Social inequity induced by Bucharest road network vulnerability

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Abstract: The concepts of road network vulnerability and social inequity induced by road closure are important when investigating the ability of road transport networks to provide continuity in operation and maintaining the level of service between acceptable limits. In a traditional approach is determinate total decrease in efficiency of network, but it is important to estimate the inequity generated for users. Our model is used to determinate how travel times are affected by a urban road closure. The paper presents a methodology to assess network vulnerability usable for urban transport network.

Key-Words: Transport network reliability, road network vulnerability, social inequity

1 Introduction

The concept of reliability is extremely important in assessing the capacity of urban transport networks to provide continuity in operation. The setting of the transport network reliability function requires the identification of the parameter(s) according to which it is expressed. [1] Bråthen and Lægran [2] 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, etc.) and climate changes.
- Traffic attributes refer to traffic flows (transport 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.

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.[3]

Issues of transport network reliability and road network vulnerability became to be studied from 80' after a series of earthquakes in Japan. Lam [4] make a literature review of the field and framework. 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. A first form of network reliability analyzed was *connectivity reliability* defined as 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 [5], [6] and [7]. Binary limitation of reliability has led to the development of new indicators such as *travel time reliability* defined as 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 [8], [9], [10] and [11], and *capacity reliability* defined as 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 [12].

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 [3]. 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 [13] distinguish two

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forms of vulnerability in transport networks: 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, and cost related vulnerability – if the degradation of one or more links on a path connecting two nodes leads to substantial increase of the generalized cost of travel between them, then the connection between those nodes is vulnerable.

An important issue for transport network vulnerability is social element and equity aspect of urban network reliability. In literature are proposed methods for quantifying the importance of network links based not only on the overall consequences but also on the disparities among user[14].

2 Road network vulnerability

2.1 Accessibility vulnerability

Taylor and D'Este [13] use accessibility and Hansen accessibility index to characterize transport networks vulnerability. The accessibility of a node *i* is

$$A_i = \sum_{j \neq i} B_j f(c_{ij}), \qquad (1)$$

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.

The Hansen index of node accessibility is defined by

$$HA_i = \frac{\sum_{j \neq i} B_j f(c_{ij})}{\sum_{j \neq i} B_j}, \qquad (2)$$

and the accessibility index for the entire network is

$$TA = \sum_i HA_i . \qquad (3)$$

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

$$\begin{aligned} \Delta HA_i &= HA_i^{(0)} - HA_i^{(k)}, \\ \Delta TA &= TA^{(0)} - TA^{(k)}. \end{aligned} \qquad (4)$$

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:

$$\begin{aligned} \%\Delta HA_i &= \frac{HA_i^{(0)} - HA_i^{(k)}}{HA_i^{(0)}}, \\ \%\Delta TA &= \frac{TA^{(0)} - TA^{(k)}}{TA^{(0)}}. \end{aligned} \qquad (5)$$

2.2 *Cost related vulnerability*

Jenelius *et al*. [15] use, as a measure of reduced performance of the transport network, the increase in the generalized cost of travel (time, distance, money) 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

$$u_{ij}^{(k)} = \begin{cases} \varphi_{ij} & \text{if } c_{ij}^{(k)} = \infty \\ 0 & \text{if } c_{ij}^{(k)} \neq \infty \end{cases}, \qquad (6)$$

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

$$\Omega(k) = \frac{\sum_i \sum_{j \neq i} \varphi_{ij}(c_{ij}^{(k)} - c_{ij}^{(0)})}{\sum_i \sum_{j \neq i} \varphi_{ij} c_{ij}^{(0)}}, \qquad (7)$$

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

$$\Omega_{uns}(k) = \frac{\sum_i \sum_{j \neq i} u_{ij}^{(k)}}{\sum_i \sum_{j \neq i} \varphi_{ij}}. \qquad (8)$$

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:

$$\Phi(i) = \max_{k \in L^{n-c}} \frac{\sum_{j \neq i} \varphi_{ij}(c_{ij}^{(k)} - c_{ij}^{(0)})}{\sum_{j \neq i} \varphi_{ij} c_{ij}^{(0)}}. \qquad (9)$$

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

$$\Phi(i) = \max_k \frac{\sum_{j \neq i} u_{ij}^{(k)}}{\sum_{j \neq i} \varphi_{ij}}. \qquad (10)$$

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2.3 Importance versus equity related vulnerability

The consequences of a link closure are operationalized by the increase in user cost. All users are assumed to minimize their travel cost when choosing what route to take from origin to destination. In a traditional approach is determinate total decrease in efficiency of network, but it is important to estimate the inequity generated for users [15].

The reduction in transport network efficiency is defined by efficiency importance, I_{eff}. The total increase in travel cost for all users, or equivalently vehicles, traveling between OD par (i,j) during the closure is $\Delta c_{ij}^{(k)}$. The efficiency importance I_{eff} of link k us the defined as the total increase in vehicle travel cost for OD pairs:

$$I_{eff}(k) = \sum_{i,j\neq 1} \Delta c_{ij}^{k} . \quad (11)$$

with normalized form:

$$\bar{I}_{eff}(k) = \frac{I_{eff}(k) - \min_{l} I_{eff}(l)}{\max_{l} I_{eff}(l) - \min_{l} I_{eff}(l)}, \quad (12)$$

where l is included in set of links.

It is important to determine how unevenly the travel cost increases are distributed among the travelers.

Jenelius [15] propose a definition of equity importance I_{eq} to estimate inequity of a link closure:

$$I_{eq}(k) = \frac{\sqrt{x\sum_{i,j\neq i}\frac{(\Delta c_{ij}^{k})^2}{x_{ij}} - (\sum_{i,j\neq i}\Delta c_{ij}^{k})^2}}{\sum_{i,j\neq i}\Delta c_{ij}^{k}}, \quad (13)$$

with normalized form:

$$\bar{I}_{eq}(k) = \frac{I_{eq}(k) - \min_{l} I_{eq}(l)}{\max_{l} I_{eq}(l) - \min_{l} I_{eq}(l)} . \quad (14)$$

And equity-weighted I_{ew} is define as:

$$I_{ew}(k) = (\bar{I}_{eq}(k))^{(1-\alpha)}(\bar{I}_{eq}(k))^{\alpha} . \quad (15)$$

With $\alpha = 0$ the (normalized) efficiency important is recovered, and with $\alpha = 1$ the (normalized) equity importance is recovered. By adjusting α one can control how much weight is to be put on the equity aspect [15].

In this case number of user affected by road closed is not taken in consideration. This aspect can influence the result obtained.

3 Framework

Our model is used to determinate how travel times are affected by a urban road closure. The paper presents a methodology to assess network vulnerability usable for urban transport network.

The network vulnerability function is computed using the *Equilibrium Assignment* algorithm (fig. 1). This method allocates the flows according to Wardrop's first principle: "Every individual road user choses his route in such a way that his trip take same time on all alternative routes ant that switching routes would only increase personal journey time."[17].

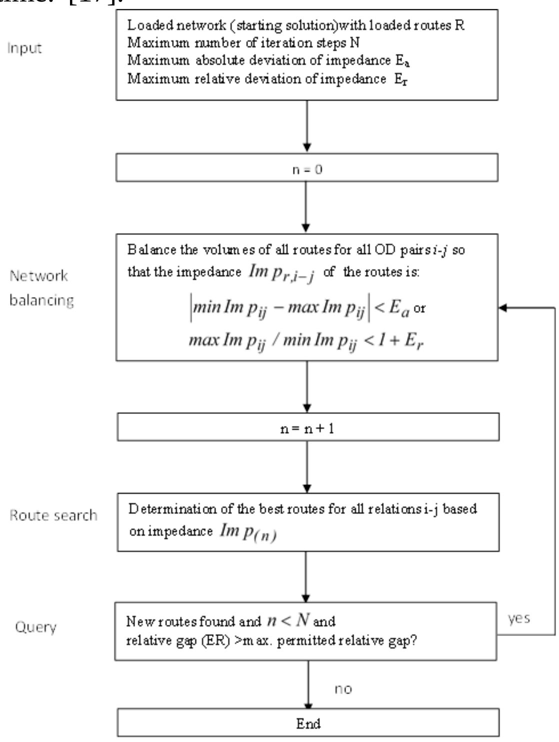

Fig. 1. Equilibrium assignment [18]

Impedance per network object $Im\,p$ is defined as a function of traffic volume φ.

The objective function of the equilibrium assignment is:

$$OF = \sum_{(i,j)} \int_{0}^{\varphi} Im\,p(z)dz , \quad (16)$$

where the sum is for all links (i,j) in the network.

The lower bound of the objective function is:

$$LB = OF - TEC , \quad (17)$$

where TEC is the total excess cost and is equal with difference between total impedance and the hypothetical impedance resulting if all vehicles took the shortest way as OD relation. The relative gap ER it is a measures for the excess cost of vehicles that

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do not take the optimum routes yet in proportion to the total impedance in the network.
To assess convergence criteria we must obtain for ER a value under a specifically threshold, where:

$$ER = \frac{TEC}{LB}. \quad (18)$$

In our paper to estimate transport network vulnerability (fig. 2) we propose an approach to calculate the increase of travel time for users induced by road closure using relation (7) where consider travel cost as travel time:

$$\Omega(k) = \frac{\sum_i \sum_{j \neq i} \varphi_{ij} (T_{ij}^{(k)} - T_{ij}^{(0)})}{\sum_i \sum_{j \neq i} \varphi_{ij} T_{ij}^{(0)}}, \quad (19)$$

and next relation to determinate the value of relative variation of travel time for affected users:

$$V(k) = \sum_{i,j \neq i} \frac{T_{ij}^{(k)} - T_{ij}^{(o)}}{T_{ij}^{(o)}}. \quad (20)$$

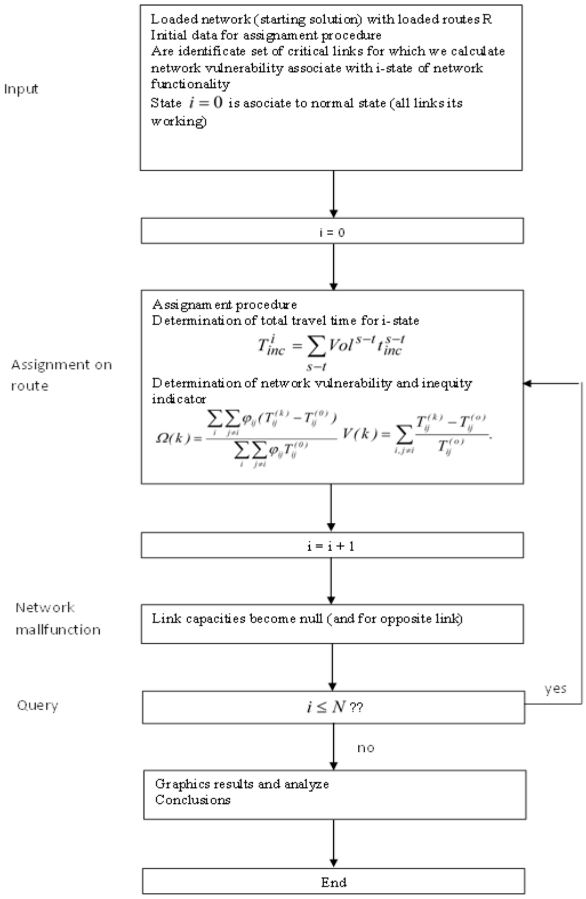

Fig. 2. Travel time vulnerability algorithm

4 Case study

In our paper we study social inequity induced by urban road network vulnerability. We concentrate on road links closed or with capacity limited for subway construction of line M4. Initial data with network attribute, travel demand, etc. are obtained from Urban Transport Master Plan 2008 [16]. In fig. 3 is represented road network from Bucharest and with red line street closed or affected by street closed.

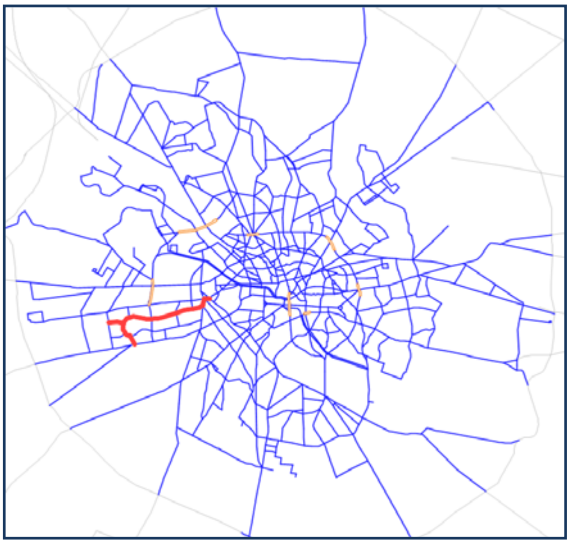

Fig. 3. Urban road network in Bucharest

Using the proposed model we obtain for a specifically attribute of urban transport network like $\Omega(k)$ -the increase of travel time and $V(k)$ - the value of relative variation of travel time in a particular case of roads closure (Valea Argeșului street, Râul Doamnei street and Moghioroș street intersection) in area of metro construction site, the next results:

Table 1. The result obtained

Study cases / Network indicator	Valea Argeșului street closed	Râul Doamnei street closed	Moghioroș street intersection closed
$\Omega(k)$	0.0038	0.0037	0.0187
$V(k)$	7.01	6.50	35.01

It is evident the importance of Moghioroș street intersection for transport network users so it is necessarily to limiting the duration of closure.

5 Conclusion

In conclusion, it is important to determinate network vulnerability but must take in consideration implications of road closure for individual user. 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

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