disengaged from the arc length. For this scope, it is possible to define *arc point* $F'(N)$ curves, which are $F(N)$ curves evaluated for each point of an arc, the risk source being the point they refer to. In this way, each arc is characterised by an *arc* $F(N)$ curve (where the cumulated frequency F is expressed in events yr^{-1}) and by *arc point* $F'(N)$ curves (where the cumulated frequency F' is expressed in events km^{-1} yr^{-1}); by integrating the *arc point* $F'(N)$ curves of all points of an arc on the arc length, the *arc* $F(N)$ curve is obtained. Since the TranSoc procedure evaluates the *arc* $F(N)$ curves through this integration, it calculates the *arc point* $F'(N)$ curves too; thus, with the same procedure both the *arc* $F(N)$ curves and the *arc point* $F'(N)$ curves can be evaluated.

Resorting to the above mentioned arcs, A and B, all their points will have the same *arc point* $F'(N)$ curves, due to the uniformity along the routes of the release frequencies and the population densities, and furthermore these curves will be identical to A and B, thus giving reasons for the fact that travelling a fixed distance on arc A is as risky as travelling it on arc B. More generally, when an arc does not have uniform release

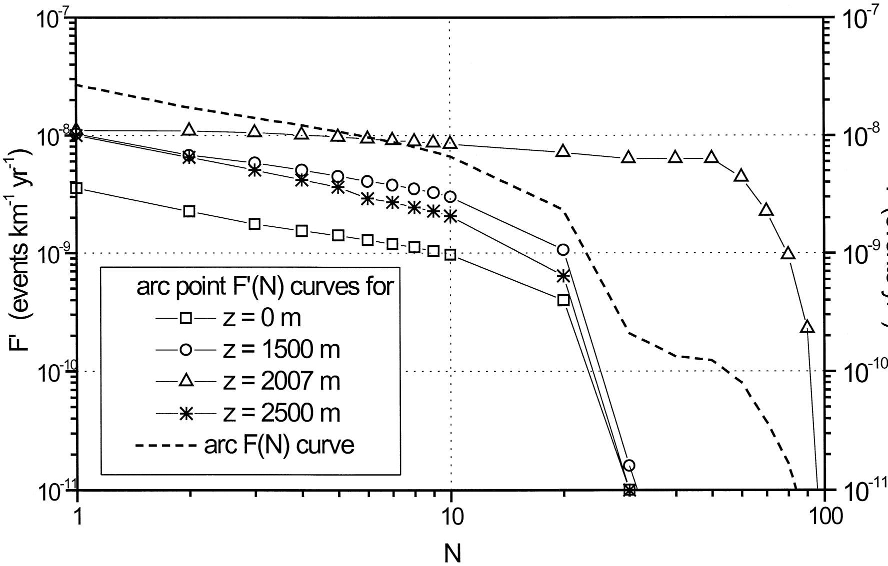

Fig. 1. Some *arc point* $F'(N)$ curves of arc (5,16) for a single ammonia shipment.

frequency and passes through areas with different population densities, each point of it will have a different *arc point* $F'(N)$ curve.

In Fig. 1, the *arc* $F(N)$ curve and some *arc point* $F'(N)$ curves of the arc going from node 5 to 16 of the test case network (Fig. 4) in the case of a single ammonia shipment are reported. In addition, in Fig. 2 the cumulated frequency F' is reported as a

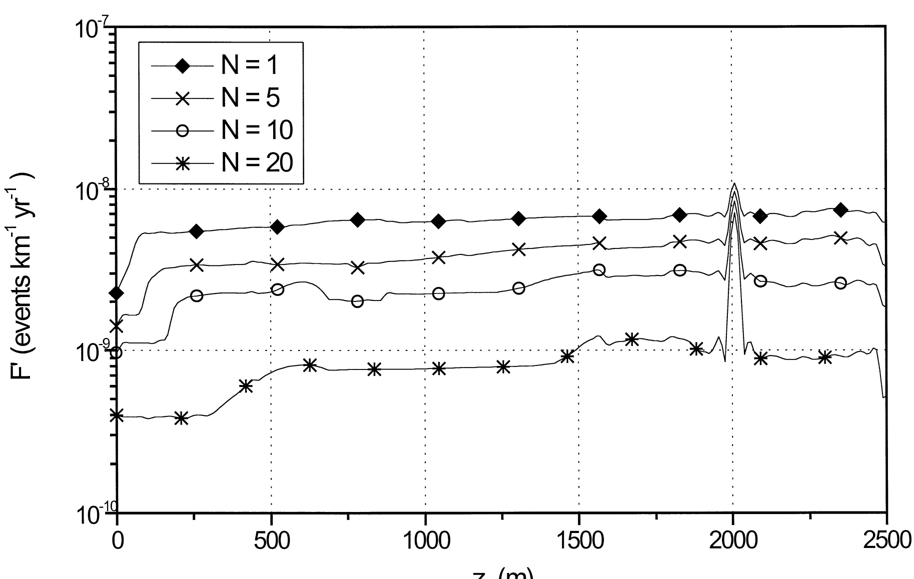

Fig. 2. F' of arc (5,16) for a single ammonia shipment as a function of the curvilinear abscissa z.

function of a curvilinear abscissa z drawn along the arc from node 5 to 16 for some values of N. From Fig. 1 it can immediately be noted that the *arc point* $F'(N)$ curves are not uniform along the arc and that the one corresponding to $z = 2007$ m extends to greater values of N — at identical F' values — than those corresponding to other abscissa values; as a consequence, the *arc* $F(N)$ curve has a shape which is quite different from the shape of the generic *arc point* $F'(N)$ curve and is not a simple translation of it on account of the arc length. The same conclusions can be also derived by examining Fig. 2, where for all values of N, the $F'(z)$ curve has a high peak of $z = 2007$ m, otherwise being near constant.

3. The determination of arc capacities through risk criteria

3.1. Risk criteria for linear risk sources

Once the risk has been evaluated, the question is whether it is acceptable or not, and in order to give an answer, the risk values have to be compared with risk criteria. The Governments of several nations have fixed tolerability values for the risks arising from fixed installations, i.e. for point risk sources, but only few steps have been taken for those deriving from linear risk sources. To our knowledge, only the Dutch Government [5] has fixed general risk criteria for the transportation of hazardous substances; risk limit values have been established both for individual risk and for the societal risk per kilometre of transport route.

Criteria for individual risk can be easily extended from point to linear risk sources: in fact it can be claimed, for instance, that at a point of a geographical area the individual risk must not exceed $1 \cdot 10^{-6}$ events yr^{-1} without knowing if the risk in this point is due to a fixed installation or to a linear risk source.

But when considering criteria on $F(N)$ curves, such an extension is not allowable. In fact, the *arc* $F(N)$ curve being the integral on the arc length of the *arc point* $F'(N)$ curves, it is proportional to an average of them. This means that an arc C with uniform *arc point* $F'(N)$ curves can have the same *arc* $F(N)$ curve of an arc D (having the same length) with some very high *arc point* $F'(N)$ curves, with those of the other points being very low. Due to the properties of the integration procedure, it can happen that a very short route E with high *arc point* $F'(N)$ curves has the same *arc* $F(N)$ curve of a route G, which is very long but has low *arc point* $F'(N)$ curves. From the above examples, it is obvious that when considering linear risk sources, a limit, and thus a tolerability value, has to be fixed not for the *arc* $F(N)$ curve, which represents an averaged value along the whole arc length, but for the societal risk evaluated for a fixed route length corresponding, in the Dutch criteria, to 1 km. This means, in other words, that the limit is established for $F(N)$ curves evaluated for stretches of a 1 km route, which we refer to as the *unitary length* $F(N)$ curves of the arc. These curves can easily be obtained by integrating the *arc point* $F'(N)$ curves along arc stretches of length equal to 1 km; this integration can be performed through the TRANSOC code.

In particular, the Dutch individual risk limit IR_{limit} corresponds to $1 \cdot 10^{-6}$ events yr^{-1}, while the $F(N)$ limit curve is a straight line on a log–log paper passing through the points $(N=10,\ F=1\cdot10^{-4}$ events $\mathrm{yr}^{-1})$ and $(N=100,\ F=1\cdot10^{-6}$ events $\mathrm{yr}^{-1})$; these risk criteria have been used to obtain the results reported in Section 6.

3.2. The '*maximum unitary length F(N) curve*'

For the evaluation of the capacity of an arc it is necessary to define the *maximum unitary length* $F(N)$ curve. In order to do this, the *arc point* $F'(N)$ curves of an arc have to evaluated in the hypothesis of a single shipment travelling on it, which we refer to as to the *virtual tanker*. Integrating these curves over strecthes of 1 km, the *unitary length* $F(N)$ curves are obtained.

If even a single *unitary length* $F(N)$ curve intersects the $F(N)$ *limit* curve, the arc will be considered too dangerous, and the risk of the hazardous substance in examination travelling on it will not be tolerable. Thus the arc has to be excluded from the network and defined as *non-allowable* from the societal risk point of view. On the converse, if all *unitary length* $F(N)$ curves of the arc, evaluated for a single tanker, lay below the $F(N)$ *limit* curve, the arc can be defined as *allowable*, and a *maximum unitary length* $F(N)$ curve can be determined for it.

In order to perform this evaluation, each *unitary length* $F(N)$ curve referring to the stretch v of an arc (i,j) going from node i to node j, i and $j\in M$, $v=1,2,\dots V(i,j)$, is compared with the $F(N)$ *limit* curve by evaluating for each of them a difference $\Delta F_v(i,j)$ resorting to Eq. (1):

$$\Delta F_v(i,j)=\min_N\left\{\frac{F_{\mathrm{limit}}(N)-F_{\mathrm{unitary\,length}}(N)(i,j)_v}{F_{\mathrm{unitary\,length}}(N)(i,j)_v}\right\}. \tag{1}$$

In this way, in each arc (i,j) some $\Delta F_v(i,j)$ are assigned to, each corresponding to a stretch of it with a 1-km length ; the stretch with the minimum $\Delta F_v(i,j)$ is that whose *unitary length* $F(N)$ curve is the *maximum unitary length* $F(N)$ curve of the arc, as shown by Eq. (2):

$$\begin{aligned}\text{max unit. length } F(N)\text{ curve}(i,j) &= \text{unit. length } F(N)\text{ curve}(i,j)_w:\Delta F_w(i,j)\\ &=\min_v\{\Delta F'_v(i,j)\}\end{aligned} \tag{2}$$

Given in Fig. 3 is a graphical representation of how the *maximum unitary length* $F(N)$ curve is determined.

3.3. The '*maximum arc individual risk value*'

Furthermore for the evaluation of the arc capacity, the *maximum arc individual risk value* of the arc $\mathrm{IR}_{\max}$ has to be determined. The *maximum arc individual risk value* for an arc is the maximum value of the individual risk which is produced in a point of the impact area in the hypothesis that a single tanker (the *virtual tanker*) is travelling on the arc in examination, while no tankers are travelling on the other arcs; it will be expressed in events yr^{-1} $\mathrm{vehicle}^{-1}$. It can be easily calculated for each arc through the previously mentioned TRANSIN code.

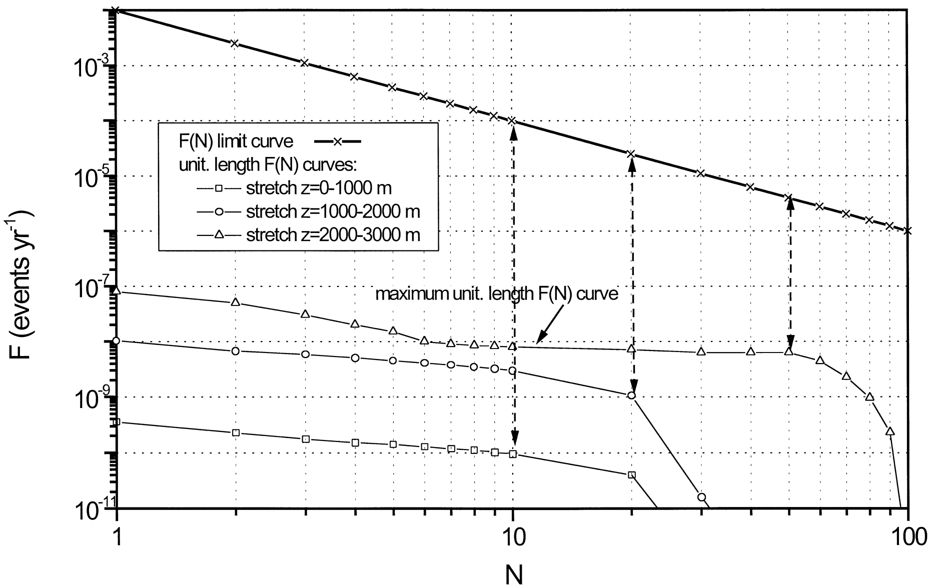

Fig. 3. Determination of the *maximum unitary length* $F(N)$ curve.

If the *maximum arc individual risk value* of an arc is greater than the individual risk limit value, the arc has to be excluded from the network as *non-allowable* from the individual risk point of view, since, from this point of view, not even a single shipment of the hazardous substance in question can travel on it without violating the individual risk limit value.

3.4. The definition of the 'arc capacities'

The definition of the arc capacities is performed for all those arcs which are *allowable* from both the societal and the individual risk point of view, since all arcs which are *non-allowable* from one of the two points of view have to be excluded from the network as non available for the HazMat transport in examination.

It is important to note that for an arc $(i,j) \in A$, the cumulated frequency F of an $F(N)$ curve depends linearly on the number of tankers travelling on it, the ratio defined by Eq. (3):

$$\underset{(i,j)\in A}{N^{F(N)}_{\mathrm{TankMax}}(i,j)} = \min_{N}\left\{\mathrm{INT}\left(\frac{F_{\mathrm{limit}}}{F_{\mathrm{max\,unit.length}(i,j)}}\right)\right\} \tag{3}$$

represents a number of tankers. In particular, it represents the maximum number of tankers $N^{F(N)}_{\mathrm{TankMax}}(i,j)$ which can travel on arc (i,j) without exceeding the societal risk limit, i.e., without bringing any of its *unitary length* $F(N)$ curves to intersect the $F(N)$ limit curve.

At the same manner the individual risk at an area point linearly depends on the number of tankers travelling on each link. Thus the ratio defined by Eq. (4):

$$\underset{(i,j)\in A}{N^{\mathrm{IR}}_{\mathrm{TankMax}}(i,j)} = \mathrm{INT}\left(\frac{\mathrm{IR}_{\mathrm{limit}}}{\mathrm{IR}_{\max(i,j)}}\right) \tag{4}$$

represents a number of tanker, and in particular the number of tankers $N^{\mathrm{IR}}_{\mathrm{TankMax}}(i,j)$ which can travel on arc (i,j), when no other tankers are travelling on the network, without exceeding the individual risk limit in every area point.

The arc capacity for each arc (i,j) can thus be determined by imposing the respect of the most severe risk limit condition, thus resorting to Eq. (5):

$$\underset{(i,j)\in A}{\mathrm{ArcCap}(i,j)} = \min\left\{N^{F(N)}_{\mathrm{TankMax}}(i,j),\, N^{\mathrm{IR}}_{\mathrm{TankMax}}(i,j)\right\} \tag{5}$$

It is important to notice the condition that the number of tankers travelling on each arc has to be less than $N^{\mathrm{IR}}_{\mathrm{TankMax}}(i,j)$ is necessary but not sufficient to ensure that in every area point the individual risk is less than the corresponding limit value. In fact $N^{\mathrm{IR}}_{\mathrm{TankMax}}(i,j)$ is calculated for each arc (i,j) in the hypothesis that no tankers are travelling on the other network arcs; in a real situation it can happen that on arc (i,j) a number of tankers equal to $N^{\mathrm{IR}}_{\mathrm{TankMax}}(i,j)$ is travelling, while on some other arcs shipments are performed, too.

4. The definition of the arc costs

4.1. The necessity of multi-criteria arc costs

Constructing the cost function means fixing the criteria that allow to judge a route, that is to say ‘it is a bad one’ or ‘it is a good one’ or ‘it is the best one’. Obviously these criteria strongly depend on the interests a category has in the transport of a dangerous good. For example, for truck drivers the best route will be that with the minimum travel time; for people whose house is next to a road the best route will probably be another road than that near which they are living; for the truck tanker company the best route will be the less expensive one; finally for public authorities the interest is focused on the prevention of accidents to persons and damage to property by means of laws which have to regulate the movement of HAZMATS without impeding it.

Results reported in Ref. [6] show, if the minimisation of risk is the sole criterion, that routes obtained are more than twice as long as the fastest alternative and so not feasible for financial reasons. This means that multi-criteria routing models have to be used and in fact in several literature papers (see, for instance, Refs. [6–9]) different criteria have been combined, like travel time, shipment distance, accident frequency, population exposure, simplified risk measures, damage to property, on-site arrival time of emergency response units. In some cases the various objectives have been added, after combining them with weight factors whose values reflect the relative importance of each criterion; while in others they have been converted into constraints, after arbitrarily establishing threshold values for each of them. The weak point of these approaches to the routing problem consists in fixing the values of the weight factors or the thresholds;

in fact, calculations have shown that different weights (or different threshold values) can produce different optimal routes, highlighting that the determination of the optimal path is strongly dependent on the decision-maker, who has to fix the value of weights and thresholds.

4.2. The definition of the arc costs

In our view a more objective approach is needed in combining conflicting strategies, and a way to obtain this is to express each in monetary terms, so that the arc cost becomes a simple sum of costs, without any weight values to be fixed. Basically there are two cost items, between which a conflict exists: 'truck operating costs' (out-of-pocket expenses) and 'risk-related costs'. In literature, truck operating costs per shipment per unit length TOC are reported: by multiplying them by an arc length the truck operating cost on this arc is obtained for a single tanker. Risk costs of an arc $(i,j) \in A$ are given by the product of the human life value HLV, also available in literature, and the 'yearly expected number of fatalities' $E(i,j)$ on this arc, which is a function of the *arc* $f(N)$ curve for a single tanker, where f is the non-cumulated frequency, as shown by Eq. (6):

$$\underset{(i,j)\in A}{E(i,j)} = \sum_{k=1}^{N_{\max}} f_{N_k}(i,j)\, N_k \tag{6}$$

Once the *arc* $F(N)$ curve of an arc is known, since F is the cumulated function of f, the *arc* $f(N)$ curve can easily be determined.

The total arc cost $\mathrm{TAC}(i,j)$ of a generic arc (i,j) of length $L(i,j)$ for a single tanker is given by the sum of the truck operating cost and the risk-related cost per shipment on that arc, as shown by Eq. (7):

$$\underset{(i,j)\in A}{\mathrm{TAC}(i,j)} = \mathrm{TOC}\ L(i,j) + \mathrm{HLV}\ E(i,j) \tag{7}$$

In this way, out-of-pocket expenses being part of the arc cost, the optimal routes should be avoided to be too circuitous and thus financially infeasible. In fact origin/destination paths, which are very long, surely have high total arc costs due to their high out-of-pocket expenses and thus will not be selected by the optimisation procedure; on the other hand, very risky routes will have high total arc costs due to their high risk-related costs, and thus will not become part of the optimal route.

Cost figures for the truck operating expenses TOC per unit length and unit vehicle and the human life value HLV have been taken from Ref. [8], being equal, respectively, to 0.86 Canadian\$ km^{-1} vehicle^{-1} and to 617 190 Canadian\$ fatality^{-1}.

5. The OptiPath optimisation procedure

5.1. The formulation of the routing problem

At this point, the routing problem can be formulated as follows. Let $G = (M, A)$ be a directed road network, with M the set of nodes, $|M| = m$, and A the set of arcs; let each arc (i,j) of A directed from node i to node j have an associated arc cost per unit tanker $\mathrm{TAC}(i,j)$, and an arc capacity $\mathrm{ArcCap}(i,j)$; let each node i of M having an associated integer number $b(i)$ representing its tankers' supply or demand, so that $b(i) > 0$ for the supply nodes, $b(i) < 0$ for the demand nodes and $b(i) = 0$ for the other nodes (obviously it must be: $\sum_{i=1}^{m} b(i) = 0$). Let $\mathrm{Tank}(i,j)$ represent the number of tankers travelling on arc $(i,j) \in A$, thus the set $\{\mathrm{Tank}(i,j), (i,j) \in A\}$ being a *flow* on the network. The optimisation procedure can be formulated through Eqs. (8)–(10) as follows:

$$\text{minimize} \sum_{(i,j) \in A} \mathrm{Tank}(i,j)\mathrm{TAC}(i,j) \tag{8}$$

subject to the mass balance constrain and the arc capacity constrain, respectively stated in Eqs. (9) and (10):

$$\sum_{(j:(i,j) \in A)} \mathrm{Tank}(i,j) - \sum_{(j:(j,i) \in A)} \mathrm{Tank}(j,i) = b(i) \text{ for all } i \in M \tag{9}$$

$$0 \le \mathrm{Tank}(i,j) \le \mathrm{ArcCap}(i,j) \text{ for all } (i,j) \in A \tag{10}$$

This problem is the well known 'minimum cost flow problem', which is a central object in the field of network flows optimisation. Many efficient algorithms have been proposed for the solution of this problem, among which is the 'successive shortest path algorithm', which has been included in the OPTIPATH procedure. The solution given by this algorithm is an exact one, that is it really represent the optimal flow distribution on the network. More details about this algorithm can be found in Ref. [10].

It is necessary to note that the 'minimum cost flow problem' models the flow of a single commodity over the network. The term 'commodity' means a single substance which has to be shipped from a set of origin nodes $\{O_1, O_2, \ldots O_{\mathrm{No}},\}$ to a set of destination nodes $\{D_1, D_2, \ldots D_{\mathrm{Nd}},\}$ in the case where there is no pairing between origin and destination nodes, i.e., being indifferent, once the tanker demand of each destination node D is satisfied, from which origin nodes the tankers satisfying this demand left. If, in the case of a single substance, the supply of each origin node has to be sent to a specific destination node (that is the origin/destination nodes are paired), or if more substances have to be distributed on the network, the optimisation problem is no more a 'minimum cost flow problem', but becomes a 'multicommodity flow problem'.

5.2. *The OPTIPATH procedure*

The optimisation procedure introduced step by step in the past sections has been implemented on the computer code OPTIPATH, whose main characteristics are now explained.

(a) For each arc (i,j) the *arc point* $F'(N)$ curves are calculated through the code TRANSOC in the hypothesis of a single tanker travelling on it; they are integrated first along arc stretches of a 1-km length to obtain the *unitary length* $F(N)$ curves of the arc, and then along the whole arc length to obtain the *arc* $F(N)$ curve.

(b) For each arc (i,j) the *maximum arc individual risk* is calculated through the code TRANSIN in the hypothesis of a single tanker travelling on it, zero being the flux on the other arcs.

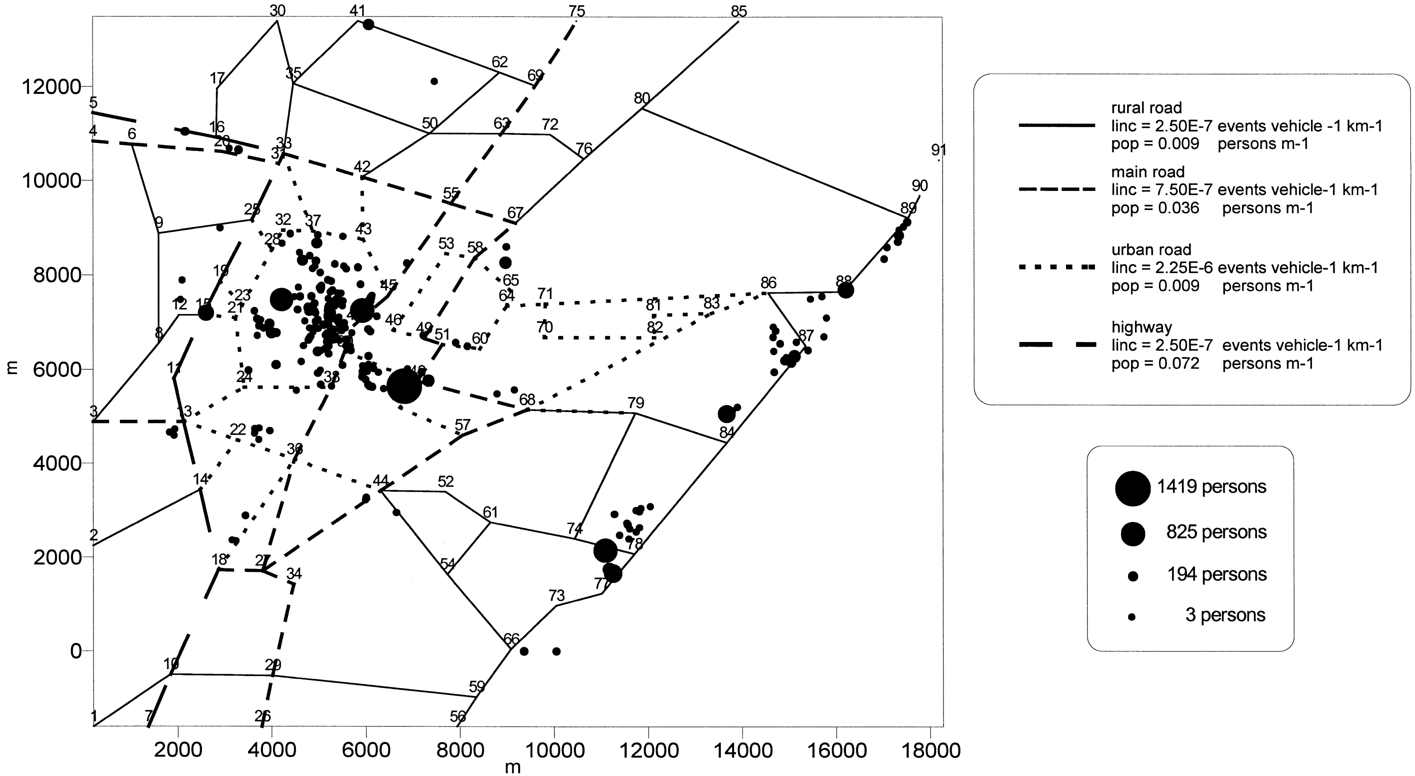

Fig. 4. Test area: routes characterization and centres of aggregated population (schools, hospitals, commercial centres etc.).

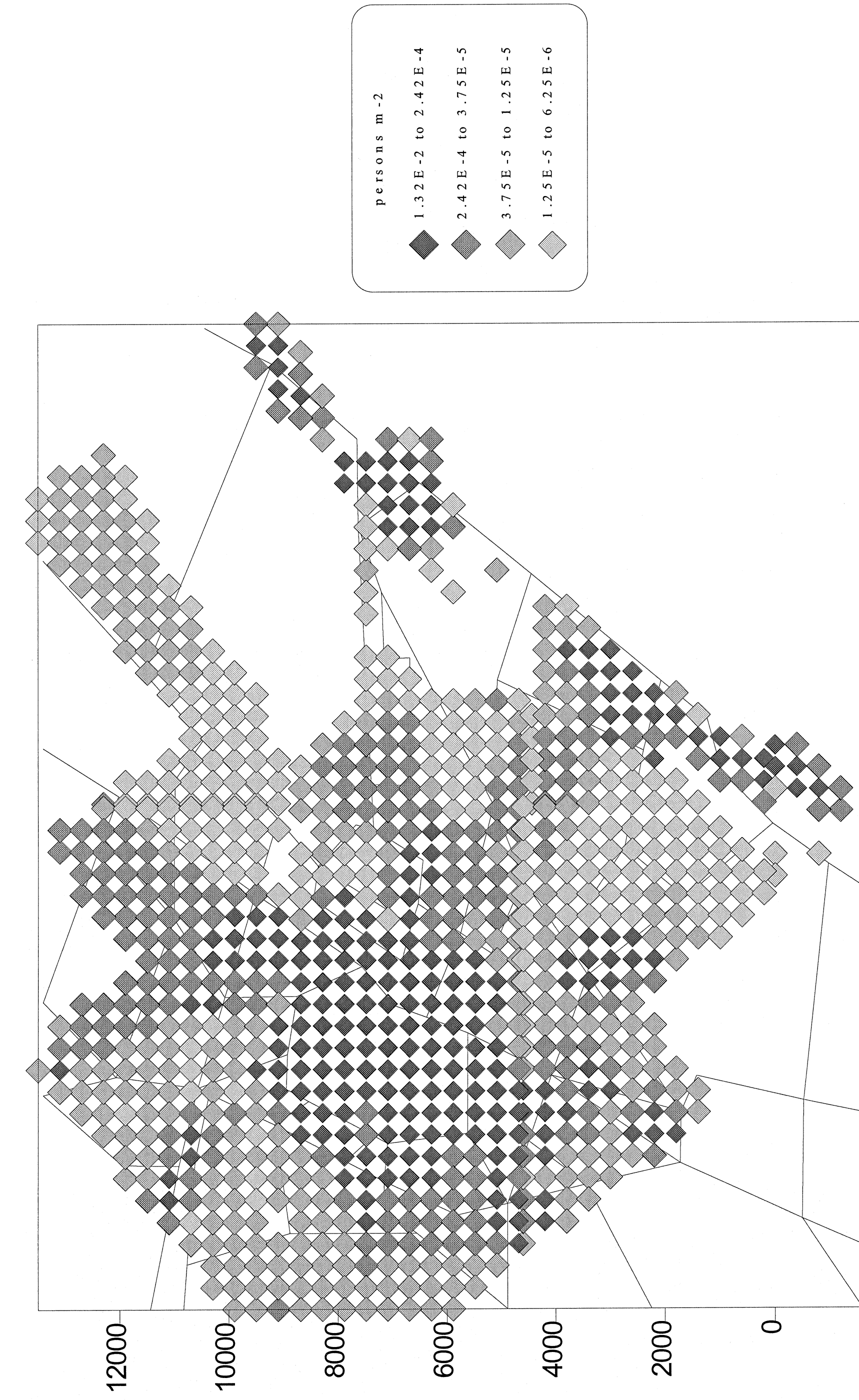

Fig. 5. Test area: description of the residential population.

(c) All arcs which have at least one *unitary length* $F(N)$ curve intersecting the $F(N)$ *limit* curve or whose *maximum arc individual risk* exceeds the individual risk limit are excluded from the network as *non-allowable*.

(d) For each *allowable* arc (i,j) the *maximum unitary length* $F(N)$ curve is found. Then each *maximum unitary length* $F(N)$ curve is compared whit the $F(N)$ *limit* curve, determining for each arc (i,j) the maximum tanker capacity with respect to the societal risk limit $N^{F(N)}_{\mathrm{TankMax}}(i,j)$; furthermore, through the *maximum individual risk* and the *individual risk limit*, the maximum tanker capacity with respect to the individual risk $N^{\mathrm{IR}}_{\mathrm{TankMax}}(i,j)$ is found. By comparison of these two maximum tanker capacities for each arc, the arc capacities ArcCap(i,j) are determined.

(e) Through the *arc* $F(N)$ curves, the truck operating cost per unit length and unit tanker, the arc length and the human life value, the arc cost TAC(i,j) is calculated for each arc.

(f) Through the ‘successive shortest path algorithm’, which requires as input the arc capacity ArcCap(i,j) and the arc cost TAC(i,j) for each arc $(i,j) \in A$, the optimal flow on the network $\{\mathrm{Tank}(i,j), (i,j) \in A\}$ is found.

6. Test results

In order to test the OPTIPATH procedure and to show its power, calculations have been performed on an hypothetical case study area, which is shown in Figs. 4 and 5, on which

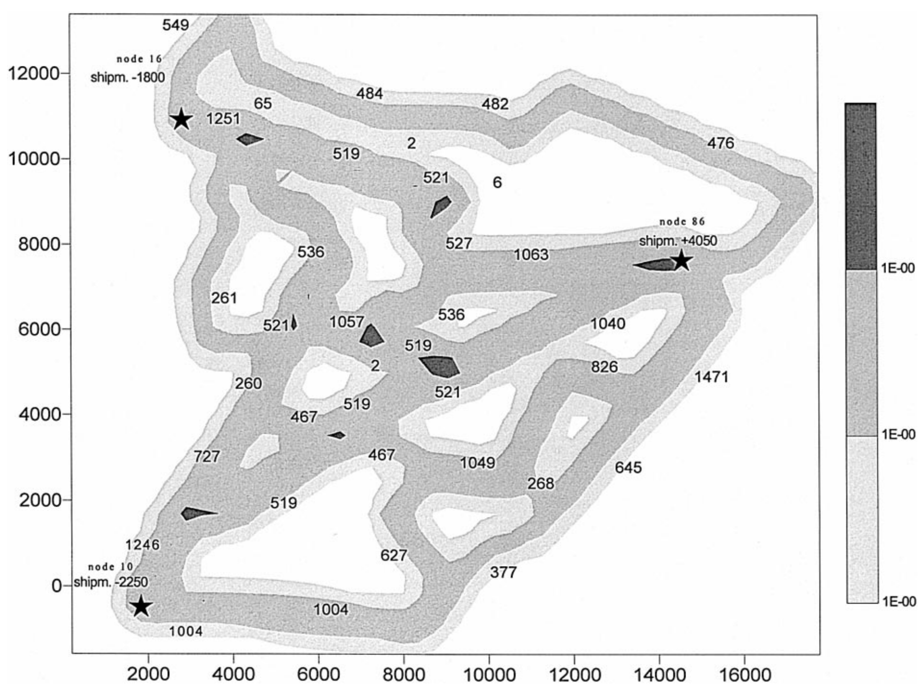

Fig. 6. ‘Optimal flow’ for ammonia shipments and individual risk mapping.

ammonia has to be shipped from node 86 (whose supply is $+4050$ vehicles yr^{-1}) to nodes 10 and 16 (whose demands are equal, respectively, to -2250 and -1800 vehicles yr^{-1}).

In Figs. 6–8 the 'optimal flow', the 'practical flow' and the 'uncapacitated minrisk flow' distributions are shown; the first one is that produced by the OPTIPATH procedure, minimising the sum of the truck operating costs and the risk-related costs on the capacitated network; the second and the third one minimise only truck operating costs and only risk-related costs on the uncapacitated network, respectively. The 'practical flow' distribution represents the one which would be chosen by the transportation company in absence of any risk-related routing policy; instead the 'uncapacitated minrisk flow' is the one which minimises only risk without taking into account risk criteria.

As it can be seen, the 'optimal flow' distribution violates the individual risk limit value in a few zones near the optimal routes. In fact, as previously stated in Section 3.4, the respect of the arc capacities, which for ammonia are equal — for the majority of arcs — to the maximum number of tankers with respect to the individual risk limit value, is only necessary and not also sufficient to ensure compliance with the individual risk limit value everywhere. The 'practical flow' violates the individual risk limit value along the whole routes joining the origin with each destination node. Eventually the 'uncapacitated minrisk flow' violates too the individual risk limit value along nearly the

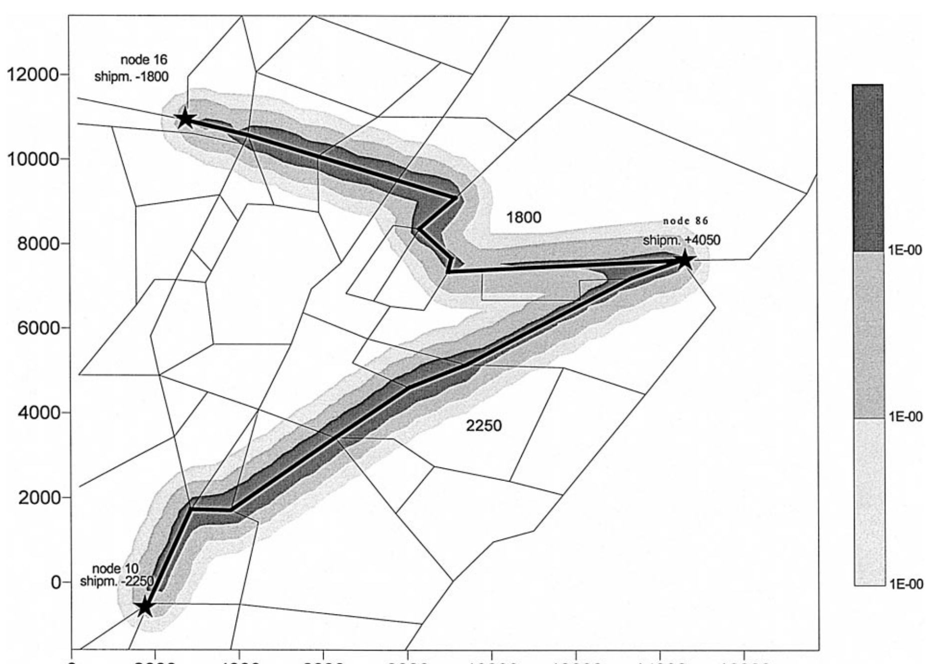

Fig. 7. 'Practical flow' for ammonia shipments and individual risk mapping.

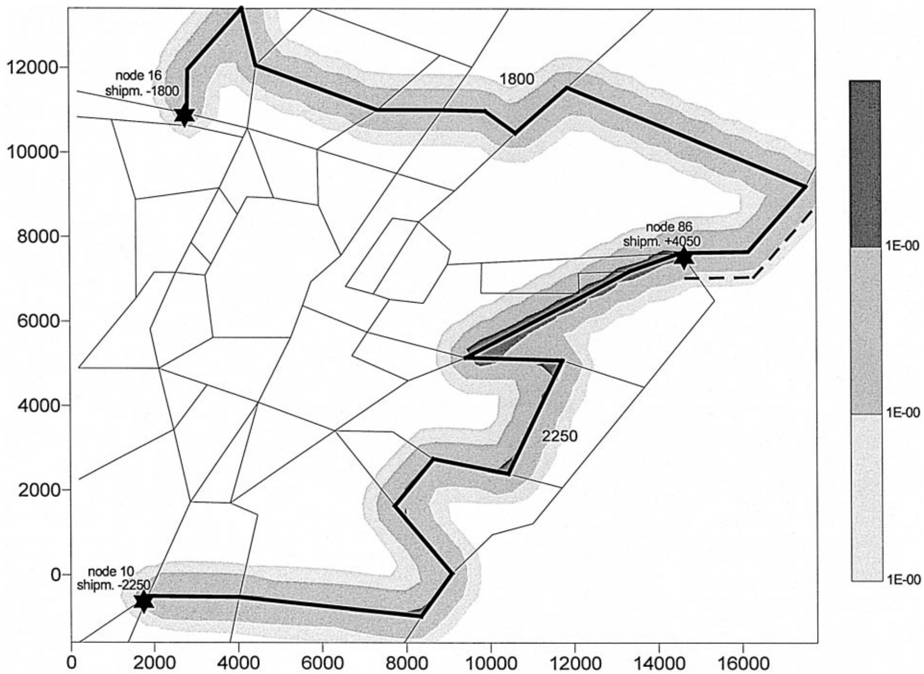

Fig. 8. ‘Uncapacitated minrisk flow’ for ammonia shipments and individual risk mapping.

whole path from node 86 to 10, while along some arcs on the path from node 86 to 16 (evidenced through the dotted line) the societal risk limit is likewise violated.

Fig. 9 shows the points corresponding to the various routing policies plotted on a Cartesian plane, reporting the risk-related costs in abscissa and the out-of-pocket expenses in ordinate (both expressed in Canadian\$ yr^{-1}). The ‘uncapacitated minrisk flow’ is that with the higher out-of-pocket expenses, since these costs do not enter the definition of the arc costs; on the other hand, the ‘practical flow’ has the minimum value of the out-of-pocket expenses and the highest risk-related costs, since the object of this policy is to minimise out-of-pocket expenses ignoring risk in the definition of both capacities and costs. Eventually the ‘optimal flow’, which minimises simultaneously out-of-pocket expenses and risk-related costs, has both cost values which are in the middle of the ranges defined, for each cost typology, by the ‘uncapacitated minrisk flow’ and the ‘practical flow’ policies.

The increment of the out-of-pocket expenses for the ‘optimal flow’ with respect to the ‘practical flow’ is about 23.0%; the increment of the out-of-pocket expenses for the ‘uncapacitated minrisk flow’ with respect to those of the ‘practical flow’ is 52.8%. This percentage increment with respect to the ‘practical flow’ policy is greater for the ‘uncapacitated minrisk flow’ than for the ‘optimal flow’ criterion: this is justified by the fact that the ‘optimal flow’ policy includes out-of-pocket expenses in the definition of the arc costs, while the ‘uncapacitated minrisk flow’ policy does not. It is rather obvious

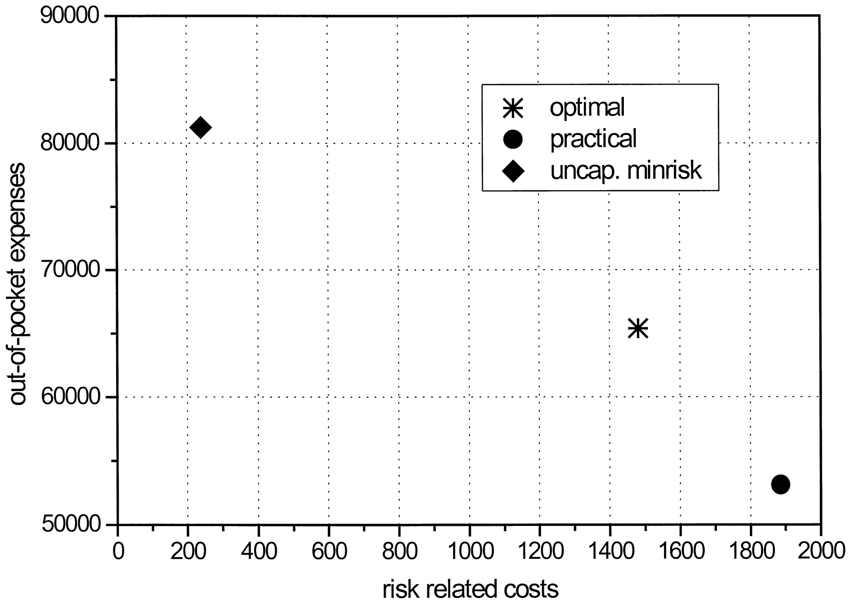

Fig. 9. Out-of-pocket expenses and risk related costs of different routing policies for ammonia.

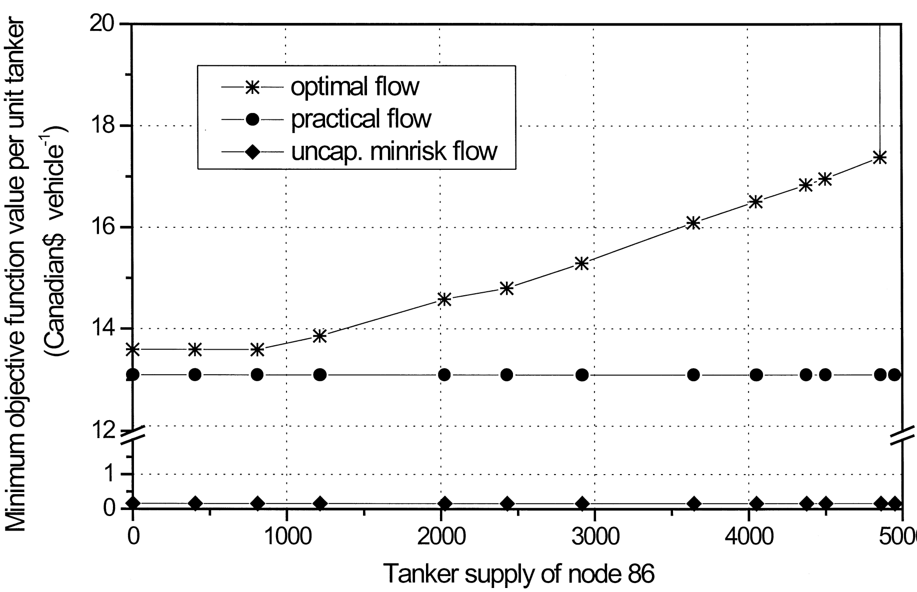

Fig. 10. Minimum objective function values per unit tanker of different routing policies as a function of the supply of node 86 for ammonia.

for a risk-based optimisation procedure to produce a flow with higher out-of-pocket expenses than those of the flow distribution which would be chosen by the trucker company when not taking risk into account. This increment is somewhat limited in the case of the 'optimal flow' distribution, since this flow takes into account the feasibility of the flow from a financial point of view; the increment, which more than doubled with respect to that of the 'optimal flow', is very high when ignoring the point of view of the trucker company.

Finally, it is important to note that since the 'optimal flow' refers to a capacitated network, the minimum — and thus optimal — value of the objective function divided for the total number of shipments to be performed depends on the supply of one of the origin nodes (in the hypothesis that the ratio $b(i)/b(j)$ remains constant for all pairs $(i,j) \in A$), and in particular it increases with the supply of this node; on the contrary, this figure is independent from the number of shipments for both the 'practical' and the 'uncapacitated minrisk flow', since they refer to an uncapacitated network. In Fig. 10 the minimum objective function values per unit tanker for the different flow policies are shown as a function of the supply of node 86; conventionally it is assumed that the objective function is infinite if the flow becomes infeasible, meaning the network is saturated.

7. Further research developments

The scope of the implementations presented in this section is to lead to a technique which can solve real case routing problems; in fact a real case routing problem differs somewhat from the case study routing problem solved by OptiPath because of the following points.

(a) Generally accident consequences are not limited to fatalities only, but comprise non-fatal damage to population, damage to property and damage to the environment. This means that all risk-related costs, beyond the cost of fatalities, have to be taken into account in the definition of the arc cost function.

(b) A real case optimisation procedure has to ensure that the optimal flow is in full compliance with risk criteria for both societal and individual risk.

(c) In real case networks shipments of a single substance have to be distributed between different origin/destination pairs (belonging, for instance, each origin/destination pair to a different company) or, more generally, different substances have to be distributed between different origin/destination pairs.

Future research developments will ensure implementations of the OptiPath routing methodology in order to take into account all risk-related costs (as explained at point (a)) and to solve real case routing problems as those stated at points (b) and (c).

8. Conclusions

In this paper a procedure has been extensively explained through which a solution to the HazMats routing problem in the case of a single substance can be found; the whole procedure has been implemented on the computer code OptiPath. This procedure involves the calculation of risk indexes suitable for linear risk sources; through these risk measures, imposing the compliance with risk criteria, arc capacities can be defined; furthermore an arc cost definition which takes into account both out-of-pocket expenses and societal-risk-related costs is introduced. The routing problem can thus be formulated as a ‘minimum cost flow problem’. Eventually test results have been presented and discussed and further research developments have been proposed.

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