Effect of Evaluation Parameters on Identification of Critical Links

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Link importance evaluation is of vital importance, both in a state of "business as usual" and in emergency situations. The study in this area is mainly focused either on development of some models for evaluating impact of link removal on accessibility and vulnerability of road network or on proposal of some index to measure link importance directly. The link importance is geometrically evaluated mainly based on its location within a network i.e. under the effect of network topology. But, in some cases, in addition to its geometric importance, other attributes like traffic volumes combined with link capacities (volume to capacity ratio), travel times, and the population of nodes are included for identification of critical links. Such measuring factors are basically used to simulate some specific scenarios like travel time variations on a congested networks at some particular time of the day, day-to-day interruptions due to accidents, or placement of rescue facilities, and can significantly affect the results. In this paper a basic measure, Network Path-length Index (NPI), has been proposed to evaluate the geometric importance of a link within a road network. This is attained by revising the shortest path lengths after removal of subject link, thereby reflecting solely the effect of network topology. In absence of congestion effects in travel time computation, travel distance is a good proxy for travel times and travel cost as well, the two parameters excessively used in literature for critical link identification. The results for identification of critical link under combinatoral effect of network topology and other node/link attributes are compared with that of results by NPI. Such comparison clearly indicated drastic change in critical link identification as a result of changing the evaluation parameters.

Key Words : *link importance, network topology, evaluation parameter, network path-length index*

1. INTRODUCTION

In a road network, link evaluation is of vital importance both in state of "business as usual" and in emergency situations. Firstly, in the case of routine matters, it is necessary for prioritization and ranking of different road links to get the best possible return value of each single dollar spent, both in investigating the feasibility of addition of a new road link in a road network or when the existing network is subjected to maintenance activities. Secondly, for preparation of any evacuation plan or in transportation of either people or goods, finding the safest and shortest path to complete the task in minimal possible time is the first step. Therefore, it is of utmost importance to identify the important road links as well as to keep these links in better working condition. There can be another scenario of critical links identification in a road network to avoid functional isolation of certain areas[1)]. The presence of such links plays a primal role in the connectivity and accessibility between its parent/adjacent nodes and the rest of nodes in the road network.

For link importance evaluation, the research is mainly focused on two different approaches. First approach is the development of some models, quantifying the link importance and criticality in terms of its contribution to network accessibility (or vulnerability). A range of different assessment parameters like accessible length of road network, connectivity between nodes, travel times, and travel costs were used. For instance, out of the recent studies about network interdiction, Church, R. et.al (2007) introduced the concept of r-interdiction and proposed a model for development of reliability envelopes to choose the best facilities to be closed. The proposed envelopes were able to draw the effect of predefined number of links closed through a successful attack on the objective values; termed as the best and the worst case efficiency. Timothy, C.M. et.al. (2007) proposed a model based on maximum flow-minimum cut theorem, capable of producing upper and lower bounds on the loss of connectivity that may result from interdiction efforts at multiple number of network linkages. A quite different approach of area covering disruption was introduced by E. Jenelius et.al. (2012) to analyze the impact of multiple link failure. The consequences of disabling multiple links falling in proposed evenly displaced grids were analyzed in terms of change in travel times of the road network.

Second approach for link importance assessment is that of introducing some indexes or direct measures. For instance, M.A.P Taylor et.al. (2006) summarized the indexes, namely Hansen integral accessibility index and Accessibility/remoteness index of Australia (ARIA). The measures are used to investigate the link importance in terms of accessibility with and without presence of that particular link. The limitations include their lesser use for smaller areas with sparse populations. Sakkakibara, H et.al (2012) proposed an index derived from molecular science, Topological Index (TI), for road network robustness. The measure proposed was effective to evaluate isolation of districts, and to specify effective road links to avoid functional isolation of different areas in disasters, as well as calculating contribution of additional road links to existing road network connectivity/robustness. Similalry, Y. Luping et.al. (2012) used user's lost time as a measure to examine the network vulnerability, (from a specific origin node to defined destinations), as a result of loss of link availability. They took into account not only the network structure, but also the traffic flow state and setting of rescue centre.

A new measure for evaluating the importance of highway segment to the overall system/network, Network Robustness Index (NRI), was proposed by D.M. Scott et.al. (2006). The measure quantified the change in travel time cost associated with rerouting all traffic in the system should that segment becomes un-available. Further, an extension of NRI to Network Trip Robustness (NTR) was proposed by J.L. Sullivan et.al (2010). A link-based capacity reduction approach for simulating both the impact of frequent day-to-day network disruptions on system-wide travel times and the isolating links, was proposed. An application of NTR to a real road network was presented by D.C. Novak et.al. (2012).

In summary, we can conclude that indexes for the link importance evaluation have been proposed in literauture by taking into account the network topology combined with some other attributes like population and traffic volumes, travel costs etc. The need for a measure to identify the critical links, only under the effect of network topology is more for underdeveloped/developing countries, where data about the evaluation parameters for a road network is hardly available. Secondly, the effect of including other parameters in identification of critical links needs to be investigated in detail. In this paper, a measure has been proposed to identify the critical links under the sole effect of network topology. A comparison between the results under network geometry only and that of with some evaluation parameters is made to investigate the impact of including such parameters on critical link identification.

2. PROPOSED MEASURE

The measure proposed, Network Path-length Index (NPI), quantifies the link importance as a fraction of increase in sum of all shortest path lengths between all OD pairs of the network as a result of link removal. The measure takes into account the effect of network topology by calculating the revised shortest path lengths in the case a link is removed.

(1) Definition

Network Path-length Index of a link L, NPI_L, is the ratio of sum of all ODs shortest path lengths when the link L becomes unusable to the sum of all ODs shortest path lengths when the link L is available.

$$NPI_L = \frac{\sum \text{All OD Path-lengths without link L}}{\sum \text{All OD Path-lengths with link L}} \qquad \textbf{(1)}$$

(2) Explaination

The equation (1) is explained with the example shown in Fig.1, which shows a simple road network comprised of 4-nodes and 5-links. The link lengths are also shown. When all of the links are intact, the sum of shortest path lengths, for all nodes as origins as well as destinations, is 76. This is termed as the base case. For calculating NPI of link AB, the link is removed and revised sum of

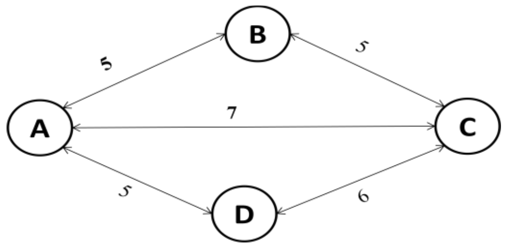

Fig.1 Sample road network for NPI explanation.

shortest path lengths from all origins to all destination nodes is calculated which comes out to be 92. The ratio between this increased sum of the shortest path lengths to the base case, which is 1.21, is the NPI of link AB.

When a link is removed, at least one of the shortest path lengths (path from node attached on one side of the removed link to the node attached on other side of the same link) is increased, causing an increase in overall sum of shortest path lengths. Therefore, the value of NPI will always be higher than 1.00 indicating the increase in path-lengths as a removal of a link.

3. EFFECT OF MEASURING FACTORS

In this section, a comparison of NPI with three indexes described briefly in section 1 is made to get a general view about the impact of evaluation parameters.

(1) Index by D.M Scott et.al 2006

The first comparison is made with Network Robustness Index (NRI), proposed by D.M. Scott et.al. (2006). The NRI was introduced because, the typical measure used for link importance evaluation, volume to capacity ratio (V/C), was argued to be misleading. The V/C ratios are typically used for qualitative assessment of road links (Level of Service: Highway Capacity Manual 2000), rather than for link importance evaluation within a network. The value of V/C ratio identifies any need for link capacity improvement based on prevailing traffic conditions. The results of NRI for one of the networks (network-c) by D.M Scott et.al. (2006) are reproduced here in Fig.2 for comparison purposes.

There were mainly two arguments stated for the proposal of NRI for identification of critical links. Firstly, the conventional V/C ratio can mislead in some cases for identification of critical links. Secondly, the proposed index is comprehensive enough than V/C ratio that in addition to effect of traffic deployed, it can take into account the effect of network topology as well by rerouting the traffic volumes of removed link. Thus the measures can be used in wider perspective of comparison between different road networks. The observations about the NRI and the road network data used for their case-study(3-networks, a,b,c with different number of links) can be summarized as follows:

(1): Increase in system-wide travel times for sparser networks with same travel demand (traffic volumes) was observed which is an obvious output, rather than indicative of the effect of network topology.

(2): For a road network with higher average V/C ratios, the effect of congestion in increased travel times will be much higher than that of network topology. This fact is pointed out in Highway Capacity Manual 2000 by stating that at a traffic volume level equal to capacity of a road link, traffic stream has no ability to dissipate even the minor disruptions and any incidence produces serious breakdowns.

(3): The road networks used for NRI calculations comprised of road links with different capacities (non-homogeneous network). If network with all links of same capacity (homogeneous network) has been selected for study, the critical links pointed out both by V/C ratio and that by the NRI may be identical.

(4): The network-c with highest average V/C ratio shown in Fig.2 was identified to be the most critical by the NRI. The mean value of V/C ratio of this network was 1.766 (max.3.485, min.0.378) for base case. For NRI calculations, average V/C ratio after link removals increased to 1.824 (max.2.085, min. 1.758). The values clearly indicate massive impact of congestion. Even the minimum V/C ratio for NRI calculations increased to the mean value prior to link removal.

A critical review of the discussion above reveals that there are mainly two components contributing to travel time calculations, as illustrated in Fig.3. First, the travel distance or the path length, and second the effect of congestion. The travel distance between any two nodes in a network, being dependent on availability of alternative/shortest path routes or connectivity, is indicat-

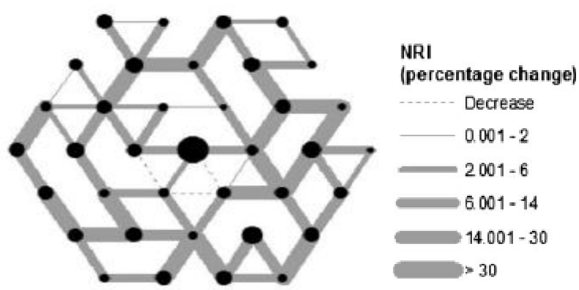

Fig.2 NRI results for trial network-c (D.M Scott et.al. 2006)

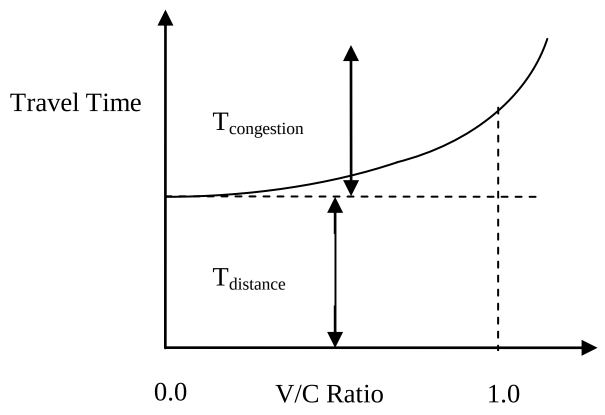

Fig.3: Travel time components and effect of V/C Ratio

ive of network topology and is more or less constant. The second component of congestion effects, being dependent on existing traffic volumes, is highly variable and is mostly taken as a qualitative measure of link performance. Higher the V/C ratio more will be the effect of this component in travel time. For a value of V/C>1.00, the effect of congestion can be more dominating than that of the effect of network topology. The results presented in Fig.2 also point out this fact, as travel times after link removal increased to values upto 375% of their original values.

In this paper, we have used a measure, NPI, to evaluate the importance of certain road link within a road network, taking into account the topology of road network solely. Using this measure, the results of percentage change in sum of shortest path lengths, from all nodes as origin to all nodes as destinations, are calculated and plotted on the same network-c shown in Fig.4 for comparison with that of NRI. The values ranged from a minimum of 0.04 percent to a maximum value of 5.5 percent. If we compare the results of NRI and NPI, the first difference is that the links identified to be critical are quite different. Also the percentage change from base case sum of shortest path-lengths is not as much higher (max. 5.5%) as that was observed

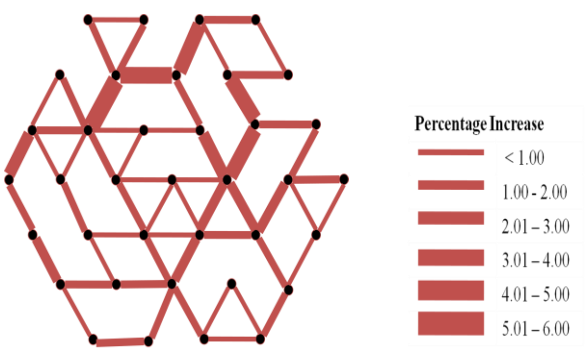

Fig.4: Percentage change in sum of shortest path-lengths from base case.

in Fig.2 (max 375%) for travel times. Secondly, none of the link removal showed decrease in sum of pathlengths, as it was the case in Fig.2, where removal of three links located near to center of road network resulted into decrease in sum of network travel times. Such a finding is contradictory to the concept of resilience as well i.e. addition of some link must provide additional alternate paths, thereby reducing the congestion and total network travel times.The authors also stated this result as “unexpected”. The NPI for these links with negative NRI values came out to be positive. Further, NPI of one link out of these three quantified it to be the critical one of moderate level (percentage change between 2.0 to 3.0).

(2) Index by YANG Luping et.al 2012

The second comparison of NPI results for critical link identification is made with that of the results of network vulnerability analysis by YANG Luping et.al.(2012). For the trial network shown in Fig.5, YANG Luping et.al.(2012) investigated the network vulnerability under the impact of network structure, origin destinations location and the placement of rescue centre. They calculated the user’s time lost, from specified origin to some destinations, for all link failures in two steps. The minimum time loss out of the two steps was taken to be the final loss time of the network user. In the first step of their study, they calculated the time lost in waiting for the rescue (for the location of rescue centers as show) if some particular link is closed because of any accident. In the second step they calculated the users lost time for seeking the substitute route to reach the destination. They assumed node “A” as origin node and “G”, “H”, “K” points as destination nodes. They found the link CE to be the most expensive in terms of time lost in case of its failure, and thus the most important, for users to travel from stated origin to destinations. For comparison purposes, we calculated the NPI values for the same network as presented in Table 1. The results are similar only upto this extent that the most critical link identified by both of the methods is found to be the same i.e. link CE. But this similarity is not more than a coincidence. A quite different link importance order/ranking can be observed by the two measures, indicating the difference between the results of NPI and that of by their method.

(3) Index by M.A.P Taylor et.al 2006

The third index compared with NPI is the index proposed by M.A.P. Taylor et.al. (2006). They summarized three indexes, the measure of generalized travel cost between a full network and dama-

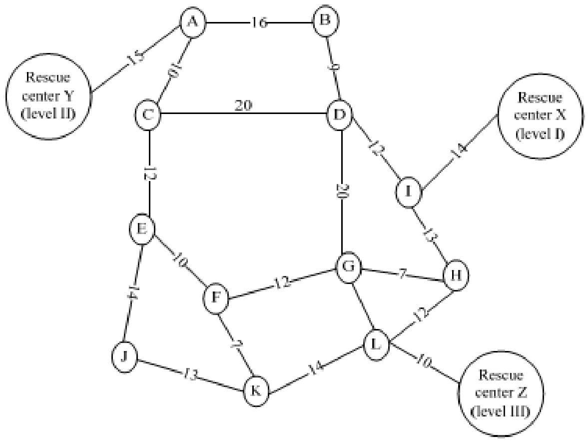

Fig.5: Trial network (YANG Luping et.al. 2012)

Table 1 Comparison between Yang et.al 2012 results and NPI

Link	Final Loss time of the network users	NPI
AB	0.22	1.024
AC	0.25	1.092
BD	0.24	1.108
CE	0.42	1.194
DI	0.19	1.061
EF	0.39	1.102
FG	0.17	1.065
FK	0.33	1.035
HI	0.19	1.049

ged network, Hansen integral accessibility index and Accessibility/ remoteness index of Australia (ARIA). The critical locations within a network were identified to be those with most severe socio-economic impacts as a consequence of network failure at those locations. The approach is similar to the one adopted in our study with the difference that another attribute of demand for movement from an origin node to the destination node (normalized weight calculated based on gravity model based on the population of origin and destination cities and the distance between them) is multiplied to the change in generalized cost with the net work intact and without the link under investigation. Then, by summing up all the OD pairs and using the calculated weights, overall network travel time increase was calculated. For our comparison purposes, the Australian National Transport (ANT) Network is simplified by using the data presented in their study as shown in Fig.6. The values of NPI are calculated for each link removal as presented in Table 2.

It is pertinent to note here that the population of each city varies greatly from each other, as shown in Table 2. The impact of population was incorporated in computation of index proposed by M.A.P. Taylor et.al. (2006). The summary presented in Table 2 depicts that Perth-Adelaide link removal causes the maximal increase in travel distance (NPI). On the contrary, M.A.P. Taylor et.al. (2006) found three cities, Sydney, Melbourne and Canberra, lying on the same highway, as the nodes suffering the most in terms of travel time increase with removal of links between these nodes. The links between these three cities were found to be least important in our results of NPI, thereby clearly suggesting the magnified impact of other factors (i.e. population) in the index proposed by M.A.P. Taylor et.al. (2006). This is also evident from the population of two major cities, Sydney and Melbourne, which are highest among all cities

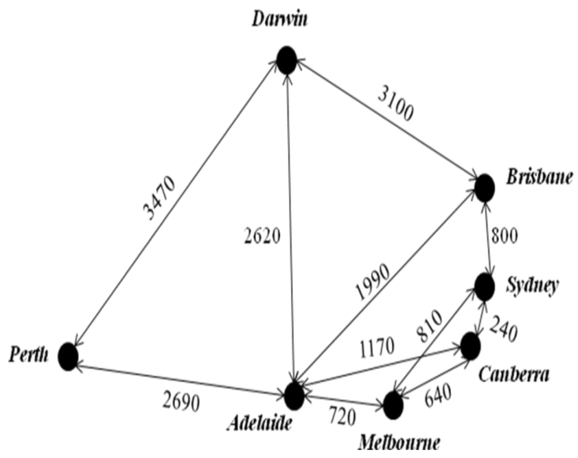

Fig.6 Simplified Australian National Transport Network (M.A.P. Taylor et.al. 2006)

Table 2 Results of NPI for ANT network

Link Removed	NPI	Population	
Perth-Adelaide	1.311	**City**	**Pop. (1000)**
Perth-Darwin	1.037	Perth	1176.5
Adelaide-Melbourne	1.066	Adelaide	1002.1
Adelaide-Canberra	1.016	Melbourne	3160.2
Adelaide-Brisbane	1.009	Canberra	339.7
Adelaide-Darwin	1.085	Sydney	3502.3
Melbourne-Canberra	1.008	Brisbane	1508.2
Melbourne-Sydney	1.003	Darwin	71.3
Canberra-Sydney	1.054		
Sydney-Brisbane	1.120		
Brisbane-Darwin	1.033		

mentioned. The third important node identified in their study, the city of Canberra, lies in between these two cities. This contradiction between the findings of the study by M.A.P. Taylor et.al. (2006) and that of our study, NPI, suggests the importance of another factor for link importance evaluation, and that is the poplation of the nodes of that road network. Higher is the population of the origin and destination nodes, more will be the importance of link connecting these nodes and vice versa.

4. CONCLUSIONS

The critical link identification is of utmost importance both in state of "business as usual" as well as in emergrncy situations. Firstly, it is necessary for prioritization and ranking of different road links when either addition of new link is to be investigated or the existing network is subjected to some maintenance. Secondly, for preparation of any evacuation plan or in transportation of people or goods, finding the safest as well as the shortest path to complete the task in minimal possible time is the first step.

The study in the area of network interdiction and link importance evaluation being derived from graph theories is not the new one. For link importance evaluation, the research is mainly focused on two different approaches. First approach is the development of some models and methods for such purposes, focusing mainly on link importance and criticality in terms of accessibility and network vulnerability. Second approach for the link importance assessment is that of introducing some indexes or direct measures.

The measure proposed in this study, Network Path-length Index (NPI), quantifies the link importance and takes into account solely the effect of network topology by calculating the revised shortest path lengths in the case a link is removed. A comparison of NPI with different indexes already proposed in literature is made. From the results, we have found that by changing the measuring parameter for critical link identification, the links identified may be absolutely different than those identified solely based on the network topology. For instance, the comparison between NPI and NRI suggested to investigate the critical relationship between the travel time components .i.e. travel times due to distance/path-lengths and that of due to congestion. In absence of congestion effects, the proposed measure of NPI, which is purely based on travel distances, can be a good proxy for travel costs and travel times. However, if congestion effects are to be taken into account, it is necessary to investigate firstly the trade-off between the two major components of travel time before drawing the conclusion about the effect of network topology or that of congestion. By comparing the results of NPI with that of M.A.P. Taylor et.al. (2006), an other contributing factor, population of a node was also found to affect the importance of links connected to this node.

It may be conclded that it is important to investigate the critical links firstly based on network geometry and connectivity, as these are permanent features of any road network. Other link or node attributes included in critical link identification are comparatively temporary and dynamic in nature. i.e. changing their values from time to time. Moreover, the data about the evaluation parameters may be hardly available in some countries. Therefore, care must be observed by transportation and emergency planners while deciding the critical links. The extent of effect of additional parameters be checked and a clear tradeoff between the geometry of the network and these evaluation parameters be known well before time.

The NPI can be used for link importance evaluation within a road network. An extension of measure for comparison between links of different road networks is suggested. Also, an example from real road network data may be discussed to illustrate the importance of proposed measure.

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