



Quantitative Assessment of Resilience and Reliability in the Urban Road Network of Karbala Using Graph Theory

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ABSTRACT: This study applies graph theory to quantitatively evaluate the structural integrity and resilience of Karbala’s urban road network. By modelling roads as edges and intersections as nodes, we assess the system using key metrics such as meshness, organicity, betweenness and closeness centrality, and global efficiency. The reliability of each road segment is evaluated using an exponential failure function derived from segment-specific travel times and estimated failure rates. Findings reveal moderate to strong connectivity and resilience with areas for potential enhancement, particularly in reducing the network’s diameter and improving redundancy. These insights support urban planning strategies aimed at enhancing infrastructure robustness.

Keywords: Road network analysis, graph theory, reliability, resilience, centrality measures.

Contents

1 Introduction	1
2 Methodology	2
3 Graph Representation of the Network	2
4 Reliability Modeling	3
5 Structural Analysis of the Network	7
5.1 Connectivity and Diameter	7
5.2 Meshness and Organicity	7
5.3 Centrality Measures	8
5.4 Global Efficiency	9
6 Results and Discussion	10

1. Introduction

Urban road networks are essential infrastructure that determines the stability of mobility efficiency, traffic safety, and urban development. Their design and configuration affect the system’s adaptability for traffic overload and disorders such as natural disasters. Recent research highlights the importance of network topology including centrality measures, Meshness, and Organicity in determining the resilience and performance of transportation systems .A resilient network ensures continued functionality under stress and facilitates rapid recovery and detour capability [1,15].This study analyzes the road network of Karbala, Iraq, by creating a graph-based model to determine its structural and functional properties. By incorporating the wrong speed data, the research expands the analysis to incorporate the reliability of individual roads .Previous research has indicated that their resilience and efficiency are much influenced by street network design. Urban design influences networks’ capacity to resist disturbances and maximize traffic flow, according to research by Wang (2015) and Kuşkan (2022) [5,8,12]. Studies by Merchán (2020) and Akram (2024) underlined even more how structural features and network topology affect travel complexity and transportation effectiveness. These results underline the need for quantitative road network analysis for infrastructure development and urban planning [13,14].

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 2020 *Mathematics Subject Classification*: 35B40, 35L70.
 Submitted February 10, 2026. Published April 17, 2026.

2. Methodology

An analytical methodology was adopted to study the reliability and characteristics of the road network in the city of Karbala. It was achieved by transforming the road network into a graphical model. Google Maps was the primary tool for mapping the city's road network. Intersections were accurately identified, and the street paths connecting these intersections were traced using the measurement tools available on the platform. Upon completing the network mapping, the actual length of each street was calculated in kilometres using Google Maps tools, and these values were assigned as edge weights in the graphical model. This representation enables precise distance evaluation and facilitates the analysis of mobility characteristics within the network. The reliability of each road within the network was assessed using indicators that reflect the road's significance in connecting various parts of the city.

3. Graph Representation of the Network

The urban road network of Karbala is modelled as a primal graph $G(n, m)$, where nodes n represent intersections and edges m represent roads. The graph comprises 104 vertices and 157 edges, as shown in Figure 1. The graph incorporates three key parameters for each edge:

- L : Road length (The length of the route was calculated using Google Maps)
- v : Road speed (estimated)
- λ : Accident rate (estimated as follows:
 - if $v = 20$, then $\lambda = 0.01$
 - if $v = 40$, then $\lambda = 0.03$
 - if $v = 60$, then $\lambda = 0.05$

Two representations are considered [2,16,17]:

- **Primal Graph**: Captures geometric details and is suited for spatial analysis.
- **Dual Graph**: Provides insight into network complexity, but is not the primary focus of this study.

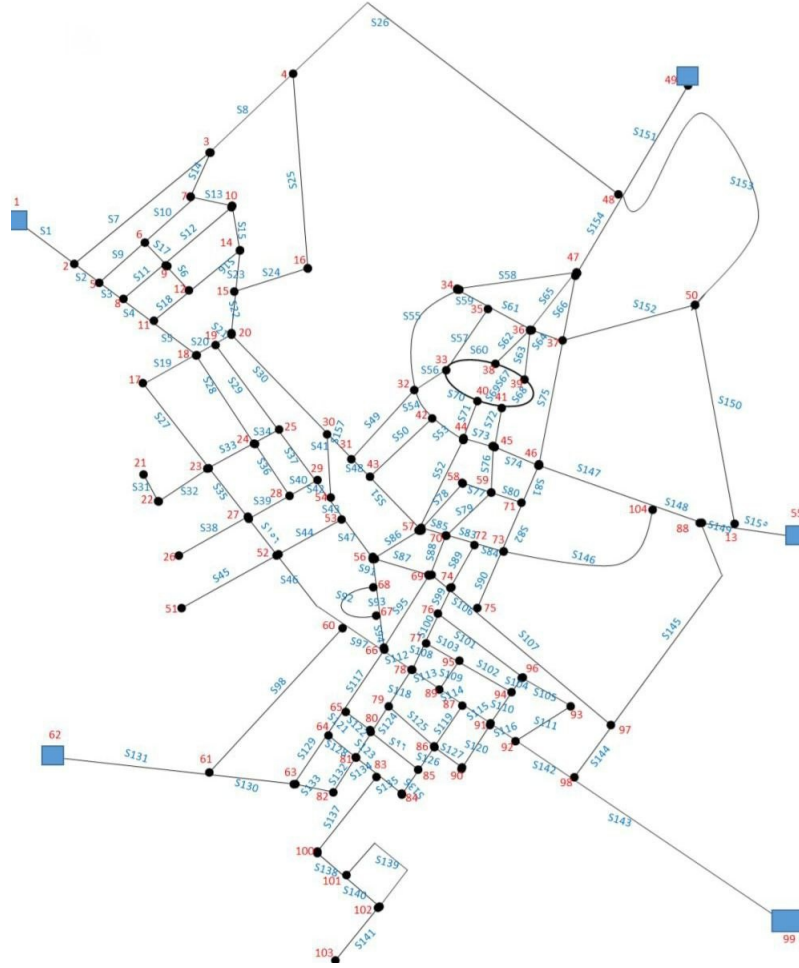


Figure 1: Graph Illustrating the Road Network Layout of Karbala

4. Reliability Modeling

To quantify road reliability, we assume that the failure probability of a road segment follows an exponential distribution. For a segment of length L and average speed v , the travel time

$$T = L/v \tag{4.1}$$

Assuming a constant failure rate λ , the reliability function is:

$$R_T(t) = e^{-\lambda t} \tag{4.2}$$

where λ is derived from estimated failure rates based on speed categories. This approach aligns with recent advances in component reliability modeling for complex systems with imperfect switching mechanisms [4,7,20,21,22,23]. Table 1 presents the calculated reliability values for each segment.

Table 1: An assessment of the reliability of each road in Karbala city.

N	Edge name	Road length (Km)	Road speed (Km/h)	Time (m)	Failure rate	Reliability
1	S1	5.5	60	5.5	0.05	0.76
2	S2	0.524	60	0.524	0.05	0.97
3	S3	0.48	60	0.48	0.05	0.98
4	S4	0.495	60	0.495	0.05	0.98
5	S5	1.05	60	1.05	0.05	0.95
6	S6	0.504	20	1.512	0.01	0.98
7	S7	2.19	40	3.285	0.03	0.91
8	S8	1.94	40	2.91	0.03	0.92
9	S9	0.452	40	0.678	0.03	0.98
10	S10	0.968	40	1.452	0.03	0.96
11	S11	0.461	40	0.6915	0.03	0.98
12	S12	0.876	40	1.314	0.03	0.96
13	S13	0.328	40	0.492	0.03	0.99
14	S14	0.858	40	1.287	0.03	0.96
15	S15	0.759	40	1.1385	0.03	0.97
16	S16	0.706	40	1.059	0.03	0.97
17	S17	0.475	20	1.425	0.01	0.99
18	S18	0.393	40	0.5895	0.03	0.98
19	S19	0.77	40	1.155	0.03	0.97
20	S20	0.332	40	0.498	0.03	0.99
21	S21	0.154	40	0.231	0.03	0.99
22	S22	0.191	40	0.2865	0.03	0.99
23	S23	0.759	40	1.1385	0.03	0.97
24	S24	2.12	40	3.18	0.03	0.91
25	S25	2.28	40	3.42	0.03	0.90
26	S26	11.96	60	11.96	0.05	0.55
27	S27	1.7	60	1.7	0.05	0.92
28	S28	1.69	40	2.535	0.03	0.93
29	S29	1.72	40	2.58	0.03	0.93
30	S30	2.87	60	2.87	0.05	0.87
31	S31	0.338	20	1.014	0.01	0.99
32	S32	0.97	20	2.91	0.01	0.97
33	S33	0.773	40	1.1595	0.03	0.97
34	S34	0.325	40	0.4875	0.03	0.99
35	S35	1.01	60	1.01	0.05	0.95
36	S36	1.07	40	1.605	0.03	0.95
37	S37	1.06	40	1.59	0.03	0.95
38	S38	1.19	40	1.785	0.03	0.95
39	S39	0.742	40	1.113	0.03	0.97
40	S40	0.318	40	0.477	0.03	0.99
41	S41	0.694	40	1.041	0.03	0.97
42	S42	0.192	40	0.288	0.03	0.99
43	S43	0.149	40	0.2235	0.03	0.99
44	S44	1.08	40	1.62	0.03	0.95
45	S45	1.73	40	2.595	0.03	0.93
46	S46	1.79	60	1.79	0.05	0.91

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N	Edge name	Road length (Km)	Road speed (Km/h)	Time (m)	Failure rate	Reliability
47	S47	0.893	40	1.3395	0.03	0.96
48	S48	0.207	60	0.207	0.05	0.99
49	S49	0.891	40	1.3365	0.03	0.96
50	S50	0.835	40	1.2525	0.03	0.96
51	S51	0.884	60	0.884	0.05	0.96
52	S52	1.03	40	1.545	0.03	0.95
53	S53	0.208	20	0.624	0.01	0.99
54	S54	0.235	20	0.705	0.01	0.99
55	S55	0.765	20	2.295	0.01	0.98
56	S56	0.236	20	0.708	0.01	0.99
57	S57	0.593	20	1.779	0.01	0.98
58	S58	1.66	20	4.98	0.01	0.95
59	S59	0.221	20	0.663	0.01	0.99
60	S60	0.349	20	1.047	0.01	0.99
61	S61	0.387	40	0.5805	0.03	0.98
62	S62	0.397	20	1.191	0.01	0.99
63	S63	0.373	20	1.119	0.01	0.99
64	S64	0.35	40	0.525	0.03	0.98
65	S65	1	60	1	0.05	0.95
66	S66	1.33	60	1.33	0.05	0.94
67	S67	0.131	40	0.1965	0.03	0.99
68	S68	0.209	20	0.627	0.01	0.99
69	S69	0.359	20	1.077	0.01	0.99
70	S70	0.145	40	0.2175	0.03	0.99
71	S71	0.138	40	0.207	0.03	0.99
72	S72	0.299	20	0.897	0.01	0.99
73	S73	0.331	20	0.993	0.01	0.99
74	S74	0.685	40	1.0275	0.03	0.97
75	S75	1.16	40	1.74	0.03	0.95
76	S76	0.561	40	0.8415	0.03	0.98
77	S77	0.348	20	1.044	0.01	0.99
78	S78	0.396	40	0.594	0.03	0.98
79	S79	0.397	40	0.5955	0.03	0.98
80	S80	0.497	40	0.7455	0.03	0.98
81	S81	0.519	40	0.7785	0.03	0.98
82	S82	0.363	40	0.5445	0.03	0.98
83	S83	0.321	40	0.4815	0.03	0.99
84	S84	0.379	40	0.5685	0.03	0.98
85	S85	0.36	40	0.54	0.03	0.98
86	S86	0.784	40	1.176	0.03	0.97
87	S87	0.786	40	1.179	0.03	0.97
88	S88	0.729	40	1.0935	0.03	0.97
89	S89	0.763	40	1.1445	0.03	0.97
90	S90	0.779	40	1.1685	0.03	0.97
91	S91	0.223	40	0.3345	0.03	0.99
92	S92	1.71	20	5.13	0.01	0.95
93	S93	1.12	40	1.68	0.03	0.95

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N	Edge name	Road length (Km)	Road speed (Km/h)	Time (m)	Failure rate	Reliability
94	S94	0.371	40	0.5565	0.03	0.98
95	S95	1.39	40	2.085	0.03	0.94
96	S96	0.635	20	1.905	0.01	0.98
97	S97	1.2	60	1.2	0.05	0.94
98	S98	1.73	40	2.595	0.03	0.93
99	S99	0.545	40	0.8175	0.03	0.98
100	S100	0.495	40	0.7425	0.03	0.98
101	S101	1.14	40	1.71	0.03	0.95
102	S102	0.762	40	1.143	0.03	0.97
103	S103	0.352	40	0.528	0.03	0.98
104	S104	0.478	20	1.434	0.01	0.99
105	S105	0.694	20	2.082	0.01	0.98
106	S106	0.244	40	0.366	0.03	0.99
107	S107	0.992	40	1.488	0.03	0.96
108	S108	0.455	40	0.6825	0.03	0.98
109	S109	0.439	40	0.6585	0.03	0.98
110	S110	0.563	40	0.8445	0.03	0.97
111	S111	1.18	40	1.77	0.03	0.95
112	S112	0.556	60	0.556	0.05	0.97
113	S113	0.355	60	0.355	0.05	0.98
114	S114	0.29	60	0.29	0.05	0.99
115	S115	0.476	60	0.476	0.05	0.98
116	S116	0.132	60	0.132	0.05	0.99
117	S117	0.574	40	0.861	0.03	0.97
118	S118	0.339	40	0.5085	0.03	0.98
119	S119	0.337	40	0.5055	0.03	0.98
120	S120	0.442	40	0.663	0.03	0.98
121	S121	0.395	20	1.185	0.01	0.99
122	S122	0.632	20	1.896	0.01	0.98
123	S123	0.397	20	1.191	0.01	0.99
124	S124	0.281	20	0.843	0.01	0.99
125	S125	0.627	20	1.881	0.01	0.98
126	S126	0.234	20	0.702	0.01	0.99
127	S127	0.531	20	1.593	0.01	0.98
128	S128	0.529	20	1.587	0.01	0.98
129	S129	0.545	40	0.8175	0.03	0.98
130	S130	1.06	60	1.06	0.05	0.95
131	S131	3.54	60	3.54	0.05	0.84
132	S132	0.162	40	0.243	0.03	0.99
133	S133	0.504	60	0.504	0.05	0.98
134	S134	0.458	20	1.374	0.01	0.99
135	S135	0.458	20	1.374	0.01	0.99
136	S136	0.181	20	0.543	0.01	0.99
137	S137	2.16	40	3.24	0.03	0.91
138	S138	0.351	40	0.5265	0.03	0.98
139	S139	1.16	40	1.74	0.03	0.95
140	S140	0.331	40	0.4965	0.03	0.99

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N	Edge name	Road length (Km)	Road speed (Km/h)	Time (m)	Failure rate	Reliability
141	S141	1.31	40	1.965	0.03	0.94
142	S142	1.93	60	1.93	0.05	0.91
143	S143	4.57	60	4.57	0.05	0.80
144	S144	1.04	60	1.04	0.05	0.95
145	S145	3.9	60	3.9	0.05	0.82
146	S146	2.28	40	3.42	0.03	0.90
147	S147	1.7	60	1.7	0.05	0.92
148	S148	1.49	60	1.49	0.05	0.93
149	S149	1.69	60	1.69	0.05	0.92
150	S150	4.66	60	4.66	0.05	0.79
151	S151	2.28	60	2.28	0.05	0.89
152	S152	5.28	60	5.28	0.05	0.77
153	S153	5.39	40	8.085	0.03	0.78
154	S154	2.8	60	2.8	0.05	0.87
155	S155	3.85	60	3.85	0.05	0.82
156	S156	0.378	60	0.378	0.05	0.98
157	S157	0.206	60	0.206	0.05	0.99

5. Structural Analysis of the Network

After mapping the city's road network, we will analyze the road structure using several key metrics relevant to the city. Below are some characteristics of the road network in the city of Karbala.

5.1. Connectivity and Diameter

The edge-to-node ratio ($m/n = 1.509$) indicates a reasonably well-connected network. The graph diameter defined as the longest shortest path between any two nodes is 20, suggesting the network may experience efficiency bottlenecks in reaching peripheral areas.

5.2. Meshness and Organicity

Meshness: Calculated using Euler's formula, it reflects the proportion of actual to possible cycles. For Karbala, $M = 0.266$, indicating moderate connectivity, where

$$M = \frac{F}{2n - 5} \quad (2)$$

Euler's theorem calculates the number of faces (except for the unbounded face, which represents the outer region of the network) [3,6,8]. Thus, we have

$$F = m - n + 1 \quad (3)$$

M represents the Meshness, F represents the number of faces, m represents the number of edges, and n represents the number of vertices. M is usually small because real cities do not have triangles or squares. This scale ranges from zero to one. Zero indicates poor network connectivity, while one indicates full network connectivity.

Organicity: Defined as the proportion of nodes with degree $\neq 2$. Karbala's value of $O = 0.7$ suggests a predominantly unplanned and organically grown network. The Organicity is described as follows [8]:

$$O = \frac{N(1) + N(3)}{\sum_{j \neq 2} N(j)} \quad (4)$$

where $N(j)$ represents the vertices whose degrees are equal to j . If the degree of the vertex is equal to 2, it is not counted. The value is also between zero and one. If it is high, the city planning is random; if it is low, it is organized. The Organicity of Karbala City is 0.7.

5.3. Centrality Measures

Betweenness centrality measures the proportional prominence of a node or edge within a network structure with respect to connectivity, which is defined in a graph G as:

$$BC_i = \sum_{j \neq g \in G} \frac{BC_{fg(i)}}{BC_{fg}} \quad (5)$$

where BC_i represents the betweenness centrality, $BC_{fg(i)}$ represents the number of the shortest paths among vertices j and g , BC_{fg} represents the number of all shortest paths among them [8]. Betweenness Centrality was calculated for each vertex of the city of Karbala. Vertices {66, 69, 52, 60, 27} exhibited the highest values, highlighting them as potential congestion points, as shown in Table 2.

Table 2: Betweenness Centrality for Each Vertex in Road Network of Karbala

vertices	Betweenness Centrality	vertices	Betweenness Centrality	vertices	Betweenness Centrality	vertices	Betweenness Centrality
1	0.00	27	758.08	53	758.07	79	173.33
2	191.53	28	199.02	54	575.70	80	392.75
3	347.13	29	154.18	55	0.00	81	465.53
4	603.28	30	652.32	56	746.91	82	57.54
5	139.22	31	369.13	57	634.64	83	402.00
6	26.45	32	289.12	58	18.81	84	71.53
7	114.58	33	161.60	59	351.08	85	176.88
8	197.22	34	138.99	60	936.67	86	197.87
9	59.39	35	29.53	61	312.72	87	144.95
10	84.69	36	139.59	62	0.00	88	487.03
11	337.33	37	377.65	63	180.34	89	150.90
12	84.93	38	31.19	64	274.02	90	68.30
13	429.08	39	47.18	65	659.09	91	258.38
14	195.17	40	140.41	66	1468.30	92	273.92
15	460.92	41	92.85	67	27.00	93	20.59
16	226.41	42	89.24	68	33.29	94	42.14
17	133.39	43	213.53	69	1202.34	95	35.68
18	473.88	44	347.13	70	605.83	96	118.08
19	209.11	45	329.40	71	147.25	97	575.06
20	582.54	46	422.59	72	143.18	98	368.00
21	0.00	47	306.79	73	148.67	99	0.00
22	102.00	48	675.30	74	609.21	100	300.00
23	499.36	49	0.00	75	340.99	101	202.00
24	324.88	50	476.22	76	266.49	102	102.00
25	89.39	51	0.00	77	127.89	103	0.00
26	0.00	52	1062.40	78	518.66	104	146.08

Closeness centrality indicates the average accessibility of a node. Measures a vertex's importance in a network by calculating the average shortest path distance to all other reachable vertices. The Closeness centrality of a node is described by [9,19]:

$$C_i = \frac{n-1}{\sum_{i \neq n \in V} d_{in}} \quad (6)$$

where d_{in} is the smallest distance between i and every other node n . A node with a small median distance from every other reachable vertex has high proximity centrality. Table 3 shows the Closeness Centrality values for each vertex of the City of Karbala. Results show minimal disparity among nodes, suggesting a balanced network layout.

Table 3: Closeness Centrality for Each Vertex in Road Network of Karbala

vertices	Closeness Centrality	vertices	Closeness Centrality	vertices	Closeness Centrality	vertices	Closeness Centrality
1	0.001101	27	0.001684	53	0.001931	79	0.00155
2	0.001241	28	0.0016	54	0.001821	80	0.001543
3	0.001325	29	0.001618	55	0.001339	81	0.001372
4	0.001466	30	0.001773	56	0.002016	82	0.001326
5	0.001232	31	0.001751	57	0.001916	83	0.001233
6	0.001179	32	0.001629	58	0.001678	84	0.001252
7	0.001248	33	0.001531	59	0.001776	85	0.001403
8	0.001267	34	0.001529	60	0.001866	86	0.001435
9	0.001209	35	0.001443	61	0.001621	87	0.001466
10	0.001276	36	0.001479	62	0.001391	88	0.001626
11	0.001339	37	0.001616	63	0.001445	89	0.001543
12	0.001302	38	0.001447	64	0.001499	90	0.001364
13	0.00155	39	0.001488	65	0.001706	91	0.001425
14	0.001377	40	0.001587	66	0.001957	92	0.001435
15	0.001534	41	0.001577	67	0.001712	93	0.001368
16	0.00146	42	0.001653	68	0.001754	94	0.001393
17	0.001473	43	0.001779	69	0.002012	95	0.001412
18	0.001462	44	0.00177	70	0.001927	96	0.001456
19	0.001477	45	0.001757	71	0.001695	97	0.001667
20	0.001645	46	0.001698	72	0.001757	98	0.001515
21	0.001181	47	0.001558	73	0.001656	99	0.001312
22	0.001342	48	0.001522	74	0.001852	100	0.001103
23	0.00155	49	0.001318	75	0.001739	101	0.000995
24	0.00149	50	0.00157	76	0.00165	102	0.000905
25	0.001506	51	0.001572	77	0.001595	103	0.000829
26	0.001437	52	0.001873	78	0.001739	104	0.001597

5.4. Global Efficiency

Network efficiency (measuring the network's ability to transmit information or facilitate movement) evaluates the performance of street networks under attacks by measuring information propagation through shortest paths. It reflects the speed and effectiveness of movement or data flow between nodes in the network [10]. The efficiency of the network is described by [11,18]:

$$E(G) = \frac{1}{n(n-1)} \sum_{i \neq n \in G} \frac{1}{d_{in}} \quad (7)$$

where $E(G)$ is the global efficiency of network communication, which is estimated at 0.244. This suggests the network is functionally efficient but could benefit from targeted enhancements.

6. Results and Discussion

The analysis of Karbala's city road network, modeled as a primal graph, shows a reasonably efficient and fairly connected infrastructure. With 104 nodes and 157 edges, the network demonstrates a connectivity index of 1.509, suggesting an adequate interconnection stage throughout the town's roads. However, the exceptionally large network diameter of 20 implies decreased performance in traversing the city, especially in long-distance journeys or emergency response situations. A high diameter reflects the maximum shortest path length between any two nodes and can imply suboptimal accessibility in peripheral areas.

The network's meshness index, calculated at 0.266, suggests a limited loop connection. This indicates that many areas of the network depend on linear or tree-like structures, which are less flexible for handling local disruption. Organicity value of 0.7 confirms that the network mainly exhibits unplanned growth patterns with irregular and non-uniform connections. These findings suggest that the city has systematically evolved with a preference for top-down planning, which is central to structural disabilities in its topology.

The reliability analysis is based on an exponential failure model that includes the roadside, estimated speed, and subordinate accident rate, indicating that most road segments maintain a high credibility point. Nevertheless, segments with long-term travel time or estimates with high failure frequency present potential weaknesses. These sections may experience the risk or increasing risk of serving the dissolution of services, especially in extreme use or unfavorable weather conditions. The opposite relationship between the speed and reliability of the vehicle seen in the results suggests that high-speed limit ways are receptive to a decrease in reliability, the possibility of the risk of serious accidents.

Centrality measurements, especially between the beach and the centrality, identified one of the important intersections - Nodes 66, 69, 52, 60, and 27 - as the most important capacitor for traffic flows. Their central roles mean that any operating failure at these points can cause disruptive resolution in the network. In contrast, it was found that nodes with low centrality values had a limited effect on the general connection and flexibility, reflecting their peripheral role in network dynamics.

Integrating the geographical information system (GIS) tool and Google Maps was important in calculating an accurate edge, increasing graph-based model reliability. This methodological approach ensured that spatial properties such as road length and approximate travel time were honestly represented in structural analysis. A summary of the key topological and performance indicators for Karbala's road network is presented in Table 4.

Table 4: A summary of Karbala's road network features and performance measures.

Indicator	Value	Description
N (Nodes)	104	Number of intersections
E (Edges)	157	Number of road segments
C (Connectivity)	1.509	Edge-to-node ratio
Diam. (Diameter)	20	Longest shortest path in the network
M (Meshness)	0.266	Proportion of actual to potential cycles
O (Organicity)	0.7	Degree of unplanned urban growth
E_{global} (Global Efficiency)	0.2440	Network performance under ideal transfer conditions

Acknowledgments

I want to thank and express my deepest gratitude to my supervisor (Dr. Hussein K. Asker) who made this work possible. He guided and advised me through all stages of writing my paper

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