An evolved concept of connectivity: the “Service reliability”

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Synopsis

During the last years, the research on transport network reliability has been focused on the multiple features of the wide concept of reliability (connectivity, terminal, capacity, travel time and cost reliability). Several indicators were introduced and many techniques were applied in order to calculate them. In this way some micro-levels of study were systemized, but at the same time the problem lost connection from a general point of view.

The study of single aspects of reliability, resulting from the specific analysis to carry out and from the aims to reach, has to be preceded by a preliminary and general study to characterize the problem at a less specific level, which can support the following strategies of study.

Connectivity surely represents the less complex step in reliability studies and at the same time it is one of the most powerful indicators currently used in research. However, its binary approach (link working or not working) on one hand represents its effectiveness and efficiency, and on the other it precludes the implementation to daily cases in which the connections work in one intermediate situation between the two limit states (temporary increases of traffic, maintenance works, incidents, etc).

A better representation of daily situations could be obtained by measuring connectivity with a variable which can assume any value in the range one-zero.

For this purpose it seems useful the already existing theory of traffic levels of service, used for planning and checking street sections, that effectively includes most of the variables affecting traffic conditions, such as geometry and flows. The indices associated to different links, related to the expected or measured levels of service, can be set in the planning stage or calculated for already existing situations, giving the methodology remarkable versatility and numerous cues of deepening.

In this study, a new method of calculation of reliability is presented. In the extreme cases it falls back in the connectivity and, in the other ones, gives a new indicator representing time and travel cost, comfort and satisfaction of the customer, supplying the searched general vision to reliability.

An evolved concept of connectivity: the “Service reliability”

During the last few years the reliability studies have given a remarkable systematic nature in specific fields of this research; methodologies regarding the following reliability sublevels have been developed:

- terminal reliability (connectivity);
- encountered reliability;
- travel time reliability;
- travel cost reliability;
- capacity reliability.

This kind of specificity, due to a great number of parameters influencing the reliability of a network, has the tendency to develop methodologies regarding a single parameter, which aggravate the general vision of the problem. Considering the more or less reliability of a network due to a single factor, the obtainable results only give one partial vision of a more complex phenomenon. Therefore, a comparison intersected with the several methodologies results becomes necessary in order to examine a network exactly and to obtain results consistent with the reality.
A methodology that gives an output index that already considers in itself the more important factors influencing the road network reliability would be more effective. In this way one would loose specificity in favour of the generality of the problem. Since traffic is a complex phenomenon that involves human beings, it is not exactly expressible (at least in the order today) through algorithms or mathematical formulas; for this reason it would seem more efficient to apply a less specific methodology but that frames the problem to a more general level.

CONNECTIVITY VERSUS SERVICE RELIABILITY

The simpler level of reliability is given from the connectivity that, on the other hand, represents a powerful tool of analysis of street networks [1], [2]. It reveals the probability of the presence or the lack of connection between one established OD pair. This simulation functions well in order to represent catastrophic events like interruptions due to earthquakes, floods or incidents that completely block one street section and therefore (at least in the transition situation) all the relative link. However, the probability that these events occur is very low and is not even calculable through historical series (reruns to other methods of calculation like the game theory). In these cases the most important thing is to reach the destination D (for first aid or for primary importance supplying) even if the travel time and travel cost are greater regarding the normal conditions, therefore connectivity becomes a very powerful tool in order to represent this situations.
Consequently, the connectivity limit means that it considers the extreme cases in which a connection can operate (working or not working). Instead of this, the causes that frequently disturb the traffic are temporary increases of the traffic demand, works of maintenance, incidents, adverse climatic conditions that do not completely block traffic, but that limit it, reducing the served capacity (i.e. considering a two tracks road they reduce the use of all the lanes and considering a single track road they impose the alternated circulation on one single lane). Therefore, the binary aspect of connectivity, expressing the existence or not of a connection has insufficient application for the situations that frequently occur.
It could turn out more efficient to assign to the state variable used for the connectivity reliability, represented here:

$$x_i = \begin{cases} 1 \text{ if the link works} \\ 0 \text{ if the link does not work,} \end{cases} \qquad (1)$$

intermediate values between 1 and 0 because that can represent the daily reality better.
How should one subdivide this numerical gap of variability in order to represent in an effective and discreet way one truth that varies punctually according to numerous parameters?
For this purpose, the classification of the levels of traffic circulation, used for planning and verification of the street sections, seems to encounter us because it effectively encloses the greater part of the variables that characterize the circulation in six categories: the levels of service.
Assigning to every link of the network an index that varies from 0 to1 and that synthesizes the state of the more important variables connected to reliability, a methodology could be found that permits examining links in series, in parallel and combinations between these two typologies. This methodology as output could give a total index that allows to estimate the reliability level of a network and that for extreme situations falls back in the connectivity (giving value zero if the considered path is interrupted). The attempt is not to establish a fixed methodology, on the contrary, to supply a methodology that is most flexible possible, that can be very adapted to the specific network and to the attempts of the person who applies it. We call the index of the

single link "service index" and we indicate it with x_i. The calculation of the service index is illustrated in [4], referring back to the same one in the case of an eventual deepening.

The service index applied to the reliability

The service index is obtained from a variable number of parameters depending on the level of complexity chosen for the determination of the index. In the first two levels the fundamental parameters are the average speed of travel and the traffic flow, within of which, through opportune coefficients, they include ulterior factors like the street geometry, the kind of users, the traffic composition and the peak hour factor. The third level of complexity, using the GLS [3], [5], [6], [7], [8], considers 54 factors for the determination of the index and indeed turns out to be the more complete methodology.

Generally speaking, the parameters influencing the service index can be divided in two categories: one for factors that are not time depending (for a fixed street typology) and the other for time depending factors whose trend can be extrapolated from surveys and therefore from curves of distribution. The application of the service index in the transport network reliability area implies establishing "an opportune" value of the service index for each link typology and therefore the determination of the probability that this index is exceeded. In order to make this possible, it is necessary to construct as many curves of distribution of the service index that are the existing street geometric typologies (fixed a combination of geometric characteristics must be considered the service index distribution correlated to the same one).

After all, the service reliability could be described as "the probability that is exceeded the attended value of the service index" (X_i^*):

$$R_i = \Pr(X_i > X_i^*) \tag{2}$$

For the calculation of the limit value X_i^* of reference, having the distributions of the afferent traffic parameters of the examined road (speed, flow, kind of user, etc.), the medium value or a value related to a fixed percentile can be used. In other cases the parameters to insert in the function of the service index can be deduced based on previsional studies of traffic or based on the speeds diagrams compiled in the planning step, therefore based on opportune hypotheses needing however of a statistical foundation. Then, extrapolating the service index trend and therefore its distribution curve, it will be enough to calculate the service index for the studied situation (in the case of interrupted link, in the case of opening link, in the case of overload network for exceptional events) and it will turn out immediately, for comparison with the distribution curve, to calculate the associate probability. As a result, in this way, a remarkable flexibility of the method is obtained. It can be "complete" if we chose the representation through the GLS (even if this would involve the necessity of a remarkable collection of data) or it can be simpler if we study one particular aspect, choosing one variable pointer and fixing all the others for the determination of the service index.

METHODOLOGY

Choice of the network

The choice of network to consider in the study refers to single OD pair. Generally the chosen possibilities of paths can be very numerous, and sometimes also unrealistic. It must introduce a criterion of network chosen that excludes the little probable alternatives. First, the connections that belong to two consecutive categories of the street classification could only be chosen (for a long distance travel it is not convenient to consider alternatives that involves provincial roads). Secondly, a time criterion could be adopted connected to the travel time that a customer is disposed to spend in order to catch up one destination in case of failure of the direct or preferential path. Given the average travel time $\bar{t}_m$, we have to found a multiplying index that expresses how many $\bar{t}_m$ we are disposed to use in order to catch up the destination D. Naturally this coefficient will be used with a certain approximation because it will indeed depend on the customers perception (it will be aleatory), on the motivation of the trip (job, vacation, family or enjoyment), on the considered modality of transport (if certain air connections were not available, how many people would be disposed to use the train or the ship for the same ones?), from the distance between the pair OD considered (for a provincial trip the coefficient surely will be more elevated with respect to one national movement. Giving an example, if it normally takes 40 minutes in order to go to Bari from Matera, many customers would be disposed to accept a coefficient equal to three, spending 2 hours of time, but how many customers would be disposed to accept the same coefficient for the trip Bari - Milan increasing the time travel from 10 to 30 hours, without changing transport modality?).

Given this multiplying coefficient, through the average travel times of the several links, we will be able to exclude all the paths exceeding this acceptable maximum time $n \, x \bar{t}_{m,p}$, where p is the index of the p-th available path.

Another adoptable criterion could be choosing travel cost like discriminating parameter: considering the maximum cost that the medium customer is disposed to spend ($C_{max,\mathbf{OD}}$) in order to reach a destination D. We would exclude all the paths whose cost exceeds this threshold. The advantage of this methodology is

that it would be the most effective appraisal of toll paths, even if the time spent for one trip would have to be assessed, indeed not a simple operation for the heterogeneity of the street users.
Supposing however that we have selected our network connecting one OD pair, in the following sections we will try to characterize the criteria in order to estimate the service reliability index relatively to links in series and parallel, considering also for these last ones, the eventuality that there is an interconnection between them.

Links in series

Having indices comprised between 1 and 0 makes it impossible to use the classic formulas of the connectivity because these have binary values both for the input and for the output. Considering a path composed from a number of links in series, the value of reliability of the path considered will have always to be comprised between 1 and 0 and, more exactly, between the limit values of the service indices assigned to the same links. For this reason it has been believed to use a weighed average, with weights given to every link that can represent its minor or greater influence in the whole path. If, as an example, we have a short link with an high risk of congestion (frequently low levels of service), the relative importance of this single link regarding the entire path will be indeed smaller regarding the case in which the same had had a greater length (with probability of constant congestion for all its length).
Therefore, the first weight could be equal to the fraction between the single link length and the length of the path of which the link belongs:

$$\alpha_{ip} = \frac{l_i}{L_{path}} \tag{3}$$

where *i* is the index pertinent to the links and *p* is the index pertinent to the path. Therefore, the same link used in different paths will assume different weight depending to the length of the different paths. On the other hand, this weight can be representative of the probability that an accident happens, generally more elevated the more extended the link is compared to the considered path. Other discriminating factors could be used in order to carry out the average weight of the service indices, like the average speed of the single link compared to the average speed of the path. However, since this factor is being considered already for the determination of the service index, this would mean considering it doubly in the methodology. Since the service index is representative of the conditions of traffic and of the street geometry and since the service index is independent from the length of the link, the use of the average weight described previously, seems simple and suitable.
Various speech could be lead for a weight that considers the average travel cost of the link *i* refered to the whole relative path *p* (related to the customer perceived cost or generalizing cost), being this not contemplated directly in the necessary parameters for the determination of the service index:

$$\alpha_{ip} = \frac{c_i}{C_{path}} \tag{4}$$

It is decided not to use this parameter because in this phase of the study the performance of the network is needed to be considered, leaving it apart from travel costs. Using the costs, moreover, it would imply the study of the consequences related to an anomalous event (when they occur it increases the average travel cost) and therefore it would imply the risk assessment related to it, for every link of the network, according to the common formula:

$$R = p \cdot I \tag{5}$$

where "p" represents the probability of an malevolent event occurring and "I" the intensities associated to it, generally expressible with the costs related to the event.
After all, therefore, using the relative weight to the length of the single links related to the length of the entire path, the value of reliability of every single path of our network will be equal to:

$$R_p = \sum_i \alpha_{ip} \Pr(x_i) \cdot \tag{6}$$

Paths in parallel

a) Indipendent paths

Considering paths in parallel related to the OD pair examined and supposing these parallel paths are independent, in order to obtain the value of the reliability index a simple algebraic sum of the values obtained for the single distances is proposed:

$$R_{OD} = \sum_p R_p \tag{7}$$

In such context the elimination of the paths described in the paragraph “choice of the network" corresponds to the operation to exclude paths with low R_p and, therefore, not significant for the calculation of $R_{OD} = \sum_p R_p$.

Applying the (7), the upper limit of the index does not remain fixed, for which, wanting to relate the result to the unit, the immediate information on the number of available paths between the OD pair would not be obtained, and it could be limiting the immediate understanding of the index. However, considering also the number of independent paths and the value of the service index, a fast estimation of the examined network can be obtained.

b) Interconnected paths

The ideal condition represented from the presence of independent connections that would guarantee the connection between OD, although if one link fails, very rarely is found in the reality: in common networks there are several interconnections between the paths and therefore every link is used by a lot of different path. In this more realistic situation a different methodology must be resorted. When a failure occurs, the connections used at the same time by more paths bring more negative effects on the whole network because they probably have a greater flow and therefore they have a greater possibility of failure regarding the others links.

Holding account of these considerations, in order to obtain the reliability of a network pertinent to a single OD pair, reductive coefficients that hold account of the interferences between paths could be used. Before finding the weight pertinent to the path, we define therefore another weight to be assigned to every link given by:

$$\beta_i = \frac{1}{n_p} \tag{8}$$

where n_p it is the number of paths that share the same single link. This weight, like that chosen for the study of the links in series, only refers to the physical conformation of the network. It could have used a weight pertinent to the afferent flows to the single paths, however, since the service index is calculated in base also to the flows, it already holds this parameter on account. The occurring of an event disturbing the traffic flow will go held on account with a new assignment of network flows, or through surveys during the period in which the effects of the event are perceived. Therefore the service index will be calculated considering the conditions of circulation related to the event. For this reason it is preferred, as for the previous section, to use a weight that only refers to the physical conformation of the net.

Then, the weight related to the path could be the average of the coefficients β, equal to:

$$\gamma_p = \frac{\sum_i^n \alpha_i \cdot \beta_i}{n} \tag{9}$$

with n equal to the number of links of the path p taken in consideration and α_{ip}, weight described in the previous paragraph. Therefore, considering the interactions between the paths, the reliability of the single path p of the OD pair will be:

$$R_p = \gamma_p \sum_i \alpha_{ip} \Pr(x_i) \tag{10}$$

In order to obtain the reliability of the OD pair (R_{OD}), the sum of the new service index of single paths could be carried out:

$$R_{OD} = \sum_p R_p \tag{11}$$

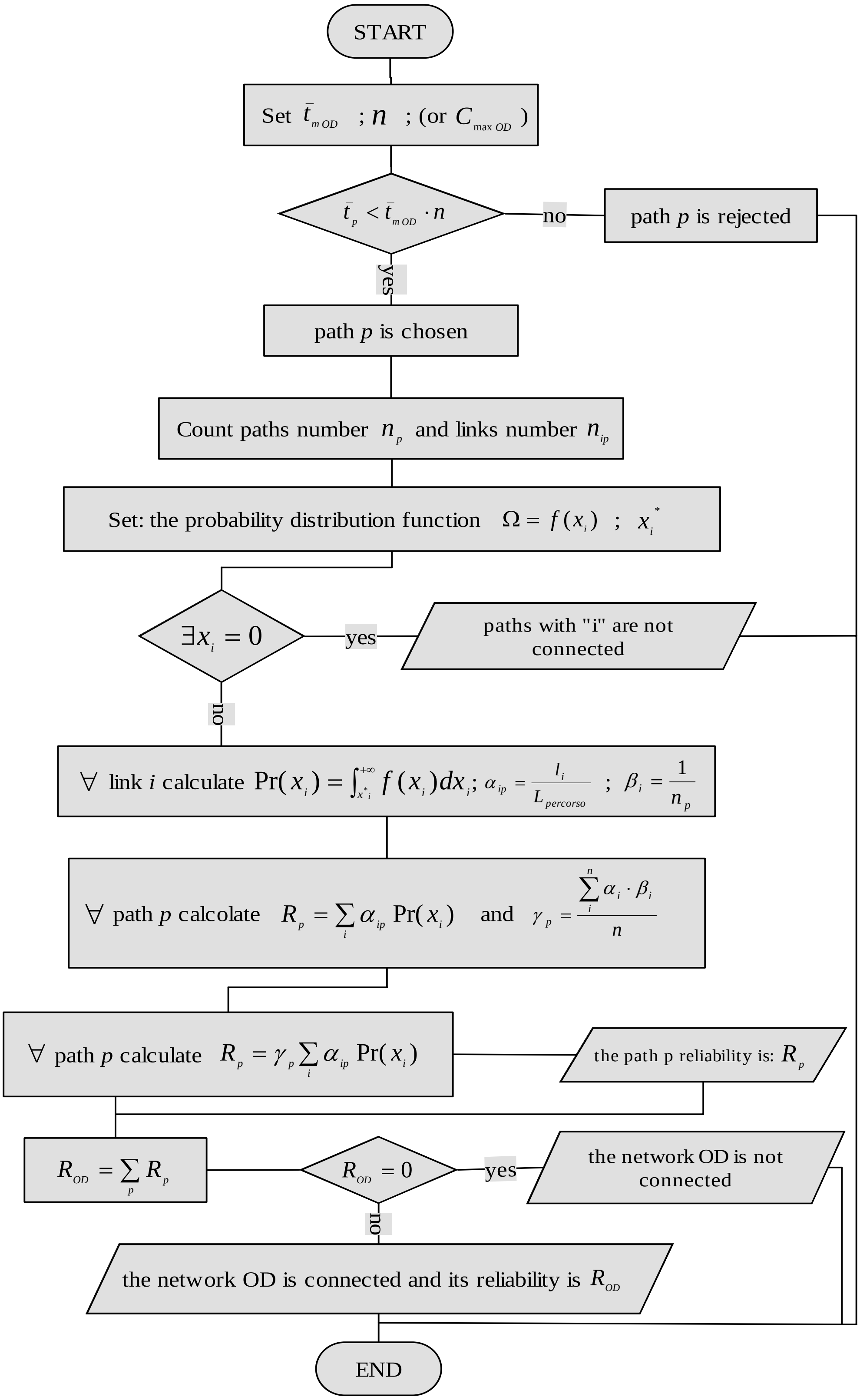
In Appendix A, a schematic flow chart of the methodology is shown representing its principle steps.

FUTURE TARGETS

Future targets of the research will be turned to the application and therefore to the setting of the methodology. The collection of traffic data and the choice of the network to implement it will turn out to be of fundamental importance in order to test the methodology. Having exceeded this first practical level, the methodology for the determination of the service index will be able to refine. The creation of a data bank afferent to each category of the present street classification would allow the methodology to assume general valence and it would turn out a powerful method of support to the decisions that the manager must take in determined circumstances. At the same time with a computer implementation it would allow an extremely effective instrument for the user.

APPENDIX A

Methodology schematic flow chart



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