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A New Method for Calculating Network Robustness Index (NRI) in Urban Transportation Networks

Kaveh Rezvani Dehaghani[1], Ali Naderan[2], Kamran Rahimov[3]
[1]Transportation Engineering Department, Science and Research Brand of Islamic Azad University, Tehran, Iran
[2]Assistant Professor, Transportation Department of Science and Research Branch of Islamic Azad University, Iran, Tehran
[3]Assistant Professor, Transportation Department of Payam-e-Noor University (PNU)
([1]kaveh.rezvani@srbiau.ac.ir, [2]naderan@srbiau.ac.ir, [3]k.rahimov@shomal.tpnu.ac.ir)

Abstract-Wide range of short-term destructive events like hurricanes, floods, fogs, fatalities and accidents occur every day in transportation network and have negative effects on the network. The purpose of this study is to discuss such accidents and investigate the effects of them on the network which is implemented by Network Robustness Index. Network robustness is proposed recently in transportation scope and is an up-to-date issue in transportation investigations. Robustness is in contrast with network the concept of vulnerability, i.e. by increasing the robustness of network, vulnerability would decrease. In this study, traffic maps were analyzed by PTV-VISUM software and Arc GIS program, and travel-cost related to each link were determined by: travel-time, Peak Hour Volume (PHV) and link length, then the most important link of network was determined by all-or-nothing assignment method and shortest-path-trees were plotted by MATLAB codes which was based on dijkstra algorithm and the cited link was called critical link. Critical link is the one which eliminating of that-in comparison to other links- leads to the most increase in travel-cost. Then, assuming a disruption to this link, maximum network robustness index was measured by calculating the difference of travel cost before and after disruption to critical link. In this investigation principal and minor arterial roads of BOJNURD city were considered as case study. Results showed that the PJ link is the critical link in the studied network; hence, by assuming disruption to this link, maximum network robustness is calculated

Keywords- *Network Robustness Index, Urban Transportation Network, Vulnerability Assessment, All-Or-Nothing Assignment, Short-term Disruption, Critical Link*

I. INTRODUCTION

Transportation's role as a lifeline is of paramount importance to countries development and people in all social classes get daily entangle with this network in direct and indirect ways. In recent years, social activities are utterly dependent on network systems; so a preponderance of the simplest people's routine activities depends upon infrastructural networks. Therefore, investigating and the importance of their elements and understanding the sensitivity of systems to disasters are necessities of analyzing these systems.

Frequent natural disasters often occur in transportation systems and cause the major damage to this system [1]. Transportation infrastructures are large collections which establish connections between different nodes. Although roads, bridges and tunnels are regarded as the most ubiquitous infrastructure, it should be known that facilities like embankments, retaining walls in urban transportation systems, or official buildings and cranes are parts of transportation infrastructures at quays, and all of the cited facilities are exposed to different natural disasters. The past catastrophic events show that transportation infrastructures are severely vulnerable due to lack of redundancy. Long-term repair, difficulties in route changing, repeated damage and mutual dependence of system components to each other, are considered as factors which could increase vulnerability of a system. Damaging of these infrastructures leads to disorder in life, business, access to emergency services and relief operations and finally has negative economic and social influences [2].

Some common disruptive events like floods, accidents or pavement damage have short-term effects on only one networks' link, but its detrimental effects on performance, capacity and travel-time of other links and whole system is remarkable. Analyzing the network's disruption is a methodological approach which leads to improvement of transportation planning difficulties, and can help specialists in determining link-importance and ultimately comes in handy in calculating network robustness assessment. Network robustness is defined as a criterion of network for controlling normal condition of network during disruption circumstances. In the other words, in a robust network travel-time does not increase impressively after occurring disruption. Generally, the concept of robustness is based on assuming disruption to different links of network and subsequently, comprising the importance of the damaged links with other ones. However, the notable point is related to opting suitable failure mechanism which must be relevant to failure cause, because disruption type can influence outcomes of study [3]. so we classified them in different groups.

Factors which impress city traffic can be discussed in three major groups:

1. Natural disasters like earthquake, flood …

2. Unforeseen events like accidents and road repairs

3. Social events like fair, sport competitions …

The mentioned factors can be studied in two expected/unexpected and repeated/unrepeated events, rectification is not possible.

II. LITERATURE REVIEW

Transportation vulnerability is a new concept in this field. Berdica was a pioneer in transportation vulnerability studying, who introduced network vulnerability as being exposed at risk in a way that leads to decrease in Level-Of- Service. In this explanation service delivery means to use joint, link or route of network in a specific time [4]. Even though D'este and Taylor by introducing a new concept called "accessibility" described a general definition for vulnerability, the mentioned explanation is being used in scientific investigations [5].

Vulnerability assessment was performed by indicators like topological index [6] and consumer surplus cost changes [7] which can be included in following equation.

$$\Delta \mathrm{E(CS)} = \frac{1}{\propto}\left[\ln(\sum e^{v_i^1}) - \ln(\sum e^{v_i^0})\right] \quad (1)$$

In the mentioned equation:

$\Delta E(CS)$ is consumer cost mathematical expectation changes, α is cost index or time travel reflect in desired function and V_j is desired value for j in 0&1 mode (before and after disorder).

Sullivan proposed other factor. This factor which called network stability has concept contrary to vulnerability; in fact, the more stable the network, the less vulnerable is. Following equation illustrates this criterion [3]:

$$NRI_a = C_a - C \quad (2)$$

The mentioned criterion is difference of travel time cost before and after link a failure.

$$C = \sum_i t_i \ x_i \quad (3)$$

$$C_a = \sum_i t_i^a \ x_i^a \quad (4)$$

In the above equations t_i & x_i are travel time and traffic flow values in a normal arc, respectively. t_i^a 7 x_i^a link the same values for the time that link a is eliminated from network.

Jenelius and Mattsson presented another criterion by developing importance index [8]. He introduced flow based and effect based redundancies. In fact, he showed that also an arc would be unimportant in normal condition, but we should consider that in the case of disorder in an arc, how can this unimportant arc relief failure.

In other investigation that was performed by Taylor and Susilawati, *remoteness* (vice versa of accessibility) and other index named ARIA were introduced. In this investigation a rural region in southeast of Australia was investigated by this criterion [9].

Nagae presented a framework for finding ways of anti-quake enhancement for urban passage network in an article. They used this scenario in Kubhi city in Japan for verification of calculations efficiency [10].

Wang in an article (Evaluation Method for Highway Network's Resistant Ability against Natural Disasters and the Conclusion Analysis), investigated different factors role in Hangzhou road network resistance ability against natural disasters by FUZZY hierarchy method. In this study three "network structure", "network stability" and "maintenance management" factors were used as main factors and sub factors as density, continuity, access, level of service and reliability were used for modeling [11].

Cheng investigated Taiwan road network vulnerability after disaster (earth quick) occurrence. In the mentioned investigation, prioritization and identifying effective factors on failure intensity of road network was studied by assuming that rescue operation after disaster is of paramount importance to officials [12].

Nogala studied part of Ireland road network. In this study, assessment of inherent vulnerability of traffic network was implemented by collection of measurable indexes like accessibility and reliability. They presented a new multivariate method which could estimate inherent vulnerability and possible relation of that with accessibility and reliability indexes [13].

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III. METHODOLOGY

A. General strategy in vulnerability and crisis management:

In most of the research mentioned above, failure mechanisms were studied regardless of failure cause; however, in the present research a five-step strategy is used to analyze the vulnerability as follows:

1) *Definition of failure scenario*: that could be accident, natural disaster, targeted military attacks and so on.

2) *Identifying influential factors*: time, position and risk factors.

3) Investigating the above factors influences on the assumed failure (before the disruption).

4) *Failure modeling*: forecasting network demand (after disruption), opting a failure mechanism related to failure scenario.

5) Presentation of new supply system (during the disruption)

B. Overview of the Research Methodology

1) The Wardrop principles

A logical assumption is that each driver tries to reduce travel time. A sustained balance is achieved when no driver can optimize his travel time by changing his route. This is the main feature of the network equilibrium discussion [14]. In this study, the network is assumed under equilibrium circumstances before disruption; hence, we followed Wardrop principle.

2) Traffic assignment

All-Or-Nothing assignment method is employed in this study for assigning traffic by taking advantage of PTV-VISSUM software and traffic maps provided by Research Institute of the Ministry of Road and Urban Development of the Islamic Republic of Iran.

Important point is that, demand rate is not the same on different days the days and even differ from hour to hour; but transportation professions -in equilibrium circumstances, assume fixed demand rate in the networks. Therefore, demand condition is assumed fixed which is in contrast with real condition. So, it is attempted to assign traffic in a given period in which network demand level is almost constant, in order to have an analysis in steady state. These periods are usually related morning and evening peak hours on a weekday - the larger the interval, the lower the accuracy.

3) Route choosing algorithm

Finding the shortest route means that we consider all the paths between the two vertices and choose the shortest one. It is very long and practically impossible to do this without the special method, because the number of possible paths between two points of the network is very high when the number of vertices is high. There are various methods that summarize the shortest path operation. The methods for computing the shortest path coded in computer software have the fastest speed to reach the shortest-path-tree, including the algorithms described by Moore, dijkstra, Belman and Floyd. The dijkstra algorithm and coding in MATLAB are used in this investigation.

4) Calculating Travel-cost

Travel-cost refers to people traveling in network by one form of transportation which could be analyzed as a financial or non-financial matter; however it is usually comparable with travel-time in transportation studies and by increasing travel-time, travel-cost correspondingly would increase. It is obvious that chaos on the roads is another effective factor in travel cost, because it can increase travel-time indirectly [15]. Travel-cost is a multiple of travel-time and a weight coefficient of origin-distention [16]. According to the mentioned definitions concerning travel-cost, a new formula is introduced in present paper which supports both cited theory.

In this study, the peak hourly volume (PHV) is considered as the relative weight of each pair of origin-destination link, and then is divided by link length to eliminate the effect of link length on travel time.

According to presented descriptions, we should calculate travel cost of all links for calculating network robustness index by following equation:

$$C_{ij} = \frac{t_{ij} \cdot PHV_{ij}}{L_{ij}} \tag{5}$$

C_{ij}: travel cost function from *i* (origin) to *j* (destination) according to arc length

t_{ij}: travel time from *i* to *j*

PHV_{ij}: peak hour volume of *ij* link

L_{ij}: *ij* arc length

5) Calculating Efficiency index

Efficiency index of transportation network is estimated by following relation in this study [17]:

$$VUL_a^G = \frac{E_0(G) - E_a(G)}{E_0(G)} \tag{6}$$

$E_0(G)$ & $E_a(G)$ are efficiency of network G in normal and disorder times of arc a, respectively.

Efficiency function is described by following:

$$E(G) = \frac{\sum_i \sum_{rs} \frac{u_i^{rs} q_{rs}}{\pi_i^{rs}}}{\sum_{rs} q_{rs}} \tag{7}$$

q_{rs} is travel demand from r to s. u_t^{rs} is passenger ratio of I group whom want to go from r to s and π_i^{rs} is the shortest travel time of this passenger group.

6) Calculating Network Robustness Index

This index was presented by Scott et al for the first time in 2006 [18], then Sulivan added some descriptions to cited concept in 2012[3]. This research tries to develop the methods presented before. In the study conducted by Scott, an index called gamma was used to determine the NRI, which is a continuity index, and indicates the relationship between the number of links and the maximum number of possible links in a network and could accept 0 and 1values. But in this study, the network reliability index is determined by travel time and traffic flow, which in fact indicates the difference in travel-cost before and after the failure of the link a. The aim of this paper is to develop the aforementioned method by employing the all-or-nothing assignment method, dijkstra algorithms and the shortest-path-tree that will ultimately result in the computation of the maximum robustness index of the urban road network.

By the method of assigning all-or-nothing and specifying the shortest-path from node *i* to any other nodes that results in a *tree graph* of node *i* to other nodes, this is called the "*shortest-path-tree*". The shortest path tree should be plotted for all nodes of the network and it can calculate the travel cost from each node to the other nodes.

The travel cost of each node ($C_i^{(n)}$) is equal to the sum of the costs of accessing to other nodes according to shortest paths tree, which corresponds to the following relation of the sum of the numbers on the graph edges of the shortest path (numbers corresponding to travel costs of each link).

$$C_i^{(n)} = \sum_i^n C_{ij} \tag{8}$$

After calculating the assigning cost of all nodes, we calculate the travel cost for the entire network, by aggregating them.

$$C_{total}^{(n)} = \sum_i^n C_i \tag{9}$$

Where $C_T^{(n)}$ represents whole travel cost of network in normal condition.

After calculating the total travel cost in normal mode, by removing one link from the network and assuming that the traffic load is spread over the adjacent links, a new travel cost of each link is calculated and the shortest path tree is plotted again with respect to the damaged link, then we draw and re-calculate the cost of each node and the total cost of the network trip according to relationships 2 and 3 and represent them with $C_i^{(f)}$ and $C_{total}^{(f)}$, respectively-under disaster condition . Finally, to calculate the *Network Robustness Index* (*NRI*) and to understand correctly the impact of a bow failure on the network, we subtract the travel cost of the crash state from the normal travel cost (Eq 4).

The *NRI* value indicates the network's shortcoming to respond to travel demand during unexpected events. This value can help experts to calculate different quantities during unexpected disasters by applying different coefficients, including: time lost, cost, increased air pollution, increased fuel consumption and increased accident rates.

$$\text{NRI} = C_{total}^{(f)} - C_{total}^{(n)} \qquad (10)$$

$C_{total}^{(f)}$ is network total travel cost in disorder condition

$C_{total}^{(n)}$ is network total travel cost in normal condition

7) Determining Critical link

According to above relationships, it is obvious that the damage and deletion of each link will impose different amount NRI on the network. But to see the maximum amount of NRI, we need to select and remove the link that has the most impact on the network assignment and its failure has the most consequences for the network, which we call the "critical link" in this study. The more critical is which, eliminating it from the transport network, increases the travel time of the network further. In previous research, variables such as V/C and performance function were used to determine the critical arc, which are explained in this section. The criterion for the selection of the critical arc in this study is the "Significance Index", first introduced by (Jenelius.E. 2006). To determine the importance index of each arc, the number of times the arc is present in the shortest path trees (all or none) and the accesses created by that arc to other nodes. Obviously, the selection of the important arc should be done under normal conditions before the disorder occurring.

In the Fig. 1 a step-by-step summary of the network reliability index (NRI) modeling hierarchy is presented.

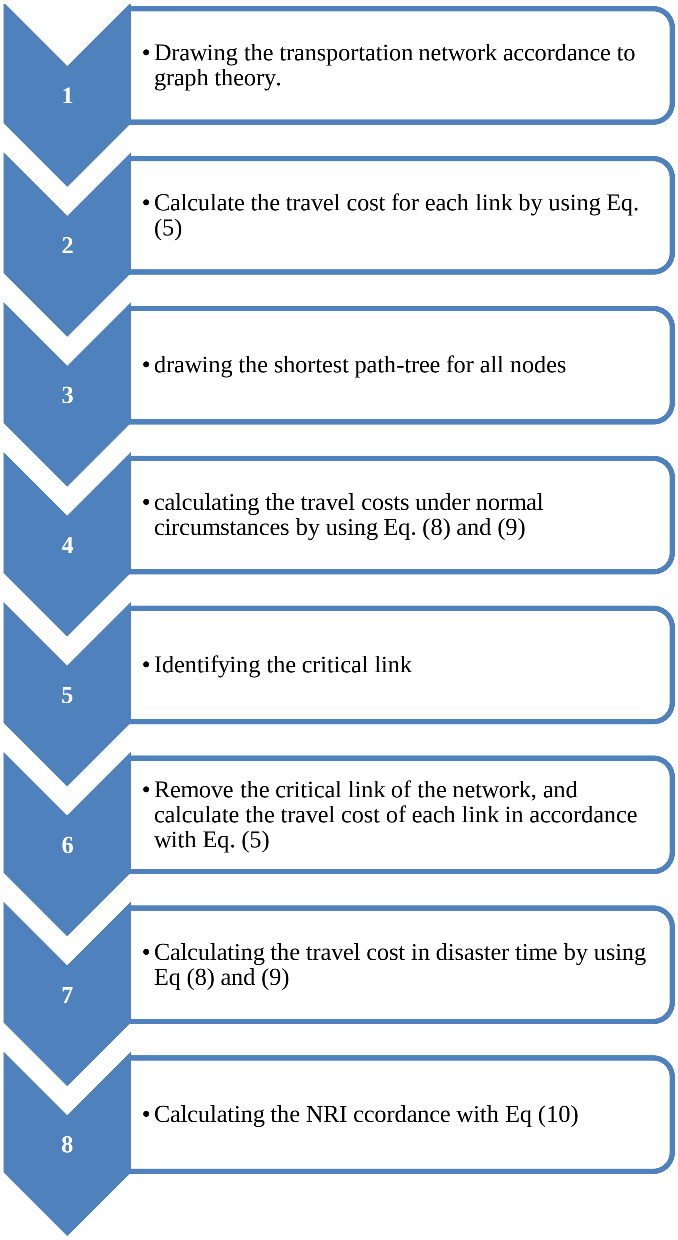


Figure 1. Summary of the network reliability index (NRI) modeling

IV. CASE STUDY

A. About Bojnourd

Bojnourd city is one of the subordinate counties of North-Khorasan province which is located in Northeast of Iran. The city with an area of 6563 square kilometers, borders Turkmenistan to the north, northeast and northwest [19].

B. Learning about road network of Bojnoud

The Bojnourd city road network has a length of about 200 kilometers, including 13 kilometers of sub-urban roads, 15 kilometers of expressways, 21 kilometers of principal arterial, 55 kilometers of minor arterial roads, 58 kilometers of collectors and 34 km of local streets [19].

C. Summarizing network and determining studied roads

As mentioned in the previous section, the Bojnourd city road network has a length of over 200 kilometers, comprising 62 traffic zones, 318 nodes, and more than 400 bi-directional links that analyzing all these links and nodes in the present study is time consuming and expensive. For this reason, the focus of the present study is on the links and nodes with the highest traffic volume. Therefore, the network of studied roads is restricted to include all expressways, principal arterial roads, paramount minor-arterial roads (in terms of traffic volume and capacity), all major intersections and squares of the city. As is shown, in Fig. 2, the main city passages network and selected passages are visible.

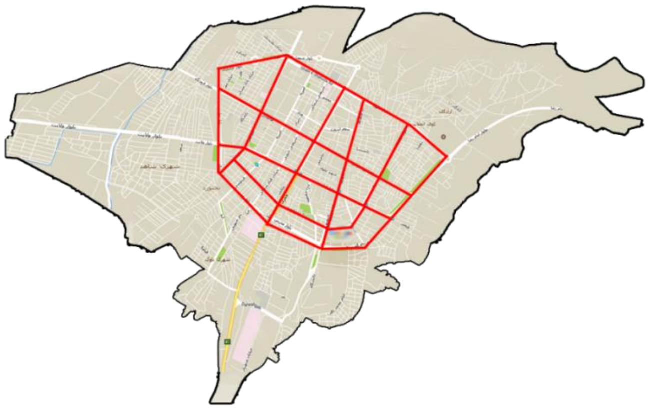


Figure 2. Selected road network of Bojnourd on map

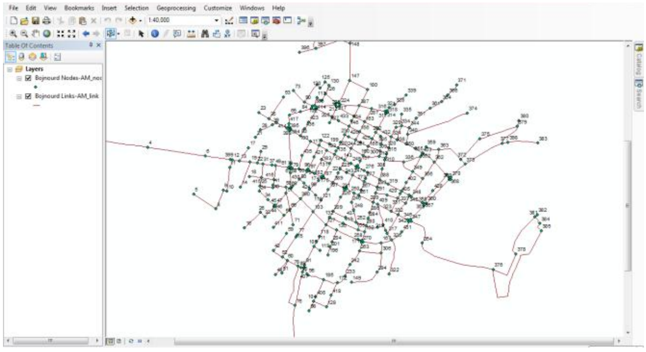


Figure 4. Network picture in Arc Gis program

D. Determining network stability index

1) Plotting the network according to graph theory

According to the hierarchy presented in the previous chapter, we first consider the network of passages in accordance with graph theory, and after naming the nodes and edges, we draw the graph of the network as follows in Fig. 3.

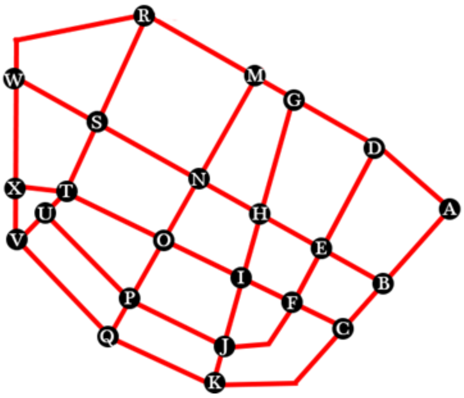


Figure 3. Network graph

2) Calculating travel cost of network link

After naming the arcs, we need to know the volume of peak hour traffic, travel time, and link length so that we can calculate the travel cost of each link using the (Eq 5) presented in the preceding chapter.

By using PTV-VISUM traffic-maps, Arc GIS software and information which is available in Bojnourd Comprehensive Transportation Studies, 2012, the information needed to calculate the travel-cost of the links, are extracted(Fig. 4). The following table illustrates initial data of some links of the network, including: link length, travel-time, travel-cost function and net travel-cost of the link. Net travel-costs of other links will be calculated in a similar way and placed on the corresponding edges of graph of the network.

TABLE I. TRAVEL-COST OF NETWORK'S KINK

		L_{ij}	t_{ij}	$DDHV_{IJ}$	Travel-cost Function	Travel-cost of link
۱	AB	۶۹۲	۴۸	۱۱۳۵	۰۵۹.۲۴	۶۵.۱۶
	BA	۶۹۲	۴۸	۱۲۰۵	۲۱۷.۲۳	۰۷.۱۶
۲	BC	۴۰۳	۳۸	۱۱۹۷	۳۵۲.۳۱	۶۳.۱۲
	CB	۴۰۳	۳۸	۱۲۱۲	۷۴۵.۳۱	۷۹.۱۲
۳	CK	۱۱۴۸	۱۱۵	۱۲۵۵	۹۲۱.۳۴	۰۹.۴۰
	KC	۱۱۴۸	۱۱۱	۱۳۴۳	۰۷۰.۳۶	۴۱.۴۱
۴	AD	۷۷۱	۶۶	۹۶۷	۹۹۳.۲۲	۷۳.۱۷
	DA	۷۷۱	۶۷	۹۰۲	۷۷۳.۲۱	۷۹.۱۶
۵	DE	۸۲۵	۹۲	۴۰۶	۵۷۶.۱۲	۳۵.۱۰
	ED	۸۲۵	۹۱	۳۶۳	۱۲۲.۱۱	۱۸.۹

3) Calculating travel cost of network link

As shown in the (table I), the travel cost of each link was calculated using Equation (5) and the corresponding cost of each link is inserted in the grid graph, which converts the grid graph into a weighted direction graph. The travel cost of each link is shown as the weight of the edge and is shown in Fig. 5. Obviously, on one-way streets, we do not see a pair of round edges and there is only one edge in one direction between the two joints.

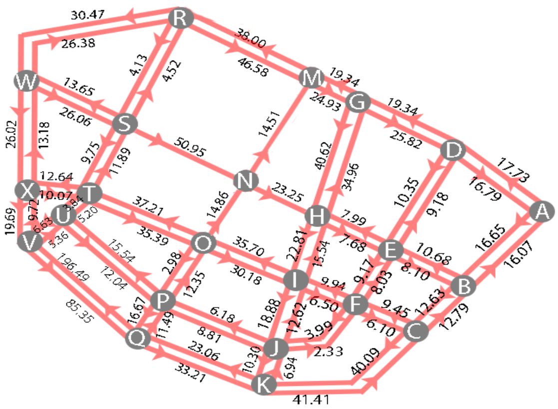


Figure 5. Weighted direction graph of network

4) All-or-nothing assignment and drawing shortest-path-tree

Once the trip cost of the arcs has been determined, the shortest path tree should be plotted for all nodes in the network. Traditionally, this process is very time-consuming and almost impossible for 23 nodes and 75 links. Therefore, due to the importance of this topic to continue the research, using dijkstra algorithm and C++ programming language, this process was done in software.

Suppose S is a pure subset of V, $u_0 \in S$, so we use $\bar{S}$, to represent $V \backslash S$. If $P = u_0 \ldots \bar{u}\ \bar{v}$ is one of the shortest paths between u_0 to $\bar{S}$, then it is clear that $\bar{u} \in S$ and (u_0, u) - part P must be the shortest (u_0, u) - path. as a result [19]:

$$d(u_0,v) = d(u_0,u) + w(u,v) \qquad (11)$$

And distance of u0 to $\bar{S}$ is calculated by following equation:

$$D(u0,\bar{S}) = \min \{ d(u0,u) + w(u,v) \} \qquad (12)$$

This formula is the basis of the dijkstra algorithm, starting with the set $S_0 = \{u_0\}$ the incremental sequence $S_0, S_1, \ldots, S_{V-1}$ of subsets V is created in this way. At the end of step i, the shortest path from u_0 to all the vertices of S_i is determined.

The first step is to determine the nearest vertex u_0. This is done by computing d $(u_0, \bar{S}_0)$ and choosing a vertex such as $u_1 \in S_0$ so that $d\ (u_0, u) = d\ (u_0, \bar{S}_0)$ [19]:

$$d(u_0,\bar{S}_0)= \min \{ d(u_0,u)+ w(uv) \}= \min \{w(u_0v)\} \qquad (13)$$

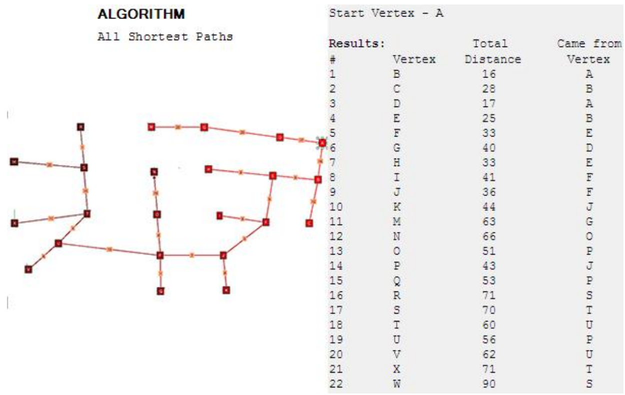
Set S_0 $\{u_0\}$, $l\ (u_0) = 0$, $i = 0$ and also for $v \neq u$ set $l\ (v) = \infty$

For each $v \in \bar{S}_I$, replace $l\ (v)$ with $\min \{l\ (v), l\ (u_0), w\ (u_i\ v)\}$ Calculate $\min \{l\ (v)\}$. If u_{i+1} is the vertex that yields the minimum, set $S_{i+1} = S \cap \{u_{i+1}\}$

If $i = v-1$ stop. If $i < v-1$, replace i with $i + 1$, go to step 2

When algorithm B is completed, u_0 to v distance is determined by the final value of $l(v)$ label. The flowchart of this algorithm is as follows [19].

In the following figure (Fig.6) the shortest-path-tree for node *A* is demonstrated and also travel cost is calculated by (Eq8).



#	Vertex	Total Distance	Came from Vertex
1	B	16	A
2	C	28	B
3	D	17	A
4	E	25	B
5	F	33	E
6	G	40	D
7	H	33	E
8	I	41	F
9	J	36	F
10	K	44	J
11	M	63	G
12	N	66	O
13	O	51	P
14	P	43	J
15	Q	53	P
16	R	71	S
17	S	70	T
18	T	60	U
19	U	56	P
20	V	62	U
21	X	71	T
22	W	90	S

Figure 6. The shortest-path-tree of node A

The figures and tables of shortest-path-tree of each node can be drawn in similar way, and summary of these data is available in the table II.

TABLE II. TRAVEL-COSTS OF NETWORK'S NODES

No.	Joint Name	Cost	No.	Joint Name	Cost
١	B	٧٥٠	١٢	N	١٢٦٠
٢	C	٦٨٣	١٣	O	٦٤٩
٣	D	٧٨١	١٤	P	٥١٩
٤	E	٦٢٩	١٥	Q	٧٣٩
٥	F	٥٤١	١٦	R	٨٣٣
٦	G	١١٧٨	١٧	S	٨٢٧
٧	H	٧٠٤	١٨	T	٦٩٨
٨	I	٧٠٢	١٩	U	٦١٣
٩	J	٥٢٦	٢٠	V	٦٦٨
١٠	K	٦٩٤	٢١	W	١٢١٨
١١	M	١٣٧١	٢٢	X	٨٩٠

5) Calculating travel cost before disaster

After calculating the cost of all nodes according to (Eq 9), we calculate the cost of traveling the entire network in equilibrium condition (before disruption occurs):

$$C_{total}^{(n)} = \sum_i^n C_i$$

$$C_{total}^{(n)} = \sum_i^n C_A + C_B + \cdots + C_X$$

$C_{total}^{(n)}$ =1069+750+683+781+629+541+1178+704+ 702+526+ 694+1371+1260+649+1371+1260+649+519+739+833+827+698+613+668+1218+890

$\Rightarrow C_{total}^{(n)}$ =21822

6) Calculating travel cost before disaster

Now, according to importance and impact of the links on the network, critical link should be determined. As mentioned in the preceding sections, the major criterions of choosing the critical link are: *a)* the number of times the link is presented in the shortest-path-trees of different nodes, *b)* the number of accesses to other joints, provided by each link.

The *importance index* of network's links are calculated and summarized in the table III.

TABLE III. IMPORTANCE INDEX OF NETWORK'S LINK

Link Name	I-I*	Link Name	I-I	Link Name	I-I
BC/CB	4	CF/FC	40	IJ/JI	0
AD/DA	7	JK/KJ	44	HI/IH	3
CK/KC	0	DE/ED	75	HG/GH	4
VU/UV	23	QV/VQ	0	PO/OP	71
XW/WX	4	MR/RM	25	PQ/QP	23
BC/CB	4	CF/FC	40	IJ/JI	0
DG/GD	41	TX/XT	40	NH/HN	17
WR/RW	0	RS/SR	59	GM/MG	24
SW/WS	4	MN/NM	16	EH/HE	52
VX/XV	4	QK/KQ	0	FI/IF	41
ON/NO	23	OI/IO	0	OT/TO	0

*importance index

As shown in the above table, the highest value is inserted in front of the PJ / JP link, followed by the slight difference between the FJ / JF link and the PU / UP and EF / FE stand on the 3rd and 4th place. As can be seen, the critical link of the network is the PJ / JP link, and it is expected that removing or disruption to the link will impose the highest cost on the network and subsequently would generate the highest value for the network robustness index. To prove this, by removing each of these links, we calculate the network travel cost similar to normal condition, except that the intended link is not present in the network and subsequently in the shortest path tree of any vertices.

7) removing important links and calculating travel cost in each node

In this step, network travel cost will be calculated after deleting PJ/JP link.

$$C_A = \sum C_{AB} + C_{AC} + C_{AD} + \cdots + C_{AX} =$$

C_A = 16 + 28 + 17 + 25 + 33 + 40 + 33 + 41 + 36 + 44 + 63 + 74 + 74 + 73 + 102 + 101 + 91 + 87 + 93 + 102 + 121 ➔ C_A=1294

8) Calculating network travel cost in disruption condition

This quantity is calculated by sum of the mentioned costs.

$$C_{total}^{(f)} = \sum_i^n \mathrm{C}_i$$

$$C_{total}^{(f)} = \sum_i^n \mathrm{C}_A + \mathrm{C}_B + \cdots + \mathrm{C}_X$$

$C_{total}^{(f)}$ =1294+1095+1013+1095+943+871+1323+1092+923+875+863+1362+1188+1113+795+800+1107+1090+960+912+1027+1484+1164 ➔$C_{total}^{(f)} = 24389$

9) Calculating the network robustness index (NRI)

The network robustness index is calculated by (Eq10) and since we have calculated this index by eliminating the critical link, maximum robustness index will be calculated.

NRI $=C_{total}^{(f)} - C_{total}^{(n)}$ ➔ $\mathrm{NRI}_{\mathrm{Max}}$ = 24389 – 21822 = 2567

V. RESULTS

As mentioned, many factors such as natural disasters or human factors such as accidents cause disruption to the transportation system. This study focused on studying of short-term disruptions in urban transport systems that have been less addressed in the past, and most studies have focused on long-term disruptions such as earthquakes; while urban transportation system face many short-term disruptions on a daily basis and their impact on the network is more tangible for users.

In this study, we attempted to identify the critical link and calculate the maximum network robustness index (NRI) in an urban transport network. For this purpose, using an all-or-nothing assignment and shortest-path-tree, an index was defined named the importance index that can be used in order for ranking the links in network according to their importance. After ranking the network links, the three important network links, namely PJ / JP, FJ / JF and PU / UP, were identified as the most important network links by 234, 233 and 199 indexes, respectively and are visible in the Fig. 7.

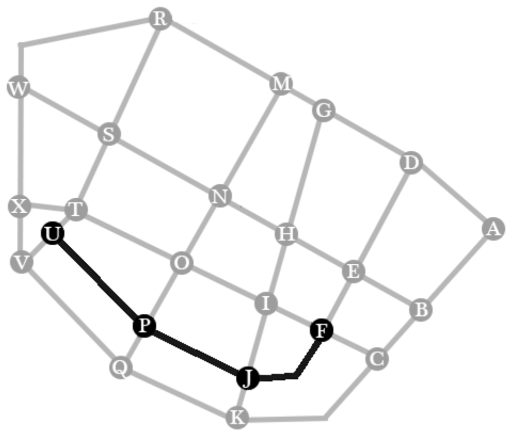


Figure 7. Network's critical links

According to explained concept of network robustness which requires the assumption of disorder in network, each of these links was individually removed from the network and its corresponding robustness index calculated. The result was that the maximum network stability index corresponded to the PJ /

JP link that had the maximum importance index, in other words was the critical link of the network, which is visible in following diagram.

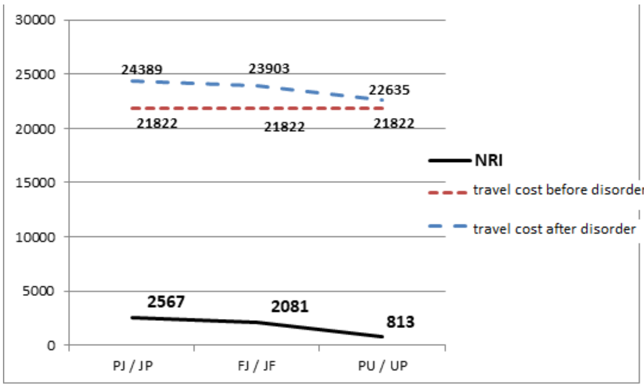


Figure 8. Network stability index diagram

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Kaveh Rezvani Dehaghani, Education: 2015–2017, M.Sc. degree: Transportation Engineering, Supervisor: Dr. Ali Naderan. 2009–2015, B.Sc. degree: Civil Engineering, Supervisor: Dr. Seyed Alireza Zarei.

- *Honors and Awards:*

2019: Acquiring “*Professional Engineer License”* from Tehran Municipality by Provincial Exam
2016-2018: Paper sub-reviewer at the 17th RSI International Conference on Traffic and Transportation Engineering (ICTTE)
2017: Ranked 3rd among M.S. students of Transportation Engineering, Science and Research Branch of Islamic Azad University, Tehran, Iran
2017: Awarded Member of Research Institute of Ministry of Road and Urban Development.
2016: Awarded Member of Iran’s Engineering Organization
2015-2016: Top 10 in National Scientific Olympiad of Civil Engineering.
2014: Top 0.5% rank in National Graduate University Degree Entrance Exam.
2010: Awarded Member of “Spaghetti Structure team” of the Islamic Azad University of Isfahan.
2009: Top 1% rank in National Undergraduate University Degree Entrance Exam among 300,000 participants.
2008-2009: Awarded Gold Medal of the First National Math league

- *Academic Experience:*

2016: Teaching Assistant, Research Branch of Islamic Azad University. Course Title: *Traffic Engineering*. Roles: taught some chapters, solved additional problems, and described problems and projects.
2017: Teaching Assistant, Research Branch of Islamic Azad University. Course Title: *Advanced Transportation Engineering*. Roles: taught some chapters, solved additional problems, and described problems and projects.

- *Research Experience:*

2017-2019: Executive Project of Ministry of Road and Urban Development: Comprehensive Transportation Studies of Isfahan Province.
2018: Research Project of Organization of National Crisis-Management: Modeling and Analysis of Bojnord’s Transportation System against natural disasters.

2017: Research Project of Municipality of Tehran: Robustness analysis of urban transport network-under critical circumstances.
2016-2017: Research Project of Air Force (Passive-Defense): Design of urban aviation relief network: locating of temporary relief airport. (In lieu of obligatory military service).
2016: Research Project of Municipality of Mashhad: Vulnerability Assessment of Urban Road Network

- *Publications:*

A. Naderan, K.Rezvani, "Evaluation of Highway Network's Resistant Ability against Natural Disasters", 16ICCTE, The 16 International Conference on Traffic and Transportation Engineering

K. Rahimov, K.Rezvani, "Evaluation method for Identifying critical network segments with single link failure mechanism", 16ICCTE, The 16 International Conference on Traffic and Transportation Engineering

K. Rezvani Dehaghani, A. Naderan, K. Rahimov "A new method for Evaluating the Urban Transportation Networks' Vulnerability with single link failure mechanism", IWCEA-2017, 3rd International Workshop on Civil Engineering and Architecture

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A. Naderan, K.Rezvani Dehaghani, F, Habibzadeh, "Analysis of road pavement maintenance management, using multiple objective genetic algorithm and Markov chain model", 17ICCTE, The 17 International Conference on Traffic and Transportation Engineering

K. Rahimov, A. Heydari, K. Rezvani Dehaghani, "Speed management in two-ways roads, by using a multinomial logit model", 17ICCTE, The 17 International Conference on Traffic and Transportation Engineering

- *Memberships:*

2016- present: Member, Iranian Society of Instrumentation and Control Engineers
2016- present: Member, Iranian Society of Mechanical Engineers
2017- present: Member, Research Institute of Ministry of Road and Urban Development

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