Characterising the structural pattern of urban road networks in Ghana using geometric and topological measures

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Road networks are an integral part of any human settlement, facilitating the movement of people, goods, and information. The structural arrangement of a road network can have a profound impact on its performance, mobility and access to critical infrastructure. This study takes advantage of a computational network science approach to examine the structural configuration of road networks using geometric and topological descriptions in districts covering 10 regional capitals in Ghana. The majority of urban road networks were found to follow a radial pattern at the global scale, with either a gridded or a branching configuration at the local scale. Only road networks in Accra and Kumasi are fine grained and of comparable density to other global cities, based on intersection and street densities. Structural indicators such as circuity, clustering, page rank, degree centrality, and betweenness centrality for urban roads in Ghana were found to be comparable to other global cities. Given the lack of adequate infrastructure for traffic monitoring in Ghana, the spatial distribution of betweenness centrality could be part of the critical resource to provide insight for traffic management. These findings provide the basis to inform transportation planning and management on critical issues, particularly, based on the spatial distribution of betweenness centrality it is possible to identify problematic locations within the road network which are most vulnerable to traffic congestion.

KEYWORDS
computational network science, geometric and topological indicators, road networks, spatial networks, transportation, urban streets

1 | INTRODUCTION

Road transportation is critical for the movement of people, goods, and information in Ghana and other parts of the world. In Ghana, it has been widely recognised to be the primary means of transportation, accounting for about 98% of passengers and 94% of freight (Salifu, 2004; Sam et al., 2018). Accordingly, road transport underpins an essential access and mobility mechanism for majority of socioeconomic activities, including healthcare, production of goods and services, and employment in Ghana.

According to the Population Division of the Department of Economic and Social Affairs, urbanisation together with the overall global population growth could add 2.5 billion people to urban areas by 2050, with about 90% of this increase...
Projected to take place in Asia and Africa. In Ghana, more than half of the population already live in towns and cities (Ghana Statistical Service, 2014). Urban sprawl leading to the expansion of towns and cities has been reported by Government of Ghana (2012). The expansion of towns and cities has direct impact on road transportation.

Rapid urbanisation and increase in vehicle-to-population ratio with its associated pressures on road networks have been widely reported in Ghana (Agyemang, 2017; Amoh-Gyimah & Aidoo, 2013; Dumedah, 2017; Nutsugbodo et al., 2018; Sam et al., 2018). This growing pressure on road networks is usually intense in urban areas, given their naturally high traffic volume and high vehicle-to-population ratio. In Ghana, the urban areas are typically associated with the 10 regional capitals where the road networks are naturally more dense and fine grained. It is noted that there are isolated cases such as Aflao, a border city with Togo, where the road network is denser than its regional capital, Ho. However, the urban areas are not well planned in Ghana, road networks are poorly laid out, and the available geographic information on road networks are limited. There is a high proportion of informal human settlements which directly leads to poor layout of road networks. The projected increases in population growth will put even greater pressure on road networks in Ghana. These challenges require a better understanding of the spatial structure of the existing road network in order to identify problem areas and better plan for future changes.

However, very little is known from the literature about the spatial structure of urban road networks in Ghana, sub-Saharan Africa, or in areas with similar informal layout of roads. As noted by Xie and Levinson (2007), the spatial structure of road networks shapes traffic flows on a network, and knowledge about this spatial structure is important in assessing the environmental, economic, demographic, and social dimensions of cities (Marshall et al., 2018). Given the rapid urbanisation and the growing pressure on urban roads in Ghana, it is important to investigate their spatial structure, efficiency, and connectivity measures in order to better inform their management and future changes; that is, the increasing pressure on road networks in Ghana requires the need for sustainable solutions with a particular consideration of their spatial configuration and arrangement.

The spatial structure of road networks is rarely considered in transport planning or urban planning schemes in Ghana. It is widely acknowledged that most traffic congestions and disruptions are usually addressed through the expansion of the road network with limited consideration of the spatial configuration of the road network. Therefore, it is relevant to establish the critical relationship between the spatial structure and the performance of road networks in terms of their traffic flow and ability to accommodate disruptions. The spatial structure of road networks are fundamental to their function and performance, especially in terms of how they can accommodate increased traffic volume, and the identification and maintenance of the critical or central locations and segments of the road network (Barthelemy, 2017; Marshall, 2005). Road networks, as an example of spatial networks, can be investigated in a computational network science approach to address questions relating to their structure and resilience, and the impact of space on the formation of networks (Barthelemy, 2018; Marshall et al., 2018). Accordingly, this study uses a spatial network approach to characterise road networks in Ghana by using several indicators to better understand their structure. An improved understanding of the structure of road networks in Ghana can lead to improved transport planning and management, and identification of problem areas to address.

Consequently, this study provides geometric and topological descriptions of urban road networks in the 10 regional capitals of Ghana, with a focus on identifying their characteristic spatial configuration towards improving traffic flow. The geometric and topological descriptions are vital in terms of determining the structural arrangements that make the road network most vulnerable and provide deeper knowledge of road performance indicators for policy makers in decision making. Also, road networks impact the proper functioning of existing urban infrastructure such as water pipes, energy, and communication networks (Freiria et al., 2015; Li et al., 2018; Liu et al., 2017; Sharifi, 2019; Teulade-Denantes et al., 2015). Accordingly, a high performing and resilient road network can directly facilitate the performance of other urban infrastructures, whereas a road network that is susceptible to disruption will negatively impact access and mobility or cause significant collapse of the road network.

1.1 | Background

Road transport is facilitated by a road network, which in primal representation comprises links (or edges) within a system of locations, identified as nodes (Barthelemy, 2011; O’Sullivan, 2014; Porta et al., 2006; Rodrigue et al., 2013). The nodes represent road intersections and dead-ends whereas the edges are the road segments connecting them (Barthelemy, 2011; Boeing, 2018b; O’Sullivan, 2014; Zhang et al., 2015). The structure of a road network based on node and edge configuration implies inherent geometric and spatial constraints together with topological properties such as the location of nodes and the length of edges (Barthelemy, 2011). These geometric and topological properties, their distribution, and structural arrangement can provide profound insight into the functional structure of road networks, with several examples in the literature including Ingvardsson and Nielsen (2018); Boeing (2018a); Li et al. (2018); Chen et al. (2017); Zhang et al. (2015);
Reggiani et al. (2015); Huang and Levinson (2015); Freiria et al. (2015); Knight and Marshall (2015); Weiss and Weibel (2014); Sanchez-Mateos et al. (2014); Wang et al. (2013); Courtat et al. (2011); Costa et al. (2010); Blumenfeld-Lieberthal (2009); Tiakas et al. (2009); Borruso (2008); Jiang (2007); Lammer et al. (2006); Crucitti et al. (2006); Buhl et al. (2006); Porta et al. (2006); and Jiang and Claramunt (2004). The number of nodes, edges, their density, structural arrangement, and capacity can influence the optimal functioning of road networks in terms of their capability to accommodate traffic, congestion, disruptions, and other performance indicators.

Spatial road networks provide the basis to study cities because of their inherent spatial and social character (Derudder & Neal, 2018; Luo et al., 2019; Ye & Liu, 2019). Studies by Bapierre et al. (2015) and Cho et al. (2011) have shown that human interaction from social networks induce travel movement, and that social network ties impact long-distance travel considerably compared with short-distance travel. The analysis of spatial road networks has been used to explain the other social activities. For example, Wang et al. (2012) demonstrated that actual traffic can be approximated based on the spatial distribution of betweenness centrality, with others including Venerandi et al. (2014); Strano et al. (2012), and Porta et al. (2009) who linked positive relationships between socioeconomic activity and betweenness centrality.

It is notable that an urban road network is influenced by several factors such as characteristics of economics, politics, urban design principles, and population density within particular geographic areas (Blumenfeld-Lieberthal, 2009; Hu et al., 2018; Tomasiello et al., 2019; Weiss & Weibel, 2014). Yet, urban road networks can also evolve organically through accretion (Boeing, 2018b, 2018c). The resulting spatial structure of urban road network constrains urban mobility, whose understanding can be used for urban planning, critical infrastructure, transportation, and location based services.

The above geometric and topological properties of road networks have been widely investigated in countries or areas where data on road networks are widely available. But in areas like Ghana where geographic data are scarce, there are limited studies which investigate these geometric and topological properties of road networks. It has been widely acknowledged that the lack of consideration of these structural properties, for example in traffic management, implies that the road networks in these areas are most likely to be inefficient and easily vulnerable to traffic congestion (Barthelemy, 2011; Wang et al., 2012). Also, the investigation of these geometric and topological properties in areas like Ghana is a relevant addition to the literature on spatial networks, with the potential to identify distinguishing features as well as commonalities between largely well planned urban settings and those that are not so well planned; that is, explicit characterisation of the structure of road networks in informal settlements are under-represented in the literature. Typically, informal settlements are associated with poor layout of roads leading to several dead-ends, poor connectivity and continuity of road segments. To facilitate this investigation, this study adopts the approaches based on a simple morphological analysis together with global importance of network elements (Marshall et al., 2018).

It is acknowledged that the primal representation of road networks used in this study is one among several other representations, and that the chosen primal representation directly influences the results presented herein. Other street modelling approaches are available, and have been comprehensively reviewed by Marshall et al. (2018), including axial lines (Hillier et al., 1993), dual approach (Porta et al., 2006), route structure analysis (Kropf, 2008; Marshall, 2005), and line structure (Marshall, 2015). Each of the street modelling approaches enforces a specific characterisation of the road network leading to a distinct interpretation of resulting outputs.

## 2 MATERIALS AND METHODS

### 2.1 Study area and data sources

The study was conducted for the 10 districts which comprise the regional capitals in Ghana, shown in Figure 1. Most of these districts for the regional capitals such as Accra, Cape Coast, Sekondi Takoradi, Kumasi, and Tamale are metropolitan areas, whereas those for Ho, Koforidua, Sunyani, Bolgatanga, and Wa are municipal areas. Though not the main focus of this investigation, the differences in terms of the density of the road network in metropolitan and municipal areas can provide underlying insight of any unique structural pattern of the road network in these areas.

The road network data were obtained from OpenStreetMap, which is a collaborative worldwide mapping project that provides spatial data usually in vector format of high spatial resolution for cultural features such as buildings, land use, railroads, roads, and waterways (Brovelli et al., 2017; Corcoran et al., 2013; Haklay, 2010; Jokar Arsanjani et al., 2015; Maron, 2015; Schneider & Possin, 2012). The OpenStreetMap is a valuable spatial dataset, particularly for countries like Ghana where geospatial science and technology (GST) is not well developed and standardised geospatial data are limited. However, the road network data available through OpenStreetMap require further processing to ensure accurate abstraction and subsequent analysis.
2.2 | Analysis framework

The OpenStreetMap data download and overall analysis framework of the study are presented in Figure 2, highlighting the key components. The street network data download and analytics were organised around OSMnx, which is a software library developed by Boeing (2017) and written in Python scientific programming language. To set up the procedure in Python, additional libraries were used including NetworkX (Hagberg & Conway, 2010), Matplotlib, Numpy (van der Walt et al., 2011), Python Data Analysis Library (Pandas; McKinney, 2011), and GeoPandas which is an extension of Pandas for working with geospatial data. OSMnx allows the download of OpenStreetMap data, and the

**FIGURE 1** Study area showing the districts covering the 10 regional capitals in Ghana, and road networks in Sunyani municipal and Kumasi metropolis.
*(data source: OpenStreetMap)*

**FIGURE 2** Data download and analysis framework of the study showing the key components and the outputs.
creation and analysis of road network data (Boeing, 2017, 2018b). The OSMnx was used in a Python environment to
download the road network for the study area from OpenStreetMap, undertake the pre-process procedures, and analyse
the road network data.

The pre-processing procedures undertaken include the building of topology, for example, to correctly identify road inter-
sections and adjacent spatial relations. Also, most GIS data may not have a correct specification of road network data that
satisfies the correct specification of nodes and edges. For example, a single road segment may be represented by several
line segments, and in some cases multiple road segments may be represented by one line segment. These pre-processing
procedures were undertaken to give a realistic specification of the location of nodes and edges in order to make the data
ready for spatial network analysis. The pre-processing step was then followed by the derivation of street network indicators
– the specific indicators are outlined in the next section. The Python NetworkX library is the main tool used to generate
the majority of the network indicators. The resulting output of the indicators was visualised using Matplotlib and is dis-
cussed in the results section. For a step-by-step procedure on the use of OSMnx to analyse road network data, the reader is
referred to Boeing (2020).

### 2.3 Measures of spatial road networks

Topology of spatial networks represents the spatial relationships, including the shape and structural configuration of the
network. Accordingly, topological measures assess the configuration, connectedness, and robustness of the network –
and how these characteristics are distributed (Barthelemy, 2011; Boeing, 2017, 2018b). Topological measures for road
networks have been widely investigated in studies including Ingvardson and Nielsen (2018); Boeing (2018b); Tian et al.
(2018); Li et al. (2018); Boeing (2017); Knight and Marshall (2015); Barthelemy (2011); and Jiang (2007). From
the literature, the basic topological measures include degrees, lengths, and densities of nodes and edges (Barthelemy, 2011;
Buhl et al., 2006; Lammer et al., 2006). For example, the average node degree measures the average number of edges
incident to a node, indicating the overall connectedness of a node in the network (Boeing, 2017, 2018b). High values
of average node degree imply high connectivity and more turn options at nodes, whereas low values indicate less con-
nectivity. It has been observed that because of space limitations in road networks, high degree values are limited as
they have to satisfy spatial constraints (Barthelemy, 2018). Average road length is the overall average of all edges in
the network, which is indicative of the block size used in determining whether a network is fine grained or coarse
grained.

Density measures are also used to determine whether a network is fine grained or coarse grained. For example, the node
density is the ratio of the number of nodes to the area covered by the network. Intersection density is the ratio of the num-
er of intersections (nodes) per unit area, which is indicative of the node density for a set of nodes with two or more roads
emanating from them, thus excluding dead-ends (Boeing, 2017; Salat et al., 2010; Sharifi, 2019). Edge density is the ratio
of the total length of all edges to the area covered by the network. Generally, high densities imply a spatially detailed net-
work whereas low values represent a less detailed network.

Circuity is the shortest network distance divided by the Euclidean distance between one origin–destination pair (Barthel-
emy, 2011; Huang & Levinson, 2015; Levinson & El-Geneidy, 2009). Accordingly, the average circuity is the edge lengths
divided by the great-circle distances between the nodes these edges connect, thus indicative of efficiency of the road pattern
(Boeing, 2017, 2018b). High values of circuity imply an indirect or a circuitous network, whereas a value of 1.0 represents
a perfectly straight network. The eccentricity of a node is the longest shortest-path distance between it and every other
node, such that the maximum and minimum eccentricity values are equivalent to the network’s diameter and radius, respec-
tively. The centre of a network is the node with eccentricity equal to the network’s radius, whereas the periphery is the
node with eccentricity equal to the network’s diameter (Boeing, 2017, 2018b).

Advanced topological measures include connectivity, centrality, and clustering. Connectivity is a measure of resili-
ence of a network which indicates the minimum number of nodes or edges that will disconnect the network if they are
removed (Boeing, 2017, 2018b). By resilience, this study refers to the definition found in Wan et al. (2018) and Reg-
giani et al. (2015), as the speed at which a network returns to its equilibrium after a shock, and the pathway along
which the disruptions can be absorbed. For a road network, the average node connectivity has been noted to be a more
practical indicator as it measures the average number of nodes that must be removed to disconnect a randomly selected
pair of non-adjacent nodes (Beineke et al., 2002; Boeing, 2017; Sharifi, 2019). High values of average node connectiv-
ity imply a good connectivity, whereas low values indicate poor connectivity. Other measures of connectivity include
intersection density (described above), the average distance between intersections, and the characteristic path length. The
characteristic path length is the average length of the shortest paths between all possible pairs of nodes in the network (Novak & Sullivan, 2014; Sharifi, 2019). The characteristic path length has been noted to be limited to only connected networks, thus it is not practical for road networks where edge removals are common cases due to disruptions. Generally, increasing the number of intersections and road segments can directly improve connectivity in a road network, as higher intersection density and shorter average distance between intersections are associated with higher connectivity (Salat et al., 2010; Sharifi, 2019).

Centrality (Barthelemy, 2011; Crucitti et al., 2006; Lammer et al., 2006; Sharifi, 2019) is used to measure the degree of importance of specific nodes or edges in a road network. When a specific node is connected to several other nodes, then the node’s importance is high in terms of degree centrality (Sharifi, 2019). Centrality has direct implications for the performance of road networks, such that any disruption to roads with high centrality can result in significant loss of accessibility or cause large parts of the road network to collapse. There are several measures of centrality, including degree centrality, closeness centrality, betweenness centrality, straightness centrality, and information centrality (or network efficiency). Closeness centrality measures the extent to which an intersection (node) is near to all other reachable intersections in the city along the shortest paths of the network (Crucitti et al., 2006; Novak & Sullivan, 2014; Porta et al., 2006; Sharifi, 2019; Wang, 2015). That is, closeness centrality aims to minimise the distance to all other nodes in the network. It has been observed that degree centrality is not very informative for road networks where a node’s degree is significantly limited by spatial constraints (Barthelemy, 2018; Porta et al., 2006). Straightness centrality is an indicator of straightness of the shortest paths between nodes; that is, it measures the degree to which a network route connecting an origin–destination pair deviates from the virtual straight route (Crucitti et al., 2006; Porta et al., 2006; Sharifi, 2019). Straightness centrality can be used to indicate the level of efficiency in terms of being direct compared with others (Porta et al., 2006). Information centrality (or network efficiency) is the average normalised efficiency of all possible origin–destination pairs of nodes in the network (Cavallaro et al., 2014; Sharifi, 2019). The efficiency of a road network provides a measure of directness of edges between network nodes.

The measure of centrality that has been widely applied and is more practical for road network is betweenness centrality, given its close relationship to movement on the network and the connectedness of subregions in the network (Barthelemy, 2011; Crucitti et al., 2006; Freiria et al., 2015; Huang et al., 2016; Lammer et al., 2006; Mishra et al., 2012; O’Sullivan, 2014; Scellato et al., 2006; Wang et al., 2013; Zhang et al., 2015; Zhong et al., 2017). Some nodes may control the movements between several non-adjacent nodes such that they have a strategic influence on them. Betweenness centrality determines the number of shortest paths in a network that pass through a given node (or edge) to indicate its importance (Barthelemy, 2011; Boeing, 2017; Freiria et al., 2015; Wang et al., 2013). Therefore, high betweenness centrality points out important locations that lie between several other locations, such that they control the functionality of the road network. For example, when movement around the network is random then the betweenness centrality locations will experience the most traffic volume or congestion (Barthelemy, 2011; O’Sullivan, 2014; Wang et al., 2013). Thus, a road network with high betweenness centrality is likely to be vulnerable to disruptions and congestions.

Clustering is a measure of how strongly connected a network is in the neighbourhood of a given node (O’Sullivan, 2014). A measure of clustering is a clustering coefficient which is an indicator of the clustering degree of a road network, providing information on local clustering. The clustering coefficient of a node is the ratio of the number of edges between its neighbours to the maximum possible number of edges that could exist between these neighbours (Boeing, 2017, 2018b). Clustering determines the connectedness of a road network by evaluating how completely the neighbourhood of a given node is linked together (Boeing, 2017; Jiang, 2007; Jiang & Claramunt, 2004). A clustering coefficient of 1.0 is a perfectly clustered network, whereas a value of 0.0 is a scattered or a poorly connected network. However, clustering may not be a useful measure for spatial networks where nodes located close together have a larger probability of being connected, leading to a large clustering coefficient (Barthelemy, 2018). Also, the condition of a network with a large range of degree variations is impractical for spatial networks (Barthelemy, 2018).

The structural measures used in this study are summarised in Table 1, which are adapted from typology of network measures found in Boeing (2018b). It is important to emphasise that the metrics of connectivity such as connectivity index, intersection density, and street density have been observed to be inconsistent and subject to the geometry, area, and the boundary of the area under consideration (Knight & Marshall, 2015). The network indicators described here and their structural characteristics are mostly limited within the primal representation of road networks and as such the resulting outputs. Also, these indicators are structural measures and may not capture the dynamical processes or the functional characteristics of road networks.
3.1 A brief morphological description of the 10 urban road networks

A brief description of the morphology of road networks in the 10 districts covering the regional capitals in Ghana is presented in Figure 3. This was undertaken by creating a square mile outline from the urban core for each city, based on descriptions in Boeing (2018b), Louf and Barthelemy (2014), and Jacobs (1995). These outlines provide a simplified morphological description of the road layout, arrangement, and configuration.

Accra is shown to have a typical grid structure with very small street blocks based on the length of individual road segments. The relatively flat topography of Accra facilitates the gridded pattern of the road layout. Kumasi depicts a radial pattern from the urban core and is associated with a branching structure at the local scale. The radial pattern is partly associated with its central location in the country from which to access other major cities in the north, south, east, and west directions. The moderately rugged topography means that road layouts were undertaken to avoid physical barriers. The road network in Tamale has a radial pattern from the urban core and is associated with a local grid structure. The radial explanation for Kumasi is applicable to Tamale as well, being an important city in the northern part of the country. The topography in Tamale is relatively flat, thus there are limited physical barriers for a gridded layout of the road network. Secondi Takoradi shows a broad branching pattern with a grid structure at the local scale. The topography in Secondi Takoradi is rugged, hence a branching road layout can facilitate the avoidance of physical barriers.

Cape Coast has a tree-like structure at the global scale and is associated with a local branching. This network has a lot of dead-ends, and the large physical spacing between road segments indicates a large block size and coarse-scale granularity. Sunyani shows a radial structure from the urban core and is associated with a grid configuration at the local scale. The gridred areas are mainly associated with a well planned road layout whereas the coarse grain areas relate to informal settlements. Koforidua depicts a tree-like radial structure that is associated with coarse-grained branching and scattered grid configuration. The high presence of dead-ends in this network are indicative of the informal layout of road networks and the topographically rugged terrain. The elongated radial pattern is also characteristic of its location as a transit city, particularly between Accra and Kumasi.

Ho is shown to have a radial tree-like structure that is associated with lots of branches at the local scale. This area is dominated with water bodies and hills which create significant barriers to road layout. These barriers also translate to the

### TABLE 1 Description of geometric and topological network measures used to evaluate road networks (adapted from Boeing (2017, 2018b))

| Measure                      | Description                                                                 |
|------------------------------|-----------------------------------------------------------------------------|
| Average streets per node     | Describes average level of connectivity and how permeable the physical form of the street network is |
| Proportion of streets per node| Describes the type, prevalence, and spatial distribution of intersection connectedness |
| Average street length        | Average length of edges in the network, which indicates the average block size |
| Node density                 | A ratio of the total number of nodes to area in square kilometres, which indicates whether the network is fine grained or coarse grained |
| Edge density                 | A ratio of the total length of edges to area in square kilometres, which indicates whether the network is fine grained or coarse grained |
| Average circuitry            | Describes how circuitous the network is by comparing the network-constrained distances to straight-line distances |
| Diameter, radius             | Network complexity in terms of max/min size, structure, and shape |
| Node/edge connectivity       | Determines the minimum number of elements that must fail to disconnect the network |
| Average node connectivity    | Average number of nodes that must fail to disconnect pair of non-adjacent nodes |
| Clustering coefficient       | The extent to which the neighbours of some nodes are connected to each other |
| Degree centrality            | The larger the number of connections between a node and other nodes in the network, the higher its importance in terms of degree centrality |
| Betweenness centrality       | The importance of an element in terms of how many shortest paths pass through it |
| Page rank                    | Ranks a node based on its importance in the structure of incoming edges |
FIGURE 3 One square mile of road network indicating the urban morphology for all 10 regional capitals, based on Jacobs (1995).
coarse-grained nature of the road network and associated dead-ends. Bolgatanga has a radial road pattern which is associated with broad and local branching, and scattered grid configuration. Outside of the gridded configuration, the majority of the network is coarse grained and there are some cases of informal road layout. The road network in Wa depicts a radial and a minor looping pattern at the urban core, together with a highly clustered gridded arrangement. The high-density grid-ded area indicates a fine-grained road network, with the remaining areas having large physical spacing between road segments.

Overall, the majority of the road networks exhibit a radial pattern at the global scale together with either a gridded or a branching pattern at the local scale. The high presence of dead-ends and lack of continuity and connectivity between road segments are mostly attributed to informal human settlements which in turn are usually associated with poor layout of road networks.

3.2 | Basic geometric and topological descriptions

The road network data for the 10 districts covering the regional capitals in Ghana were analysed using OSMnx and NetworkX. The geometric and topological indicators listed in Table 1 were then derived for the 10 districts, and the results are presented in the following sections. The results of the geometric and topological measures for the 10 regional districts are presented in Table 2. The area in square kilometres indicates that the individual districts cover different sizes of land area. These different sizes directly affect other measures, such as the diameter, the radius, and the number of nodes and edges in each district. But other measures such as page rank and betweenness centrality have inherent normalisation to facilitate their comparison across different networks (Barthelemy, 2018).

In terms of granularity of road network, which is independent of the coverage of individual districts, density measure can be used to identify the fine-grained and coarse-grained road networks. The granularity identification is illustrated using the intersection density and the street density in Figure 4, both plotted in increasing order. Accordingly, the fine-grained road networks are located in Accra and Kumasi, with the coarse-grained ones located in Ho and Sunyani. The fine-grained road networks in Accra and Kumasi are supported by shorter average street lengths of 112 and 115 m respectively. Also, the coarse-grained road networks in Ho and Sunyani are associated with longer average street lengths of 162 and 155 m, respectively.

These results show a close matching between intersection density and street density such that regional capitals identified with high intersection density are associated with high street density. The opposite is true where low densities of intersection are associated with low street densities. However, Bolgatanga municipality is relatively distinct such that its low intersection density is associated with medium street density. Spatially, this means that the road segments are uniquely longer in Bolgatanga relative to the other regional capitals. This is supported by the average street length result showing Bolgatanga to have the highest value of 166 m.

The intersection density varies from 58 per km² for Accra to 4 per km² for Ho, whereas the street density is from 10.8 km/km² for Accra to 2.2 km/km² for Ho. The intersection and street densities for Accra and Kumasi which cover relatively smaller land areas are comparable to Denver in the USA based on findings from Boeing (2018a). Aside from Accra and Kumasi, the remaining eight urban cities have very small intersection and street densities, indicating a marked difference in the granularity of road networks.

The efficiency of the road pattern indicated by the average circuitry for the districts covering the 10 regional capitals indicates similar values ranging from 1.046 for Accra to 1.104 for Sekondi Takoradi, based on Table 2. That is, road routes are mostly straight and more efficient or less circuitous in Accra whereas Takoradi has the most circuitous road network. As a coastal plain, Accra is almost topographically flat and there are limited physical barriers to constructing straight roads. Also, the morphology of the road network in Accra has been identified to be a gridded configuration, which facilitates straight routes between locations. The terrain in Takoradi is more rugged topographically with rock formations which present physical barriers to constructing straight roads. These physiographic features directly impact the circuitry of road networks in the various cities. The average circuitry results obtained are comparable to those of most cities in the USA and other parts of the world, based on findings from Boeing (2018a), and also Huang and Levinson (2015).

3.3 | Node configuration

Further, we examine the node configuration in terms of clustering and page rank. The average clustering coefficient for the districts covering the 10 regional capitals range from 0.08022 for Wa to 0.03641 for Ho, based on Table 2. The results show Wa municipality as the most clustered road network, with Ho municipality and Kumasi metropolis as the least clustered road networks. Clustering can indicate connectedness of a road network with the assumption that nodes which are
TABLE 2 Results of the geometric and topological indicators for the districts covering the 10 regional capitals in Ghana

| Measure                              | Accra  | Bolgatanga | Cape Coast | Ho     | Koforidua | Kumasi  | Sunyani  | Takoradi | Tamale | Wa     |
|--------------------------------------|--------|------------|------------|--------|-----------|---------|----------|----------|--------|--------|
| Area (km²)                           | 162.917| 236.921    | 139.942    | 520.328| 143.977   | 271.788 | 462.429  | 200.619  | 386.452| 424.912|
| Diameter (km)                        | 28.701 | 32.923     | 24.334     | 45.177 | 22.740    | 29.722  | 52.940   | 26.254   | 44.634 | 32.350 |
| Radius (km)                          | 14.304 | 16.471     | 12.234     | 26.135 | 11.687    | 14.890  | 26.733   | 13.182   | 22.347 | 17.215 |
| n – number of nodes                  | 11,283 | 3,716      | 3,240      | 2,943  | 4,048     | 15,530  | 4,490    | 5,422    | 6,885  | 5,194  |
| m – number of edges                  | 28,781 | 10,440     | 7,839      | 7,343  | 10,063    | 41,432  | 11,748   | 13,660   | 19,691 | 15,104 |
| Average node degree                  | 5.10   | 5.62       | 4.84       | 4.99   | 4.97      | 5.34    | 5.23     | 5.04     | 5.72   | 5.82   |
| Intersection count                   | 9,517  | 3,238      | 2,386      | 2,168  | 3,017     | 13,026  | 4,179    | 6,201    | 4,771  |        |
| Average streets per node             | 2.82   | 2.84       | 2.52       | 2.54   | 2.54      | 2.75    | 2.75     | 2.60     | 2.92   | 2.93   |
| Total edge length (km)               | 3,269.66| 1,735.58  | 984.67     | 1,197.84| 1,294.53  | 4,745.38| 1,846.85 | 1,865.87 | 2,470.35| 2,033.10|
| Average edge length (m)              | 114    | 166        | 126        | 163    | 129       | 115     | 157      | 137      | 125    | 135    |
| Total street length (km)             | 1,766.49| 872.11     | 504.40     | 601.60 | 663.34    | 2,437.35| 945.45   | 950.20   | 1,250.09| 1,019.98|
| Average street length (m)            | 112    | 166        | 124        | 162    | 129       | 115     | 155      | 135      | 125    | 134    |
| Count of street segments             | 15,819 | 5,267      | 4,067      | 3,721  | 5,137     | 21,246  | 6,119    | 7,035    | 9,997  | 7,592  |
| Node density (per km²)               | 69     | 16         | 23         | 6      | 28        | 57      | 10       | 27       | 18     | 12     |
| Intersection density (per km²)       | 58     | 14         | 17         | 4      | 21        | 48      | 8        | 21       | 16     | 11     |
| Edge density (km per km²)            | 20.069 | 7.326      | 7.036      | 2.302  | 8.991     | 17.459  | 3.994    | 9.300    | 6.392  | 4.785  |
| Street density (km per km²)          | 10.842 | 3.681      | 3.604      | 1.156  | 4.607     | 8.968   | 2.045    | 4.736    | 3.235  | 2.401  |
| Average circuity                     | 1.046  | 1.070      | 1.093      | 1.077  | 1.097     | 1.059   | 1.097    | 1.104    | 1.053  | 1.070  |
| Self-loop proportion                 | 0.00149| 0.00000    | 0.00153    | 0.00082| 0.00159   | 0.00089 | 0.0017   | 0.00154  | 0.00030| 0.00026|
| Mean average neighbourhood degree    | 2.79   | 3.01       | 2.79       | 2.87   | 2.84      | 2.91    | 2.88     | 2.83     | 3.03   | 3.04   |
| Mean average weighted neighbourhood degree | 0.0404 | 0.0298     | 0.0405     | 0.0334 | 0.0318    | 0.0342  | 0.0353   | 0.0329   | 0.0370 | 0.0395 |
| Average degree centrality            | 0.0045 | 0.00151    | 0.00149    | 0.00170| 0.00123   | 0.00034 | 0.00117  | 0.00093  | 0.00083| 0.00112|
| Average clustering coefficient       | 0.04440| 0.05880    | 0.05158    | 0.03641| 0.04228   | 0.0370  | 0.04321  | 0.04493  | 0.05674| 0.08022|
| Average weighted clustering coefficient | 0.00086 | 0.00118   | 0.00098    | 0.00048| 0.00038   | 0.00262 | 0.00073  | 0.00120  | 0.00078| 0.00076|
| Max PageRank value                   | 0.00037| 0.00088    | 0.00088    | 0.00126| 0.00076   | 0.00024 | 0.00060  | 0.00061  | 0.00046| 0.00058|
| Min PageRank value                   | 0.00001| 0.00005    | 0.00006    | 0.00005| 0.00005   | 0.00001 | 0.00004  | 0.00003  | 0.00002| 0.00003|
| Average closeness centrality         | 0.000125| 0.000159  | 0.000177   | 0.000146| 0.000164  | 0.000093| 0.000142 | 0.000148 | 0.000148| 0.000163|
| Average betweenness centrality       | 0.000540| 0.01075    | 0.01311    | 0.01313| 0.01100   | 0.00517 | 0.01096  | 0.00906  | 0.00749| 0.00822|
| Average node connectivity (for 2 km grid) | 2.154 | 2.169       | 1.361       | 1.570   | 1.485     | 1.769   | 1.843    | 1.450    | 2.169  | 2.331  |
FIGURE 4 Geometric measures of the intersection density (left image) and street density (right image) both plotted in increasing order for districts covering the 10 regional capitals.
clustered are more likely to be connected. Accordingly, Wa is well connected with several spots of node concentrations instead of a single centralised cluster. The clustering result for Wa is indicative of the morphology of its road network presented in Figure 3, with distinct agglomeration of streets at the urban core. The comparison of the clustering results against those obtained for three sets of road networks in Portland, Oregon in Boeing (2017) show a value less than 0.001 for both the Downtown area and Northwest Heights, and 0.108 for Laurelhurst. These results are also comparable to values found in Boeing (2018a).

The evaluation of the arrangement of nodes based on page rank also provides useful information about the structure of the road network. The maximum value of page rank for the districts covering the 10 regional capitals range from 0.00126 for Ho to 0.00024 for Kumasi, based on Table 2. As noted, page rank provides a ranking of a node’s importance based on the structure of incoming edges. A high value of page rank indicates that the node is very critical for efficient functioning of the road network and that any disruption to this node will affect a large portion of the network. Ideally, a low value of page rank that is well distributed over the entire network will be preferred, such that a failure at any node will not significantly disrupt large portions of the road network. It is notable that Kumasi metropolis has nodes that are less clustered and the lowest maximum value of page rank. The low maximum value of page rank is preferred for most road networks, meaning that there are alternative nodes to use in case of congestion at other nodes, whereas a less locally clustered network is unlikely to be strongly connected. It is notable that the road network in Ho has a tree-like structure with branches which serve independent areas. The comparison of the maximum value of page rank results against those obtained for three sets of road networks in Portland, Oregon in Boeing (2017) showed about 0.030 for both the Downtown area and Laurelhurst, and 0.106 for Northwest Heights.

3.4 Connectivity of road networks

The relevance of connectivity in road networks has been widely recognised in the literature (Beineke et al., 2002; Knight & Marshall, 2015; Mishra et al., 2012; Reggiani et al., 2015; Turnbull et al., 2018). Based on Table 2, the results show Wa municipality as the most connected road network, with Cape Coast as having the least connected road network. A close comparison of the connectivity results with the clustering output shows a strong relationship between high connectivity and high degree of clustering. For example, the districts covering Wa, Tamale, and Bolgatanga are associated with both strong clustering coefficient and strong connectivity. But the opposite is not necessarily true, such that a low clustered network will not always be associated with a poorly connected network.

It is acknowledged that there are several measures of street network connectivity, and that the one used in this study which is average node connectivity focuses on the number of nodes which need to fail in order to disengage a pair of non-adjacent nodes; that is, average node connectivity does not encompass all the aspects of network connectivity. The average node connectivity as used in this study is applicable within the primal network representation with a focus on structural connectivity instead of the dynamical processes or functional connectivity (Turnbull et al., 2018). Streets are not just discrete linear elements but can be viewed broadly as a setting of social and economic interactions, which is particularly evident for pedestrians (Marshall et al., 2018). In the context of the multifaceted nature of streets, network connectivity needs to be considered in multiple dimensions to account for all unique features of street systems.

3.5 Centrality of road networks

Centrality of road networks has been investigated in greater detail in the literature (Barthelemy, 2011; Crucitti et al., 2006; Freiria et al., 2015; Huang et al., 2016; Lammer et al., 2006; Mishra et al., 2012; O’Sullivan, 2014; Scellato et al., 2006; Sharifi, 2019; Wang et al., 2013; Zhang et al., 2015; Zhong et al., 2017) because of its importance in providing a practical insight into characterising a road network. As an intrinsic property of networks, centrality allows the assignment of global importance to network elements (Marshall et al., 2018). Accordingly, we examine the results for degree centrality and betweenness centrality for the districts covering the 10 regional capitals presented in Table 2. Based on degree centrality result, Ho municipality has the highest degree centrality whereas Kumasi metropolis and Accra metropolis have low values of degree centrality. This result means that there are more critical locations in the road network in Ho municipality making it more vulnerable to congestion, whereas Kumasi and Accra have fewer of those vital locations.

As noted, betweenness centrality provides a practical measure to organise flows in the network; that is, to move around or along the road network from one location to another. As observed by Barthelemy (2018), the pattern of betweenness centrality for spatial networks is a fine balance between space and topology in a way that it captures important aspects of the network and its structure. The betweenness centrality result presented in Table 2 shows a close matching to the degree
centrality, such that regional capitals identified with high degree centrality are associated with high betweenness centrality. Again, Bolgatanga is an anomaly to this trend, having a high degree centrality but a medium value for betweenness centrality. This emphasises the relevance for the use of multiple topological indicators to better characterise the structure of the road network. The comparison of the average betweenness centrality results against those obtained for three sets of road networks in Portland, Oregon in Boeing (2017) showed about 0.07 for both the Downtown area and Laurelhurst, and 0.137 for Northwest Heights. These results are also comparable to values found in Barthelemy (2017); and Lammer et al. (2006).

Further, we examine the spatial pattern of betweenness centrality for individual road segments in each district covering the 10 regional capitals from Figures 5 to 14. The spatial distribution of betweenness centrality is a very useful indicator of the potential local traffic, where highly congested road segments are indicated by very large values of betweenness centrality. Barthelemy (2018) and Barthelemy (2011) observed that the localisation of congested nodes with high betweenness centrality can provide useful insight into the organisation of the network and the pattern of flow on it. Betweenness centrality has been shown to be particularly crucial for urban systems with illustrated correlations with income in Venerandi et al. (2014), the locations of shops and other micro-economic activity in Porta et al. (2009), urban growth in Barthelemy (2017), Strano et al. (2012), and Barthelemy et al. (2013), and as a simplest proxy with information about real traffic in Wang et al. (2012).

To facilitate the presentation, betweenness centrality shown for the road segments as lines are overlaid with the page rank values for nodes which are represented as dots and a grey shaded heatmap. The road segments are sized based on betweenness centrality values where thick lines represent high betweenness centrality (or important road segments) and fine lines represent low betweenness centrality. Similarly, nodes represented as dots are sized based on page rank values such that large dots represent high page rank value and small dots represent low page rank value. To aid the spatial visualisation, the page rank values are also represented as heatmaps where dark shaded areas represent high values of page rank and light shaded areas represent low values of page rank.

**FIGURE 5** Map of network topological measures of betweenness centrality of road segments and page rank of nodes for Accra metropolis. Dark shaded areas represent high values of page rank and light shaded areas represent low values of page rank.
Betweenness centrality for road segments and page rank values for nodes for Accra are presented in Figure 5. Important roads identified by high values of betweenness centrality connect different parts of Accra, whereas the less important road segments are shorter and are mostly associated with dead-ends. Important nodes based on page rank values are quite spread out throughout the entire road network, and are not always associated with high values of betweenness centrality. Potential road segments of traffic congestion are clearly indicated, and are mostly associated with trunk routes between major intersections. There are few clustered nodes but the overall road network is consistently dense. This network has a grid structure and is considered fine grained given the spatial proximity between road segments, which is indicative of the small block size over the entire area.

The betweenness centrality and page rank for Kumasi are presented in Figure 6. High values of betweenness centrality showing the important road segments are mostly longer, spatially central, and connect distant parts of the road network. There are some isolated shorter road segments that have high betweenness centrality values. The important roads follow the general radial pattern and are associated with branching at the local scale. The proportion of important roads based on betweenness centrality is fewer, indicating that there are alternative routes in the event of major road disruptions. Quite notable is that the road segments connect to each other and there are fewer dead-ends. There are several low betweenness centrality road segments that are distributed over the entire network, which is ideal to facilitate movement along the network. Similarly, the high page rank nodes are spread over the entire network and are not only associated with important road segments. The road network in Kumasi is considered fine grained based on the spatial density of road segments.
The betweenness centrality and page rank for Tamale are presented in Figure 7. There are several important roads identified by high values of betweenness centrality which are located in the city centre and on the outskirts. This high proportion of road segments with high betweenness centrality is problematic in terms of the capacity of the network to accommodate disruptions. The important roads follow the general radial arrangement from the urban core, and are associated with partial concentric loops which are indicative of the expansion of the road network over time. In most sections, the road network is well connected with most dead-ends located on the outskirts. Aside from isolated cases of clustered nodes with high values of page rank, the majority of the important nodes are spread out through the entire network. Given the mix of clustered and sparsely distributed road segments at the central location and on the outskirts, respectively, the network is moderately fine grained.

The results for betweenness centrality and page rank for Cape Coast are presented in Figure 8. The important road segments based on high values of betweenness centrality values are few and are spatially central in the network. Mostly, these important roads follow a tree-like branching arrangement which is typical of the entire road network. The spatial proximity of these important road segments means that road congestions or disruptions can easily spread to other parts of the network, causing further congestion. The values for betweenness centrality for this network are generally higher compared with the other cities, which further indicates the potential for a larger traffic congestion on this network. Another key feature of this road network is the high number of dead-ends, which is highly undesirable for efficient mobility. In terms of node configuration, there are spatially distinct clusters of important nodes identified based on page rank. Also, there are not many nodes with high values of page rank, which means that a disruption or failure of a few nodes will not negatively impact the network in a significant way. The road network in Cape Coast is coarse grained based on the sparse distribution of road segments and its low spatial density.

For Sekondi Takoradi, the results for betweenness centrality and page rank are presented in Figure 9. Based on high values of betweenness centrality, the important roads are of longer segments and are spatially central to the network. The important roads depict a near-parallel arrangement, indicating the accretion of the road network over time. Also,
these important roads show a branching configuration which is partly due to the rugged topography. The majority of dead-ends are located on the outskirts of the network. The road network is not strongly clustered, but there are a few node clusters associated with high values of page rank. The distribution of page rank values shows that several nodes are critical to the proper functioning of the road network, thus the network will be vulnerable to potential disruptions. The road network is considered moderately fine grained due to the combination of dense road segments and scattered roads at some locations.

Betweenness centrality for road segments and page rank values for nodes for Ho are presented in Figure 10. Important road segments identified based on high values of betweenness centrality are of longer segments and are spatially dominant. The spatial distribution and proportion of these important roads make the road network highly vulnerable to congestion and significant disruption, should any of these road segments fail. As in the case of Cape Coast, the values for betweenness centrality for this network are high compared with the other cities, indicating the potential for larger traffic congestion on this network. In the central location of the network, road segments with high values of betweenness centrality are spatially close; this can easily propagate congestion leading to further disruption. These important roads depict a radial arrangement from the urban core, which is typical of the entire road network. Further, the page rank results show a high proportion of critical nodes which have the potential to negatively impact mobility along the road network. The road network is coarse grained based on the sparse distribution of road segments and its low spatial density.

The results for betweenness centrality and page rank for Koforidua are presented in Figure 11. Road segments with high values of betweenness centrality are mostly of longer segments and located in the middle of the network. Generally, these important roads follow a tree-like pattern and are associated with a branching structure at the local scale. The accretion of road networks mostly occur along the major tree in the network; this is in concert with Koforidua as a transit city. There are several dead-ends which negatively impact the continuity and connectedness of the road network. As noted, the high presence of dead-ends is due to a combination of physical barriers to road layout and informal human settlements. A notable feature is the high proportion and clustering of important nodes identified based on high values of
page rank. This makes almost every node critical, which will negatively impact mobility along the road network. The road network is considered moderately fine grained due to the combination of dense road segments and scattered roads at some locations.

For Sunyani, the results for betweenness centrality and page rank are presented in Figure 12. The road segments with high values of betweenness centrality are located in the city centre and on the outskirts. The important roads follow a typical radial pattern from the urban core towards the outskirts. The radial pattern of these important roads facilitates the accretion of new road networks where they branch from the major routes. The proportion of these important road segments is considerable, which reduces the number of alternative routes in the event of disruptions. This network has several spatial clusters, with strong connectedness within individual clusters. But the high number of dead-ends significantly impacts the continuity and connectedness of the entire network. Based on page rank, the majority of the important nodes are spread out through the entire network. Given the mix of clustered and sparsely distributed road segments at the central location and on the outskirts, respectively, the network is moderately fine grained.

For Bolgatanga, the results for betweenness centrality and page rank are presented in Figure 13. High values of betweenness centrality which identify the important road segments are located mostly in the middle of the network. The important roads depict a branching arrangement, which is typical of the entire network. The proportion of the most critical road segments is small, meaning that the number of road segments which are susceptible to congestion is low, a feature that is preferable for most road networks. But there are several cases of dead-ends, an undesirable feature which will negatively impact the continuity and connectedness of the entire network. In terms of page rank, the distribution of critical nodes is interspersed with low page rank nodes, making the network less vulnerable to any disruption at these nodes. The network is coarse grained based on the sparse distribution of road segments and its low spatial density.
The final betweenness centrality for road segments and page rank values for nodes is presented for Wa in Figure 14. There are several important road segments identified based on high values of betweenness centrality which are located in the city centre and on the outskirts. The important roads show a typical radial pattern with minor parallel loops which are indicative of expansion of the road network. The considerable proportion of road segments with high betweenness centrality means the likelihood of congestion and less capability of the network to accommodate disruptions. This network is highly clustered with strong connectedness within individual clusters, an ideal feature to facilitate local mobility. Also, there are fewer dead-ends in this network, with the majority found on the outskirts. In terms of page rank, there is a high proportion and clustering of important nodes identified based on high values of page rank. This makes almost every node critical, which will negatively impact mobility along the network. Given the mix of clustered and sparsely distributed road segments at the central location and on the outskirts, respectively, the network is moderately fine grained.

**FIGURE 10** Map of network topological measures of betweenness centrality of road segments and page rank of nodes for Ho municipality. Dark shaded areas represent high values of page rank and light shaded areas represent low values of page rank.

The final betweenness centrality for road segments and page rank values for nodes is presented for Wa in Figure 14. There are several important road segments identified based on high values of betweenness centrality which are located in the city centre and on the outskirts. The important roads show a typical radial pattern with minor parallel loops which are indicative of expansion of the road network. The considerable proportion of road segments with high betweenness centrality means the likelihood of congestion and less capability of the network to accommodate disruptions. This network is highly clustered with strong connectedness within individual clusters, an ideal feature to facilitate local mobility. Also, there are fewer dead-ends in this network, with the majority found on the outskirts. In terms of page rank, there is a high proportion and clustering of important nodes identified based on high values of page rank. This makes almost every node critical, which will negatively impact mobility along the network. Given the mix of clustered and sparsely distributed road segments at the central location and on the outskirts, respectively, the network is moderately fine grained.

**4 | CONCLUSIONS**

This study has critically investigated the structural configuration of road networks in districts covering 10 regional capitals in Ghana in terms of their geometric and topological descriptions. To provide this knowledge of urban road networks in Ghana, four key analysis procedures undertaken by this study are: simple morphological analysis, basic geometric and topological descriptions including node configuration, and betweenness centrality of road networks. A summary of the findings from these results and their implications is presented in the following paragraphs.

The majority of urban road networks in Ghana followed a radial pattern at the global scale, with either a gridded or a branching configuration at the local scale. The local grid structure is associated with topographically flat areas, and locations which are well planned with a structured layout of the road network. The level of informal human settlement was
found to contribute to the abundance of dead-ends, leading to the lack of continuity and connectivity in the road networks. These morphological descriptions are important in determining optimal approaches and finding best practices which are suitable for these kinds of street morphology towards improved decision making for transport planning and management. For example, finding an optimal solution for traffic management in a road network with a gridded configuration could be different compared with the radial structure of a road network.

Several geometric and topological measures were used to evaluate the road networks, with each indicator providing independent descriptions of the road network. The characterisation of the road network using multiple geometric and topological indicators is shown to provide a deeper description of the network that is not available from any single indicator alone. Some geometric and topological measures provide an explanation for the pattern of other indicators, for example, the linkage between network clustering and connectivity. In terms of granularity of urban road networks in Ghana, only Accra and Kumsi were found to be fine grained and of comparable density to other global cities, based on intersection density and street density. The majority of the road networks are coarse grained, and associated with large physical spacing between road segments. The efficiency of road networks in terms of the average circuity for urban roads in Ghana was found to be between 1.046 for Accra and 1.104 for Sekondi Takoradi. These results are consistent with other road networks studied in Boeing (2018a) and Newell (1980).

Further, betweenness centrality was determined for individual road segments in the network for each urban city in Ghana, showing its spatial distribution. As an indicator of the global importance of network elements, the betweenness centrality of road segments identifies the important edges which lie between several origin–destination locations in a way that they control the functionality of the road network. For a random flow in the network, betweenness centrality identifies the potential local traffic, and could serve as the simplest surrogate for real traffic (Barthelemy, 2011; O’Sullivan, 2014; Wang et al., 2012, 2013). Accordingly, the generated spatial distribution of betweenness centrality for the road networks point to the potential traffic distribution in each city. Overall, the important roads based on the high values of betweenness centrality depict a radial pattern from the urban core for the majority of the cities. Given the lack of adequate infrastructure for traffic

![Map of network topological measures of betweenness centrality of road segments and page rank of nodes for Koforidua municipality. Dark shaded areas represent high values of page rank and light shaded areas represent low values of page rank.](image-url)
monitoring in Ghana, the spatial distribution of betweenness centrality could be part of the critical resource to provide insight for traffic management. The spatial distribution of betweenness centrality would also facilitate general transport planning and management to better plan and manage flows on road networks. For example, due to cost limitations most road repair operations are ranked in terms of priority; betweenness centrality can be used as one of the controlling factors to prioritise repair operations as it is an inherent indicator of the global importance of road elements. Also, betweenness centrality can be used as a controlling variable in ticket pricing for parking in a way that identified critical locations can be highly priced to reduce congestion in those areas.

Clearly, some urban road networks stand out in terms of their morphology, and geometric and topological descriptions. Accra followed by Kumasi are the most fine-grained road networks, with Accra having a typical grid structure and Kumasi depicting a radial pattern with local gridded configuration. Accra was found to be consistently dense with no distinct clustering, its node configurations are flexible given its gridded structure, and it has adjustable flow based on its betweenness centrality. Apart from its radial pattern, Kumasi has similar geometric and topological descriptions as Accra. On the extreme end of granularity, Ho was found to have the most coarse-grained road network. The road network in Ho has a radial pattern with no distinct clustering, its node configuration shows high dependency, and its flow is critically dependent on specific nodes and edges which make the network vulnerable and susceptible to multiple structural weaknesses. It is notable that Ho has the most severe physical barriers, including large water bodies, hills, and rugged terrain which limit the layout and configuration of road networks.

In terms of the cities identified either as a municipality or a metropolis, the key distinguishing feature is the density of nodes and road segments, with municipalities having lower densities and metropolis having higher densities. Aside from

**FIGURE 12** Map of network topological measures of betweenness centrality of road segments and page rank of nodes for Sunyani municipality. Dark shaded areas represent high values of page rank and light shaded areas represent low values of page rank.
this property, there are no sets of geometric or topological properties which separate municipal road networks from those of metropolis. Accordingly, area definition based on either a municipality or a metropolis is not a distinguishing criterion on the geometric and topological properties for the road networks examined. Instead, the road network in each regional capital evolves and exhibits unique structural patterns based on several drivers, including socioeconomic activities, politics, and the environment.

This study is a relevant addition to the literature on the structure of road networks in areas with less developed geospatial technology, with a particular focus on urban roads in Ghana. More critical investigations are needed in these areas to increase their representation in the literature, given that the layouts of road networks in these areas are not well developed and are highly informal. The structural descriptions for the road networks investigated provide the basis for transportation planning and management on critical issues in Ghana. In particular, based on the spatial distribution of betweenness centrality it is possible to identify problematic locations within the road network which are most vulnerable to traffic congestion and disruption. To accommodate growing population pressure on road networks and increased need for mobility, critical considerations of the geometric and topological properties of road networks are essential in transport planning and policy. In relation to future changes, the geometric and topological descriptions provide the foundation to guide planning schemes and the layout of future road networks.

Finally, it is acknowledged that the results and findings of this study are subject to the method of representation and the model of analysis used for road networks. As noted, the indicators examined in the study are mostly structural, such that they are limited in providing insight for dynamical processes or functional characteristics of road networks. From a computational network science perspective, the road network was converted into a graph representation, with a specific generalisation as a primal representation. A simple morphological analysis together with the global importance of network elements were used as models of analysis. Accordingly, the results and findings of this study are limited within this paradigm of representation and analysis, and so the potential applications must satisfy these conditions.
FIGURE 14  Map of network topological measures of betweenness centrality of road segments and page rank of nodes for Wa municipality. Dark shaded areas represent high values of page rank and light shaded areas represent low values of page rank.

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