# Evaluation of reliable path in risk areas

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## Abstract

The reliability of a system can be defined as the capability to work properly, within a certain period of time and in the predicted conditions. For a transportation system, this can be represented, in normal conditions, as the possibility to connect each other to the several origins and destinations of displacements and, in emergency conditions, as the guarantee that links are able to bear stresses and flows due to evacuation avoiding congested situations. Starting from this background, a problem that arises, principally in planning evacuation and/or coming to aid to population, is to define paths that also take into account the potential vulnerability of links, using those algorithms and procedures commonly adopted in planning operation tools. In order to give a contribution on this particular aspect, in this paper an analytical procedure is presented to define link costs that can be adopted within the commonly used path generation algorithms in order to take into account the potential vulnerability of part of the network. In particular a modification in the formulation of commonly used link cost functions is suggested in order to take into account the environmental condition of each link so that the conventional path search algorithms adopted in commercial software can be used. Furthermore, results of applications to a test network are reported.
*Keywords: network reliability, vulnerability.*

## 1 Introduction

A large amount of studies concerning vulnerability of single structures can be found in literature, whilst more rarely such studies concern vulnerability of either transportation or territorial systems.

Aims of a vulnerability reduction policy are to favourite emergency management in order to guarantee timely aids to victims and an orderly and


doi:10.2495/RISK060351

gradual evacuation of population, taking care in avoiding congestion phenomena on links. As a matter of fact interventions to reduce vulnerability of a transportation system allow not only to enhance the capacity to evacuate a certain area, if a hazardous event occurs, but also to reduce those accessibility problem that can occur in certain settlements.

Reliability of a system can be defined as the capability to work properly, within a certain period of time and in the predicted conditions. This, for a transportation system, can be represented, in normal conditions, as the possibility to connect each other the several origins and destinations of displacements and, in emergency conditions, as the guarantee that links are able to bear stresses and flows due to evacuation avoiding congested situations.

An increase in the interest in road network reliability by scientific community can be observed since 1990s. In particular, after the seismic event of Kobe in 1995, a significant interest has been concentrated in those aspects concerning reliability of transportation network.

Several definitions and classifications of reliability have been proposed in literature [1]. A first classification of the studies conducted on transportation network reliability can be done between those methodologies considering only supply system and those ones that take into account also interaction between demand and supply.

Within the first case it is possible to distinguish two aspects: in the first one, concerning connectivity reliability [2], [3], analytical procedures are proposed to individuate reliability of connections; moreover D'Este and Taylor [4] suggest some indicators to evaluate weakness points of a network. The second one take into account capacity reliability [5], [6] defined as the probability that a network, whose state may be normal or degraded, is able to satisfy a certain level of demand that is can accept a fixed traffic volume. This probability is defined by Chen et al. [5] as the probability that residual capacity of a network results, once fixed the capacity loss due to degradation, greater than or equal to the required demand.

In the latter case reliability of travel times has been considered, defined as the probability that a journey between an origin-destination pair is concluded within a definite time interval [2]. To evaluate travel time reliability several measure methodologies have been proposed [7], [8].

Starting from this background, a problem that arises, especially in planning evacuation and/or coming to aid to population, is to define paths that take also into account of potential vulnerability of links, using those algorithms and procedures commonly adopted in planning operation tools.

In this paper some developments and applications concerning an analytical procedure to define link costs that can be adopted within the commonly used path generation algorithms, recently proposed by the author [9] are presented.

## 2 Proposed approach

In case of evacuation of a risk area, path evaluation should take into account of the different level of risk that can be related to each arc of the network in order to select, within a set of effective paths, those ones that make smaller the level of risk. This can be done by means of a modification in the evaluation of costs [9] so that conventional path search algorithms adopted in commercial software can be used.

Let G(N, L) be a graph representing a transportation network with {N} representing the set of nodes and {L} the set of links; a *risk level* (a probability value) $r_i \in [0,1]$ can be associated to each link i $\in$ {L} depending on the vulnerability of the link respect to the hazardous phenomenon taken into consideration.

Considering a path $p$ connecting an Origin/Destination pair, risk (probability) connected to the path, under the hypothesis of independence among links, can be expressed as come $R_p = \Pi_{i \in p}\, r_i$. Introducing a *safety probability* $s_i$ defined as $s_i = 1 - r_i$, the evaluation of minimum risk paths can be carried out by using common techniques of path search considering as link cost the value $c_i = \ln(1/s_i)$.

To consider not only risk but also generalized costs in determining paths connecting Origin/Destination pairs, it is possible to define, for each link, a cost function given by the generalized transportation cost (i.e. an homogeneous combination of time, distance and monetary cost) weighted by means of the level of risk associated to the link. Assuming that, in the case here considered, the role of risk can be associated similarly to the one played by saturation level in congested networks, the relationship between the here introduced weighted link cost and the traditional generalized transportation link cost can be written as follows:

$$Cw_i = Cg_i \cdot \{ 1 + \alpha[\ln(1/s_i)]^{\beta} \} \tag{1}$$

where:

$Cw_i$ is the weighted link cost associated to link i;
$Cg_i$ is the generalized transportation cost of link i;
$s_i$ is the above defined *safety probability*;
$\alpha,\beta$ are parameters to be calibrated.

In particular, parameter $\alpha$ can be used to take into account of the nature of the hazard (i.e. in case of pollutant, for the same risk level, effects potentially produced depend on the type of contaminant).

Once introduced this modified cost, an assignment procedure is performed in order to evaluate paths followed to connect the Origin/Destination pairs. In the approach here followed, the computation of paths is performed introducing probabilistic path choice models and, in particular, C-Logit formulation proposed by Cascetta et al. [10]. In such approach path choice is based on the mathematical framework of a multinomial Logit model with a modification in systematic utility given by:

$$V^*_k = V_k - CF_k \tag{2}$$

where $CF_k$, defined as *commonality factor* of path $k$, takes into account of the overlapping of path $k$ with all the other paths belonging to the set $K_{od}$ connecting the o/d pair $od$. In particular, considering the D-C-Logit model developed by

Russo and Vitetta [11], for each link *i* crossed by effective paths connecting the o/d pair od it is possible to evaluate link choice probability as:

$$p_{i,od} = w_{i,od} \,/\, \Sigma_{j\in B(i)}\, w_{j,od} \tag{3}$$

where $w_{j,od}$ represents the link weight, depending on the considered pair *od* and *B(i)* represents the set of the links entering the final nodes of link *i*. In order to determine such weight, the link multiplicity $N_{j,od}$ of link *i* respect pair *od* is defined, it indicates the number of paths crossing link *i* that connect o/d pair *od*.

## 3 Sample application

An application to a test network has been conducted in order to check the proposed approach. The network is shown in Figure 1 where all the links are considered two-ways and a value of risk level has been associated to each one of them. For a better intelligibility, labels indicating node numbers are not reported in the figure. The main hypothesis is that an event has occurred in the highlighted node 26 (i.e. fire) and there is the necessity to evacuate zones corresponding to nodes 101, 103 and 105 since can be interested by the evolution of the event but, due to wind, a plume. In order to better test the proposed cost model, destination have been chosen so that generated paths cross the interested area; Origin/Destination pairs 101-106; 103-104 and 105-102 have been considered in path evaluation and links with risk level greater than zero are listed in Table 1.

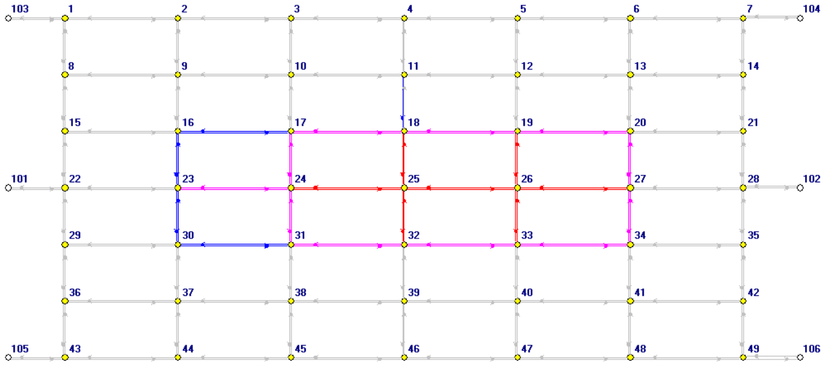


Figure 1: Test network and associated values of risk level.

The aim of this application is to show how the introduction of the weighted cost model here described in a generic path choice model yields to paths that restrict the use of the more vulnerable links.

For this purpose, a set of random value of generalized transportation sampled from a normal distribution having a mean cost value $\mu$ = 10 and with a variation coefficient $Cv$ = 0.1 (where $Cv = \sigma/\mu$) has been considered for the whole set of links and the above described D-C-Logit assignment procedure has been used to evaluate path connecting the above described Origin/Destination pairs. The demand value assumed for each O/D pair has been considered equal to 100 so that flow resulting from the assignment of each pair can be considered as the choice probability of each link.

A first assignment procedure has been performed considering only the transportation cost ($\alpha$ = 0); links belonging to the sets of paths of each O/D pair are shown in Fig.2, where the thickness of each link is proportional to the link choice probability. As expected, all the links with a risk level greater than 0 are interested by the evaluated paths since they belongs to the more suitable paths connecting the considered O/D pair.

Table 1: Links having risk level greater than zero.

| $r_i$ | Links |
|---|---|
| 0.30 | 16-17; 17-16; 16-23; 23-16; 23-30; 30-23; 30-31; 31-30 |
| 0.50 | 17-18; 18-17; 18-19; 19-18; 19-20; 20-19; 23-24; 24-23; 31-32; 32-31; 32-33; 33-32; 33-34; 34-33; 17-24; 24-17; 24-31;31-24; 20-27; 27-20; 27-34;34-27 |
| 0.80 | 24-25; 25-24; 25-26; 26-25; 26-27; 27-26; 18-25; 25-18; 25-32;32-25; 19-26; 26-19; 26-33; 33-26 |

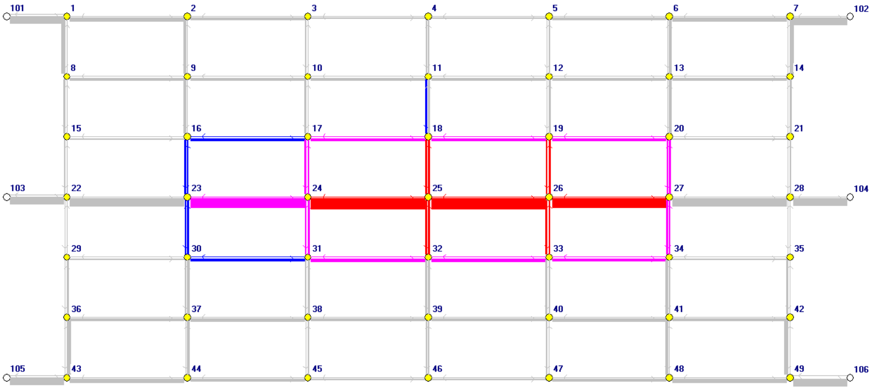


Figure 2: Flows obtained using generalized transportation link cost.

In a following assignment procedure the application of the weighted link cost has been performed by considering values of $\alpha$ = 3 and $\beta$ = 4, values that represent a good compromise, as shown in [9]. As it is shown in Fig. 3, choice probabilities of those links close to the location of the hypothetic event vary significantly, and it can be seen that only a subset of the links with a risk level greater than 0 are interested by the evacuation paths.

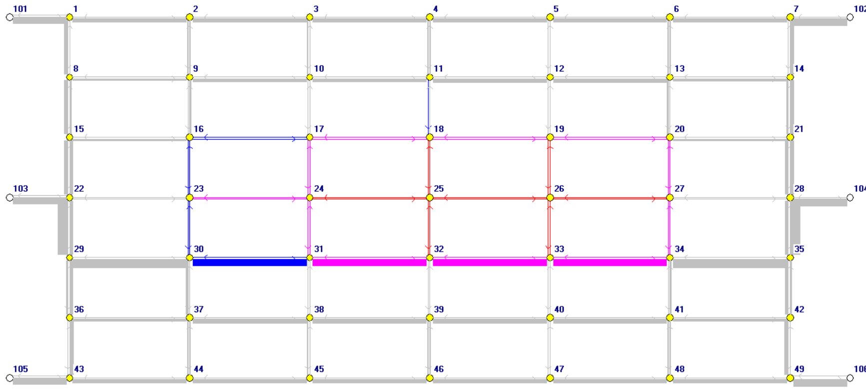

Figure 3: Flows obtained using weighted link cost.

# 4 Concluding remarks

In this paper it is presented an analytical procedure to define link costs taking into account of risk level that can be adopted within the path choice models normally used in the most common assignment procedures. Such method has been developed in order to take into account of potential vulnerability of part of the network in case of hazardous events. Results obtained from the applications to a test network are encouraging and show the effectiveness of the proposed method. The proposed method can be used in those cases where the hazardous event, either industrial or natural, can generate dangerous indirect effects (i.e. moving toxic plumes, landslides generated by flood) on the networks. More deep investigations, in particular on the functional form of cost function and in the role assumed by risk within this context, are in progress.

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