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Analysis of Hill Road Network Structure in Developing Countries

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ABSTRACT : *The purpose of this paper is to identify the critical road links and intersections in a road network which have a great influence on the road network. A framework of road network structure measurement model is proposed. The node importance number and the link importance number are introduced in this model to define road network structure. Using this model, the critical components of the road network can be identified. Then, necessary interventions in a road network can be designed to improve its structure either adding a new link/s or upgrading the properties of the existing link/s or node/s (e.g. geometry, safety, capacity). The road network of the hill town of Tansen in Nepal is analyzed by using this model. The network structure measurement method proposed in this paper can be generalized to hill road network in developing countries.*

KEYWORDS: *road network, link importance number, small hill town*

I. INTRODUCTION

The expansion of cities has changed over time, and modern towns experience rapid, often uncontrolled patterns of growth [1]. Most of these networks display natural systems [10]. However, many issues related to connectivity and capacity of road network system in cities is a complex problem. Robustness of network is one of the critical issues in urban road networks. Blockage at intersections or road segments due to some causes (e.g., earthquake, flooding, landslide, erosion, and incidents) can hamper the accessibility to basic and emergency urban services. More specifically, it can hamper accessibility to the urban public facilities (hospitals, ambulances, fire brigades, schools, major administrative offices). In this way, Road network is the most basic and important issue in our daily lives and emergency evacuation.

For example, in 1995, Kobe earthquake nearly destroyed all the surrounding transportation systems with many roads, railways, and high-speed inter-city rails damaged. Similar kind of catastrophic disasters and transportation network disruptions have exposed our lack of knowledge about the extent and impact of these disruptions. Many areas suffered extensive loss of life and property damages along road networks. These events have highlighted the fact that disruptions in transportation systems have a huge impact on the safety of the infrastructure, mobility and accessibility for people, the efficiency and the vitality of the economy [12]. In many literatures, Graph Theory has been utilized to characterize road networks [5], [6], [11], [10]. Indexes α, β, and γ give the basic measures of the structure of road networks [14]. However, these indexes cannot reflect the role of every link or node in the network connection or they cannot directly measure the impact of the disruption of links or nodes on the network. Hence, an alternative method has been developed to define the structure of networks [7], [8]. Further, the concept has been extended to define the structure of road networks in an efficiency-based model [15].

Alternatively, the robustness of a network is studied how it becomes fragmented as an increasing fraction of nodes is removed from the network [3]. Still, these models cannot quantify the most likely visited nodes and links so that the role of each node and edge in a network. Hence, a study on identifying the role of nodes and edges in urban road network especially in developing countries is a relevant issue, and this represents a scope of this paper. The concept of robustness may be approached from different angles mainly dealing with overloaded network links. In this effort, however, we focus on the importance of network links and nodes as links are not congested. In this context, this paper studies the application of network connectivity model on the structure of a road network. The model is applied to Tansen hill town road network. The connectivity of each node and link is given to identify which are important nodes and links. The outline of this paper is as follows: Section 2 presents the road network structure measurement model. Section 3 discusses the case studies in the small hill town, Tansen Town in Nepal. Finally, Section 4 presents the conclusions and issues to be carried over for further studies.

II. ROAD NETWORK STRUCTURE MEASUREMENT MODEL

We can use **G** to represent the structure of road network with N vertices and E edges. **G** represents the both structure of the existing road network or the network with removed a part node or link. The graph G has N × N adjacency matrix $[a_{ij}]$ whose entry a_{ij} is 1 if there is an edge joining vertex i to vertex j, otherwise is 0. Then, road network can be taken as undirected graphs which show the general structure of road network without considering the actual flow. The network property of **G** is then can be described by N × N distances matrix $[l_{ij}]$. In the distances matrix $[l_{ij}]$, l_{ij} is the geographical distance between intersections i and j. When there is no link between i and j, $l_{ij} = +\infty$. The shortest path length d_{ij} between i and j is the smallest sum of the distances throughout all the possible paths in the graph from i to j (Floyd-Warshall algorithm, 1962). The matrix $[d_{ij}]$ can be calculated by using the information contained in the distances matrix $[l_{ij}]$. So $d_{ij} \geq l_{ij}$, $\forall$i, j, the equality being valid when there is an edge between i and j. L is the average distance between two generic vertices of the road network structure given by the following equation [13]:

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

For a small-world network [8], the model can be based on undirected weighted networks. In terms of properties of the graph, basic measures of the structure of the road network α, β, and γ indexes can be calculated. Moreover, we introduce node importance number (I_n) and link importance number (I_l) in the road network as network properties to quantify how the nodes and links of the network likely attract the flow. These numbers can be calculated based on the use of node or link used during formation of the short path matrix $[d_{ij}]$ and can be normalized to the highest value. This study measures the numbers in the road network and average short path length. If a road link or intersection is interrupted, the vehicles can find an alternative short path. Hence, the concept of using short path is used in this study as the network is not congested and lies in similar road geometry in similar terrain. The node importance number (I_n) can be considered as the centrality measure among the nodes of the road network and link importance number (I_l) on the other hand, can be considered as the importance of the link among the links within the road network considered. Hence, the impact of removing/adding a road link or intersection in a road network can be determined by comparing the importance numbers of existing/new road link or node. These numbers allow us to directly compare the importance of each road link or intersection.

A framework for the study of road network structure can be used as shown in Fig. 1. The framework has 9 Steps. The short path matrix in Step 3 can be calculated using Floyd-Warshall algorithm [4]. Step 1 to Step 7 can be utilized to calculate the connectivity level of the existing network structure. Step 8 is for the necessary intervention to improve the connectivity level of the network structure.

Step 1: Extraction of Road network topology from a map.
Step 2: Formation of planar graph G from the network. Obtain adjacency $[a_{ij}]$ and physical distance matrix $[l_{ij}]$ of the network.
Step 3: Calculation of short path matrix $[d_{ij}]$ from the physical distance matrix $[l_{ij}]$.
Step 4: Calculation of average distance (L) from the short path matrix $[d_{ij}]$.
Step 5: Calculation of node Importance number (I_n) and link Importance Number (I_l) from the short path matrix $[d_{ij}]$: Connectivity situation of the network considered.
Step 6: Removal of node/s or link/s: Repeat Step 2 to Step 5.
Step 7: If all interested nodes or links covered Stop: Comparison of the network structure.
Step 8: Addition of node/s and link/s or link/s: Repeat Step 2 to Step 5: Connection situation of the improved network.
Step 9: End.

Figure 1. Framework for studying a road network structure.

Case Study: Tansen hill town is developed at a hill top of elevation 1400 msl on its own way since many years back. The population of the town is 29,095 [2]. The map of its road network is shown in Fig. 2. The town road network structure is transformed into a planar graph G, the graph nodes correspond to road intersections and edges correspond to the links between the intersections. The road network of the town in terms of graph topology is shown in Figure 2. The town road network has 9 intersections and 9 links. Hence, the graph has 9 nodes (N1, N2, · · · , N9) and 9 links (R1, R2, · · · , R9), respectively. The length of each link is marked on the edges of the graph.

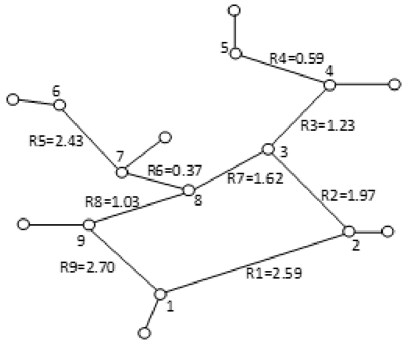

Figure 2. The graph of the road network (km).

From the topology of the road network, the 9×9 adjacency matrix [a_{ij}] and the physical distance matrix [l_{ij}] is obtained. Then, the shortest path matrix [d_{ij}] is calculated using the Floyd-Warshall algorithm [4]. According to equation (1), the average path length L is calculated as 3.43 km. Utilizing the values of [d_{ij}], the structural properties of the network are calculated as node importance number I_n and link importance number l_l of each node and link of the existing network. For the existing network, these numbers are determined and shown in Table 1 and the graphical presentation of the importance number is shown in Figure 3.

Table 1: Node and Link importance numbers for existing road network.

Node	Importance Number, I_n	Link	Importance Number, I_l
1	0.21	R1	0.27
2	0.33	R2	0.60
3	0.95	R3	0.87
4	0.55	R4	0.57
5	0.22	R5	0.53
6	0.21	R6	0.93
7	0.56	R7	1.00
8	1.00	R8	0.67
9	0.36	R9	0.27

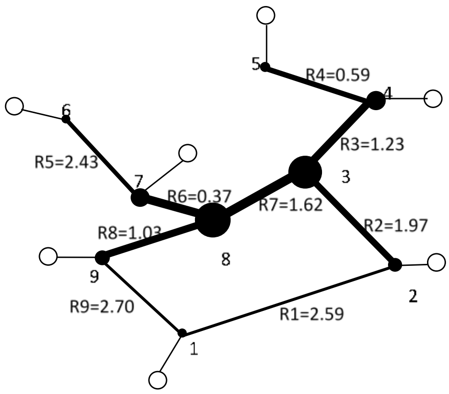

Figure 3. Road network structure for existing network.

The link R7 has the highest link importance number, 1. From the past records, the link R7 is found the most vulnerable road due to accidents, public ceremonies, and strikes. The total estimated number of days of closure of road link is around 20 days in a year. Hence, for the test instance, the above process is repeated removing R7 link from the existing road network. Now, the graph properties and network properties are changed. The average path length is increased to 5.73 km from 3.43 km in the previous network. Travel pattern will change, it's obvious to use R1 maximum and the link R1 will have the highest importance number as 1. The travel cost may increase significantly. As an improvement intervention, let us introduce a new link, R10 (2.85 km) linking nodes 5 and 6 as shown in Figure 4 and let us calculate the impact in the network. Without link R7 in the network, the travel pattern has become more or less uniform in all links as shown in Table 2.

Table 2: Node and Link importance numbers for the road network after removal of link R7 and addition of R10

Node	Importance Number, I_n	Link	Importance Number, I_l
1	0.71	R1	0.71
2	0.71	R2	0.71
3	0.77	R3	0.83
4	0.92	R4	1.00
5	1.00	R5	1.00
6	1.00	R6	1.00
7	1.00	R7	-
8	0.96	R8	0.92
9	0.81	R9	0.71
		R10	1.00

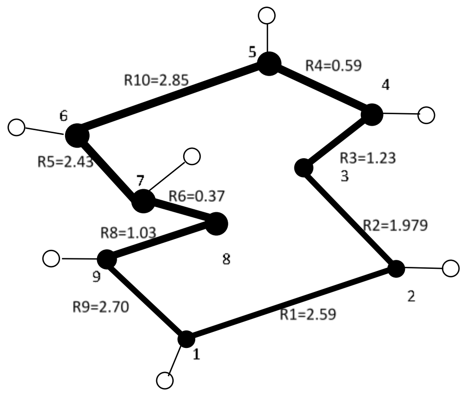

Figure 4. Road network structure after removal of link R7 and the addition of link R10.

We can note that the new link has the highest importance number. In this case, the average path length of the network reduces to 4.32 km from 5.73 km. This also indicates the significant minimization of travel costs after this intervention. Hence, the addition of new link R10 may be justified. The impact of addition of link R10 in the network is significant during the disruption of R7 as predicted above. Otherwise, the link acts as a redundant link, which is very important for the road network robustness.

III. CONCLUSION

The network structure measurement model is used to define the structure of road network in this paper. The implementation of the model on the network shows that it can effectively identify the critical components of the road network utilizing graphs and propose a required intervention in the road network to improve the road network robustness. Further, this model can be combined with the economic cost of new link construction to consider the economic feasibility and rationality of the decision.

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