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Transportation Research Procedia 5 (2015) 221 – 232

Transportation Research Procedia

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SIDT Scientific Seminar 2013

Ranking links in a road transport network: a practical method for the calculation of link importance

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Abstract

This paper deals with the issue of road network vulnerability and describes the implementation of a methodology which ranks the links of a network according to their importance for maintaining a proper connectivity between all origin-destination pairs. Such a ranking can be easily used by practitioners and decision-makers for prioritising maintenance investments along the links of a road transport network.

In this regard, following a conceptual approach well consolidated in transport literature, vulnerability is assumed to be related to the concept of importance, i.e. a measure of the consequences of the collapse of a network's element.

In the present study, the definition of importance – with respect to a given link –simultaneously includes two aspects: the level of usage, i.e. how many people typically use the link for their trips, and the impact that the closure of the link itself can have on the general functionality of the network as a whole. These two aspects are considered in the link importance index formulation, as two different functions that can be properly weighted by means of different coefficients.

The methodology proposed has been implemented in the framework of Paramount EU project, to obtain a ranking of importance for the links of a real-scale network, i.e. the road network of Bolzano, a highly mountainous province located in the Italian Alps. The application of the methodology led to satisfactory results represented by a ranking of links, in decreasing order importance scores. Furthermore, Spearman's rank correlation coefficient has been used to quantify the variation of the importance ranking caused by the variation of its coefficients.

Peer-review under responsibility of the Società Italiana dei Docenti di Trasporti (SIDT).

Keywords: link importance; link disruption; generalized trip cost; Spearman correlation coefficient

1. Introduction

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Peer-review under responsibility of the Società Italiana dei Docenti di Trasporti (SIDT).
doi:10.1016/j.trpro.2015.01.003

Serious lack of funds in infrastructure maintenance is forcing national, regional and local governments to carefully prioritizing their interventions. Therefore reliable quantitative tools are needed to help decision-makers in choosing their interventions for maintaining, repairing and extending infrastructure segments, so that the allocation of available resources is optimized.

This paper proposes and discusses the implementation of a methodology which ranks the links of a network according to their importance for maintaining a proper connection between all origin-destination pairs. To measure such importance a new index is proposed, which is given by the weighted sum of two contributions that account for both link importance within a road network. Local importance is related to the level of usage of a link, while global importance is related to the consequences on the entire network after the total closure of a Calibration coefficients have been introduced in the link importance formulation, thus allowing analyst to calibrate them accordingly to the specific context. Moreover, an evaluation of the sensitivity of the importance index with respect to its calibration parameters has been carried out. This analysis calls for the computation of the Spearman's rank correlation coefficient for the importance rankings, for different values of the calibration coefficients.

The proposed methodology has been tested on a real-scale network, that of the territory administrated by Bolzano, in the Italian Alps. However, this methodology may be applied for practical purposes in other contexts. Results can be particularly helpful for prioritising ordinary and extraordinary maintenance investments to be planned along the links of a road transport network.

This paper is organized as follows: in Section 2 an overview of the methodological framework developed for measuring link importance and determining importance rank is presented. In section 3, our methodological approach and the indicators of link importance are presented. In Section 4 the Spearman's rank correlation coefficient is discussed. Section 5 describes the main features of the case study to which the methodology has been applied and results. Conclusions are presented in Section 6.

2. Conceptual framework

To this day, a widely accepted definition of vulnerability has not been established (Berdica, 2002; D'Este and Taylor, 2003, Knoop et al., 2008, Taylor and Susilawati, 2012,): to numerous definitions present in literature correspond numerous methodologies and indicators which try to describe and quantify the consequences of hazardous events (such as debris-flows, avalanches, rock-falls, car-accidents or even natural disasters or terrorist attacks) or, more generally, of disturbances, in terms of functionality of a transport network. These disturbances occur with a certain probability and have as primary effects a link capacity reduction and/or a variation in demand (Snelder et al., 2012).

Among the first studies on transport network vulnerability are those of Berdica (2002) and D'Este and Taylor (2003). Berdica defines ''vulnerability'' as ''a susceptibility to incidents that can result in considerable reductions in road network serviceability'', where serviceability of a link/route/road network is interpreted as "the possibility to use that link/route/road network during a given period". This notion of vulnerability has been adopted by Jenelius and Mattsson (2012).

D'Este and Taylor (2003) introduced the concept of accessibility in vulnerability assessment studies, considering that a network link is critical if the loss of the link significantly diminishes the accessibility of a particular node. This approach has been confirmed by Sohn (2006) for a highway networks links under the flood damage and by Taylor and Susilawati (2012), upgraded with the introduction of accessibility's inverse, remoteness.

Other well-known aspects leading back to vulnerability are robustness and reliability. According to Knoop et alii (2012) the term robustness and vulnerability are used as opposites: the authors define the robustness as the ability of the network to maintain his functionality under conitions that deviate from the normal condition. But although reliability and robustness are correlated, they are not identical (Snelder et al., 2012): robustness focuses on the impact of the disturbance, while reliability focuses on the frequency of occurrence of the disturbance, or better, on its probability.

Also D'Este and Taylor (2003) has pointed to the difference between vulnerability and reliability, given to the latter a probabilistic characterization: they claim that the concept of vulnerability is related to the effects of a road disruption, without considering the probability of that disruption. Furthermore, Husdal (2004) separates the two aspects of reliability and vulnerability of a transport network: if reliability can be considered as a measure of network stability, vulnerability should be intended as a measure of the consequences of a collapse (or under-functioning) of a network's element.

Jenelius et al. (2006, 2009, 2010) compare the concept of vulnerability to that of criticality of the elements of a network. Criticality is given by the combination of two concepts: weakness and importance. In other words, an element can be defined as critic if it is at the same time weak – i.e. the probability of its failure is high – and important – i.e. the consequences of its loss are relevant for the whole system (Nicholson and Du, 1997). According to Li and Ozbay (2012) the evaluation of link criticality is concerned with finding the links that cause severe deterioration in network performance (e.g. total user travel time) when degradable.

Bearing in mind the well-known risk theory (UNDRO, 1980; CCPS, 1995; Russo and Vitetta, 2006), where risk is the product of probability and effects of a disrupting event, in this paper the evaluation of risk distinguishes the component referring to the probability of a disruption to occur, from the component referring to the consequences that such a disruption determines to the functioning of the network as a whole. Thus, in this research vulnerability analysis focuses on the latter aspect, and it does not call for an accurate quantification of the incidence of disrupting events (Sarewitz et al., 2003, Luathep et al. 2011).

3. Methodology

3.1 Link importance index

The present study aims to answer the following question: which links are the most critical ones for the functioning of a mountainous road transport network? In such a perspective, following the work of Nicholson and Du (1997) and Jenelius (2006, 2009, 2010), link importance is defined as the measure of the consequences of a link disruption. Therefore, the vulnerability analysis of a road transport network corresponds to the design of a process for creating a ranking of links according to their importance with respect to the preservation of network serviceability. In the context of vulnerability studies, a methodology that provides tools for the prioritization of network facilities is important for determining which of them should be reinforced and which should be left as it is (Taylor, 2012).

For this purpose, a set of relevant links are assumed to be successively and completely – considering both directions – closed, which forces all travelers driving along such links to choose other and less advantageous routes.

In the present study, the definition of importance – with respect to a given link –simultaneously includes two aspects: the level of usage, i.e. how many people typically use the link for their trips, and the impact that the closure of the link itself can have on the general functionality of the network as a whole. In brief, link importance depends on both demand-related factors and topological characteristics of the network.

For this reason, the following expression for the index of link importance (LI) has been introduced to evaluate the importance of a generic link j:

$$LI(j) = k \cdot F(ADT_j) + (1-k) \cdot G(\Delta C_j) \tag{1}$$

where F is a function that is directly proportional to ADT_j, i.e. the average daily traffic along link j, G is a function that is directly proportional to ΔC_j, i.e. the increase in the network users' total cost due to the interruption of link j (calculated with respect to ordinary undamaged network configuration) and k is a calibration coefficient. In this paper the first function $F(ADT_j)$ will be referred to as "local importance", while the second function $G(\Delta C_j)$ as "global importance"; the following paragraphs 3.2 and 3.3 will more extensively examine these two components of the link importance index.

The coefficient k in (1) allows for weight differently the two distinct functions of local and global importance. By acting on the coefficient k the analyst can decide to evaluate as more important whether the most used links or the most "strategical" ones, in terms of network functionality. In particular the k coefficient is assumed to range between 0 and 1: the higher the value of k, the higher the weight of the local importance function and, therefore, the reliability of the measured average daily traffic, and vice-versa. For instance, in case k is assumed equal to 0.5, the two functions F and G are assigned the same weight in the computation of the link importance index. Such a decision could be based on "political" assumptions regarding the concept of vulnerability (see Jenelius et al., 2006, regarding the aspects of equal opportunity and social efficiency), but also on specific considerations about the quality of the available data. For transport planners and practitioners, in fact, a crucial issue is the accuracy of input data, specifically the demand model (origin - destination matrix) and the network model. If, for instance, the simulation models used for the determination of the global importance would result poorly accurate, it would be possible to assign a higher weight to the *ADT* data – generally less affected by accuracy issues – thus improving the overall reliability of the final importance evaluation.

3.2 Local Importance

Regarding the local importance function, link importance is considered proportional to link traffic: if a link is travelled by a high number of vehicles, its vulnerability is higher with respect to other less travelled links. In order to account for this consideration, the local importance indicator F_j has been introduced, proportional to the ratio between the average daily traffic of a certain link j and the maximum *ADT* measured on the links of the network:

$$F_j = \min\left\{1; \max\left[\frac{ADT_j}{ADT_{\max}}; \frac{ADT_j + h \cdot (ADT_j - ADT_p)}{ADT_{\max}}\right]\right\} \tag{2}$$

Basically, F_j is computed as the ratio between the *ADT* measured along the considered link j and the maximum *ADT* measured for the set of links under study. Local importance indicator thus calculated ranges from 0 to 1, being 0 the score assigned to the less travelled link in the ranking, and 1 the score assigned to the more travelled one.

In order to increase the local importance values of those links subjected to high traffic volumes, so that the importance of busy links is stressed, analysts can act on two parameters, h and ADT_p.

ADT_p can be determined fixing the percentile p of links whose F_j scores are intended to be amplified by the analyst. For example, by assuming $p=90\%$, the top *10%* travelled links will get their local importance score amplified.

Coefficient h can be fixed by the analyst at any value higher or equal to zero. In case h is assumed to be equal to zero, F_j is given by the simple ratio ADT_j/ADT_{max}.

By acting on both h and p it is possible to decide to what extent the weight of the busiest links has to be amplified in the definition of the link local importance function.

3.3 Global Importance

Regarding the global importance function, it represents the variation in the generalized trip cost for all the users of the network over a given time interval, which results from the assignment of the transport demand to the network when the link in exam is closed. According to Nagurney et Qiang, (2008), Berdica and Mattsson (2007), Jenelius (2006), Sullivan et al. (2010), the importance of a link, in terms of network functionality, is proportional to the increase in the overall network-wide trip cost due to the removal of the link itself. Thus, the first step for the evaluation of the global importance function consists into evaluating ΔCj, i.e. the total trip cost variation of the network caused by the closure of a generic link j:

$$\Delta C_j = C_j - C_0, \quad \forall j \in B \tag{3}$$

where C_j is the total cost of the network assuming link *j* being interrupted (damaged network conditions) and C_0 is the total cost of the network calculated when all links in the network are normally functioning (undamaged network condition) and *B* is the set of links under study of which the average daily traffic is known. The total trip cost C of the network is the sum of all generalized trip costs paid by all users, thus is obtained as:

$$C = \sum_{OD} \sum_{k \in I_{OD}} C^*_k \cdot V_k \tag{4}$$

where C^*_k is the generalized cost and V_k is the simulated volume of a generic route *k* between the generic origin *O* and the generic destination *D* and I_{OD} is the set of existing routes connecting *O* to *D*.

Considering the function (3), in order to calculate the total trip cost variation ΔC_j, the assignment of the demand to the network must be carried out firstly for the undamaged condition (obtaining C_0), and later for all the jth damaged conditions (where link *j* is missing).

In brief, such a procedure to estimate the increase in total cost for a damaged network calls for the following steps:

1. the undamaged network is simulated and both traffic flows and the generalized trip costs are estimated, so that the total cost on the undamaged network can be calculated, which is suffered by all network users when completing their trips;
2. link *j*, which belongs to the sub-set of links whose importance is to be calculated, is completely interrupted – considering both directions – and, as a result a new model is obtained representing the damaged network missing the bi-directional link *j*;
3. the *j*-th damaged network is simulated, leading to the calculation of the total-trip costs for this network; moreover, if the closure of link *j* determines the isolation of part of the network, instead of total-trip cost, unassigned demand is calculated;
4. steps 2, 3 and 4 are repeated for all links included in the sub-set of links whose importance is to be calculated.

As it will be illustrated in Section 4, for the application of these steps an automated procedure has been elaborated, thanks to the adoption of a simulation software.

A relevant problem resulting from completely removing a link, in order to model link-disruption, is the possible disconnection of the network in two isolated parts. Depending on the topology of the network, when dealing with real-scale networks, the closure of a certain link can cause a disconnection between two parts of the network, leading to some centroids remaining isolated. In other words, this happens when the topology of the network does not provide any rerouting alternative for a given *O-D* pair. Those links which, if closed, determine such a disconnection of the network are called "cut links" (Jenelius, 2006). It is worth notice, as it will be shown when illustrating the application to the specific case in exam, that cut links are particularly frequent for road networks serving mountainous areas, as the topology of the network presents a low degree of connection, i.e. many origin-destination pairs are connected by a single route.

Evidently, in case a link is a cut link, the total cost variation ΔC_j, as just calculated for determining the global importance of the link, assumes an infinite value - since the cost paid by part of the users, function of the travel time, becomes infinite. In this case D^j_{OD} is the demand from origin *O* to destination *D* which cannot be satisfied due to the closure of link *j*, in the absence of any connection between said *O-D* pair. The higher the unsatisfied demand, the higher the accessibility reduction caused by the closure of a cut link. One popular approach for addressing problems associated with isolating links has been to use a high percentage-based link-capacity disruption level (Sullivan et al. 2010), for example 99% capacity reduction. Such an approach, though, appears scarcely rigorous, since the level of link-capacity reduction is completely arbitrary.

The approach proposed by Jenelius, instead, consists in considering a measure of importance for these isolating links (named "cut links") based on the unassigned demand, instead of total-trip cost variation. The higher the unassigned demand, the higher the cut link importance measure.

It should be noticed that one of the aims of the study is to obtain a unique ranking of links in terms of their importance. For this reason, it becomes necessary to introduce a different formulation to quantify the importance, valid both in case of cut links and non-cut links. To define this formulation, it can be considered that cut links are more important than non-cut links in the global network perspective: indeed their closure causes not only an extra cost for network users but the isolation of part of the users, who find no way to complete their trip.

Considering the presence of cut links, the importance of a link for the operation of the road network as a whole, g_j, can be computed as:

$$g_j = \begin{cases} \Delta C_j, & \forall j \in B \quad D_{OD}^{j} = 0 \\ \Delta C_j + \alpha \cdot D_{OD}^{j}, & \forall j \in B \quad D_{OD}^{j} \neq 0 \end{cases} \tag{5}$$

where α is equal to the value of a missing trip between the generic origin O and destination D due to the closure of link j. Such a formulation assures that a higher measure of global importance is associated to cut links.

Among cut links, the higher the unsatisfied demand resulting from their closure, the higher the global importance measure obtained from (5).

Since the objective is to combine global importance with local importance as shown in (1), this calls for normalizing the above described g_j (5) indicator as follows:

$$G_j = \frac{g_j}{g_{\max}} \tag{6}$$

where g_{min} and g_{max} are respectively the minimum and the maximum g_j obtained among the set of links under study.

The indicator G_j thus defined ranges between 0 and 1, being 0 the score assigned to the less important link in the ranking, and 1 the score assigned to the more important one.

Once calculated the two components as illustrated, i.e. local importance score and global importance score, they can be and combined and weighted to determine the link importance.

4. Importance rankings

Importance scores and rankings may significantly vary according to the assumption made by the analysts, and, consequently, on the value of the calibration parameters of the importance index *LI(j)*.

In order to properly assess the sensitivity and thus the reliability of the importance index proposed, Spearman's rank correlation coefficient has been used, which can lead to a synthetic and quantitative measure of rank modifications following modifications of the index itself (produced by varying the calibration coefficients, k, h, and p).

More in detail, the correlation coefficient r provides a measure of the correlation (linear dependence) between two variables X and Y (Spiegel et al., 2000). This coefficient (r) is computed as the covariance of the two variables X and Y divided by the product of their standard deviations.

When data are provided through a rank in order of size (e.g., links importance rank in a road network) the above described coefficient can be conveniently adapted to the situation (Spiegel et al., 2000).

The ranks are the integers 1 through n. Taking n values for x and n corresponding y values, and being x_j the rank given to the j-th x value, and y_j the rank given to the j-th y value, Spearman coefficient allows quantifying the global rank variation accounting for the variation in rank position of each y_i with respect to x_j. The mean of the x_j is then:

$$\bar{x} = \frac{1+2+\ldots+n}{n} = \frac{n \cdot (n+1)/2}{n} = \frac{n+1}{2} \tag{9}$$

while the variance is:

$$s_x^2 = \overline{x^2} - \bar{x}^2 = \frac{1^2 + 2^2 + ... + n^2}{n} - \left(\frac{n+1}{2}\right)^2 = \frac{n \cdot (n+1) \cdot (2 \cdot n+1)/6}{n} - \left(\frac{n+1}{2}\right)^2 = \frac{n^2 - 1}{12} \tag{10}$$

Similarly, the mean and the variance of Y are equal to $(n+1)/2$ and $(n^2-1)/12$, respectively. Now if $d_j = x_j - y_j$ is the generic deviations between the ranks, the variance of these deviations is given in terms of variance of X and Y:

$$s_d^2 = s_x^2 + s_y^2 - 2 \cdot r_{rank} \cdot s_x \cdot s_y \tag{11}$$

Then, the correlation coefficient r_{rank} between ranks is:

$$r_{rank} = \frac{s_x^2 + s_y^2 - s_d^2}{2 \cdot s_x \cdot s_y} \tag{12}$$

Since the mean value of d_j is equal to 0 and its variance equals $(\Sigma d^2)/n$, formula (12) becomes

$$r_{rank} = \frac{(n^2-1)/12 + (n^2-1)/12 - \left(\sum d^2\right)/n}{(n^2-1)/6} = 1 - \frac{6 \cdot \sum d^2}{n \cdot (n^2-1)} \tag{13}$$

The coefficient r_{rank} in (13) is known as Spearman's rank correlation coefficient. It ranges from −1 to 1. A value of 1 implies that a linear equation describes the relationship between X and Y perfectly, with all data points lying on a line for which Y increases as X increases. A value of −1 implies that all data points lie on a line for which Y decreases as X increases. A value of 0 implies that there is no linear correlation between the variables.

In the next section, these comparisons will be presented and discussed on the basis of the computed r_{rank} values for the sample road network of Bolzano.

5. Case study

The methodology described have been implemented for the case of Bolzano, an autonomous province in northern Italy, in order to rank the links of the investigated network on the basis of the importance index *LI(j)*, as illustrated in Section 3.

The road network of Bolzano serves a mountainous area populated by more than 500,000 people, 7,400 km^2 wide, crossed by motorway A22 from north to south and by national roads SS12, SS38, SS49, SS238 and SS621 crosswise. It has been represented using a graph constituted by 1,600 nodes (of which 293 centroids) and 3,500 bi-directional links.

The importance index has been computed for a sub-set of 2,158 bi-directional links where *ADT* values have been measured and made available by Bolzano administration. Among those links, 1,254 resulted to be cut links.

Regarding the demand model, the *O-D* matrix has been provided by Bolzano administration, referring to the week-day A.M. peak-period of a few years ago; it provided the demand between the 293 centroid nodes included in the network model. This matrix has been updated by using information about more recent traffic counts along a set of links.

The importance index *LI(j)* has then been computed following the procedure illustrated in Section 3. As above mentioned, in order to calculate the total-trip cost of the network for each damaged scenario - each one considering the removal of a link – as well as eventually the unassigned demand, the simulation has been run thanks to a commercial software, i.e. Cube by Citilabs: once the network and demand models has been imported, a specific script has been elaborated for the assignment procedure. For the assignment, a Deterministic User Equilibrium (DUE) model has been adopted.

a b

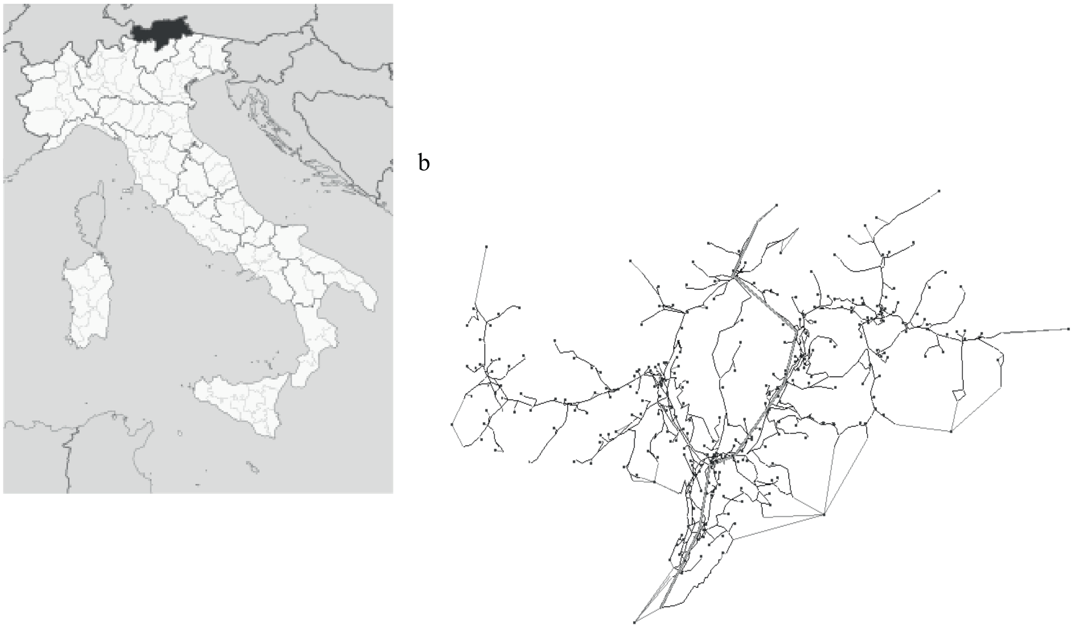

Fig. 1. (a) Province of Bolzano, Italy, (b) network graph developed in “CUBE”

More in detail, link flows have been firstly simulated in the base scenario (undamaged network) and the model has been corroborated comparing the simulated flows with the measured ones and computing the Root Mean Square Error. Thus, the total-trip cost for the undamaged network has been determined, considering the function (4). Then the software allowed us to re-run the assignment procedure, each time removing a bi-directional link j, calculating link flows and total-trip cost on the damaged network (4); in case the link j was a cut link, the software provided the unassigned demand as well.

Finally, the importance measure of each link has been computed by using the formulation described in Section 3 (1), (2), (5), (8). Regarding the coefficients for (1) and (2), in accordance with the indications of the Bolzano administration technicians, it was firstly assumed the calibration coefficient k equal to 0.5, the percentile p equal to 75%, and the multiplier coefficient h equal to 2. At the end of the procedure performed, the desired ranking for all links of the network, in order of decreasing importance, has been obtained.

Table 1 reports the top 10 links in the final link importance ranking – with a comparison with the different ranking obtained considering either the local or the global importance. The most critical link of the network is part of the national road SS38, with an ADT of 17,000 veh/day and an unassigned demand of 1194 veh/hour estimated in case the link is interrupted. Other links belonging the same road SS38 follow in the ranking. Although these links do not have the highest *ADT*, they are located on roads with relatively high traffic volumes where there are no alternatives routes. Thus, if closed, part of the demand remain unassigned, hence they present high values of global importance index. Other particularly important links are those on the national roads SS621, SS12 and SS42. It is worth noting that the top 3 links in the ranking are cut links. Other cut links, with lower *ADT* values, follow next in the ranking.

If just the global importance measure is considered, cut links take the top of the global importance ranking and follow a decreasing order of unsatisfied demand. Then, non-cut links follow with a measure of global importance proportional to the total trip cost increase imposed to network users by the interruption of the link.

It should be noticed that highly congested links usually present alternatives in case they are interrupted. Thus, although their local importance is high, the increase in the generalized trip cost produced by their closure is often not as high as the one produced by the closure of less congested cut links.

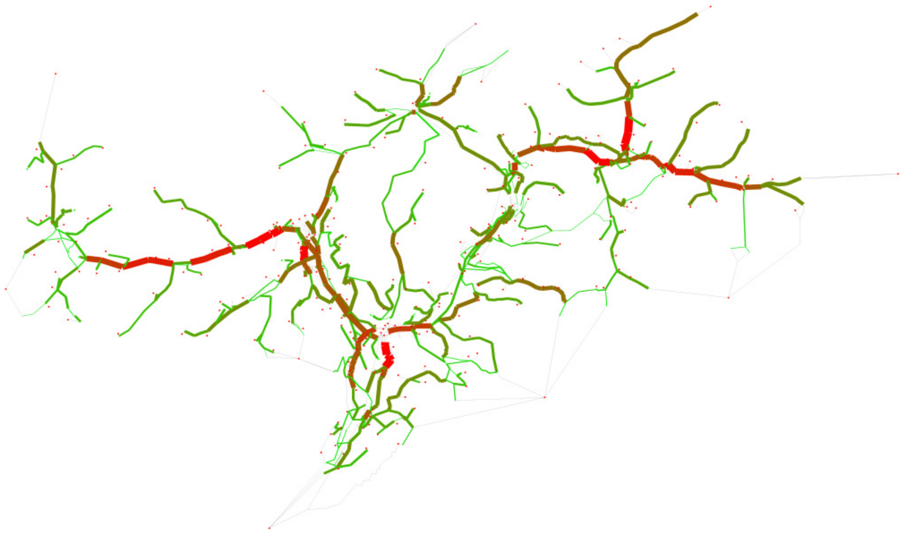

Fig. 2. Graphical output of the analysis for the case under study: for each bi-directional link of the road network vulnerability is represented with an histogram bar, whose height is proportional to the link vulnerability index (the most vulnerable links are also depicted in red color)

Table 1. Top 10 important links of the road network.

Link code	Road name	ADT_j (veh/day)	D_{OD}^{j} (veh/hour)	Rank based on F_j	Rank based on G_j	Rank based on LI_j
841	SS38	17,000	1,194	46	3	1
836	SS38	16,214	1,123	55	4	2
1002	SS621	16,560	975	51	5	3
797	SS12	34,099	0	2	181	4
881	SS42	25,000	0	11	182	5
879	SS42	23,593	0	12	186	6
846	SS38	26,292	0	10	193	7
742	SS12	34,099	0	3	197	8
851	SS38	30,544	0	5	199	9
852	SS38	35,913	0	1	203	10

To evaluate the significance of each of the parameters that define the importance index, $LI(j)$, Spearman's rank correlation coefficient has been computed, with reference to the rank obtained as described above, but changing the values of the parameters one-by-one, keeping fixed the other two, and re-running the whole procedure.

In particular, parameter *k* has been varied from 0 to 1, with a 0.1 step. Parameter *h* has been modified assuming the following values: 0, 1, 3, and 4. Lastly, parameter *p* has been changed from 0 to 100% with a 10% step.

The importance index of each link under study has been computed for every abovementioned case. Then, importance ranks, obtained by listing the links in a decreasing order of *LI(j)* have been drawn up.

Secondly, those ranks have been compared to the one obtained in the base case (*k*=0.5, *h*=2, and *p*=75%) by computing the Spearman's rank correlation coefficient. The results of these comparisons are shown in the following figures (Figure 3, Figure 4, and Figure 5).

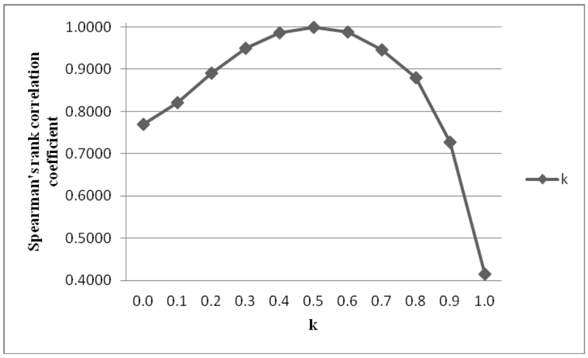

Fig. 3. Sensitivity analysis varying parameter *k*

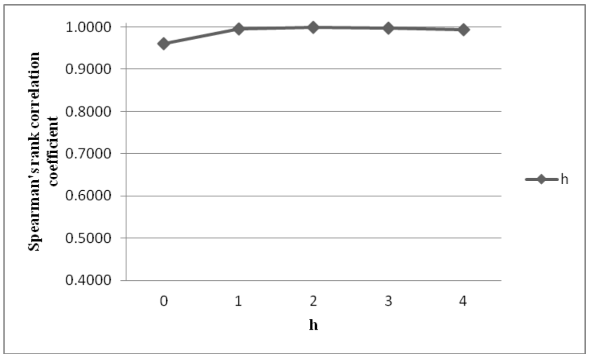

Fig. 4. Sensitivity analysis varying parameter *h*

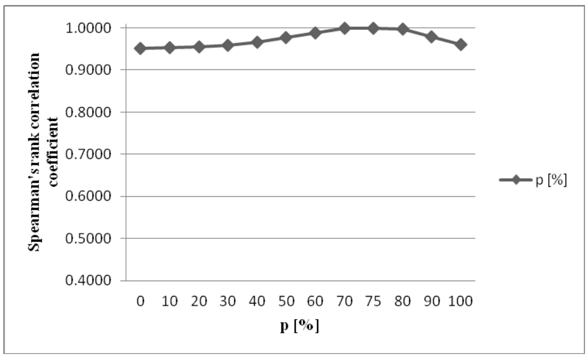

Fig. 5. Sensitivity analysis varying parameter *p*

As it has been explained in Section 3, the coefficient k allows the analyst to give different weight to the two functions, local and global importance, constituting the final importance measure $LI(j)$. This particular possibility should be taken into consideration in case of poorly accurate results from the simulation process involved in the computation of global importance. In fact, if the input data – demand model or network model – are affected by a scarce level of accuracy, the analyst can assign a higher weight to the measured *ADT*.

From these analyses, parameter k resulted the one to which the importance index $LI(j)$ is more sensitive. In particular, increasing k, which means increasing the importance of the measured *ADT* in the computation of the importance index $LI(j)$, the variation is stronger than the case in which k is assumed to be lower than the reference-base case. Parameters h and p, instead, do not seem to have a significant impact in the computation of the importance index.

6. Conclusions

The methodology implemented in this research deals with the vulnerability of a real-scale road transport network by considering the importance of its links with respect to the preservation of network functionality. The methodology illustrated considers the importance of a link as composed by two factors: the level of usage, i.e. how many traffic units typically travel on the link itself, and the impact that its closure have on the general functionality of the network as a whole. The first factor, referred to as local importance, calls for a measure based on the average daily traffic (*ADT*). The second factor, referred to as global importance, is evaluated as a function of the total-trip cost variation (ΔC_j,) by comparing the undamaged scenario with the damaged scenario, where the link j, whose importance is to be determined, is assumed to be completely closed.

Besides, in order to account for the presence of cut links – i.e. those links which, if closed, determine a disconnection between two parts of the network – a special formulation for global importance measure has been defined, based on the unassigned demand resulting from the closure of a cut link. The implementation of the procedure illustrated in this paper allow to obtain a unique ranking of the links of the network, in decreasing order of importance.

The methodology has been tested on the real-scale network of the road system of Bolzano, which is a highly mountainous area located in the Alps (northern Italy). The topology of this network is characterized by a significant presence of cut links, about the 40% of the total links. The application of the methodology led to satisfactory results represented by a ranking of links, in decreasing order of their importance scores.

The results obtained can be easily used by practitioners and decision-makers and can be relevant, for instance, for the determination of a list of priorities in the allocation and/or orientation of economic resource for infrastructure maintenance and improvement.

Furthermore, Spearman's rank correlation coefficient has been used to quantify the variation of the importance ranking caused by the variation of its coefficients.

This analysis highlights that importance ranks are particularly sensitive to the variation of parameter k, which defines the weight of the two contributions (local and global importance) of the index $LI(i)$. At the same time, those analyses allow estimating the relative weight of each calibration parameter of the index thus providing the analyst useful information for future applications of the index to practical cases.

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