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Analysis of Rural Road Networks Considering Redundancy

Jagat Kumar Shrestha

Civil Engineering Department, Pulchowk Campus,Institute of Engineering, TU
Kathmandu, Nepal

ABSTRACT

A new evaluation method for the redundancy of rural road-links is introduced in this paper. The study provided the distance based link redundancy measures. The methodological contribution in this paper comes in exploiting the evaluation concept with a view of Link Redundancy Index (LRI). This method will be useful to the decision makers as a simple tool for predicting and monitoring the road performance to improve the rural road network to a robust network for the mobility of goods and services in rural hilly areas.

Keywords—rural road network, redundancy, Link Redundancy Index

I. INTRODUCTION

Rural road networks are the backbone of physical and social development in hilly areas of Nepal. The networks are being developed in Nepal but in a haphazard way. This has created many landslides making the hill environment very vulnerable to disasters. On the other hand, we need sufficient level of connectivity in the network even in a reserve level to serve in the situation of blockage and disaster. These networks are to be developed optimally considering the need of the road in the hilly regions of Nepal and cost of construction and maintenance. There is always a trade-off between them to utilize scarce resources in an optimal way. Hence, ananalysis of rural road networks considering redundancy has been envisioned in this research which will develop a scientific tool and helpful to make rational decisions in construction, maintenance and development of rural road networks in Nepal to save huge junk of resources.

In 2014, Arniko highway in Nepal was suffered from floods. It was the international highway to China, only the gateway to trade to China. There was no alternative link to the Chinese boarder. Further, the road was heavily damaged by the 2015 Gorkha Earthquake. Still the road is in the blockage stage. Also, despite major calamities, blockage of mountainous road due to landslides is the common problem during every monsoon in Nepal. Further in rural areas, the problem is more common as the hill roads are commonly earthen and gravel roads. The earthen roads are pliable in the dry seasons only. Due to this reason, most of the people residing the mountainous hilly region has no options for alternative connection by roads in the time of natural disaster and accidents. The problem of delivering goods and services to the affected people and the region is the common problem and a critical issue. Hence, alternative links to the existing road network is required to minimize the degree of the problem. However, cost is always associated with any intervention. Hence, the investment is to be based on the need and identification of the situation and the predicting the possible intervention based on a rational decision making tool.This work is devoted to develop the tool that evaluates the existing situation and propose the optimal intervention which will be useful to the decision makers to plan and develop an optimal road network considering the spare links for route diversity.

II. REDUNDANCY IN ROAD NETWORKS

The concept of redundancy has been studied in different disciplines including reliability engineering, water distribution system, internet network, and so on. In reliability engineering, redundancy is the existence of more than one means for accomplishing a given function, and each means of accomplishing the function is not necessarily identical [10]. Redundancy in water distribution system is defined as the existence of alternative pathways from the source to demand nodes or excess capacity in normal operating conditions when some components of the system become unavailable [11]. In transportation network, Redundancy is one of the four “Rs” (Robustness, Redundancy, Resourcefulness, and Rapidity) proposed byBruneau et al. (2003) [9] for assessing resiliency of the system. Some researchers have introduced variousmeasures for assessing the resiliency of transportation networks and redundancy is one of those measures. Forexample, Godschalk (2003) [11] and Murray-Tuite (2006) [12] defined redundancy as the number of functionally similarcomponents which can serve the same purpose, and hence the system does not fail when one component fails. Arelevant concept of redundancy is diversity, which refers to a number of functionally different components thatprotect the system against various threats (e.g., alternative transport modes). Similarly, Goodchild et al. (2009)[8] defined redundancy as theavailability of multiple alternate routing options in the freight transportation network. Jenelius (2010) [2] proposed the concept of redundancy importance to consider the importance of links as backup alternatives whenother links in the network are disrupted. Two measures (i.e., flow-based and impact-based) were proposed toquantify the redundancy importance. The flow-based measure considers a net traffic flow that is redirected to thebackup links and the impact-based measure considers an increased travel time (cost) due to the rerouting effect.However, these two measures assess only the localized redundancy importance of a transportation network. In otherwords, they are not able to capture the diversity of alternatives, an important property for measuring networkredundancy. He argued that the diversity of available routes when the primary choice is inoperative needs to beexplicitly considered in the redundancy characterization. Furthermore, the route diversity alone may not be a sufficientmeasure of redundancy as it lacks the interaction between transport demand and supply (i.e., congestion effect dueto limited network capacity). Indeed, redundancy should also indicate the state of backup or spare capacity of anetwork. However, in the case of rural road network, the capacity of a network is not a problem.Therefore, the concept of redundancy can be limited and dealt with single dimension of route diversity.

III. EVALUATION OF REDUNDANCY IN ROAD NETWORKS

Some researchers has evaluated redundancy considering the static conditions of the network such as **road density** in the road transport network. Jenelius (2009) [1]stated that a higher road density to some extent guarantees a higher availability of alternative paths. However, road density only considers the fully operational link status e.g. by adding the link length to the whole network length or subtracting link length when the link is fully closed. Hyder Consulting (2010) [3] estimated the redundancy value of a link as the total number of motorways,A roads, and B roads within a 10 kilometre radius of the link (A roads – ‘major roads intended to provide large-scale transport links within or between areas; Broads – roads intended to connect different areas, and to feed traffic between A roads and smaller roads on the network’ [4]. However, that will not be the situation in rural areas like in mountainous terrain in Nepal. Both approaches [4] [2] introduced static, purely topological indicators. Graph theory has also been used to quantify the redundancy of networks by using a number of indices, such as a clustering coefficient and the number of independentroutes [5]. The clustering coefficient, also known as transitivity, is a measure of redundancy as it represents the overall probability for the network to have interconnected adjacent nodes [6], which could be measured by different indicators [5]. The clustering coefficient is a significant characteristic of road transport network redundancy, though, it only considers the directly neighbouring nodes or links and neglects possible capacity limitations which may restrict redundancy.

Jenelius (2010) [2] introduced a ‘redundancy importance’ concept as a new way to study the role of the link in network redundancy. The author quantified the importance of redundancy in two ways. Firstly, the importance of flow-based redundancy was calculated as the weighted sum of the difference in flow arising from the closure of all links in the network. Secondly, an impact based redundancy importance measure was computed as the weighted sum of the difference in the impact measure arising from the closure of all links in the network.

Average path length concept is also used in network topology that is defined as the average number of steps along the shortest paths for all possible pairs of network nodes. It is a measure of the efficiency of information or mass transport on a network.

Average path length is one of the three most robust measures of network topology, along with its clustering coefficient and its degree distribution. The average path length distinguishes an easily negotiable network from one, which is complicated and inefficient, with a shorter average path length being more desirable.

IV. AVERAGE PATH LENGTH

In complex networks, the distance d_{ij} between nodes i and j is defined as the minimumnumber of the sides connecting the two nodes; the network diameter is defined as the largestdistance of two random nodes; the average value of the distances of all the node pairs of thecomplex networks is marked with L, which reflects the degree of separation between nodesand can be calculated by the following formula[7]:

$$L = \frac{1}{N(N-1)} \sum_{i \neq j} d_{ij} \tag{1}$$

where N is the node number.
The path length of urban road network is the distance from one intersection to anotherand the average path length L refers to the average value of the shortest path length betweenall intersection pairs.

V. DEFINITION OF THE LINK REDUNDANCY INDEX (LRI)

The earliest studies on road network disruption provided the concept of road network vulnerability [13], and such provisionwas the starting point of the increase in the number of studies on road network performancein terms of vulnerability or robustness. The studies on vulnerability orrobustness of road network are often associated with link criticality analysis, which is usedfor ranking the importance of road network component like bridges [13]. As a network component is more critical, the malfunctionof the component would give more severe damage to the network system, and the vulnerabilityof certain area including the component would then be greater. Thus, analysingcriticality of each component under disruptive situation would be the pre-process of vulnerabilityanalysis. Note that the term in this paper, criticality, has a similar meaning to theterm, 'importance' used by Jenelius, Petersen, andMattsson (2006) and Jansuwan and Chen(2015), which represents only the degree of consequence of disruptive event regardless ofthe probability of such event occurring.

Several measures of road link criticality have been proposed, and the measures providedby Jenelius, Petersen, and Mattsson (2006) [14] are the prime examples. The importance measure proposed by Jenelius, Petersen andMattsson (2006) [14] depends on the increase of travel cost for all OD pairs of the non-failedlinks within a network. They derived the values of importance measure for eachroad link in the form of increased travel time per vehicle. Scott et al. (2006) [15] proposed ameasure called Network Robustness Index (NRI), which is an expression of increased travelcost when a link is failed.

In the similar fashion, in the context of rural hill road network where the network is uncapacited as the traffic volume is very less (less than 100 vehicles/day), we can define a new measure, the Link Redundancy Index (LRI), for evaluating the critical importance of agiven roadlink (i.e., network link) to the overallsystem as the change in travel-time cost associated withrerouting all traffic in the system.For this situation In formulating the measure, let the distance d_{ij} between nodes i and j is defined as the shortest distance between the node i and node j. The link-specific index isderived in two steps.

First, the system-wide, we can calculate average path length removing the link, La, is given by the followingequation:

$$La = \frac{1}{N(N-1)} \sum_{i \neq j} d_{ij}\ \delta_{ij} \tag{2}$$

Where,

$$\delta_{ij} = \begin{cases} 1; if\ link\ a\ is\ not\ removed \\ 0; \text{otherwise} \end{cases}$$

Second, this La is compared to the system-wide, L incurred when all links are present in the network(i.e., the base case) which canbe calculated using Eq. (1).

$$R = La - L \tag{3}$$

R is the value of the LRI for link a in units such as km. Although we define Eq. (3) in terms of changein distance, the index can be generalized tomeasure change in monetary cost.

VI. CASE STUDY IN THE REAL ROAD NETWORK

The case study is carried out to demonstrate the concept of LRI in a rural road networks.For this purpose, the road network (171 km) of BhimsenGaupalika of Gorkha district, Nepal has been considered whichcovering101.25 km2. A Gaunpalika is the second lowest administrative division of Nepal. For the test instance, the Minimum Spanning Tree (MST) of the road network is formed to identify the backbone links in the network. In the hilly road networks, the MST is taken as the minimum level of connectivity necessary for the region to provide access to the settlements and public facilities. Furthermore, additional links are necessary in the network for the diversity for the time of disruption of any link. This network contains 93 nodes and 106 links. The network contains all type of links including tracks of the under construction roads.

Figure 1: BhimsenGaupalika road network

Table1: LRI in BhimsenGaupalika road network

S.N.	Removed Link ID	Length (km)	Average Length (km)	R=La-L
1	Not Removed	171.401	11.324	
2	117	167.342	11.726	0.40
3	145	170.553	12.332	1.01
4	146	169.774	12.580	1.26
5	157	170.291	13.042	1.72
6	160	168.847	12.143	0.82
7	216	167.628	11.781	0.46
8	220	169.928	12.086	0.76
9	209	169.664	12.330	1.01
10	206	170.228	12.215	0.89
11	113	170.427	11.731	0.41
12	114	170.724	11.589	0.26
13	111	167.198	11.319	(0.01)
14	194	170.341	11.935	0.61

Based on the analysis, Table 1 has been obtained in which link 157 in the road network (Figure 1) has the highest LRI and is the most critical link in the network. There must be the spare links for route diversity to divert the traffic through the link. Hence, a circuit of network is required, the role of non-backbone links (black thick links in Figure 1) which are in circuit with the link 157 are now important to quickly bypass the traffic. Otherwise, the traffic should detour a long distance to reach the nearby nodes, and will have huge impact on cost and importance of delivery of goods and services during emergency. In this context, constituting appropriate management strategies for road links in a certain network system is an important process for minimizingperformance loss of the system under disaster situations. This information is also important for maintenance andrepair works period. For this matter, evaluatingthe LRIindex of each link in road network has to be performed,because such information would be useful while constituting the development strategiesfor road links in the network.

VII. CONCLUSION

A new evaluation method for the redundancy of rural roadlinks is introduced in this study. The study provided the distance based link redundancy measures.Such measure is derived by comparing the behaviours of the road network in normal and eventsituations.

The methodological contribution in this paper comes in exploiting the evaluation conceptwith a view of Link Redundancy Index (LRI). As a link of a network isdisrupted, the path for some vehicles would be altered and this would cause a local influenceof traffic. Due to the local influence, traffic in the disrupted network should detour a long distance in the network, and so will impact the cost and performance of the network. Such phenomenondue to the local influence can be captured for evaluating the LRIof the disrupted link.

An advantage of using this LRI measure is that we may not even require afull microscopic simulation to predict the network performance loss. Particularly in termsof monitoring the performance in real-time, the information of OD demand distribution ordriver's routing is very difficult to be obtained in real-time a cost endeavour. So, instead of usingODtravel information, with the LRI measure,the road performance loss also can be predicted only with the simple link length data collection in the rural road network. This method will be useful to the decision makers as a simple tool for predicting and monitoring the road performanceto improve the rural road network to a robust network for the mobility of goods and services in ruralhilly areas.

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