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Assessing Road Network Connectivity, Robustness, and Accessibility in Chautara Sangachowkgadhi Municipality

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Abstract

Road networks are crucial not only for connectivity and accessibility but also for disaster response and recovery. This study evaluates the connectivity, robustness, and accessibility of the road network in Chautara Sangachowkgadhi Municipality, Sindhupalchowk District. Using hand-held GPS devices, travel distances and times were recorded, while travel costs were gathered through local interviews. Demographic data was obtained from municipal reports and local consultations. Analysis of the road network, represented in a 198x198 matrix, revealed low connectivity ($\gamma = 0.442$), complexity ($\beta = 1.313$), and circuitry ($\alpha = 0.161$), indicating that the network is insufficiently connected. A custom desktop C-program application was developed to evaluate network metrics and offer potential applications in other municipalities. The Minimum Spanning Tree (MST) analysis showed that 48% of the distance, 44% of travel cost, and 42% of travel time are required for minimal connection, with 82% of the links identified as critical. Node analysis indicated that node 41 ("Aaldanda") has the highest degree of connectivity, while 111 nodes are moderately connected. Wards 2, 6, 11, 12, and 14 were found to have the poorest accessibility. The study concludes that the existing road network is poorly connected, with many links critical for disaster preparedness and low accessibility to service centers. It is recommended to add new road linkages, with priority given to words 2, 6, 11, 12, and 14.

Keywords: Road network connectivity; Minimum spanning tree; Disaster preparedness

1. Introduction

The structure and functionality of road networks are essential for both day-to-day transportation and critical for disaster response and recovery. Road networks support the efficient movement of people and goods, promote economic activities, and provide essential access to healthcare, markets, and education. In areas with challenging terrain and high disaster vulnerability, like Nepal, the resilience of road networks becomes particularly important to ensure that communities remain connected and accessible during emergencies (Cronk, 2018; Du, Jiang, & Cheng, 2017). Robust road network systems are crucial to minimizing the socioeconomic impacts of disruptions, facilitating timely disaster relief, and reducing recovery time (World Bank, 2008).

The municipality of ChautaraSangachowkgadhi in Nepal faces unique challenges concerning road connectivity due to its mountainous geography, the risk of earthquakes, and variable weather patterns. A well-connected road network allows for optimized travel routes, reducing distance, time, and associated costs. However, even a highly connected network is susceptible to inefficiency if robustness—its ability to withstand and adapt to disruptions—is compromised (Jenelius, 2010). For instance, the devastating Gorkha earthquake in 2015 highlighted the vulnerability of Nepal's road infrastructure, with numerous road blockages isolating communities and delaying critical relief efforts (Shrestha et al., 2013). The earthquake demonstrated that when main routes are disrupted, the existence of alternative paths is essential for effective disaster response and maintaining accessibility to affected areas (DDRC, 2015). Network connectivity, robustness, and accessibility are core concepts in assessing transportation systems. Connectivity in a road network describes the system's capability to maintain efficient links between nodes (or points of interest) across various locations. Robustness, meanwhile, measures the network's resilience in preserving functionality under adverse conditions, ensuring that alternative paths are available when specific links are compromised (Snelder, 2010; Mens et al., 2011). Accessibility refers to the ease with which people can reach essential services, which may vary based on factors

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like distance, travel time, and road quality (Duran-Fernandez & Santos, 2014). Together, these measures provide a comprehensive picture of a road network's reliability, informing strategies for improving resilience and functionality, particularly in disaster-prone areas.

An analytical approach to road network resilience can be beneficial for municipalities like Chautara Sangachowkgadhi. By calculating the Network Robustness Index (NRI) and the Network Accessibility Index (NAI), road planners and engineers can identify critical links which enables to enhance network resilience and accessibility (Liao & van Wee, 2016). Furthermore, accessibility measures can also reveal spatial disparities in access to essential services such as healthcare, education, and emergency response facilities. The application of algorithms, such as the Floyd-Warshall algorithm, for assessing shortest paths enables a systematic evaluation of travel distances, costs, and time across various network configurations, thus optimizing network connectivity (Shehzad & Shah, 2009). In rural and disaster-prone areas, connectivity is not merely about proximity; it encompasses the reliability and efficiency of routes to support life-sustaining activities. After a major disruption, transportation networks may exhibit reduced capacity, impacting everything from daily commutes to critical emergency services (Umoren et al., 2010). As demonstrated in various case studies, regions with robust and accessible road networks show better resilience, with higher recovery rates following disasters (Kapucu, 2018). For example, network analysis models like the Minimum Spanning Tree (MST) and network density measures are essential for identifying key nodes and connections, providing valuable insights for infrastructure improvement that enhances robustness and reduces vulnerability (Assad & Xu, 1992). This study focuses on evaluating road connectivity, robustness, and accessibility within Chautara Sangachowkgadhi Municipality, using a comprehensive approach to understand the network's current strengths and weaknesses. The research objectives include assessing the network in terms of travel distance, cost, and time, while proposing strategies to enhance its resilience. These findings inform local policymakers, road planners, and disaster management officials, enabling them to make data-driven decisions aimed at improving transportation infrastructure resilience in the municipality (Acoss, 2018).

2. Materials and methods

This study examines the road network of Chautara Sangachowkgadhi Municipality, focusing on travel distance, cost, and time to provide recommendations for policy makers on enhancing its resilience (Bell, 2000). Primary data is collected through field surveys using a Garmin eTrex 10 GPS to chart the existing network, supplemented by secondary data from topographic maps, strategic road maps, and demographic resources. Further insights are gathered from Google Earth imagery, the District Transport Master Plan (DTMP), and the Municipality Transport Master Plan (MTMP) (Chautara Sangachowkgadhi Municipality, 2015; DOLIDAR, 2012). Stakeholder consultations with municipal officials and local business leaders provide valuable context on service flow and demographic inventory via the Central Bureau of Statistics (CBS, 2011) and Department of Survey (DOS, 2017). The study applies a quantitative approach, calculating the Network Accessibility Index (NAI) and Network Robustness Index (NRI) for each node and link based on weighted distance, cost, and time, to assess network resilience and inform infrastructure decisions. This comprehensive methodological framework (Figure 1) integrates relevant literature, guidelines, and established data analysis techniques to support well-informed decisions on network connectivity, robustness, and accessibility, ensuring the resilience of the region's road infrastructure.

2.1 Study area

Chautara Sangachowkgadhi Municipality, located in the Sindhupalchowk district approximately 75 km from Nepal's capital, Kathmandu, serves as the study area. Selected due to its significant vulnerability following the 2015 Gorkha earthquake, this municipality is also a central economic hub for the district, contributing substantially to regional development (GON, 2015). According to the Ministry of Physical Infrastructure and Transport (MOPIT), Nepal's total road network spans 80,078 km, with Sindhupalchowk district accounting for 2,608 km (DOR, 2016). This district's road infrastructure comprises 206 km of strategic roads, 605 km under the District Road Core Network (DRCN), and 1,796 km in the Village Road Core Network (VRCN). Within the former Chautara Municipality, the total road length is 103.5 km (DOLIDAR, 2016), while the surveyed network extends to 336 km.A comprehensive map of the study area's road network is also presented in Figure 1, providing a visual framework for assessing network connectivity, robustness, and accessibility.

2.2 ConnectivityAnalysis

Alpha Index **(α)** is a measure of the redundancy of the network, calculated using Equation 1.

$$\alpha = (L - V + 1)/(2V - 5) \quad (1)$$

Where, L is the number of links and V is the number of nodes, the index usually ranges from 0 to 1 but can be also expressed by percentage. When α = 1 (or 100%), it describes a completely connected network, which occurs rarely in reality (Rodrigue et al., 2011).

Beta Index (β) calculates the degree of connectivity using Equation 2

$$\beta = L/V \quad (2)$$

Where, $L$is the number of links and V is the number of nodes, β < 1 indicates a disconnected network (e.g. a tree pattern), β =1 a single circuit, β > 1 implies greater complexity of network connectivity (i.e., more than one circuit). The minimum value of β is 0 and the maximum is 3. For a network comprised of a fixed number of nodes, the higher the number of links, the higher the number of paths possible in the network.

Gamma Index **(γ)** assesses the proportion of actual links to possible links, and it is estimated using Equation 3.

$$\gamma = L/3 * (V - 2) \quad (3)$$

Where L is the number of links and V is the number of nodes.

2.3 Shortest path and minimum spanning tree analysis

The Floyd-Warshall algorithm was applied to evaluate the shortest path between nodes, considering distance, travel time, and cost. The algorithm's output included the shortest path matrix for each of these criteria (Boccaletti, 2006). To identify the most efficient connectivity with minimal road length, the Kruskal's Minimum Spanning Tree (MST) algorithm was used on the road network, based on the same criteria. This approach is consistent with methods for analyzing network efficiency in transportation systems (Cascetta et al., 2016).

2.4 Robustness and accessibility evaluation

Network robustness index (NRI) is the robustness of the road network was analyzed by calculating the NRI, which identifies critical and non-critical links, helping to evaluate the vulnerability of the network in case of disruptions. First, the system-wide, travel-time cost of removing the link, ca, is given by the Equation (4).

$$C_a = \sum_1^n t_a \, x_a \quad (4)$$

Second, this cost is compared to the system-wide, travel time cost incurred when all links are present in the network (i.e., the base case).

$$\mathrm{q_a = c_a - c} \quad (5)$$

Where,

$$c = \sum_1^n t_a \, x_a \quad (6)$$

And q_a is the value of the NRI is for linking a in units such as minutes.

The robustness analysis is performed using the Network Robustness Index (NRI), which is calculated in two steps. Initially, the Total Travel Time (TTT) is determined when all links in the network are present. TTT is the sum of the product of travel time and traffic flow across all links. Removing a single link may not always increase the TTT, which means the NRI value could be either positive or negative. This method highlights network vulnerabilities and helps identify critical links (Scott et al., 2006; Iida, 1999).

Network Accessibility Index (NAI)was measured using the Network Accessibility Index (NAI), focusing on ease of access across the municipality by analyzing distance, time, and cost (Cotula et al., 2006; Kwan, 1998). By applying a gravity model and using a negative exponential impedance function, accessibility was calculated from the municipal level down to individual wards, following methods like those detailed by Gorod and Sauser (2007) and Hansen (1959).

Municipality/ward Accessibility Approach:Out of many approaches of defining accessibility this accessibility measures is defined in equation (7).

$$PopAcc_i = \sum_{j=1}^{n} p_j^{\times} e^{-\alpha \times t} \tag{7}$$

Where, P_J = Population of each ward, e = Exponential function of =0.1 which is constant and t = May be Distance in (Km), time in (minute) or cost in (Rupees) respectively.In literature, the range for the factor reaches from 0.5 at a regional level to 0.01 for Europe (Schürmann et al., 1997). In the present study, the factor is taken as 0.1 and kept constant across periods.

2.5 Road density and accessibility analysis

The road density of the municipality was determined using population and area data. Accessibility indices for each ward were assessed by calculating the average distance, time, and cost required to reach key locations within the network (Glover & Simon, 1975; Gupta, 2010). This approach ensures a comprehensive evaluation of the municipality's infrastructure and connectivity, factoring in various transportation elements to assess overall accessibility (Hu, Janowicz, & Couclelis, 2016).

$$Road\ density\ as\ per\ 1000\ Population = L/(P_J/1000) \tag{8}$$

$$Road\ density\ as\ per\ area = L/A \tag{9}$$

where, P_J **is** population of each ward, L is the length of road in km, and A isarea in Sq.km.

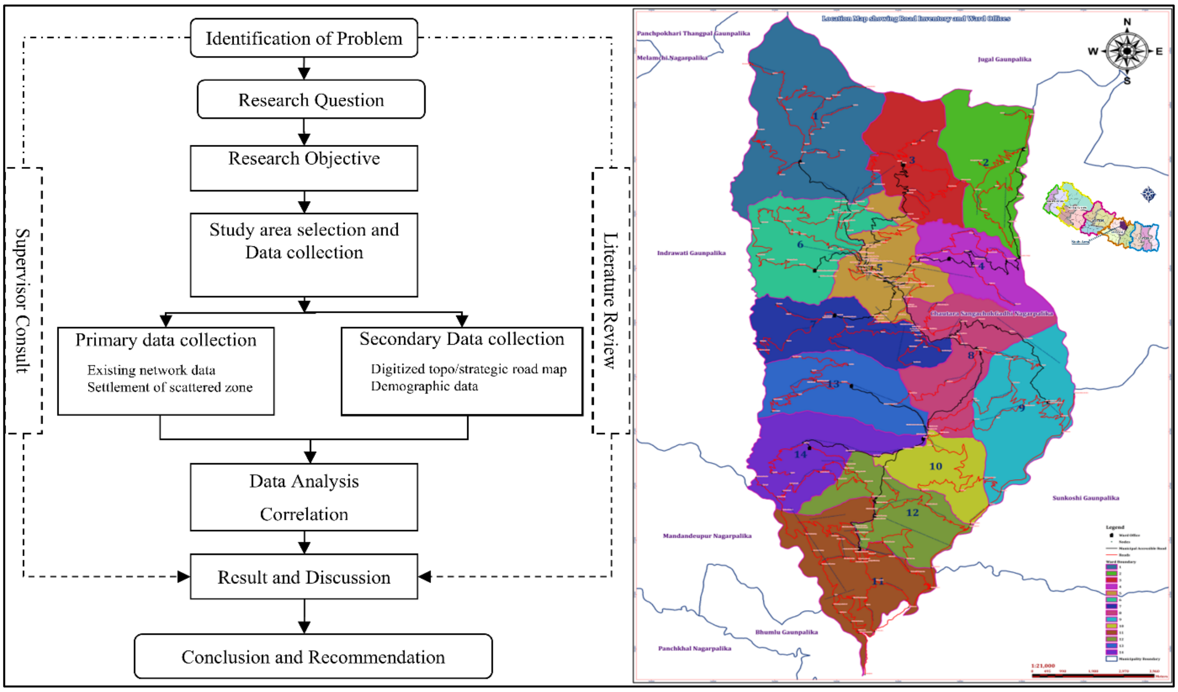

Figure 1. Overall methodological framework (on left) and study area (DCC, 2017 and DOS, 2017) with road network on the right

2.6 Date acquisition and processing

The data collection for this study integrated both primary and secondary sources to thoroughly assess the road network of Chautara Sangachowkgadhi Municipality. Primary data were gathered through extensive field observations using a handheld GPS (Garmin eTrex 10) to record travel distance and time. Data collection methods included traveling on local buses while tracking routes with GPS and traversing inaccessible routes by motorcycle at a controlled average speed of 15 km/h to capture variations in distance and time due to passenger loading and unloading. These GPS-based travel distances were cross-verified with local bus travel data and Google Earth plots to confirm route accuracy. Travel cost data were recorded, with rates set at a minimum of Rs. 5 per km on most roads and Rs. 8 per km on Village Road Core Network (VRCN) routes, ensuring consistency across the dataset.

2.7 Algorithms development

The initial phase of the research involved the development of a computer program designed to analyze road network functionality through a series of critical parameters, such as distance matrix values, shortest path weights, and Minimum Spanning Tree (MST) networks. These parameters also included indices like Alpha, Beta, Gamma, the Network Accessibility Index (NAI), and the Network Robustness Index (NRI). The program, implemented with the aid of application software, processed input data from Excel files to model the road network. Through pseudocode algorithms, the network data was structured in phases, identifying existing connections and using the Floyd-Warshall algorithm to calculate the shortest path matrices. After defining nodal points, Kruskal's algorithm was used to link these nodes and create an MST supported by (Gupta, 2010; Nagne et al., 2013). The NRI was determined using link-break pseudocode within the Kruskal framework, while Alpha, Beta, and Gamma indices were coded in C#. This coding approach simplified the otherwise complex analysis of network configurations by consolidating calculations into a single desktop application, streamlining tasks that would be challenging to perform manually (GeeksforGeeks, 2018).

2.7.1 Distance matrix value

The calculation of the distance matrix plays a pivotal role in the analysis of network connectivity by systematically computing distances between node pairs. This matrix is beneficial for managing large datasets, as it is represented as a square matrix reflecting connectivity values between consecutive nodes. Higher values in the matrix indicate greater accessibility between nodes, enhancing their linkages across the network (Shahid et al., 2009; Kwan, 1998). The utility of distance matrices is especially evident in post-disaster transportation planning, where such matrices assist in prioritizing routes and evaluating robustness (Konstantinidou, Kepaptsoglou, & Karlaftis, 2014; Zhang, Song, Shen, & Wu, 2018). Manually calculating the matrix for larger datasets can be complex, so the application software computed it instantly, supporting further in-depth network analysis.

2.7.2 Shortest path weighted values

To optimize the road network within constraints such as time, distance, and cost, the model applies the Floyd-Warshall algorithm. This algorithm produces a shortest-path matrix that identifies central, nodal points in the network, ensuring the most efficient routes to other settlements. The application processes pre-existing network data, running the algorithm to generate the matrix. This matrix is essential for understanding node accessibility and recalculating alternative routes when disruptions occur in the network (Pokharel & Ieda, 2012; Sedgewick & Wayne, 2011). Source-destination pairs are examined within the algorithm with intermediate vertices considered as per the connection structure, ensuring thorough network optimization (Shehzad & Shah, 2009; GeeksforGeeks, 2018).

2.7.3 MSTNetwork

To establish a minimum spanning tree (MST) of the network, Kruskal's algorithm was employed. This algorithm connects all vertices with the smallest possible edge weights to ensure minimal travel costs while avoiding cycles. MST effectively eliminates redundancy and enhances efficiency across the network by ordering edges in ascending order, forming a tree structure that preserves connectivity with minimized edge weights. This configuration is instrumental in network optimization as it reduces overall travel costs, thus promoting an efficient structure across nodes (Raid, 2002).

2.7.4 Data analysis

Analysis for Connectivity Using Planar Graph Theory: Applying planar graph theory, the network was modeled as a directed graph (G = (v, e) with nodes and edges representing its structure (Devkota, 2015). Indices such as Alpha (α), Beta (β), and Gamma (γ) were utilized to evaluate the network's circuitry, complexity, and connectivity. Higher values in these indices suggested better connectivity, with the Alpha index representing alternative paths between nodes, the Beta index reflecting the ratio of links to nodes, and the Gamma index comparing actual versus potential links. These indices were instrumental in evaluating network connectivity, providing insights into the extent and strength of connections within the network as supported from the (Patarasuk, 2013; Rodrigue et al., 2011).

Analysis for Robustness: The robustness of the network was assessed using the Network Robustness Index (NRI), evaluating each segment's critical role within the network. The NRI calculates travel-time costs and assesses the impact of rerouting traffic if segments are disrupted. Calculating NRI involves estimating the total travel time cost (TTT) as shown in Equations 4, 5, and 6, respectively, with all links active, followed by measuring the effect of removing each link. This assessment is crucial for prioritizing network links, highlighting those with the most significant influence on travel time when rerouted or removed (Scott et al., 2006).

Analysis for Accessibility: Accessibility was measured using a gravity model framework with twelve gravity-type measures and various impedance functions, including inverse power and negative exponential functions. The accessibility model captures transport costs associated with distance and time, producing numerical indices for accessibility across the municipality's wards. These indices were used to calculate the Network Accessibility Index (NAI) for each ward, assessing linkage to the central municipal office, a measure that holds significance for disaster response and resource distribution. Nodes with greater accessibility are identified as more connected, a critical finding for networks with larger nodes and alternate pathways, as supported by (Liao & van Wee, 2016).

3. Results and discussion

3.1 *Existing Road network in a planar graph*

The road network in Chautara Sangachowkgadhi Municipality consists of 198 nodes and 260 links, two of which are strategic roads: the Araniko Highway and the Dolalghat-Chautara Feeder Road. These vital roads connect the municipality to Kathmandu, the capital city, providing essential links for economic activities and disaster response. Given the lack of alternative transportation options, such as airways, road networks serve as the primary means of transportation, playing an essential role in both everyday development activities and emergency response. Internal mobility within the municipality is largely reliant on this road system, underscoring the significance of efforts to expand rural roads. To evaluate connectivity and accessibility, a tree diagram was constructed to illustrate the distances, travel times, and costs involved in reaching district service centers from each ward as supported by findings from (Hu, Janowicz, & Couclelis, 2016; Sreelekha, Krishnamurthy, & Anjaneyulu, 2016). Table 1 provides a breakdown of these metrics for each ward, further detailing the infrastructural reach and highlighting variations in accessibility across the municipality.

Table 1. Travel to the district service centers from each Ward

Ward or zone no.	Ward name	Total area (km^2)	Population as of CBS 2011	Population as of 2017 (0.61%)	Total Road length (km)	Travel to district service centers		
						Distance (km)	Travel time (minutes)	Travel cost (NPR)
1	Syaule	22.91	3630	3475	27.3	5.76	29	35
2	Batase	11.61	2541	2432	22.43	15.46	77	93
3	Batase	10.52	2341	2241	19.58	8.65	43.25	51.9
4	Kubinde	7.93	3298	3157	16.62	4	20	24
5	Chautara	9.65	6156	5893	28.4	1.1	5.5	6.6
6	Pipaldada	12.38	3167	3032	28.36	3.73	18.65	22.38
7	Sanosirubari	11.05	3274	3134	20.79	10.5	52.5	63
8	Irkhu	12.44	3446	3299	25.55	6.33	31.65	37.98
9	Kadambas	13.83	3373	3229	29.32	12.35	61.75	74.1
10	Sangachok	6.95	3151	3016	15.35	12	57.45	69
11	Sangachok	13.56	3584	3431	43.13	18.42	90	107.46
12	Sangachok	10.03	2942	2816	21.15	17	80	95.46
13	Thulosirubari	11.16	3881	3715	18.82	14	70	84
14	Thulosirubari	11.16	2106	2016	19.2	16	82	99

3.2 Existing Road Density

The analysis of road density reveals a significant correlation between population density and road development, as supported by findings from Glover and Simon (1975), which indicate that population increases stimulate new road construction or link developments. This trend is observable across various wards, such as wards 2, 3, 5, 7, 8, 9, 12, and 14, where population density aligns with higher road density. Conversely, Ward 1 exhibits one of the lowest road densities per area (1.192 km/sq.km) and per capita (7.856 km per 1000 people), indicating lower infrastructure investment relative to population. Ward 2, in comparison, has a road density of 1.932 km/sq.km and 9.223 km per 1000 people.

Figure 2 (A) provides a ward-wise comparison of road density, with road density per area on the vertical axis and ward numbers on the horizontal axis. Despite Ward 11's high road density in terms of area (3.181 km/sq.km) and population (12.571 km per 1000 people), Ward 5, with a density of 2.943 km/sq.km and 4.819 km per 1000 people, shows a contrasting distribution. The overall data indicates that none of the wards meet the DUDBC standard of 7.5 km/sq.km, suggesting an infrastructure gap that needs addressing.

3.3 Road Network Circuitry, Complexity, and Connectivity

The connectivity, complexity, and circuitry levels of the network were assessed using Alpha, Beta, and Gamma indices, yielding values of 0.161, 1.313, and 0.442, respectively. These values fall significantly below the ideal values (Alpha = 1, Beta = 2.96, and Gamma = 1.0), indicating limited connectivity within the municipality. The connectivity levels vary among wards, with Ward 11 achieving the highest Alpha, Beta, and Gamma values (0.175, 1.29, and 0.46, respectively), reflecting better connectivity due to its central location and proximity to service centers. Ward 5, hosting the district headquarters, also exhibits relatively high connectivity indices (0.155, 1.263, and 0.444), emphasizing its infrastructural importance within the municipality. This pattern of connectivity is in line with findings on network robustness and accessibility (Mens et al., 2011; Minwei, 2008), helping identify further areas of improvement (Mens et al., 2011; Schürmann, Spiekermann, & Wegener, 1997).

3.4 Road Network Robustness and Critical Links

The study applies the Network Robustness Index (NRI) to evaluate the resilience of the road network by simulating link failures and assessing potential rerouting options. A total of 212 out of 260 links (82%) are identified as critical, emphasizing the network's vulnerability, particularly in wards like 12 and 6, which exhibit the highest proportion of critical links at 95% and 94%, respectively. The analysis of critical versus non-critical links, visualized in Figure 2 (B), illustrates the limited redundancy within the network, highlighting the need for strategic improvements to enhance resilience and facilitate efficient rerouting in post-disaster scenarios.

3.5 Evaluation of Accessibility of the Road Network

The accessibility of each node within the road network was assessed based on node degree and valued graph. Nodes with higher connectivity degrees demonstrate greater accessibility. For instance, Node 41 (Aaldanda) possesses the highest degree at 5, indicating strong connectivity with neighboring nodes. Other nodes, such as nodes 11, 57, 61, 96, 98, 111, 132, 151, 157, and 193, have a degree of 4, demonstrating moderate accessibility. Figure 2 (C) and Figure 2 (D) further depict the ward-wise accessibility indices in terms of distance, time, and cost, providing insights into the infrastructural gaps across the municipality. Notably, Ward 5, encompassing the district headquarters, exhibits high accessibility across all metrics, whereas Ward 14 displays low time accessibility despite relatively good distance and cost accessibility, indicating logistical challenges in accessing key services.

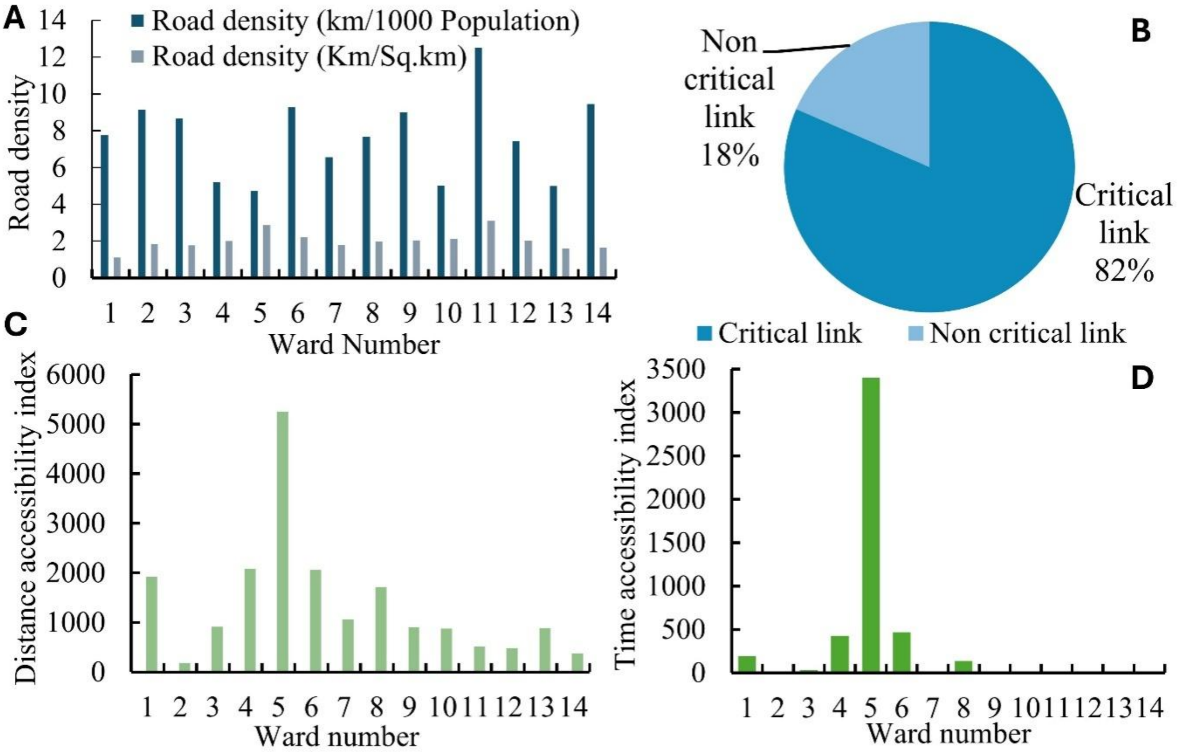

Figure 2 Comparison of road density for all wards (Figure A), critical and non-critical Links shown in pie chart (B), comparative study of distance accessibility index in every Ward (C), comparative study of travel time accessibility index in every Ward (D)

3.6 Minimum spanning tree and network optimization

To optimize the network's efficiency, a Minimum Spanning Tree (MST) was created using the Kruskal algorithm. This resulted in a 47% reduction in the network's total travel distance (from 336 km to 175 km), a 42% decrease in travel time (from 2814 minutes to 1621 minutes), and a 44% reduction in travel cost (from Rs. 2183 to Rs. 1218). The MST network minimizes the resources required to maintain essential connectivity, presenting a practical solution for improving road accessibility in resource-limited settings. Table 2 compares the network metrics before and after MST application, demonstrating significant resource savings while maintaining critical connections.

Table 2. Formation of the MST network on the all road network

S.no.	Parameter	Before MST	After MST	Optimization	Remarks
1	Distance	336 km = 7.15 km/hr	175 km = 6.5 km/hr	47.92%	
2	Time	2814 minute = 47 hrs	1621 minute = 27 hrs	42.40%	
3	Cost	2183 Rupees	1218 Rupees	44.21%	

3.7 Evaluation of Application Software

The custom software developed for this study facilitated the calculation of connectivity, robustness, and accessibility indices across the municipality. This software, written in C, utilizes object-oriented programming principles to efficiently process the extensive data on road networks, utilizing node-to-node connectivity data in matrix form. The program's output includes a variety of indices, critical and non-critical link distinctions, and the formation of the MST, which significantly streamlined the complex task of road network analysis. Figure 3 displays the software's output interface, demonstrating the program's efficacy in mapping and analyzing network connectivity, robustness, and accessibility.

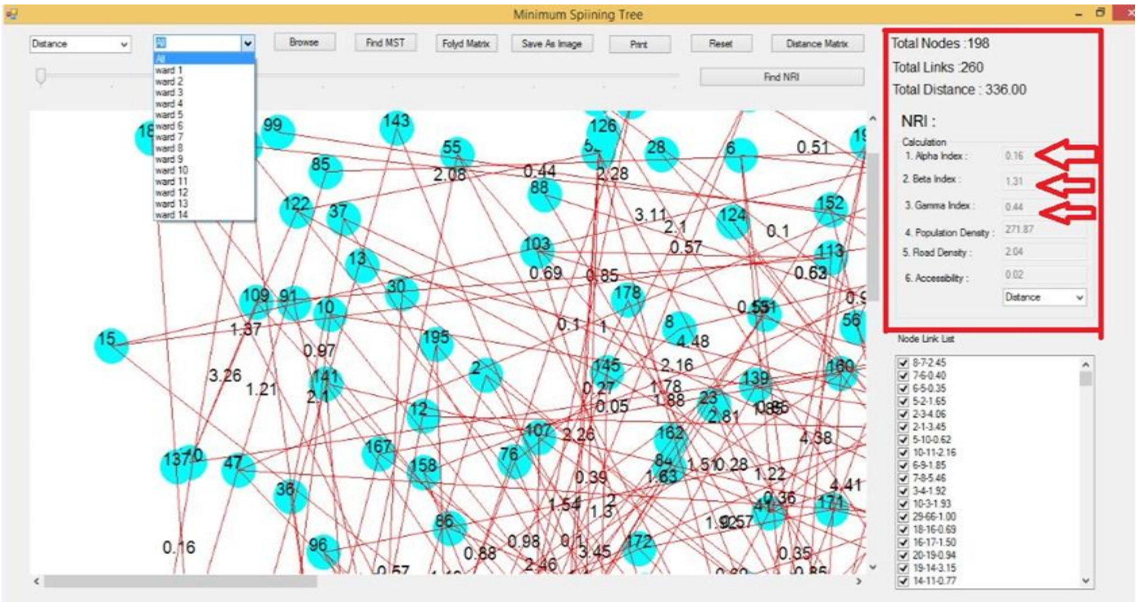

Figure 3. A part of the result from computer program

4. Conclusion

This research, titled "Assessment of Road Network Connectivity, Robustness, and Accessibility: A Case Study of Chautara Sangachowkgadhi Municipality in Sindhupalchowk District, Nepal," provided a comprehensive analysis of the existing road network's robustness and accessibility. A significant outcome of this study is the evaluation of accessibility, connectivity, and robustness for each ward as well as the development of a computer program to evaluate the road network using these indicators.

The findings reveal that the current road network's connectivity is considerably deficient compared to ideal standards. Specifically, the connectivity metrics- circuitry, $\alpha = 0.161$ (range 0-1), complexity, $\beta = 1.313$ (range 0-2.96), and connectivity, $\gamma = 0.442$ (range 0-1), highlight the urgent need for enhanced road infrastructure to foster a more robust and disaster-responsive network. Moreover, the road density analysis indicates that none of the wards meet the targeted DUDBC standard of 7.5 km/sq.km, suggesting that new linkages are essential across all wards. The local authority's plans to incorporate road linkages in line with the Municipal Transport Master Plan (MTMP) recommendations are a promising step toward improving connectivity. The robustness assessment reveals that 82% of the 260 links within the Municipality are critical from a disaster management perspective. Notably, ward number 12 has over 95% of its links classified as critical, emphasizing the importance of these roadways in emergencies. Conversely, wards 5, 11, and 14 show a significant proportion of non-critical links, underscoring the disparity in infrastructure resilience across the Municipality.

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