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Complex Network Analysis of Urban Road Systems: A Case Study of Bandar Lampung, Indonesia

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Abstract

Urban road networks can be examined as complex systems in which the arrangement of intersections and road segments determines how different parts of a city are connected. The Bandar Lampung road network is treated as a directed graph derived from OpenStreetMap data. The largest weakly connected component contains 23,920 nodes and 58,492 directed edges, with a density of 0.000102 and an average total directed degree of 4.89. Most nodes have low to moderate degree, whereas only a small subset has markedly more direct connections. High-betweenness nodes occur repeatedly along several major corridors, notably Jalan Bypass Sukarno Hatta and Jalan Gatot Soebroto. PageRank gives a less corridor-dominated pattern, with highly ranked locations on both arterial and local streets. The difference is expected because the measures capture different structural roles: direct connectivity, position on shortest paths, and influence transmitted through neighboring nodes. Taking together, the results provide a topological baseline for Bandar Lampung and identify locations that can be examined further using traffic volume, travel time, road capacity, weighted networks, and other operational data.

1. INTRODUCTION

Changes in the urban area and in travel demand can alter the way intersections and road segments are linked. What matters here is not only the individual road elements, but the pattern of connections among them. The Bandar Lampung network is therefore examined as a directed graph, using degree centrality, betweenness centrality, PageRank, and network density to describe its topology. These quantities characterize the graph itself; they do not provide direct observations of congestion, demand, travel time, or other operating conditions.

1.1 Background and Motivation

Road development is constrained by the setting in which it takes place. In Bandar Lampung, terrain, available land, the coastal boundary, land use, and road hierarchy limit where new links can be formed and how alternative routes can develop. The role of terrain is particularly relevant because highland and mountainous areas have influenced the spatial pattern of urban development (Mulyasari et al., 2019).

Bandar Lampung also has a coastal setting with continuing expansion of built-up and settlement areas. Recent work documents change in coastal settlements and built-up areas alongside infrastructure development (Putri, 2025). Such changes can affect the locations at which road links are feasible and the routes available between different parts of the city. Bandar Lampung therefore provides a useful setting for examining how its spatial characteristics are reflected in road-network topology.

Transportation studies examine urban mobility through different forms of evidence, including traffic observations, travel-demand analysis, simulation, and individual travel histories. Longitudinal mobility records can be used to reconstruct trip patterns and examine how individuals move through urban space over time (Fisu et al., 2024). These approaches provide information on realized mobility, but they address a different question from the structural organization of the road network. Complex network analysis provides a way to examine that structure by representing intersections and road segments as interconnected graph elements and quantifying their relationships(Porta et al., 2006).

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1.2 Theoretical Framework

Urban road networks can be represented as graphs in which intersections form the nodes and road segments form the edges. The representation allows the organization of connections between road elements to be examined with graph-theoretic measures (Mark Newman, 2018).

The three centrality measures are not interchangeable. Degree records the immediate directed links of a node. Betweenness instead reflects whether the node lies on shortest paths between other nodes (Freeman, 1977; Crucitti et al., 2006). PageRank adds information about the structural importance of neighboring nodes, so a node can obtain a higher score through its links to other influential nodes (Amy N. Langville & Carl D. Meyer, 2006). These measures therefore do not identify the same type of importance. Consequently, an intersection with many direct links need not be an important intermediary, while a node with fewer links may connect otherwise distant portions of the graph. Reading the three measures together preserves this distinction rather than reducing importance to one centrality score.

A directed graph is used because connectivity in an urban road network can be asymmetric, particularly where one-way restrictions are present. Degree-based measures and PageRank are consequently interpreted according to the direction of the extracted network. Betweenness centrality, meanwhile, is calculated from unweighted shortest paths. The resulting values refer to route topology; they are not measures of distance, travel time, traffic volume, or operational performance.

1.3 Research Gap

Complex-network methods are already used to describe urban transportation structure, yet the three centrality measures do not always appear in a common analysis. Degree reflects local connectivity; betweenness identifies intermediary positions; PageRank incorporates the influence of neighboring nodes. Treating them separately can blur the distinction among these roles, particularly when an intersection is highly connected but is not an important connector between distant parts of the network. The directed representation is also important because the degree value depends on link orientation rather than only on the number of physical road segments meeting at an intersection.

Structural prominence also needs to be read against the spatial setting of the city. In Bandar Lampung, terrain, the coastal boundary, urban development, and road hierarchy shape the urban form. Earlier work describes both the geomorphological setting and continuing changes in built-up and coastal settlement areas (Mulyasari et al., 2019). What remains less clear is how these conditions are expressed in the road topology and whether corridors with a distinctive structural position can be identified from the network itself (Sreelekha et al., 2020).

The present analysis combines degree, betweenness, and PageRank on a directed representation of the Bandar Lampung network. The comparison is used to separate the different forms of structural importance and to see which corridors recur across the rankings. In this way, the study provides a topological description of a medium-sized Indonesian city whose road development is shaped by both coastal and topographic conditions (Wang et al., 2022).

1.4 Research Objective and Contribution

This study examines the topological structure of the Bandar Lampung urban road network using OpenStreetMap data and a directed graph representation. The four measures are used for different purposes: degree for local connectivity, betweenness for shortest-path position, PageRank for neighboring-node influence, and density for overall connectivity.

The analysis separates three situations that can otherwise appear similar: many local connectivity, an intermediary position between locations, and connections to influential parts of the graph. Direction is retained in the road representation, so links are not assumed to be mutually accessible. The spatial results are then used to examine whether high-ranking nodes recur along particular corridors and how those locations fit the city's spatial organization.

2. METHODS

2.1 Data Acquisition and Preprocessing

The road data came from OpenStreetMap and were retrieved with OSMnx, which provides functions for constructing street networks as graph-based spatial data (Boeing, 2017). The resulting graph can then be used to examine topological and spatial properties of the extracted streets (Boeing, 2020; Boeing, 2025).

The study area was defined from the administrative boundary returned by the OSM geocoder for the query "Bandar Lampung, Indonesia." This boundary was used during network extraction because the selected spatial extent can affect the resulting topological characteristics and the location of high-centrality components (Cheng et al., 2023).

Network extraction used `graph_from_place()` with `network_type= "drive"` and `simplify =True`. This setting retrieves roads intended for motor-vehicle travel and removes intermediate geometry nodes while retaining intersection and dead-end nodes. No further filtering was imposed by highway class, road width, speed limit, or traffic function; so that segments returned by the OSMnx drive definition were retained as extracted.

The extracted graph represents the drivable road topology available in OSM rather than a traffic-capacity or operational network. The extraction settings are summarized in Table 1.

Table 1. OSMnx parameters used for road network extraction.

No	Parameter	Value
1	Study area	Bandar Lampung
2	Data source	OpenStreetMap
3	Data retrieval date	8 August 2026
4	Extraction function	graph_from_place()
5	OSMnx version	2.1.0
6	`network_type`	`drive`
7	`simplify`	`True`
8	`retain_all`	`True`
9	Graph representation	Directed graph
10	Additional road-class filtering	None
11	Edge weights for centrality	None

Setting `retain_all=True` preserved the components returned by OSMnx. The resulting directed graph contained 24,159 nodes and 58,920 directed edges before component selection, distributed among 54 weakly connected components (WCC) and 96 strongly connected components (SCC).

The largest WCC was selected as the final analysis graph. The largest WCC retained 23,920 nodes and 58,492 directed edges, or 99.01% of the nodes in the original graph. The selection excluded 239 nodes and 428 directed edges from subsequent network-metric calculations. Overall, approximately 0.99% of the extracted nodes were excluded from the centrality analysis. The connectivity characteristics before and after component selection are presented in Table 2.

Table 2. Connectivity characteristics before and after component selection

No	Measure	Original graph	Largest WCC
1	Number of nodes	24,159	23,920
2	Number of edges	58,920	58,492
3	Weakly connected components	54	1
4	Strongly connected components	96	43
5	Nodes excluded	–	239
6	Edges excluded	–	428
7	Nodes retained	–	99.01%

2.2 Network Modeling

The urban road system was represented as a directed graph, as defined in Equation (1):

$$G = (V, E) \qquad (1)$$

In this context, nodes V represents intersections and edges E represents road segments.

After simplification, the OSMnx graph uses intersections and network endpoints as nodes and the road segments between them as directed edges. Direction is retained in the edge orientation. This graph representation makes the organization of road connections measurable and is widely used for transportation-network analysis (Mark Newman, 2018; Barthélemy, 2011). With this representation, the road system can be viewed as a complex network whose larger structure arises from many individual connections among intersections and road segments. Earlier studies have reported non-random structural patterns in urban road networks that affect connectivity and their overall organization (Duncan J. Watts & Steven H. Strogatz, 1998; Crucitti et al., 2006).

2.3 Network Metrics

2.3.1 Degree Centrality

For a node i, the degree centrality is defined as Equation (2):

$$C_D(i) = k(i) = k_{in}(i) + k_{out}(i) \quad (2)$$

where $k_{in}(i)$ and $k_{out}(i)$ represent the number of incoming and outgoing directed edges associated with node i, respectively.

The degree values were obtained with the `nx.degree(G)` function in NetworkX. For the directed graph, the measure combines incoming and outgoing edges; consequently, a bidirectional road may appear as two reciprocal links. Degree is used to describe local topological connectivity. A larger value means more direct graph connections, but it does not by itself imply a central position on shortest paths or strong global influence (Freeman, 1978; Porta et al., 2006).

For this graph, degree refers to incoming plus outgoing directed edges as it is not a count of physically distinct road segments at the intersection. This distinction is important because a bidirectional road can be represented by two reciprocal directed edges in the graph.

2.3.2 Betweenness Centrality

Equation (3) defines betweenness centrality in terms of a node's occurrence on shortest paths between other node pairs:

$$C_B(v) = \sum_{s \neq v \neq t} \frac{\sigma_{st(v)}}{\sigma_{st}} \quad (3)$$

Here, σ_{st} denotes all shortest paths from nodes s to node t, while $\sigma_{st(v)}$ represents those paths that pass-through node v (Crucitti et al., 2006).

Betweenness was computed on the directed graph without assigning distance or travel-time weights to the edges. The measure therefore reflects a node's position along topological shortest paths rather than accessibility based on physical or temporal impedance. Similar use of betweenness for identifying structurally important locations has been reported for urban street networks (Altaweel et al., 2021; Wang et al., 2022). The betweenness values represent topological shortest-path intermediation and should not be interpreted as direct measures of traffic flow, congestion, travel time, or operational bottlenecks.

2.3.3 PageRank

PageRank evaluates node influence from the directed connections in which each node participates. PageRank is calculated recursively according to Equation (4):

$$PR(i) = \frac{1-d}{N} + d \sum_{j \epsilon M(i)} \frac{PR(j)}{L(j)} \quad (4)$$

where d represents the damping factor, N is the total number of nodes, $M(i)$ denotes to the set of nodes adjacent to node i, while $L(j)$ is the number of outgoing edges from adjacent node j. Unlike degree and betweenness,

PageRank incorporates the structural importance of neighboring nodes when determining the influence of a given node (Amy N. Langville & Carl D. Meyer, 2006).

Using the directed graph, PageRank adds a measure of structural influence that is not captured by direct degree or shortest-path intermediation alone. It has also been applied to urban street networks for ranking intersections according to their surrounding connection structure, including directed and spatial settings (Zhang et al., 2021).

2.3.4 Network Density

Network density represents the ratio of observed directed connections to the maximum possible number of directed connections in a graph without self-loops, as given in Equation (5):

$$D = \frac{|E|}{|V|(|V|-1)} \qquad (5)$$

where $|V|$ represents the number of nodes and $|E|$ denotes the number of edges.

Density summarizes the proportion of possible directed links that are present. In a spatially embedded street system, geography and urban morphology restrict the number of feasible links, so a low density is not, on its own, evidence of poor transportation performance (Boeing, 2020;Boeing, 2022)

2.4 Computational Implementation

All computations were performed in Python, with OSMnx used for road-network extraction and NetworkX for graph analysis. Both libraries support the analysis of large graph datasets and reproducible network-analysis workflows (Aric A. Hagberg et al., 2008; Boeing, 2017; Boeing, 2019a).

Betweenness centrality was estimated using (`k=200`) sampled nodes with `seed=42` to maintain reproducibility. An approximate implementation in NetworkX was selected because the extracted network contains more than 23,000 nodes, making exact betweenness computation computationally intensive. Sampling reduces the processing requirements while retaining information about structurally important nodes.

No edge-weight attribute was assigned during the analysis. Shortest paths were therefore determined from network topology alone rather than physical distance, travel time, road capacity, or observed traffic conditions (Brandes & Pich, 2007). The resulting betweenness values should consequently be interpreted as topological centrality measures. The computational settings are summarized in Table 3.

Table 3. Computational settings for network metric calculation

No	Network Metric	Python Function	Settings
1	Degree Centrality	`nx.degree()`	Default implementation; total degree = in-degree + out-degree
2	Betweenness Centrality	`nx.betweenness_centrality()`	Directed graph; `k=200; seed=42;` unweighted
3	PageRank	`nx.pagerank()`	Directed graph; default damping factor
4	Network Density	`nx.density()`	Directed graph

As summarized in Table 3, all network metrics were computed using NetworkX. Approximate betweenness centrality was applied only to reduce computational cost for the large road network, whereas degree centrality, PageRank, and network density were obtained using their standard implementations. All subsequent network metrics were calculated on the largest weakly connected component, denoted as $G_{largest}$.

2.5 Analysis Workflow

The procedure begins with the study boundary and OSM extraction, followed by graph construction and selection of the component used for analysis. Degree, betweenness, PageRank, and density are then calculated, after which their spatial patterns are examined. Keeping these stages separate makes the computational procedure easier to reproduce and inspect (Boeing, 2020; Barthélemy, 2011). Figure 1 summarizes the sequence used in this study.

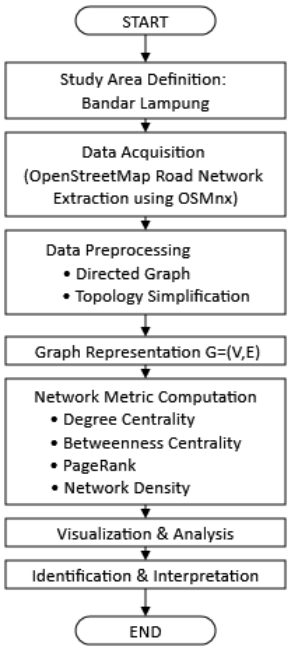


Figure 1. Research workflow of the proposed complex network analysis methodology.

The workflow starts with the Bandar Lampung boundary and the road network retrieved from OpenStreetMap using OSMnx. After road extraction, the network is simplified and converted to a directed graph, and the largest weakly connected component is retained for analysis. The four network measures are calculated from this final graph. The resulting values are summarized numerically and mapped to show where the different topological patterns occur.

3. RESULT

All reported metrics refer to the largest weakly connected component of the Bandar Lampung network. Degree, betweenness, PageRank, and density are used to characterize that component. The resulting values concern network topology; they are not direct observations of traffic volume, congestion, travel time, or road capacity.

3.1 Network Structure Overview

The overall network structure of the urban road system is presented through basic topological statistics. Table 4 summarizes the main topological properties of the final road network graph.

Table 4. Summary of key topological properties of

No	Metric	Value
1	Number of nodes	23920
2	Number of directed edges	58492
3	Network density	0.000102
4	Average total directed degree	4.89
5	Betweenness nodes	23920
6	PageRank nodes	23920

From Table 4, the largest weakly connected component comprises 23,920 nodes and 58,492 directed edges, giving a density of 0.000102. Thus, only a small fraction of all theoretically possible directed links occurs in the graph. Similar sparsity has been reported for spatially embedded street networks, where geographic and urban-form constraints limit feasible connections (Boeing, 2022).

The average total directed degree is 4.89. This value combines the incoming and outgoing directed edges in the graph and therefore should not be read as the number of physical road segments meeting at an intersection. For example, a bidirectional road can appear as two reciprocal directed edges. The average consequently describes connectivity within the graph representation rather than the physical number of road approaches at an intersection.

3.2 Degree Distribution Analysis

Figure 2 shows the distribution of total directed degree across the 23,920 nodes in the analyzed network.

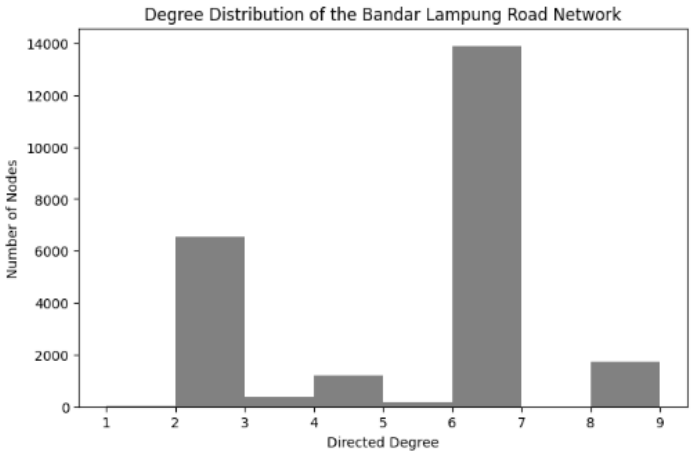


Figure 2. Degree distribution of urban road network of Bandar Lampung

Degree values are concentrated between two and six, with the largest frequency around degree six. Only a small fraction of nodes extends into the higher-degree range. This distribution is consistent with the role of degree as a local connectivity measure; it does not indicate where a node sits within the network as a whole (Chen et al., 2023; Xiao & Yang, 2023). The limited range of degree values is also consistent with previous work showing that spatial embeddedness and planarity constrain the degree distribution of urban street systems (Akbarzadeh et al., 2018).

Nodes with larger total directed degree have more incoming and outgoing connections in the graph and are therefore locally well-connected. The measure remains local; however, a high degree does not indicate whether a node serves as an intermediary between more distant parts of the network.

3.3 Betweenness Centrality Analysis

Structurally critical nodes within the network were identified by computing and spatially visualizing betweenness centrality as Figure 3.

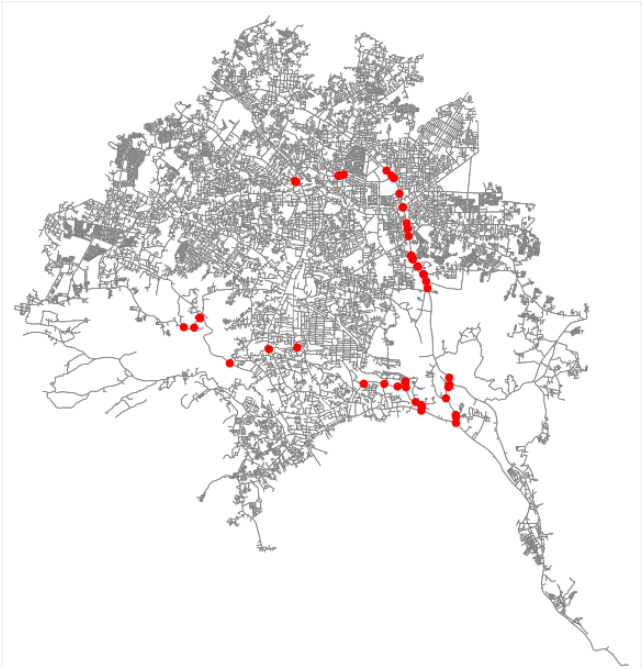


Figure 3. Spatial distribution of nodes with high betweenness centrality
in the urban road network of Bandar Lampung with red nodes represent critical connectors

Figure 3 shows the spatial distribution of the 50 nodes with the highest betweenness centrality values. The high-betweenness nodes are concentrated around several major road corridors rather than being spread evenly across the network. Their graph positions place these intersections on many shortest paths between other nodes. Previous work has likewise used betweenness centrality to locate structurally important positions in spatial road networks (Altaweel et al., 2021).

To further identify and quantify the most critical nodes in Bandar Lampung, the top 50 nodes with the highest betweenness centrality values are extracted and summarized in Table 5.

Table 5. Top 50 nodes with the highest betweenness centrality values in the Bandar Lampung road network

Rank	Node ID	Betweenness Centrality	Connected Road Names
1	6697200109	0,142515111	Jalan Bypass Sukarno Hatta, Jalan Kyai Haji Agus Salim
2	5256284136	0,130047153	Jalan Bypass Sukarno Hatta
3	7601346754	0,123875784	Jalan R. Sentot, Jalan Yos Soedarso
4	676490101	0,120424154	Jalan Raden Imba Kusuma
5	634179299	0,119777958	Jalan Gatot Soebroto, Jalan Yos Soedarso
6	634179312	0,119209191	Jalan Gatot Soebroto
7	4066102479	0,118140298	Jalan Selamet Riyadi I, Jalan Selamet Riyadi IV, Jalan Selamet Riyadi II
8	634179378	0,1173599	Jalan CV Kota Agung, Jalan Gatot Soebroto
9	634179307	0,117000862	Jalan Gatot Soebroto
10	4066102452	0,11697623	Jalan Gatot Soebroto
11	634179356	0,116198535	Jalan R. Sentot
12	634179326	0,116158406	Jalan Gatot Soebroto
13	4066102475	0,115945557	Gang Horas, Jalan Selamet Riyadi IV
14	6128381486	0,115589777	Jalan Kyai Haji Agus Salim, Jalan R. Sentot
15	7565323749	0,115379554	Jalan Kyai Haji Agus Salim
16	6128380271	0,115342761	Jalan Kyai Haji Agus Salim
17	6128380265	0,115297421	Jalan Kyai Haji Agus Anang, Jalan Kyai Haji Agus Salim
18	10543638076	0,115194858	Jalan R. Sentot, Gang Masjid
19	5969085357	0,11295193	NA
20	5969085349	0,112907381	NA
21	9732172276	0,112606942	Jalan Raden Imba Kusuma
22	6904579658	0,112411246	Jalan Raden Imba Kusuma
23	11491834958	0,109182011	Jalan Gatot Soebroto, Jalan Selamet Riyadi II
24	4066102494	0,109133759	Jalan Selamet Riyadi II
25	11182809294	0,108313714	Jalan Teuku Umar
26	4073194037	0,108271904	Jalan Sultan Agung, Jalan Zainal Abidin Pagar Alam
27	11671683138	0,107057464	Jalan Bypass Sukarno Hatta
28	3950002195	0,106502361	Jalan Bypass Sukarno Hatta, Alimuddin Umar, HR M. Mangoendiprodjo
29	7675827193	0,106359927	Jalan Bypass Sukarno Hatta
30	676495256	0,106318118	Jalan Bypass Sukarno Hatta
31	5255935105	0,106238245	Jalan Bypass Sukarno Hatta
32	4062629735	0,104660369	Jalan Doctor Wahidin Sudirohusodo, Jalan Robert Wolter Monginsidi
33	4062795099	0,103343376	Jalan Bypass Sukarno Hatta, Jalan Jamrud
34	7673306893	0,102249373	Jalan Bypass Sukarno Hatta
35	5256284150	0,102076102	Alimuddin Umar, Jalan Bypass Sukarno Hatta
36	4062673919	0,101649722	Jalan Bypass Sukarno Hatta
37	1936251377	0,099450022	Jalan Sultan Agung, Jalan Ki Maja
38	1937480228	0,099254676	Jalan Sultan Agung, Gang Mawar
39	1805688070	0,099138546	Jalan Endro Suratmin, Jalan Bypass Sukarno Hatta
40	11539545703	0,098773264	Jalan Bypass Sukarno Hatta
41	4062629429	0,098726958	Jalan Diponegoro, Jalan Doctor Wahidin Sudirohusodo
42	10543533172	0,098398309	Jalan Bypass Sukarno Hatta
43	9189252849	0,098361637	Jalan Sultan Agung
44	676495231	0,098209238	Jalan Bypass Sukarno Hatta
45	7723316168	0,097506921	Jalan Bypass Sukarno Hatta
46	5256284131	0,097301846	Jalan Bypass Sukarno Hatta
47	7205157241	0,096985644	Jalan Urip Sumoharjo, Jalan Bypass Sukarno Hatta
48	4062795337	0,096046392	Jalan Bypass Sukarno Hatta
49	7723316169	0,096017945	Jalan Bypass Sukarno Hatta
50	3950002358	0,09575376	Jalan Bypass Sukarno Hatta

Among the 50 nodes with the largest betweenness values, the scores extend from 0.1425 at rank 1 to 0.0958 at rank 50. The same corridors recur several times in this group, most notably Jalan Bypass Sukarno Hatta, Jalan Gatot Soebroto, Jalan Raden Imba Kusuma, Jalan Kyai Haji Agus Salim, and Jalan Dr. Wahidin Sudirohusodo.

Among the 50 highest-ranked nodes, J Jalan Bypass Sukarno Hatta appears most frequently among the top-ranked nodes, followed by repeated occurrences of Jalan Gatot Soebroto, Jalan Raden Imba Kusuma, Jalan Kyai Haji Agus Salim, and Jalan Dr. Wahidin Sudirohusodo. The recurrence of these road names indicates that shortest-path intermediation is concentrated along a limited number of corridors in the extracted network.

Two nodes in the top 50 list do not have an associated road name in the available OpenStreetMap attributes. Their missing road-name information does not affect the betweenness ranking because the ranking is based on graph topology rather than the availability of road-name attributes.

The high scores mark positions that are prominent in the graph's shortest-path structure. They do not establish that the corresponding intersections are current traffic bottlenecks or carry unusually large flows. That interpretation would require independent observations such as traffic counts, speeds, travel times, or road-capacity data.

3.4 PageRank and Node Influence

PageRank was calculated on the directed network to examine node influence from the recursive structure of network connections. Table 6 presents the five highest-ranked nodes.

Table 6. Top 5 nodes with highest PageRank in the Bandar Lampung road network

Rank	PageRank	Node	Road Name
1	0.000098	5941198186	N/A
2	0.000094	6128415130	Jalan Bypass Sukarno Hatta
3	0.000092	4073195514	Gang Pegadaian
4	0.000085	4066069979	N/A
5	0.000085	3950002202	N/A

From Table 6, node 5941198186 has the highest PageRank value at 0.000098, followed by node 6128415130 with 0.000094 and node 4073195514 with 0.000092. The fourth- and fifth-ranked nodes both have values of 0.000085. The relatively small differences among these values indicate that the top-ranked nodes have comparable PageRank scores within the analyzed network.

The top five are not confined to major arterial roads. One high-ranked node is associated with Jalan Bypass Sukarno Hatta and another with Gang Pegadaian, while three have no road name in the available OSM attributes. The ranking therefore reflects the arrangement of graph connections rather than road class alone.

PageRank and betweenness highlight different features of the same graph. PageRank propagates influence through neighboring connections, whereas betweenness is tied to the frequency with which a node lies on shortest paths (Zhang et al., 2021). A node may therefore rank highly by PageRank without having a comparable betweenness position. The two rankings are complementary rather than interchangeable.

4. DISCUSSION

4.1 Spatial Constraints and Overall Network Organization

The density value needs to be interpreted in relation to the city's spatial setting. Roads cannot be connected arbitrarily: geography, land use, urban form, and the historical development of Bandar Lampung restrict the locations at which links can be formed. A low density may therefore result from these physical constraints rather than from weak connectivity (Barthélemy, 2011; Boeing, 2020).

The effect is relevant in Bandar Lampung, whose urban landscape includes coastal areas, hills, and varied terrain. Geomorphological studies identify fluvial, structural, volcanic, and denudational units, including hilly and steep-slope areas (Putri, 2025; Mulyasari et al., 2019). These features can limit both where roads are built and the directions in which connections can be made, helping to account for the sparse topology observed here.

The low density is therefore better read as a property of a spatially constrained system than as a simple lack of connectivity. Local, collector, and arterial roads still provide numerous connections among intersections.

Similar relationships between spatial constraints and network organization have been reported in other geographically embedded transportation networks (Porta et al., 2006; Boeing, 2019b; Boeing, 2020).

4.2 Local Connectivity versus Shortest-Path Intermediation

The degree and betweenness results point to different structural roles within the road network. Degree counts the immediate links of a node, while betweenness concerns its position on shortest paths between other nodes (Freeman, 1977; Crucitti et al., 2006). A highly connected intersection can therefore remain relatively peripheral in terms of shortest-path intermediation. This distinction is consistent with previous research showing that changes in road-network topology can be captured more effectively through spatially explicit topological measures than through conventional connectivity measures alone

The Bandar Lampung results illustrate this difference at the intersection level. Nodes with relatively high degrees provide several direct connections to neighboring road segments, indicating strong local connectivity. Their structural role, however, cannot be inferred from degree alone. Research examining centrality at different spatial scales has similarly shown that betweenness patterns can change with the scale of movement: larger-scale centrality tends to occur along larger streets, whereas smaller-scale patterns may emerge around local urban areas (Kaoru et al., 2021).

The high-betweenness nodes are best interpreted through their positions in the shortest-path structure of the OSM-derived graph. Their scores alone cannot show whether the corresponding intersections currently experience heavy traffic or congestion. In graph-theoretic terms, the measure indicates intermediary position (Freeman, 1977).

4.3 Structural Importance of Major Corridors

Several road corridors recur among the nodes with the highest betweenness centrality: Jalan Bypass Sukarno Hatta, Jalan Gatot Soebroto, Jalan Dr. Wahidin Sudirohusodo, Jalan Kyai Haji Agus Salim, and Jalan Raden Imba Kusuma. Their repeated appearance in the ranking indicates that shortest-path intermediation is not distributed uniformly across the network but tends to occur around a limited set of corridors.

Jalan Bypass Sukarno Hatta appears most prominently in the ranking. It forms part of the national road network and provides a regional link through Bandar Lampung. Previous transportation research identifies the Soekarno-Hatta Bypass as a primary arterial in the city (Jaya, 2021). Its repeated appearance is consistent with that position in the road hierarchy, although the graph result by itself cannot establish concentrated traffic flow along the corridor.

Jalan Gatot Soebroto appears several times among the nodes with high betweenness values at Table 5. In the network analyzed here, several intersections along this road are located on shortest paths connecting different parts of the city. This may explain why the corridor is repeatedly identified in the betweenness ranking. Studies of urban street networks have also found that larger or more connected streets often occupy more central positions (Kaoru et al., 2021; Wang et al., 2022). In this case, however, the result describes the position of Gatot Soebroto in the modeled network and should not be taken as an indication of traffic congestion or high traffic demand.

Jalan Dr. Wahidin Sudirohusodo is also represented among the high-betweenness locations. One of the nodes in the top 50 is located at the connection with Jalan Robert Wolter Monginsidi (Table 5). The position of this intersection within the extracted graph means that paths between other nodes can pass through it, resulting in a relatively high betweenness value. The importance of an intersection in this sense depends on its location within the network and its connections with surrounding streets, rather than simply on the class or name of the road (Chen et al., 2023). The finding therefore points to a topological role of the intersection in the Bandar Lampung road network, while its actual role in traffic movement would require additional traffic and operational data.

Repeated appearances in the rankings point to several corridors where shortest-path intermediation is concentrated. The pattern is compatible with the hierarchy of urban road systems, in which local streets connect to collectors and larger corridors link different urban areas (Porta et al., 2006; Barthélemy, 2011). Recent work similarly emphasizes road hierarchy and spatial structure in urban transportation analysis (Alviani et al., 2026).

4.4 Distributed Node Influence from PageRank

The PageRank results reveal a different distribution of structural importance from that obtained with betweenness centrality. Whereas the highest-betweenness nodes are concentrated along several major corridors, the highest PageRank values occur at locations associated with both arterial and local roads. Structural influence in the network is therefore not confined to the upper levels of the road hierarchy.

Jalan Bypass Sukarno Hatta appears among the highest PageRank locations, consistent with its extensive connectivity within the network. Gang Pegadaian also occurs among the top-ranked nodes, while several highly ranked nodes do not have a road name in the available OSM attributes. This pattern indicates that PageRank does not simply reproduce road hierarchy, since node importance is also affected by the structure of connections to other nodes (Zhang et al., 2021). The absence of road names for some ranked nodes may instead reflect incomplete attribute information in the underlying OpenStreetMap data (Boeing, 2017).

The distinction comes from the information used by PageRank. It does not count how often a node lies on shortest paths; instead, importance is passed recursively through neighboring connections (Amy N. Langville & Carl D. Meyer, 2006; Mark Newman, 2018). A node on a secondary or local street may therefore rank highly when it is linked to influential parts of the graph. The appearance of both arterial and local roads among the top positions is consistent with this mechanism and adds information to the betweenness results.

4.5 Limitations and Implications

The scope of the findings is limited by the data used. The analysis relies on the topology of the OpenStreetMap-derived network and contains no observations of traffic volume, vehicle speed, travel time, road capacity, or congestion. A high degree, betweenness, or PageRank score should therefore be read as structural prominence within the graph rather than as evidence of current traffic conditions. Table 7 summarizes the scope of the data and analyses included in the present study.

Table 7. Scope and limitations of the present study

No	Aspect	Included	Not Included
1	OpenStreetMap road network	✓	
2	Directed graph representation	✓	
3	Degree centrality	✓	
4	Betweenness centrality	✓	
5	PageRank	✓	
6	Network density	✓	
7	Traffic volume		✓
8	Travel speed		✓
9	Road capacity		✓
10	Travel time		✓
11	Traffic congestion observations		✓
12	Network robustness simulation		✓
13	Edge weighting by distance/travel time		✓

Centrality-based screening has also been used as an initial step in transportation studies, while operational decisions still require information beyond topology (Ahmed et al., 2023). The locations identified here should therefore be regarded as candidates for further investigation, not as direct justification for capacity expansion, signal changes, or other operational interventions.

The immediate practical use of the results is as a screening layer. The identified nodes and corridors can guide traffic counts, travel-time measurements, capacity assessments, or more detailed transportation simulations. Combining those observations with the present topology would allow structural prominence to be compared with actual operating conditions. Longitudinal mobility data could provide an additional behavioural and spatiotemporal layer by showing how individuals interact with different urban locations across time. Previous research has demonstrated that repeated mobility histories can reveal the role of particular urban spaces in daily travel patterns that cannot be inferred from physical network structure alone (Fisu et al., 2025). Integrating such observations with network centrality could therefore help determine whether structurally prominent locations are also prominent in realized urban mobility.

A useful next step is to combine traffic observations with weighted edges and robustness tests to assess whether structurally prominent nodes are also vulnerable to network disruption. Recent global analysis has

demonstrated the usefulness of targeted-disruption simulations for assessing street-network vulnerability beyond static topological indicators (Boeing & Ha, 2024).

5. CONCLUSIONS

The Bandar Lampung road network was analyzed as a directed graph derived from OpenStreetMap. The largest weakly connected component used for the final analysis contains 23,920 nodes and 58,492 directed edges. Degree, betweenness, PageRank, and density were then used to describe different structural features of this graph.

The final graph is sparse, with a density of 0.000102 and an average total directed degree of 4.89. Most intersections have moderate degree, while only a small subset has many direct links. Higher local connectivity is consequently distributed across the network rather than concentrated in a few hubs. The pattern is consistent with a road system whose possible connections are restricted by geography, land use, and road geometry.

Betweenness identifies a smaller set of nodes that occur frequently on shortest paths. For the 50 highest-ranked nodes, the values range from 0.1425 to 0.0958, with repeated locations along Jalan Bypass Sukarno Hatta, Jalan Gatot Soebroto, Jalan Doctor Wahidin Sudirohusodo, Jalan Kyai Haji Agus Salim, and Jalan Raden Imba Kusuma. These locations are structurally prominent in the modeled graph. The ranking does not, however, establish congestion or capacity problems because traffic volume, speed, travel time, and road-capacity data were not included.

PageRank produces a less hierarchy-dependent ranking: both arterial and local roads occur among the highest-ranked locations. This follows from its use of neighboring-node influence rather than shortest-path position alone. Degree, betweenness, and PageRank therefore highlight three different roles in the graph as local connectivity, intermediary position, and recursively derived influence. Using them together gives a fuller structural picture than any one measure alone.

The procedure provides a reproducible way to examine urban road topology from openly available geospatial data. The high-centrality nodes and recurring corridors are best used to select locations for subsequent transportation investigation, rather than as direct grounds for capacity expansion, signal changes, or other operational interventions.

A fuller transportation assessment would require traffic counts, speed, travel-time, capacity, and other operational observations. Future studies could also introduce weighted network representations and robustness or targeted-attack simulations to examine how the structurally important locations identified here respond to network disruption and how their topological roles relate to transportation performance under different operating conditions.

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7. REFERENCES

Ahmed, M. A., Kays, H. M. I., & Sadri, A. M. (2023). Centrality-based lane interventions in road networks for improved level of service: the case of downtown Boise, Idaho. *Applied Network Science*, *8*(1). https://doi.org/10.1007/s41109-023-00532-z

Akbarzadeh, M., Memarmontazerin, S., & Soleimani, S. (2018). Where to look for power Laws in urban road networks? *Applied Network Science*, *3*(1). https://doi.org/10.1007/s41109-018-0060-9

Altaweel, M., Hanson, J., & Squitieri, A. (2021). The structure, centrality, and scale of urban street networks: Cases from pre-industrial Afro-Eurasia. *PLoS ONE*, *16*(11 November). https://doi.org/10.1371/journal.pone.0259680

Alviani, E., Usman, K., Persada, C., Niken, C., & Karami, M. (2026). Integrating AHP-GIS and Public Preference for Prioritizing Urban Rail Stations in Bandar Lampung. In *Jurnal Aplikasi Teknik Sipil* (Vol. 24, Number 1).

Amy N. Langville, & Carl D. Meyer. (2006). *Google's PageRank and Beyond: The Science of Search Engine Rankings*. Princeton University Press. https://doi.org/.https://doi.org/10.2307/j.ctt7t8z9

Aric A. Hagberg, Daniel A. Schult, & Pieter J. Swart. (2008). Exploring Network Structure, Dynamics, and Function using NetworkX. *Proceedings of the 7th Python in Science Conference (SciPy 2008)*. http://conference.scipy.org/proceedings/SciPy2008/paper_2

Barthélemy, M. (2011). Spatial networks. In *Physics Reports* (Vol. 499, Numbers 1–3, pp. 1–101). https://doi.org/10.1016/j.physrep.2010.11.002

Boeing, G. (2017). OSMnx: New methods for acquiring, constructing, analyzing, and visualizing complex street networks. *Computers, Environment and Urban Systems*, *65*, 126–139. https://doi.org/10.1016/j.compenvurbsys.2017.05.004

Boeing, G. (2019a). Street Network Models and Measures for Every U.S. City, County, Urbanized Area, Census Tract, and Zillow-Defined Neighborhood. *Urban Science*, *3*(1). https://doi.org/10.3390/urbansci3010028

Boeing, G. (2019b). Urban street network analysis in a computational notebook. *Region*, *6*(3), 39–51. https://doi.org/10.18335/region.v6i3.278

Boeing, G. (2020). Planarity and street network representation in urban form analysis. *Environment and Planning B: Urban Analytics and City Science*, *47*(5), 855–869. https://doi.org/10.1177/2399808318802941

Boeing, G. (2022). Street Network Models and Indicators for Every Urban Area in the World. *Geographical Analysis*, *54*(3), 519–535. https://doi.org/10.1111/gean.12281

Boeing, G. (2025). Topological Graph Simplification Solutions to the Street Intersection Miscount Problem. *Transactions in GIS*, *29*(3). https://doi.org/10.1111/tgis.70037

Boeing, G., & Ha, J. (2024). Resilient by design: Simulating street network disruptions across every urban area in the world. *Transportation Research Part A: Policy and Practice*, *182*. https://doi.org/10.1016/j.tra.2024.104016

Brandes, U., & Pich, C. (2007). Centrality Estimation in Large Networks. *International Journal of Bifurcation and Chaos*, *17*(7), 2303–2318. www.worldscientific.com

Chen, H. H., Mumm, O., & Carlow, V. M. (2023). A computational approach for categorizing street segments in urban street networks based on topological properties. *Frontiers in Built Environment*, *9*. https://doi.org/10.3389/fbuil.2023.1216888

Cheng, Z., Ouyang, M., Du, C., Zhang, H., Wang, N., & Hong, L. (2023). Boundary effects on topological characteristics of urban road networks. *Chaos: An Interdisciplinary Journal of Nonlinear Science*, *33*(7), 073123. https://doi.org/10.1063/5.0145079

Crucitti, P., Latora, V., & Porta, S. (2006). Centrality measures in spatial networks of urban streets. *Physical Review E - Statistical, Nonlinear, and Soft Matter Physics*, *73*(3). https://doi.org/10.1103/PhysRevE.73.036125

Duncan J. Watts, & Steven H. Strogatz. (1998). Collective dynamics of "small-world" networks. *NATURE*, *393*, 440–442.

Fisu, A. A., Syabri, I., & Andani, I. G. A. (2024). How do young people move around in urban spaces?: Exploring trip patterns of Generation-Z in urban areas by examining travel histories on Google Maps Timeline. Travel Behaviour and Society, 34, 100686. https://doi.org/10.1016/j.tbs.2023.100686

Fisu, A. A., Syabri, I., & Andani, I. G. A. (2025). Gen-Z and individual third spaces: Examining youth mobility in urban areas in the context of space and time. Cities, 161, 105889. https://doi.org/10.1016/j.cities.2025.105889

Freeman, L. C. (1977). A Set of Measures of Centrality Based on Betweenness. *Sociometry*, *40*(1), 35–41.

Freeman, L. C. (1978). Centrality in Social Networks: Conceptual Clarification. *Social Networks*, *1*, 215–239. https://doi.org/https://doi.org/10.1016/0378-8733(78)90021-7

Jaya, B. D. , P. S. , D. I. W. and K. M. (2021). Pengaruh Kegiatan Samping Jalan Terhadap Kecelakaan Lalu Lintas (Studi Kasus Ruas Jalan By Pass Soekarno-Hatta Bandar Lampung). *Jurnal Rekayasa Sipil Dan Desain (JRSDD)*, *9(4)*, 669–678.

Kaoru, Y., Yusuke, K., & Yuji, Y. (2021). Local Betweenness Centrality Analysis of 30 European Cities. In *Urban Informatics and Future Cities* (pp. 527–547). Springer.

Mark Newman. (2018). *Networks (2nd Ed.)*. Oxford University Press. https://doi.org/10.1093/oso/9780198805090.001.0001

Mulyasari, R., Utama, H. W., & Haerudin, N. (2019). Geomorphology study on the Bandar Lampung Capital City for recommendation of development area. *IOP Conference Series: Earth and Environmental Science*, *279*(1). https://doi.org/10.1088/1755-1315/279/1/012026

Porta, S., Crucitti, P., & Latora, V. (2006). The network analysis of urban streets: A primal approach. *Environment and Planning B: Planning and Design*, *33*(5), 705–725. https://doi.org/10.1068/b32045

Putri, H. T. (2025). Exploring Coastal Settlement Decisions: A Quantitative Study in Bandar Lampung. *Jurnal Perencanaan Wilayah Dan Kota*, *20*(2), 65–76. https://doi.org/10.29313/jpwk.v20i2.6780

Sreelekha, M. G., Krishnamurthy, K., & Anjaneyulu, M. V. L. R. (2020). Urban Road Network and its Topology: Case Study of Calicut, India. *European Transport*, *78*(6).

Wang, D., Gong, Y., Zhang, X., & Lin, Y. (2022). The Impacts of Multiscale Urban Road Network Centrality on Taxi Travel: A Case Study in Shenzhen. *Complexity*, *2022*. https://doi.org/10.1155/2022/1780667

Xiao, H., & Yang, T. (2023). *Extracting Spatial Interaction Patterns between Urban Road Networks and Mixed Functions*.

Zhang, P., Wang, T., & Yan, J. (2021). *PageRank centrality and algorithms for weighted, directed networks with applications to World Input-Output Tables*. http://arxiv.org/abs/2104.02764

.