Development Patterns and Transport Network Analysis (TNA) across Wards in Howrah City for urban growth estimation

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Abstract: Urban development relies on the efficiency and structure of transportation networks, which play a crucial role in connectivity, accessibility, and regional growth. This study analyses the development patterns and transport network connectivity across wards in Howrah City, West Bengal, to estimate urban growth using GIS-based methods. Key network indices such as Alpha, Beta, Gamma, Eta, Theta, Pi, Detour, and Cyclomatic were computed to assess the spatial and structural characteristics of the transport system. The findings reveal significant spatial disparities, with the northeastern regions exhibiting higher connectivity and better-developed networks, while the western areas face moderate to low connectivity. The results underscore the potential of GIS-based Transportation Network Analysis (TNA) to guide urban planners and policymakers in designing equitable and efficient transport infrastructure. This research bridges the gap between theoretical frameworks and practical applications, providing a pathway for sustainable urban development.

Keywords: Accessibility, Connectivity, GIS, Howrah City, Spatial disparities, Transport infrastructure, Urban growth

I Introduction

Urban development is intricately linked to the efficiency and structure of its transportation networks, as they form the backbone of regional connectivity and accessibility. Transportation systems support the movement of people and goods and serve as a critical determinant of a region's economic vitality, spatial organisation, and social cohesion. A well-planned transportation network facilitates economic growth, ensures accessibility to essential services, and significantly contributes to the overall quality of life in urban areas. The pivotal role of transportation infrastructure in shaping the development trajectory of cities underscores the need for advanced analytical tools like Transportation Network Analysis (TNA), which offers insights into the spatial connectivity and accessibility of urban infrastructure. TNA has become indispensable for urban planners and policymakers aiming to foster sustainable urban growth while addressing the challenges of rapid urbanization. TNA focuses on the intricate relationship between road networks and their connectivity indices, which are vital for understanding the dynamics of urban expansion and improving livability. These indices quantify the efficiency, accessibility, and robustness of transport networks, providing a framework for assessing urban growth. The advent of technologies like Geographic Information Systems (GIS), remote sensing, and graph theory has revolutionized the field by introducing precise, scalable, and efficient methods for analyzing transport networks (1) and (2). As emphasized by Lee and Chi, quantitative approaches leveraging high-resolution imageries offer unprecedented accuracy in characterizing transportation environments. These indicators play a significant role in guiding transportation and urban planning processes and in facilitating meaningful comparisons across urban regions (3). Theoretical insights into network connectivity have also evolved significantly. Dayalan highlighted the robustness of the Theta measure compared to traditional metrics such as Eta and Pie. Theta remains consistent across varying network structures, making it a powerful tool for analyzing complex urban systems. This consistency provides urban planners with a reliable metric for evaluating transport networks under diverse conditions, enabling more informed decision-making. Similarly, the work of (4) in Aurangabad City, Maharashtra, underscores the importance of GIS in assessing urban road connectivity. Their findings demonstrate how GIS technology can efficiently compute connectivity levels, serving as a crucial aid for urban planning and decision-making processes. Furthermore, (2) explored the utility of graph theory in GIS-based road connectivity evaluations, revealing its potential to not only analyze existing road structures but also to propose new routes that enhance accessibility. Their research reaffirms the role of GIS as a powerful analytical and predictive tool for urban planning. (5) extended this perspective by emphasizing how GIS and network analysis techniques address enduring challenges in transportation planning. Their findings highlighted the transformative potential of these methods in creating more effective datasets for urban planners, aiding in better planning and development of transport networks. Remote sensing and GIS technologies offer more than just analysis tools; they act as comprehensive decision-support systems.(6) emphasized the role of these technologies in addressing dynamic urban requirements, offering heuristic solutions to complex challenges. By integrating RS and GIS, urban planners can leverage an extensive range of tools to address transportation planning needs, effectively supporting the dynamic and multi-faceted nature of urban growth. These technologies not only enable planners to manage existing urban infrastructure but also anticipate and prepare for future developments (7) .This paper aims to analyse the development patterns and transport network connectivity across the wards of Howrah City to estimate urban growth. By utilizing advanced network analysis techniques, the study seeks to explore the relationship between urban expansion and transport infrastructure, offering critical insights for urban planners and policymakers. The research bridges the gap between theoretical frameworks and practical applications, contributing to the ongoing discourse on sustainable urban development and planning. The key goals and objectives of the study include assessing the accessibility and connectivity of the transport network, analysing network density, and examining the spatial distribution of the road network using GIS. (8), in the paper titled "Transport Network Analysis: A Case Study of Perambalur District (Tamil Nadu) Using GIS," examined the road transport system in Perambalur district, Tamil Nadu, utilizing various connectivity indices to assess the efficiency and structure of the transportation network.(4), in their paper titled "Urban Road Network Connectivity Analysis Based on GIS for Aurangabad City, Maharashtra," focused on analyzing the road network of Aurangabad City, emphasizing major junctions, retail junctions, major corridors, road density, and overall connectivity.

II Study Area

The Howrah Municipal Corporation, located in West Bengal, India, lies between $22°35'30''$ North Latitude and $88°21'0''$ East Longitude on the west bank of the Hooghly River (Figure 1). The city is known for its rich heritage, historical landmarks, and vibrant culture. Howrah is also home to India's largest and busiest railway station, Howrah Junction, a key transport hub that connects the city to a vast network across the country, driving both economic and social interactions. Its strategic location and robust infrastructure make Howrah an essential node in the region's transport network, supporting its urban growth and development. Figure 1 illustrates the study area's key features and infrastructure.

III Materials and Methods

In this study, a comprehensive approach combining Geographic Information System (GIS) techniques and software tools was utilized to analyse the structural and functional characteristics of a road network. The datasets were primarily processed using ArcGIS 10.4 software, which facilitated the extraction and manipulation of spatial data, as well as the computation of network metrics. The road network shape file, a crucial input, was sourced from open-access platforms, ensuring accessibility and reliability. Preliminary data pre-processing included cleaning and correcting topological inconsistencies to prepare the dataset for analysis (Figure 2). Microsoft Excel played a pivotal role in calculating various indices

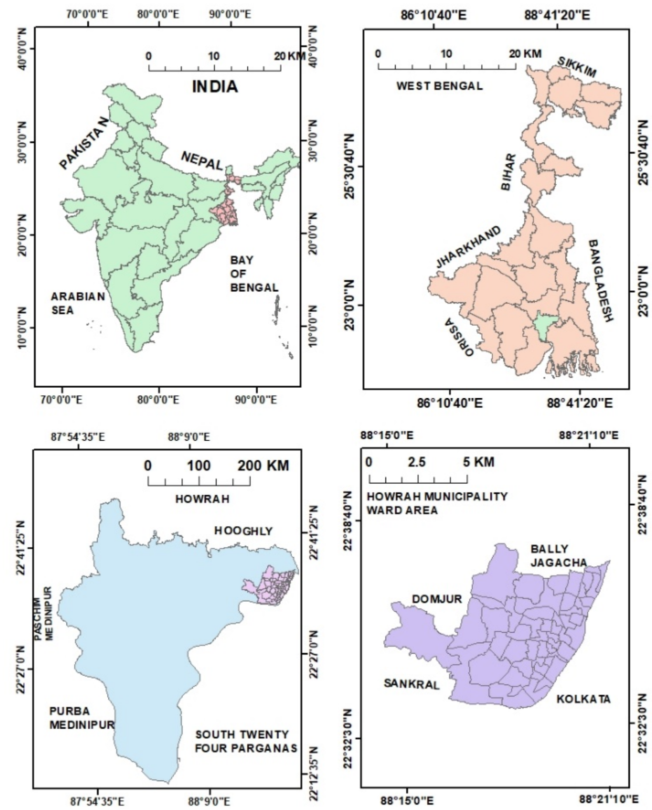

Figure 1: **Location of the area studied**

that characterize the road network's properties. The road network was analysed based on the number of edges (e) and vertices (v) systematically identified within the GIS environment. Additionally, sub graphs (p) were quantified to understand the network's complexity. These parameters were further used to compute a set of indices that describe the network's connectivity, completeness, and efficiency.

The Alpha index α was calculated using the formula $\frac{e-v}{2v-5}$, which measures the connectivity of the network by examining the relationships between edges and vertices. The Gamma index γ, defined as $\frac{e}{3(v-2)}$, and provided insights into the network's completeness by comparing the actual number of edges to the maximum possible edges in the network. The Beta index β was determined using the formula e/v, representing the ratio of edges to vertices and offering a basic measure of network connectivity. To assess the network's spatial characteristics, the Theta index θ was computed as $\frac{TotalNetworkDistance(L)}{NumberofVertices(V)}$, which evaluates the average length of the network per vertex. Similarly, the Eta index η was derived using the formula $\frac{TotalNetworkDistance(L)}{NumberofEdges(E))}$, indicating the average length per edge. The Pi index π was expressed as $\frac{TotalNetworkDistance(L)}{DistanceofDiameter(A)}$, reflecting the relationship between the total network length and the diameter, a measure of its longest straight-line distance. Another important metric was the Detour index (Di), calculated as $\frac{anActualLine}{StraightLine}$, which captures the deviation of the network from straight-line distances. Lastly, the Cyclomatic index μ, computed using the formula e-v+p, assessed the redundancy within the network by examining the number of closed loops or cycles. All calculations were systematically performed in Microsoft Excel, where the extracted parameters were input and the formulas applied to derive the indices (Table 1, 2). The results were cross-verified for accuracy by manually computing a subset of indices. The processed data and resulting indices were visualized using

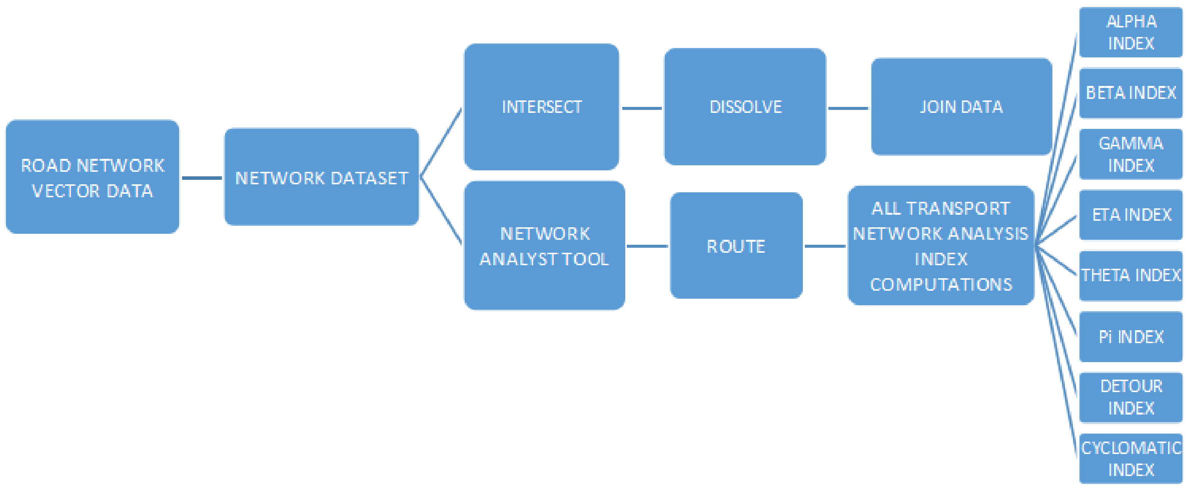

Figure 2: **Methodological flowchart**

ArcGIS 10.4, generating informative maps and charts to support the interpretation of findings. This methodical framework ensured a detailed and accurate assessment of the road network's structure and efficiency.

Table 1: The formulas used for the computation of various indices

Indices	**Formula**
ALPHA	$\frac{e-v}{2v-5}$
GAMMA	$\frac{e}{3(v-2)}$
BETA	$\frac{e}{v}$
THETA	$\frac{\text{Total Network Distance (L)}}{\text{Number of Vertices (V)}}$
ETA	$\frac{\text{Total Network Distance (L)}}{\text{Number of Edges (E)}}$
Pi	$\frac{\text{Total Distance of Network (L)}}{\text{Distance of Diameter (A)}}$
DETOUR (Di)	$\frac{\text{Actual Line}}{\text{Straight Line}}$
CYCLOMATIC	$e-v+p$

Note: Where e = the number of edges, v = the number of vertices, p = the number of subgraphs.

IV Results and discussion

This study evaluated the structural and functional characteristics of the road network in Howrah City using various GIS-based indices. The findings provide valuable insights into the connectivity, accessibility, and efficiency of the transport network. The results reveal significant variations in the indices across different parts of the city, highlighting spatial disparities in road network structure and functionality (Figure 2). The Alpha (α) index (Figure 3), which measures the connectivity of a network on a scale from 0 to 1, indicates that the connectivity in Howrah City varies considerably. A value closer

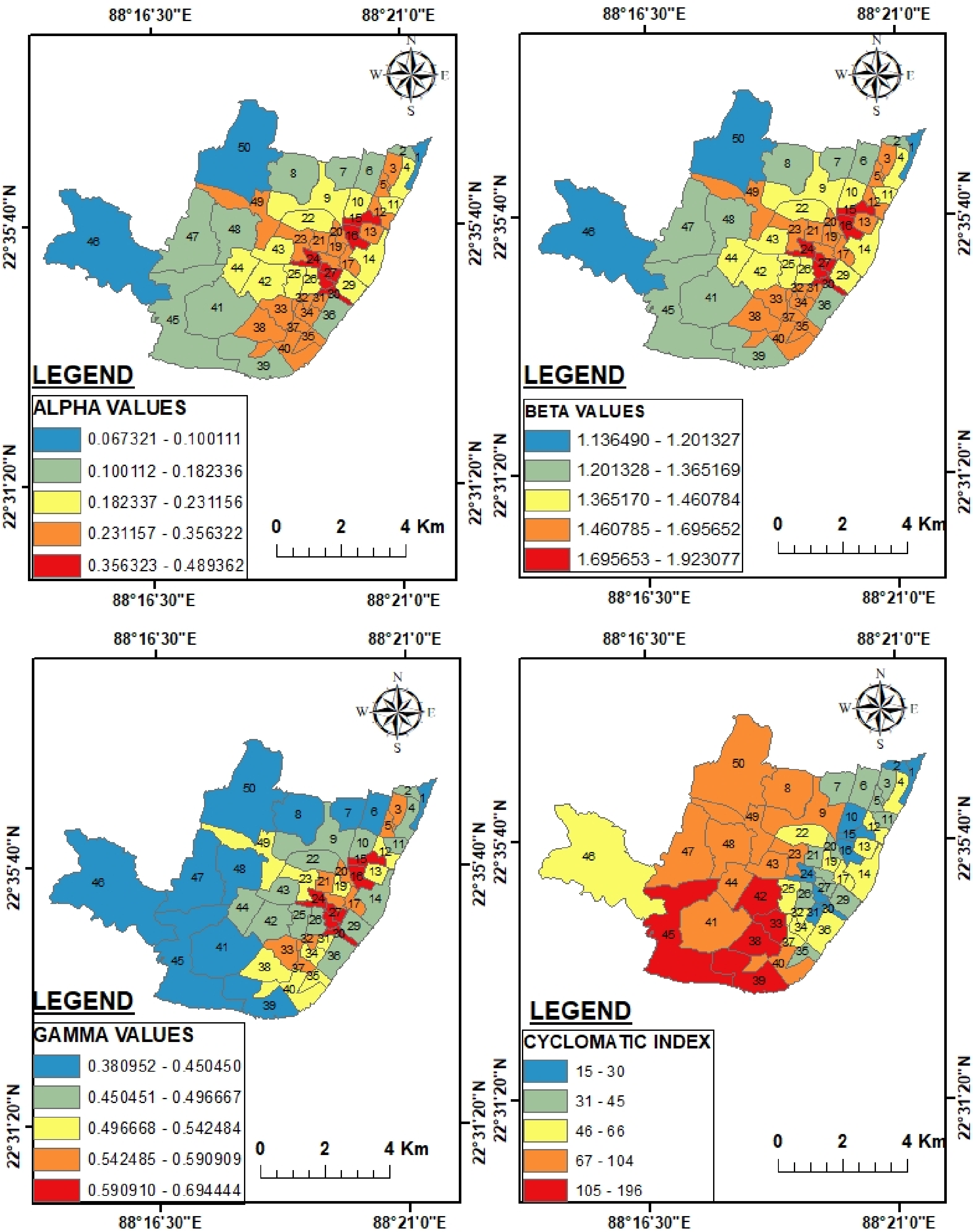

Figure 3: **Alpha index, Beta index, Gamma index, Cyclomatic index**

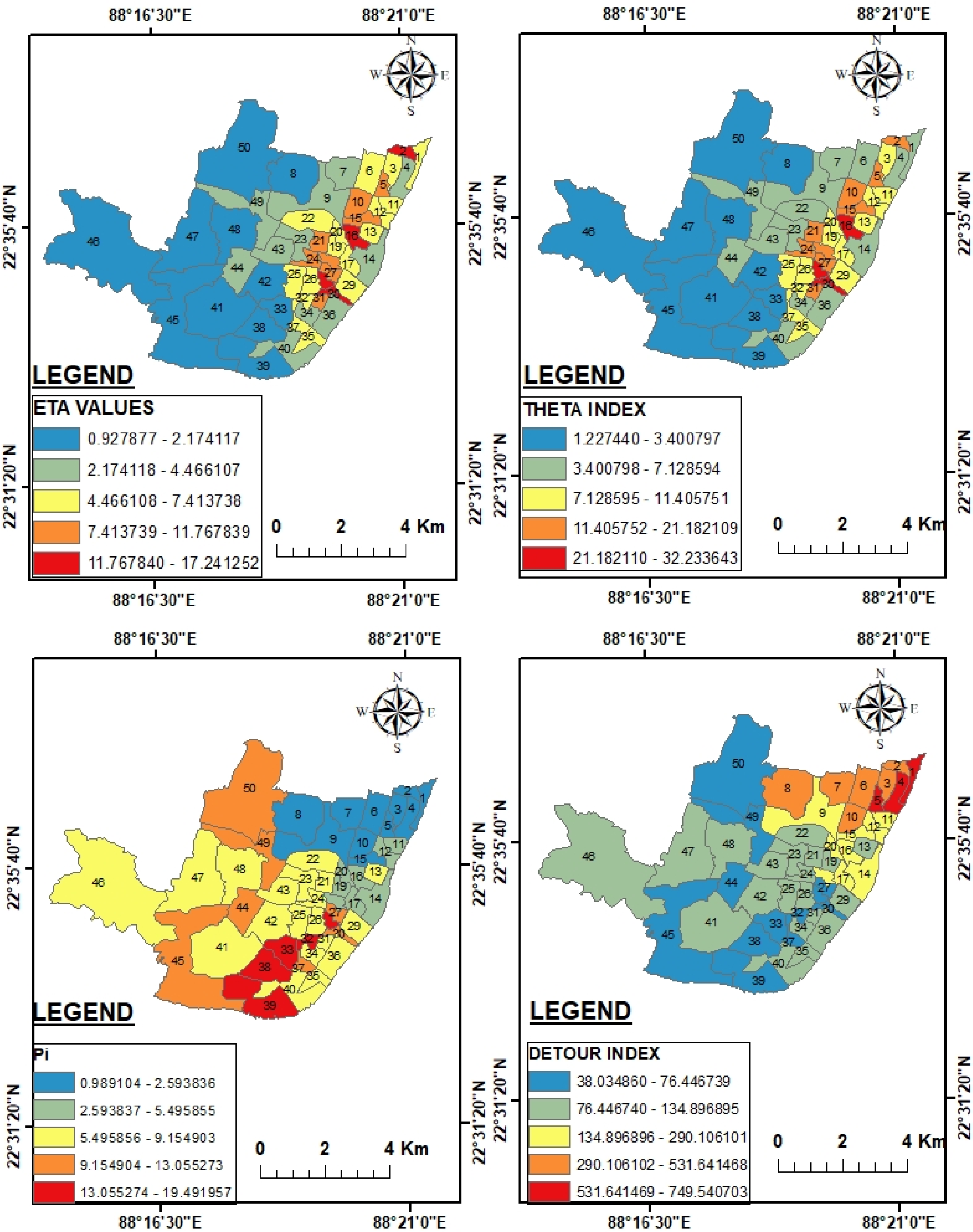

Figure 4: **Eta index, Theta index, Pi index, Detour index,**

Table 2: Calculation Table for Various Indices

Ward No.	Node (V)	Edge (E)	Alpha Index	Beta Index	Gamma Index	Cyclometric Index	Eta Index	Theta Index	Detour Index	Pi Index
1	108	129	0.09	1.19	0.41	22.00	5.75	6.86	749.5	0.99
2	43	57	0.16	1.33	0.46	15.00	13.01	17.24	387.0	1.92
3	66	106	0.31	1.61	0.55	41.00	6.99	11.23	531.6	1.39
4	119	168	0.21	1.41	0.48	50.00	4.41	6.23	669.2	1.11
5	46	78	0.36	1.70	0.59	33.00	9.50	16.12	663.6	1.12
6	111	145	0.15	1.31	0.44	35.00	5.11	6.68	429.6	1.73
7	145	183	0.13	1.26	0.43	39.00	4.05	5.11	357.3	2.07
8	295	393	0.17	1.33	0.45	99.00	1.89	2.51	452.9	1.64
9	166	242	0.23	1.46	0.49	77.00	3.06	4.47	290.1	2.56
10	55	78	0.21	1.42	0.49	24.00	9.50	13.48	368.9	2.01
11	134	176	0.14	1.31	0.44	43.00	4.32	5.86	479.1	1.56
12	90	120	0.17	1.33	0.46	31.00	7.00	9.33	396.4	1.88
13	67	98	0.23	1.46	0.49	32.00	7.36	10.19	328.5	2.27
14	123	167	0.19	1.36	0.47	45.00	5.00	6.94	355.6	2.10
15	158	214	0.22	1.35	0.46	57.00	3.94	5.52	394.3	1.89
16	203	278	0.27	1.37	0.46	76.00	2.88	4.09	312.7	2.39
17	44	65	0.27	1.48	0.50	22.00	11.20	15.45	368.9	1.95
18	84	114	0.18	1.36	0.47	31.00	7.43	10.36	419.5	1.77
19	146	189	0.16	1.30	0.44	44.00	4.29	5.80	479.1	1.51
20	103	139	0.16	1.35	0.46	37.00	5.41	7.58	452.0	1.68
21	195	263	0.22	1.35	0.46	69.00	3.06	4.63	426.9	1.73
22	128	169	0.16	1.32	0.45	42.00	4.64	6.42	387.4	1.97
23	157	211	0.17	1.34	0.46	55.00	3.96	5.64	369.7	2.08
24	289	390	0.18	1.35	0.46	102.00	1.92	2.64	390.6	2.19
25	96	130	0.18	1.35	0.46	35.00	6.92	9.61	419.1	1.82
26	68	101	0.24	1.49	0.50	34.00	7.29	10.54	349.7	2.35
27	105	143	0.18	1.36	0.47	39.00	5.51	7.72	396.5	1.89
28	180	241	0.20	1.34	0.46	62.00	3.69	5.16	320.1	2.34
29	154	207	0.17	1.34	0.46	54.00	4.11	5.83	469.2	1.72
30	99	136	0.17	1.37	0.47	38.00	6.58	9.16	420.8	1.81
31	190	258	0.22	1.36	0.47	69.00	3.16	4.74	398.2	2.05
32	125	164	0.15	1.31	0.44	40.00	4.58	6.30	420.5	1.85
33	138	183	0.15	1.32	0.45	46.00	4.11	5.84	437.9	1.77
34	177	235	0.21	1.33	0.45	59.00	3.25	4.65	366.3	2.13
35	88	120	0.18	1.36	0.47	33.00	7.27	10.20	398.7	1.76
36	213	293	0.23	1.38	0.47	80.00	2.64	3.76	379.3	2.02
37	145	194	0.17	1.34	0.46	50.00	4.48	6.36	364.5	2.15
38	120	159	0.15	1.33	0.45	40.00	5.22	7.07	428.2	1.62
39	195	268	0.23	1.37	0.47	74.00	2.89	4.06	395.7	2.07
40	106	144	0.18	1.36	0.47	39.00	5.50	7.72	362.9	2.13
41	220	304	0.24	1.38	0.47	85.00	2.39	3.48	389.6	2.22
42	97	131	0.18	1.35	0.46	35.00	6.88	9.59	418.1	1.83
43	143	190	0.17	1.33	0.45	49.00	4.45	6.39	379.2	2.04
44	183	246	0.21	1.34	0.46	64.00	3.59	5.05	386.7	1.92
45	109	147	0.18	1.35	0.46	39.00	5.42	7.56	420.3	1.79
46	172	230	0.20	1.34	0.46	58.00	3.71	5.31	398.2	1.94
47	104	142	0.18	1.37	0.47	38.00	6.46	9.06	426.4	1.84
48	186	251	0.21	1.35	0.46	65.00	3.29	4.85	372.7	2.18
49	110	149	0.18	1.35	0.46	39.00	5.41	7.56	419.3	1.81
50	201	272	0.22	1.35	0.46	71.00	3.05	4.63	401.2	2.01

to 0 reflects poor connectivity, while a value nearing 1 denotes a highly connected network. The analysis shows that the Eastern part of Howrah exhibits higher connectivity, with Alpha values ranging between 0.35 and 0.48. Conversely, the westernmost parts demonstrate very low connectivity, with values between 0.06 and 0.10. These findings highlight that the Eastern regions benefit from better network integration, possibly due to higher levels of urban development and infrastructure investment. The Beta (β) index (Figure 3), which represents the ratio of edges to vertices, indicates the complexity of the network. A value of 0 implies no edges, 1 signifies a simple circuit, and values greater than 1 indicate a more intricate network. The Beta values for Howrah City range from 0 to 3, signifying that certain areas have very complex networks with multiple circuits. These areas are likely urban centres with well-developed transport systems. The Gamma (γ) index (Figure 3), which compares the actual number of links to the maximum possible links, further supports the findings of varying connectivity levels. In the study area, Gamma values range from 0.38 to 0.69. The highest Gamma values (0.59 to 0.69) occur in the Eastern parts, indicating better-developed transport networks. The lowest Gamma values (0.38 to 0.45) are observed in the Western areas, pointing to limited connectivity and fewer alternative routes. Finally, the Cyclomatic (μ) index (Figure 3), which measures the redundancy and alternative routes within the network, indicates that higher values correspond to better connectivity. The Cyclomatic numbers calculated in this study show that areas with higher values have well-connected transport systems, with multiple alternative routes supporting resilience and flexibility in traffic management.

The Eta (η) index (Figure 4), which measures the relationship between total network distance and the number of edges, indicates that areas with low Eta values have better accessibility, while higher values suggest less connected regions. In this study, the highest Eta values range from 11.76 to 17.24, corresponding to regions with relatively low connectivity. Conversely, areas with low Eta values (0.92 to 2.17) exhibit high accessibility, suggesting better integration of routes within these parts of the city. The Theta (θ) index (Figure 4) provides additional insight into accessibility. Areas with low Theta values are more accessible, while higher values indicate reduced accessibility. The Theta index values in this study range between 7 and 11, indicating moderate accessibility in most parts of the city. These results suggest that while certain areas are reasonably accessible, there is potential for improvement in others to enhance overall network efficiency. The Pi (π) index (Figure 4), which compares the total network length to its diameter, highlights the relationship between connectivity and network design. Higher Pi values signify greater connectivity. In this study, areas with high Pi values exhibit well-integrated networks, whereas lower values point to regions requiring connectivity enhancements. The Detour *(Di)* index (Figure 4), which assesses the efficiency of the transport network by evaluating route directness, reveals that lower values indicate more direct routes. In this study, the Detour index values range from 38 to 76, showing that some areas offer efficient routing, while others face significant detours due to less direct paths. Overall, the results demonstrate a clear spatial variation in the road network's connectivity and accessibility in Howrah City. The Eastern regions emerge as better connected and accessible compared to the Western parts, underscoring the need for targeted infrastructure improvements in under-connected areas. These findings can guide policymakers and urban planners in designing and implementing strategies to optimize the transport network, fostering equitable access and efficiency across the city.

V Conclusions

The study provides a comprehensive analysis of the road network in Howrah City, highlighting significant spatial variations in connectivity, accessibility, and efficiency. The findings indicate that the northeastern parts of the city exhibit higher connectivity and well-integrated transport networks, as evidenced by higher Alpha, Gamma, and Beta index values. These regions likely benefit from greater urban development and investment in infrastructure. Conversely, the westernmost areas demonstrate low connectivity and accessibility, characterized by lower index values and fewer alternative routes, signalling the need for targeted infrastructural interventions. Indices like Eta and Theta reveal moderate to high accessibility in specific areas, with opportunities for improvement in poorly connected regions. Similarly, the Pi and Detour indices underscore variations in route efficiency and design, while the Cyclomatic index highlights redundancy and alternative pathways in more connected zones. These results underscore the importance of adopting a data-driven approach to urban planning, using GIS-based methodologies to identify gaps and opportunities in transport infrastructure. Policymakers and urban planners can leverage these insights to design equitable and efficient transport systems, addressing disparities in connectivity and accessibility across Howrah City. This research contributes to fostering sustainable urban growth by providing actionable strategies to optimize the transport network for future development.

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