RELIABILITY AND VULNERABILITY OF TRANSPORT NETWORKS

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ABSTRACT. Transport infrastructure modernizing and extension according to land use and sustainable development requirements still represents a challenging issue among policy makers, regional/local communities and scientists. The reliability and vulnerability are discussed in a complementary way, outlining the specific features of each one. Reliability is described under connectivity, travel time and capacity aspects, whereas vulnerability is analyzed through the consequences of links or nodes failure, irrespective of the probability of failure, and mainly through changes of Hansen index of accessibility and users total cost. The case study investigates the Romanian rail/road network vulnerability related to Danube crossing and its mitigation by improving network topology.
Key words: *critical infrastructures, transport networks, reliability, vulnerability, accessibility.*

1. RELIABILITY AND VULNERABILITY – INTERCONNECTED CONCEPTS

The concepts of reliability and vulnerability are quite important in assessing the ability of transport networks to provide continuity in operation. Transport networks are exposed to various factors that can lead to decrease of serviceability. Bråthen and Lægran (2004) identify three categories of network attributes or features responsible for its disruption:

- *Structural features* relate to network topology, connectivity, infrastructure physical body, curvature, art works, weight restrictions etc.;
- *Natural factors* take into consideration the attributes of the natural environment (land topography), the natural incidents (flood, avalanche, rock fall, snowing and icing, fog, earthquake) and climate changes;

- *Traffic features* include attributes regarding traffic flows (demand, O-D matrix, route choice, links debit, peak-hours and weekend/season variability) as well as maintenance operations, construction sites and accident clear-up.

None of these three aspects acts on an individual basis. Even though a specific failure addresses one of the aspects, the entire network could be exposed to the full set of determinant factors. Reliability and vulnerability assessment should consider each attribute separately and, at the same time, as a whole. The impact of nodes or link disruption could be quite significant. The transport planners or policy makers need methods and decision support tools to evaluate threats to transport networks facilities and to assess the consequences of network functionality disruption and failure of its elements. Economic, social and environmental benefits come from the possibility to evaluate, manage and minimize the impacts of transport networks degradation.

The reliability of transport networks elements is a probabilistic measure that refers their ability not to fail or malfunction, during a specific period, given a set of performance guidelines. Even if some elements of the transport network are failed, the network could remain functional although with less performances. One differentiates three forms of network reliability (Bell and Iida, 1997; Taylor and D'Este, 2007):

- connectivity *reliability* – the probability that two nodes in a network remain connected, i.e. there still is a path connecting them when a set of links have been cut off;
- travel *time reliability* – the probability that a trip between an origin and a destination node can be completed within a given time interval; the travel time can be affected by the imperfect knowledge of drivers and variation of link flows due to route choice decision;
- capacity *reliability* – the probability that a network can accomplish a given level of travel demand, i.e. the reserve capacity can accommodate the required demand for a specific capacity loss due to network degradation.

In contrast to reliability, the concept of vulnerability is related to the consequences of network elements failure, irrespective of the probability of failure. It is possible that a link failure may have a very small probability, but when the event occurs, the adverse social, economic and environmental impacts may have such an intensity to indicate a major problem.

Vulnerability analysis provides a way to find structural weakness in the network topology that makes it vulnerable to consequences of failure or degradation. Taylor and D'Este (2007) distinguish two forms of vulnerability in transport networks:

- *cost related vulnerability* – if the degradation of one or more links on a path connecting two nodes leads to substantial increase of the generalised cost of travel between them, then the connection between those nodes is vulnerable;
- *accessibility vulnerability* – a node is vulnerable if the failure of a small number of links in the network results in a severe decrease in the accessibility of that node.

2. CONNECTIVITY RELIABILITY

The probability that two nodes in a network remain connected can be computed by establishing the paths set between nodes and their reliability. The reliability $P(\mathbf{X}_{ij})$ of a series of links $\mathbf{X}_{ij}=(ik, kl, ..., sj)$ connecting two nodes i and j, can be calculated as $P(\mathbf{X}_{ij})=\prod_{kl\in \mathbf{X}_{ij}} p_{kl}$, where p_{kl} is the expected reliability of the link *(kl)*. If $p_{kl}=1$ the link is certainly operational and if $p_{kl}=0$ the link is certainly failed. The reliability of nodes is considered 1. Their disruption probability can be transferred to the incident links. Each network can be decomposed into minimal paths and minimal cuts set. A minimal path between two nodes is a series of links connecting the two nodes where a failure of a link results in the failure of the connection. For every minimal path A_{ij} connecting the nodes i and j, there is a logical function $\alpha(A_{ij})$ that takes the value 1 if the path is operational and 0 otherwise.

$$\alpha(A_{ij})=\bigcap_{kl\in A_{ij}} x_{kl}\ , \qquad (1)$$

where $x_{kl}=1$ if the link (*kl*) is functional and 0 if it is failed.

The minimal cut is a set of links where the recovering of a link results in recovering of the connection between the two nodes. For every minimal cut B_{ij} assigned to the pair of nodes i and j, there is a logical function $\beta(B_{ij})$ that takes the value 0 if all links included are failed and 1 when at least one link is operational.

$$\beta(B_{ij})=\bigcup_{kl\in B_{ij}} x_{kl}\ . \qquad (2)$$

The network structure can be represented as a system of parallel minimal paths and serial minimal cuts. Because the links belong to several paths and cuts at the same time, the independence of elements cannot be assumed in computing the reliability of the network (Bell and Iida, 1997; Raicu *et al.*, 2005). Thus it is possible to calculate the lower and the upper bounds of the connectivity reliability for each pair of nodes (i,j):

$$\prod_{s=1}^{S}\left[1-\prod_{kl\in B_{ij}^{s}}\left(1-p_{kl}\right)\right] \le P(\mathbf{X}_{ij}) \le 1-\prod_{q=1}^{Q}\left(1-\prod_{kl\in A_{ij}^{q}} p_{kl}\right), \quad (3)$$

where S is the number of minimal cuts and Q the number of minimal paths for the pair of nodes (i,j).

For large networks, it is quite difficult to identify all minimal paths and cuts. Monte Carlo simulation is a more effective technique to evaluate connectivity reliability in large transport networks. The method uses the random generation of different states of the network and computes the probability of connection between each pair of nodes (Raicu and Roşca, 2004).

3. NETWORK VULNERABILITY

3.1 Accessibility related vulnerability

Taylor and D'Este (2007) use accessibility and Hansen accessibility index to characterize transport networks vulnerability. The accessibility of a node i is

$$A_i = \sum_{j\neq i} B_j f(c_{ij}), \quad (4)$$

where B_j is the attraction measure of node j, c_{ij} represents the generalized cost of travel from node i to j and $f(c_{ij})$ the impedance function of the journey. Usually, the impedance function is the inverse of the generalized cost of travel (distance, time or money units) or a negative exponential function (e.g.: $f(c_{ij}) = e^{-\beta c_{ij}}$, where β is a calibration parameter).

The Hansen index of node accessibility is

$$HA_i = \frac{\sum_{j\neq i} B_j f(c_{ij})}{\sum_{j\neq i} B_j}, \quad (5)$$

and the accessibility index for the entire network is

$$TA = \sum_i HA_i . \quad (6)$$

An incident occurred in the network that causes the failure of the link k results in nodes and network accessibility decreasing:

$$\Delta HA_i = HA_i^{(0)} - HA_i^{(k)}, \quad \Delta TA = TA^{(0)} - TA^{(k)}. \tag{7}$$

where the index (0) refers to the undamaged network and the index (k) to the network with the link k inoperable.

Relative variation of accessibility for nodes and the whole network could also be computed:

$$\%\Delta HA_i = \frac{HA_i^{(0)} - HA_i^{(k)}}{HA_i^{(0)}}, \quad \%\Delta TA = \frac{TA^{(0)} - TA^{(k)}}{TA^{(0)}}. \tag{8}$$

3.2 Cost related vulnerability

Jenelius *et al*. (2006) use, as a measure of reduced performance of the network, the increase in the generalized cost of travel (time, distance, money units) for the users. When a link k is closed, the network may be divided into several disconnected parts, so that a number of trips from origin i are not able to reach the destination j. Thus results an unsatisfied demand

$$u_{ij}^{(k)} = \begin{cases} \varphi_{ij} & \text{if } c_{ij}^{(k)} = \infty \\ 0 & \text{if } c_{ij}^{(k)} \neq \infty \end{cases},$$

where φ_{ij} represents the travel demand from node i to node j and $c_{ij}^{(k)}$ is the generalized cost of travel from node i to j when link k is closed.

Therefore, there is a dichotomy of the link importance according to travel cost increasing and unsatisfied demand into the network. If the link k belongs to the set of non-cut links (L^{n-c}), the importance of the link k for the whole network is

$$\Omega(k) = \frac{\sum_i \sum_{j \neq i} \varphi_{ij} (c_{ij}^{(k)} - c_{ij}^{(0)})}{\sum_i \sum_{j \neq i} \varphi_{ij} c_{ij}^{(0)}}, \tag{9}$$

where $c_{ij}^{(0)}$ is the generalized cost of travel from node i to node j in the undamaged network.

The importance regarding the unsatisfied demand of a link k is

$$\Omega_{uns}(k) = \frac{\sum_i \sum_{j \neq i} u_{ij}^{(k)}}{\sum_i \sum_{j \neq i} \varphi_{ij}}. \tag{10}$$

In addition, the link disruption is translated into nodes exposure. The demand weighted exposure of node *i* is the maximum value over all non-cut links:

$$\Phi(i) = \max_{k \in L^{n-c}} \frac{\sum_{j \neq i} \varphi_{ij} (c_{ij}^{(k)} - c_{ij}^{(0)})}{\sum_{j \neq i} \varphi_{ij} c_{ij}^{(0)}}. \quad (11)$$

The exposure regarding the unsatisfied demand for the node *i* is

$$\Phi(i) = \max_{k} \frac{\sum_{j \neq i} u_{ij}^{(k)}}{\sum_{j \neq i} \varphi_{ij}}. \quad (12)$$

4. CASE STUDY. DANUBE CROSSING AND ROMANIAN TRANSPORT NETWORK VULNERABILITY

Transport infrastructure, and especially road and railway networks are in permanent expansion and modernizing at European level. The investments in transport infrastructure represent a core in the budget of each member state. Comparing to new comers, Romania still faces a delay in the absorption of EU structural convergence funds. Despite its direct connection with EU, Romania has a marginal geographic position. The transport Pan-European corridors (IV and IX) are crossing Romania, but their international use on the national sector is still reduced due to (Raicu *et al.*, 2007):

- unsatisfactory infrastructure physical body;
- reduced possibilities to run on high-ways or high-speed railways;
- crossing through many rural and urban centers;
- lack of detour roads of the great urban areas;
- level of transport services.

Among the directions of the sustainable development of Romania, the transport system restructuring represents a priority because it generates externalities for the environment and local communities. At the same time, Romania barely satisfies the economic equity of a sustainable transport system. The OECD vision of a sustainable transport is defined in term of accessibility, namely the possibility to access spaces, goods, and services. For Romania, this principle still represents a desiderate. The metropolitan and regional polarization results in the isolation of a great number of local communities and increasing time and distance to access to jobs, medical care, social/cultural life or tourist points. The desert of rural space is an acute phenomenon.

The poor density, connexity and connectivity of the transport networks generate their vulnerability to structural, natural and traffic factors. The 2005 flood in several regions of Romania is a remarkable example of cumulative actions of the whole set of vulnerabilities. The flush out of the bridge spanning the Buzău river at Mărăcineni became a political, social, and economic issue. Its direct consequences (disruption of rail/road major line, traffic diversion, large spaces isolation and increasing travel time) persisted for almost twelve months. Danube crossing in the Southeast region of Romania also represents a vulnerable line. The two European roads crossing Danube at Cernavodă and Giurgeni and the sole rail crossing at Cernavodă are limitative for the accessibility in the region and vulnerability generating factors (Fig. 1).

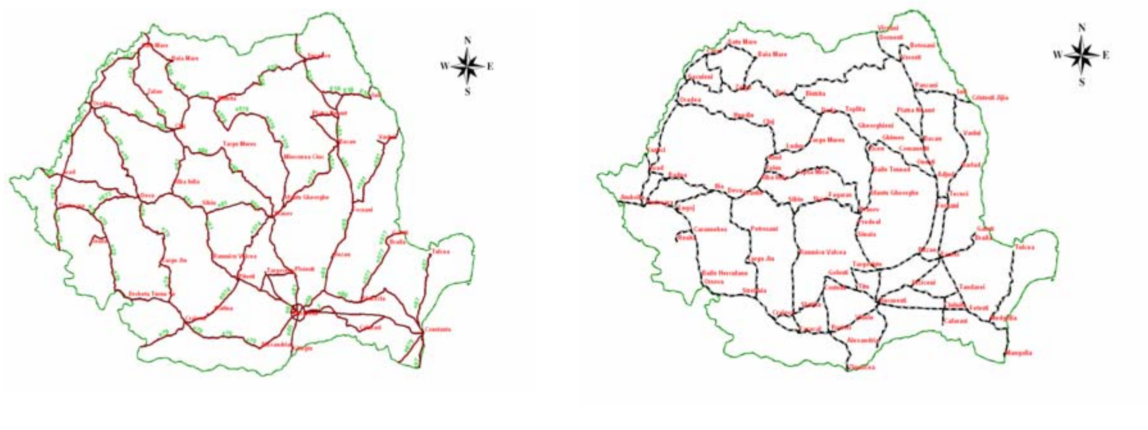

Fig. 1 Romanian road and rail networks (main lines)

As figure 2 shows, the fail of the present Danube crossing points generates important decreasing in the accessibility of the cities in the influence area, and mainly for the cities on the right shore of the river. The link containing the Cernavoda Bridge is an important line of the network. Its fail results in 17% accessibility decreasing for Constantza and 11% for Tulcea. The influence propagates even to Bucharest that has a 4.5% decreasing.

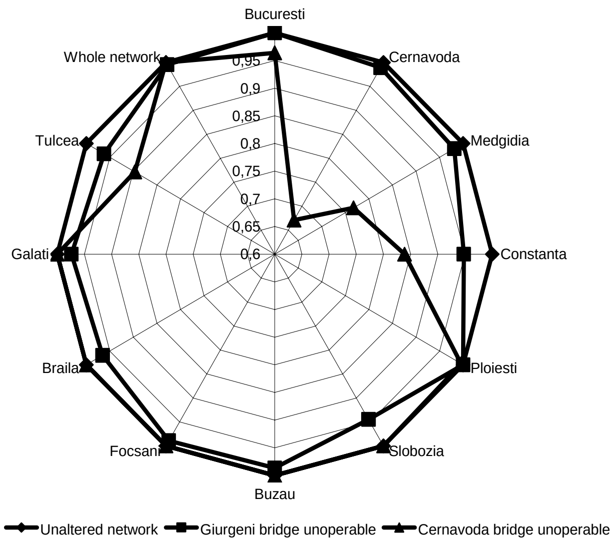

Fig. 2 Road accessibility decreasing for different inoperable Danube crossings

The fail of Giurgeni-Hârşova link generates loss of accessibility for all the cities included in the Southeast developing region. The opening of a new bridge spanning Danube at Brăila or Galați will increase accessibility in the region and will reduce the vulnerability of the network.

5. CONCLUSION

Transport network reliability and vulnerability demand an integrated approach. Both technical and non-technical factors are of great importance. Assessment methodologies based on multiple perspectives are recommended. Proactive measures are needed in order to prevent disruptions and to assure that the network will be able to maintain an acceptable level of service. It is important to prevent the network from failure, but if this occurs, it is also important to minimize the extent of the negative effects and to restore the normal state as quick as possible. The methods presented are useful for the transport planners and traffic engineers in focusing their efforts in refining techniques for identifying network weakness, evaluating cost-effective risk management and remedial responses such as reducing risk profile, modernizing current infrastructure, creating alternative routes and minimizing socio-economic impacts in terms of location and accessibility to markets, services and facilities.

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