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Appraisal of Road Network Spatial Connectivity in Abuja City, Nigeria

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Abstract

Road network creates a pivotal base for social co-existence, resource exploitation, production and consumption opportunities. These in turn lead to attainment of enhanced lifestyle and overall growth of cities. However, the pattern of road network and its performance on transportation, urban form and land use in Nigerian cities remain scarcely explored. This study investigates the spatial connectivity of road network and its influence on transport and urban form in Abuja city. Forty planning districts were used as spatial units for the analysis. GIS approach was applied to generate the road network spatial structure from open street map imagery. Graph theory indexes were used to evaluate road pattern connectivity. The study confirms that there is spatial disparity of road connectivity across the districts of Abuja metropolis. Although majority (72.5%) of the districts have fair (4.17 – 11.72 km/ km^2) distribution of road density most (60%) of the districts have 6.66 – 46.23 Aggregate Transportation Score (ATS) values, indicating low road network connectivity. Generally, road density and connectivity are high in the inner-city centre and sparse in the outer-inner city and city (edge) peripheral regions. The outcome of this research could aid the planning authority in detecting and finding solution to the problems associated with the physical road network in Abuja metropolis. Thus it would encourage the development of more roads to enhance economic growth, social stability, unity and quality of life within the entire city.

Keywords: Road network; density; connectivity; spatial disparity; Abuja city

Introduction

Network embodies a set of nodes signifying spatial locations and a set of links symbolizing connections (Xie & Levinson, 2007). Road network is the framework of functional relations of road pattern in a territory (Borruso, 2003). It possesses numerous essential components that exhibit both geometrical and topological differences. The desired property of road network configuration observed by commuters during transit such as comfortability is a vital pointer to the quality of urban transportation planning (Xie & Levinson, 2007). It is also a major determinant of the lifestyle and the overall impression of urban environment. Hence, superb form of road network in the city creates a pivotal basis for the existence of cordial relationship among people, production and consumption opportunities. Thus leads to achievement of enhanced lifestyle and overall efficient growth in the city (Holzapfel, 2015).

The innate influence of road system construction on the performance of transport system and its consequent impact on urban form and land use prompted concern for evaluating the spatial structure of road network (Gauthier, 1966; Marshall, 2004; Xie & Levinson, 2007). Quantification of road network properties also permits comparison of diverse road arrangements (Cardillo et al, 2006; Chang, 2012). Curiosity in such understanding instigated studies dating back to the classical works on regional transportation networks based on graph theory (Garrison, 1960; Garrison & Marble, 1961; Haggett & Chorley, 1969; Kansky, 1963). However, such early works were restrained by limited data, computational power, and modelling techniques (Strano et al., 2013; Xie & Levinson, 2007).

Recently, increase in accessibility to spatial and time geo-referenced data, has improved studies on real world transport structure. This in turn has attracted significant contributions from scholars (Barthélemy, 2011; Strano et al., 2013). However, most analysis predominantly focus on national, regional and sub-regional transport structure. Urban road transport system has scanty theoretical research (Sreelekha et al, 2016). Existing empirical studies on urban road networks mostly analyse the connection pattern of highways and primarily centre on European, American and Asian cities (Dyett & King, 1980; Taylor et al, 1995). In contrast, African urban transportation network, particularly West African cities like Abuja remains an essential and continual prospect for exploration. On this premise, GIS technology and graph theory model were applied to explore the extent of density, connectivity and spatial disparity of road network in Abuja municipality.

Materials and Methods

The Study Area

Abuja city is the federal capital of Nigeria located north of the confluence of River Benue and River Niger covering an area of about 256 km^2. The capital city is centrally situated in the country (Figure 1b) between Latitude 8° 56' N & 9° 8' N of the Equator and Longitude 7° 22' E & 7° 32' E of the Greenwich Meridian. The city is the municipal area of the six local area councils in the Federal Capital Territory (FCT) (Figure 1c) (Dawan, 2000). The topography is characterized by two popular rock structures comprising Zuma Rock located to the north-west and Aso Rock situated east of the city (Abubakar, 2014).

In line with most developing world mega cities, Abuja is characterized by dual urban form (municipal area and satellite towns) which experience excessive population explosion. Its annual urban growth rate of 8.32% makes Abuja the highest African growing city (Myers, 2011). Such rapid pace of population explosion is overwhelming in the satellite towns which experience almost 20% annual growth rate. Presently the city, that is, Municipality and Satellite towns jointly accommodate over 3 million inhabitants which makes it the fourth most populated city in Nigeria after Lagos, Kano and Ibadan (Abubakar & Doan, 2010). This study is limited to the municipal area which constitutes about 1 million of the fore mentioned city population. However the tremendous influence of the overwhelming populace residing in the satellite cities cannot be over emphasized.

Abuja municipality consists of three regions, namely the inner-city centre, outer-city centre and the city suburb region (Figure 1c). Each city region comprises of several district areas formed by four to five neighbourhoods. District is a mixture of residential, commercial, educational and recreational land uses (Jibril, 2015). Apart from being the seat of federal government agencies, the city-centre consists of residential areas including Asokoro, Garki, Guzape, Maitama and Wuse districts. The outer city-centre region is mainly residential comprising Utako, Jabi, Gudu, Apo, Kado, Wuye, Gwarimpa and Nbora districts among others. The suburb region consists of residential interspersed by educational institutions and industrial areas.

There are four categories of roadway existing in Abuja city. These includes expressway, arterial road, collector road and local streets. Expressways are the principal networks which carry heavy traffic to important places in and out of the city. Arterial roads radiate at intervals from the city-centre linking the outer residential areas. Collector roads are spread in the residential, commercial and industrial areas to convey traffic from local streets to arterial roads. Local streets are open access from dwellings, educational and commercial areas. Overall, Abuja Municipality has an average road density of 6.0 km /Km^2 and a total road network length of 1738.95 Kilometres. Paved roads have a total length of 1,028.8 Kilometres while unpaved roads cover a distance of 710.15 Kilometres.

Geographic Information Systems (GIS) is becoming ever more vital for analysis of real world transport network (Bagloee et al, 2017; Levy, 2017). This is because the technology has been identified as one of the most excellent tools used to encode, modify, analyse and display information on transport network (Rodrigue et al, 2013). Hence GIS technology was applied to extract road network data in this study. Road network data was generated through online digitization of open street map using ArcGIS 10.3. Abuja transportation network map was used for preliminary data processing including creation of spatial reference, geo-referencing and geographic coordinate system of the city. Other base maps comprising Abuja street guide, google map, and international road imagery were used for verification of road network segments and district boundaries. ArcGis 10.3 was used for data processing, district delineation and digitization, attribution and mapping of features. Road intersections and road end-points were digitized as point features. Road segments (edges) and district boundary were digitized as line, while district area coverage was digitized as polygon feature. ArcGis network analyst was used to calculate the network geometrical properties comprising edge/node counts, edge length and district area coverage.

Graph theory is an essential means used for evaluating the properties and characteristics of real world transport network (Derrible & Kennedy, 2011; Xie & Levinson, 2007; Xu & Sui, 2007). It is a mathematical illustration of transport network structure (Costa et al, 2007). Thus the approach was adopted in this research to evaluate road network connection pattern. Table 1 outlines the structural indices assessed in order to achieve the purpose of this study.

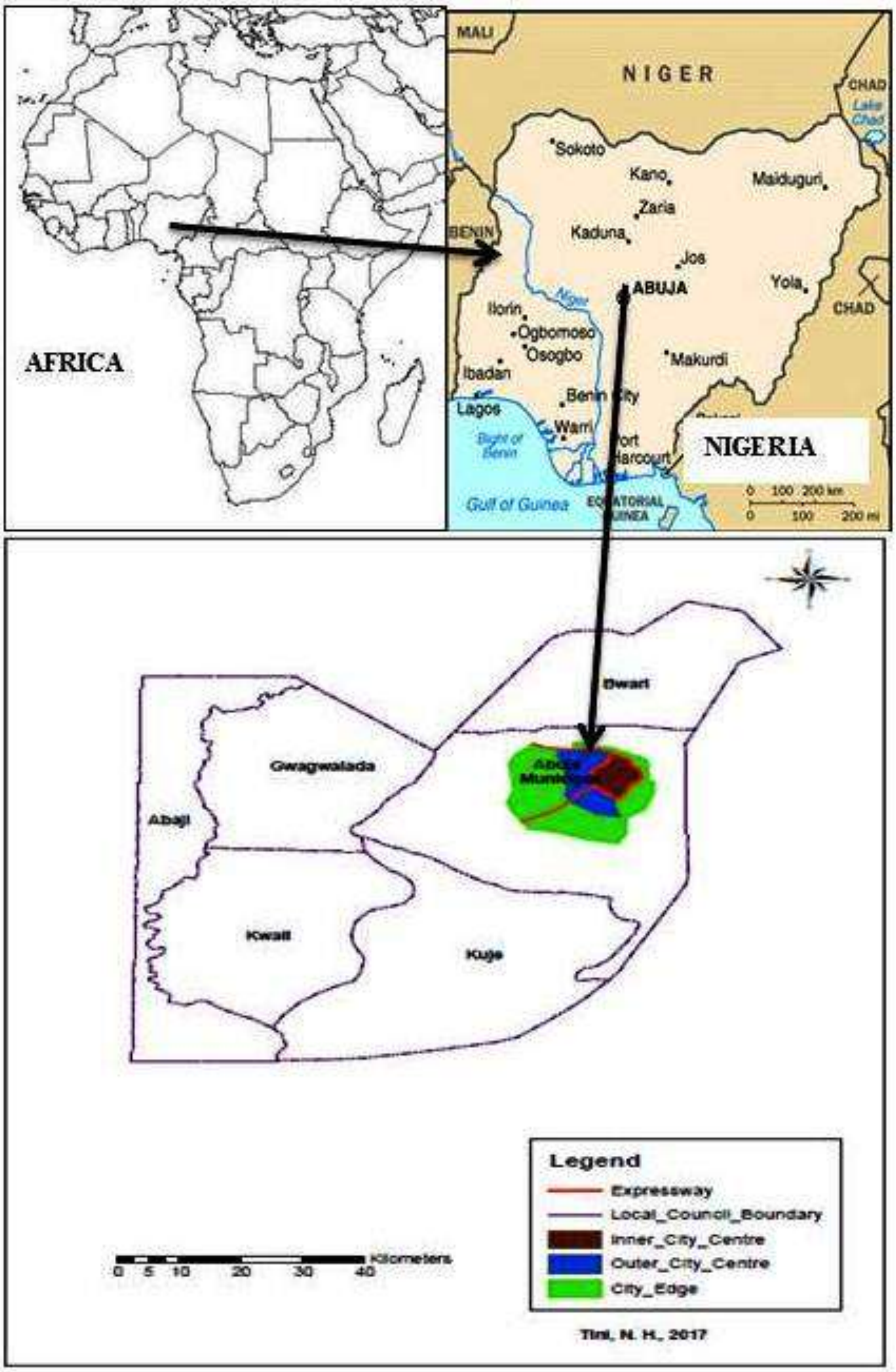

Figure 1: Study Area

Table 1: Transportation Network Connectivity Measures

Network Measure	Description	Formula	Correlation with Connectivity
Network Density (ND)	Measure the spatial distribution of road network.	$ND = \frac{\text{Road Length}}{\text{Area (Km}^2\text{)}}$	Higher density signify higher road development
Beta Index (β)	Measure the ratio of edges to node.	$\beta = e/v$	Increase road connectivity indicates by higher value
Eta Index (∩)	Measure length of graph over the number of edges.	$= \frac{L(G)}{E}$	Increase road connection reflects higher value
Gamma Index (γ)	Relationship between the observed number of limits and the peaks of network.	$\gamma = e/3(v-2)$	Increase road connectivity signifies higher value
Alpha Index (α)	Ratio of the actual number of circuits on planar network	$\alpha = \frac{e-v+1}{2v-5}$	Increase road connectivity shows higher value
Cyclomatic Number (∪)	Indicates tree type graph.	$\cup = e - v + 1$	Increase road connectivity specifies higher value
Aggregate Transport Score (ATS)	Summation of connectivity indices value	$ATS = \beta + \cap + \gamma + \alpha + \cup$	Increase road connectivity and efficiency indicated by greater value

Results and Discussion

Road Network Density

Road network density is the coverage of road indicating the level of road network development within a geographical entity (Sarkar, 2013). The normal concentration of road system linkage in Abuja Municipal area is 6.0 km^2. The road network density show significant spatial variation across the districts as portrayed in Table 2. Majority (42.5%) of the districts have between 6.46 – 11.72 road densities. About 30% districts own 4.17 – 5.83 road densities, while 27.5% districts possess 2.09 – 3.92 road densities. Fascinatingly, the districts with most road network densities concentrate in the inner city region. This means that the greatest pace of road development hub in the city core, neglecting the outer city and city suburb regions.

The concentration of road network density at the city centre is in consonant with Abuja master plan (FCDA, 1979).This was aimed at ensuring swift and free traffic flow at the city centre which is likely to attract significant levels of travel due to concentration of activities. The less density of road network in most districts outside the inner city region is aligned to incomplete development of roads proposed in the master plan. Consequently, this partial road development coupled with concentration of activities in the city centre often generate crowdedness and congestion of traffic flow as people who live in the periphery and satellite towns commute on daily basis to the city for work, transaction and social activitie.

Road Network Connectivity

Proportion of Edges per Vertex

Beta index evaluates the proportion of edges (links) per Vertex (node) in a transportation network (Nagne & Gawali, 2013). A network with beta index value greater than 1 represents a better-linked, while much greater values signify complex networks (Sarkar, 2013). Table 3 indicates that approximately 30% of the capital city districts own 1.05 – 1.08 beta index. Majority (45%) of the districts have between 1.20 and 1.28 beta index, while 25% districts possess 1.30 – 1.42 beta values. The entire districts have greater than 1 beta index. This signifies that the proportional number of edges to Vertex of road networks in the entire districts is connected.

Table 2: Road Network Density

Network Density Value		District Score	Number of Districts	Percent
Lower Value	2.09 -3.92 km/ km^2	Dape (2.09), Galadima (2.47), Instns & Resch A (2.59), Kukwaba (2.71), Apo (2.97), Salini (3.10), Gwarimpa 2 (2.34), Dakibiu (3.49), Katampe (3.58), Gaduwa (3.79), Industrial Area 2 (3.92),	**11**	**27.5%**
Moderate Value	4.17 – 5.59 km/ km^2	Kabusa (4.17), Dutse (4.35), Kado (4.45), Wumba (4.58), Guzape (4.73), Durumi (4.81), Jahi (4.93), Duboyi (5.38), Asokoro (5.42), Jabi (5.58), Karimu (5.59), City-centre (5.83),	**12**	**30%**
Higher value	6.46 – 11.72 km/ km^2	Mabushi (6.46), Kafe (6.76), Dakwo (6.92), Wuye (7.46), Gwarimpa 1 (7.74), Nbora (7.78), Gudu (8.25), Maitama (8.26), Kado (8.45), Utako (8..49), Bunkoro (8.56), Wupa (9.15), Wuse 2 (9.85), Garki 2 (10.05), Lokogoma (10.97), Wuse 1 (10.98), Garki 1 (11.72)	**17**	**42.5%**
Total			**40**	**100%**

Network Circuitry

Circuit refers to circle or closed path reflecting the extent to which links are connected in a network (Zhao et al, 2016). The ratio of existing cycles to the maximum potential cycles in a network is determined using Alpha index. Table 3 highlights that majority (50%) of the districts in Abuja metropolis possess 0.10 – 0.14 alpha values. Almost one third (32.5%) districts have between 0.15 and 0.22 alpha value. Few (17.5%) districts own less than 0.10 alpha values. None of the districts have up to (≤ 0.50) alpha index value. Rather, the entire districts have less than 0.30 alpha index values, indicating low circuitry.

Network Cyclomatic Number

Cyclomatic Number is the amount of closed routes in a network (Hopkins, 1987; Koulakezian, 2016). This is determined by estimating the difference between the capacity of edges and vertices in a transport network. Higher value of cyclomatic number indicates more developed and complex transportation system (Rodrigue et al., 2013). Table 3 clearly shows that majority (60%) of districts in Abuja city have low value of cyclomatic numbers, indicating less dense road network. Only 22.5% districts are moderately crowded, while 17.5% districts have highly clustered road network in the metropolis. This implies that most of the districts have less close or sparsely distributed road network.

Proportion of Network Routes

The proportion of existing routes to potential routes in a network is assessed using Gamma Index. The index is used to determine the growth of network over a period of time (Rodrigue et al., 2013). Table 3 attests that most (65%) of the districts in Abuja municipality have between 041 – 0.44 gamma index values. About 20% of the districts have 0.45 – 0.48 gamma index. Only 15% of the districts have low (0.37 – 0.4) gamma value. This denotes that majority of the districts have fair potentiality for future road network growth.

Network Route Length

The average length of each route (edge) in a transport network is referred to as eta index (Rodrigue et al., 2013). This index expresses the relationship between the entire network system and individual routes (edges) of the network (Kansky & Danscoine, 1989). Table 3 establishes that most (72.5%) districts in Abuja city have 0.17 – 0.24 eta index. About 12.5% districts have 0.06 – 0.17 eta index. Similarly, 12.5% districts have moderate (0.30 – 0.44) eta index. Only 2.5% districts have high (0.52) eta index value. On the whole, 85% of the districts have low eta index. Thus reveals less average length per link, signifying poor network connectivity in majority of the districts in Abuja metropolis.

Aggregate Network Connectivity

The summation of individual elements or components of transport network is known as Aggregate Transportation Score (ATS) (Florea et al, 2016)**.** ATS depicts the overall connectivity of network system in an area (Sarkar, 2013). In this regard, ATS was adopted to determine the overall connectivity and effectiveness of road system in the current study. Figure 2 illustrates the spatial distribution of road network connectivity in Abuja city. The inner city districts comprising Wuse 1, Maitama, City-Centre and Asokoro have high ATS values, indicating more road connectivity. Other districts (Wuse 2, Garki 1 and Garki 2) in the city core portray moderate ATS values. Only Guzape district has low ATS value in the inner city region. This reveals that there is high connectivity of road network in the inner city. Bulk of the districts in the outer city centre and city (edge) suburb regions portray low ATS values, signifying less road network connectivity.

Overall, the districts are categorized into three based on ATS value (Table 3). Most (60%) of the districts have 6.66 – 46.23 ATS values, indicating low road network connectivity. Only 22.5% and 17.5% of the districts respectively have moderate and high ATS values. This implies that majority of districts in Abuja metropolis have less overall road network connectivity.

Generally, road density and connectivity are high in the inner-city centre and sparse in the outer-inner city and city (edge) peripheral regions. This generates a wide and persistent inequality among the city regions. The spatial pattern of road network has played a significant role in shaping the urban form of Abuja city. Expressways and arterial roads radiate at intervals from the city-centre towards the western, north-western and south-western regions (Figure 3). Thus makes the city to portray a shuttle-like urban form.

Table 3: Computed Values of Road Network Structural Indices

District	Total Nodes (V)	Total Edges (E)	Total Edge Lengths (Km)	Eta Index	Beta Index	Alpha Index	Gamma Index	Cyclomatic Number	Aggregate Transport Score
Apo	142	163	34.79	0.21	1.15	0.08	0.39	22	23.83
Asokoro	399	497	96.48	0.19	1.25	0.12	0.42	99	100.98
Bunkoro	343	431	83.86	0.19	1.26	0.13	0.42	89	91.00
Ct-Centre	368	468	93.36	0.20	1.27	0.14	0.43	101	103.04
Dakibiu	57	68	25.35	0.37	1.19	0.11	0.41	12	14.09
Dakwo	175	223	42.92	0.19	1.27	0.14	0.43	49	51.04
Dape	82	86	19.14	0.22	1.05	0.03	0.36	5	6.66
Duboyi	126	137	15.7	0.11	1.09	0.05	0.37	12	13.62
Durumi	76	91	20.38	0.22	1.20	0.11	0.41	16	17.94
Dutse	105	127	24.7	0.19	1.21	0.11	0.41	23	24.93
Gaduwa	80	94	16.96	0.18	1.18	0.10	0.40	15	16.85
Galadima	230	306	16.96	0.06	1.33	0.17	0.45	77	79.00
Garki 1	514	588	58.12	0.10	1.14	0.07	0.38	75	76.70
Garki 2	349	421	57.59	0.14	1.21	0.11	0.40	73	74.85
Gudu	239	298	51.3	0.17	1.25	0.13	0.42	60	61.96
Guzape	93	125	30.48	0.24	1.34	0.18	0.46	33	35.23
Gwrpa 1	196	237	37.21	0.16	1.21	0.11	0.41	42	43.88
Gwrpa 2	102	130	19.41	0.15	1.27	0.15	0.43	29	31.00
Indstl A. 2	377	489	93.58	0.19	1.30	0.15	0.43	113	115.07
Instns A	353	459	82.7	0.18	1.30	0.15	0.44	107	109.07
Jabi	102	134	29.94	0.22	1.31	0.17	0.45	33	35.15
Jahi	123	154	46.03	0.30	1.25	0.13	0.42	32	34.11
Kabusa	50	59	13.27	0.22	1.18	0.11	0.41	10	11.92
Kado	98	129	27.29	0.21	1.32	0.17	0.45	32	34.14
Kafe	100	120	23.4	0.20	1.20	0.11	0.41	21	22.91
Karimu	122	156	35.07	0.22	1.28	0.15	0.43	35	37.08
Katampe	112	125	38.33	0.31	1.12	0.06	0.38	14	15.87

Kaura	108	117	19.27	0.16	1.08	0.05	0.37	10	11.66
Kukwaba	64	82	35.88	0.44	1.28	0.15	0.44	19	21.31
Lokgoma	487	602	87.98	0.15	1.24	0.12	0.41	116	117.92
Mabushi	55	67	19.96	0.30	1.22	0.12	0.42	13	15.06
Maitama	564	671	104.28	0.16	1.19	0.10	0.40	108	109.84
Nbora	245	325	46.34	0.14	1.33	0.17	0.45	81	83.08
Salini	51	59	30.69	0.52	1.16	0.09	0.40	9	11.17
Utako	119	162	35.23	0.22	1.36	0.19	0.46	44	46.23
Wumba	109	129	27.09	0.21	1.18	0.10	0.40	21	22.89
Wupa	109	137	23.87	0.17	1.26	0.14	0.43	29	30.99
Wuse 1	412	555	84.1	0.15	1.35	0.18	0.45	144	146.13
Wuse 2	284	358	57.2	0.16	1.26	0.13	0.42	75	76.98
Wuye	121	172	32.74	0.19	1.42	0.22	0.48	52	54.31
Total	7841	9751	1738.95						

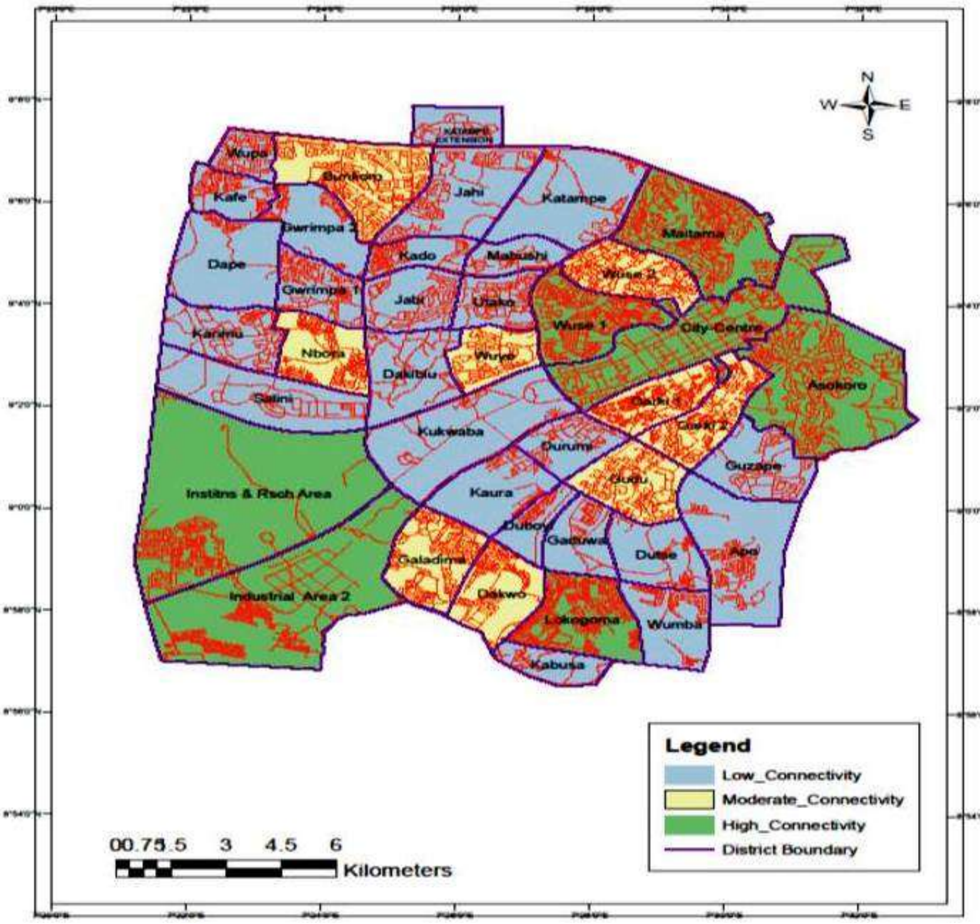

Figure 2. Road Network Connectivity in Abuja City

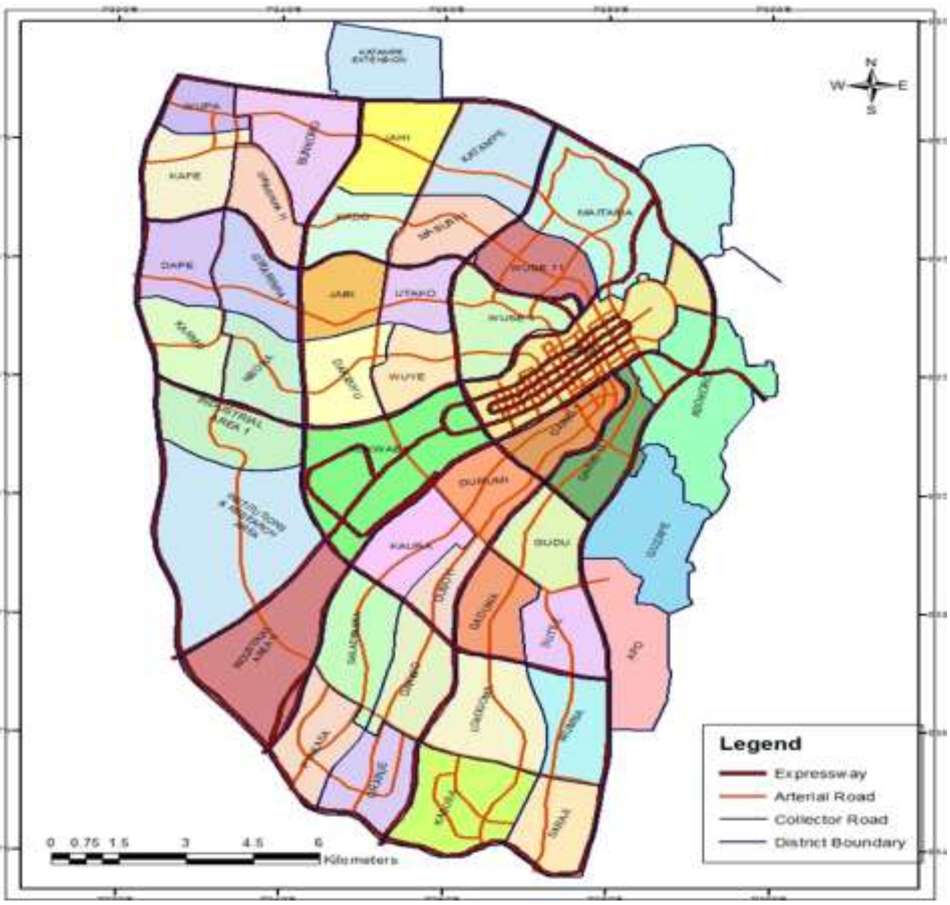

Figure 3: Road Network Pattern in Abuja City

Conclusion

In contrast to the extant literature on spatial pattern of urban road network in European, American and Asian cities, little is known about the structural properties of roads in Nigeria cities. This research have offered an assessment of road network topology in Abuja city. The analysis basically concentrated on connection pattern of road networks in the city. The result is useful for planning and informing policy formulation towards ensuring road development and connectivity in Abuja municipality. Further work could focus on complex network analysis to evaluate the betweenness, centrality, homogeneity and heterogeneity of road network structural properties in the study area.

The study discovered that the spatial pattern of road network plays a significant role in shaping the form of Abuja city into a shuttle-like urban form. It also confirms that the structural properties of road network vary across the districts. The work equally revealed that there is high density and connectivity of road network in the city core. While the outer inner city and city suburb regions experience poor road network connectivity. Hence, a wide and persistent inequality exists among the city regions**.** Such generates swift traffic flow in the inner city centre and severe traffic congestion on main expressways/arterial roads linking the periphery with the city core. This creates negative effects on people's lifestyle instigated by excessive travel cost, travel delay, noise and air pollution, physical and psychological retardation. It is therefore necessary and imperative to focus and intensify effort towards development of road network in the districts with very low road network density and connectivity so as to curtail regional imbalance. This will ensure economic growth as well as maintenance of social equity and stability, unity and quality of life among the entire dwellers of Abuja city.

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