Evaluation of Road Network Topological Pattern in Abuja Municipality, Nigeria

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Abstract

Road network topology has great influence on people's movement, traffic safety, land use efficiency and liveability in the city. Hence, proper insight to the characteristics and properties of network patterns offer vital guidance for planning and improvement of road system. However transportation researchers are silent about the relationship between graphical and topological logic of road networks. This study analyses the spatial pattern of road networks with the help of GIS technology. It also highlights the performance of each type of road network on transportation system. Then evaluates the topological formation of road networks using GTP metrics. Graphical analysis reveals that Abuja municipality is generally characterized by grid road network patterns. Majority of the districts have variety of pure network pattern types; while limited districts have combination of two or more patterns. The topological coherence of the road networks range from minimal to moderate standards. Outcome of this research offers suitable insight into the road network design which provides a proper guide to planners and policy makers in decision for future planning and development of roads in city.

Keywords: Road network; spatial pattern; logical formation; efficiency

1. Introduction

Transport system and land use spatial pattern interchangeably influence each other. As cities evolve, road networks grow in tandem. Such process eventually shape the social activities and future pattern of urban development. Hence road network, as a mainstay of city, has become an imperative research object. This is driven by desire to understand the evolution and appearance of cities (Snellen, Borgers, & Timmermans, 2002), spatial and social relation in urban roads(Lin & Ban, 2013)**,** traffic flows and travel patterns of urbanites(Newell, 1980; Xie & Levinson, 2009).

Assessment of road network structural pattern is known to be a major focus of transport investigation in the recent pass decades (Sreelekha, Krishnamurthy, & Anjaneyulu, 2016; Zhao, Sun, Wu, Gao, & Liu, 2016). This is aimed at offering an expedient insight into the diverse characteristics shown by road transport system and its impact on other urban sectors. It also supposes to facilitate better plan for movement of people, goods, and activity-location. It as well intends to unveil the kind of road system that is better for land use, urban expansion, and the environment (Xie & Levinson, 2007, 2009). More importantly, it is expected to provide guidance for developers, planners and policy makers' decision which consequently might result to efficient attainment of overall city growth (Sreelekha et al., 2016; Zhang, Wang, Zeng, & Chen, 2011).

Prevailing studies predominantly dwell on categorizing network patterns base on visual intuition and self-judgment of road network graphical structures. Such classification process is subjective and the result could be influenced by personal judgment. Whereby similar pattern might be classified into different patterns by various scholars. Such grouping tend to be more confusing and incorrect especially where there are mixed patterns that cannot be classified under specified patterns. Additionally, mere classification of networks by pattern does not clearly describe how their consistency, connectivity, and shape influence traffic condition.

Furthermore, the relationship between graphical and topological formation is scarcely explored. Equally, the real road networks are not well captured in topological analyses. Since road network exhibit both geometric and topological disparities, a better approach may be to investigate both the graphical and topological logic concurrently and establish the link between them. Thus road network is be better understood by using GTP topological measure that can quantitatively describe road network pattern coherence and connectivity. In due course, the motivation for this study is to explore the relationship between graphical and topological features of road network patterns. Specific objectives of this study includes identification of network graphical patterns, highlighting the performance of each network pattern on transport system and evaluating the topological coherence of real road networks. GIS was used as a fundamental instrument to delineate the graphic character of road transport system. Graph theory GTP index was used as a powerful tool to elucidate and quantify the topology of road network functional properties.

2. Overview of 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 1a) between Latitude 8° 56' N & 9° 8' N of the Equator and Longitude 7° 22' E & 7° 32' E of the Greenwich Meridian. Abuja city is the metropolitan area of the six local area councils in the Federal Capital Territory (FCT) (Figure 1b). 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 (Ismaila Rimi Abubakar, 2014).

Like most developing country mega cities, Abuja is branded with dual urban form, that is, metropolis and satellite towns) which experience extreme population explosion. Its annual urban growth rate of 8.32% makes Abuja the highest expanding city in Africa(Myers & Klein, 2011). Such fast pace of population growth is awesome in the satellite towns which experience about 20% yearly growth rate. Presently, both the municipality and satellite towns together house more than 3 million people which makes it the fourth highest populated city in Nigeria after Lagos, Kano and Ibadan (Ismaila R Abubakar & Doan, 2010). The present study is restricted to the municipal area which inhabits about 1 million of the earlier mentioned population. Nevertheless the tremendous influence of the awesome populace residing in the satellite cities cannot be over stressed.

Abuja municipality has three regions, specifically the inner-city centre, outer-city centre and the city suburb region (Figure 1c). Each city region encompasses some district areas made of four to five neighbourhoods. Every district is characterised by mixture of residential, commercial, educational and recreational land uses (Jibril, 2015). In spite of being the seat of federal government agencies, the city-centre comprises of residential areas namely Asokoro, Garki, Guzape, Maitama and Wuse districts. The outer city-centre region is largely residential including Utako, Jabi, Gudu, Apo, Kado, Wuye, Gwarimpa and Nbora districts among others. The suburb region consists of residential intermixed by educational institutions and industrial areas.

There are four categories of roadway existing in Abuja city. These comprise 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 (Figure 1c). 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.

Figure 1a: Location of Abuja in Nigeria

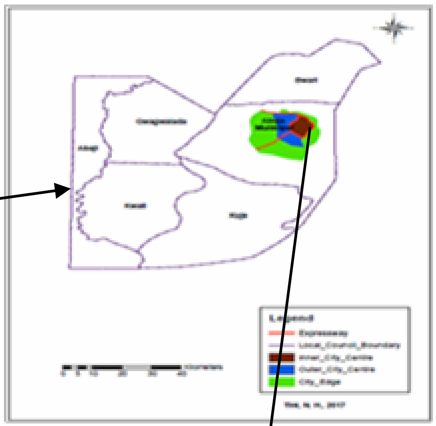

Figure 1b: Location of Abuja City in FCT

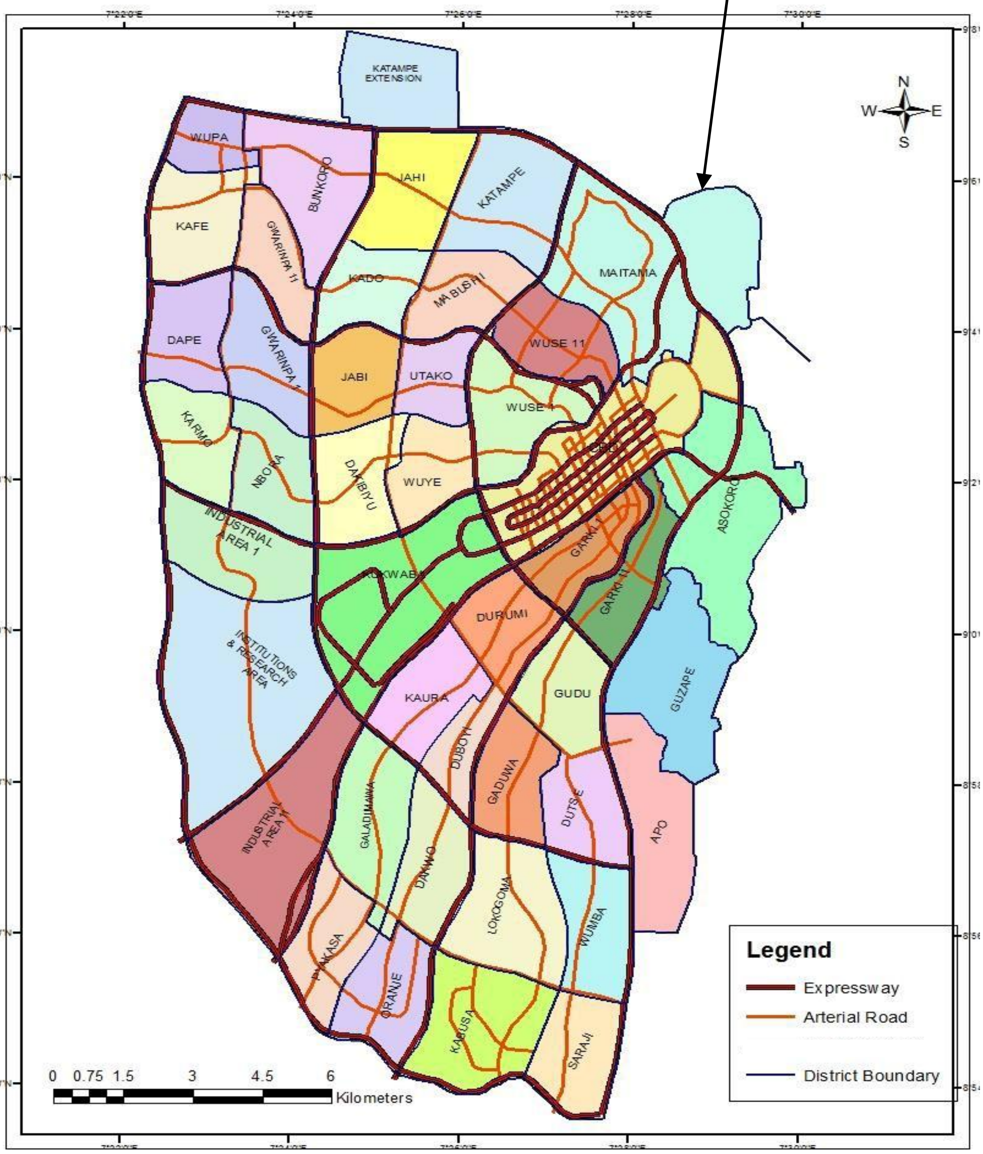

Figure 1c: Road Network Pattern in Abuja Municipality

3. Data and Methods

3.1 Data Sources

The datasets used in this paper is of two categories, constituting real road network map and geometric data. Geographic information system (GIS) technology and GTP index computational technique simplified the spatial analysis of urban road networks. The real road network map was generated from remotely sensed imagery. ArcGIS 10.3 software was used to extract the road transport structure online from Abuja open street map. All category of roads including expressway, arterial roads, collector roads and local streets were digitized as polyline feature in each of the forty districts within Abuja municipality. The statistical data was generated from ArcGIS network analyst geometric calculation environment.

3.2. Network Graphical Representation

Transport network structure is mathematically illustrated as a graph(Costa, Rodrigues, Travieso, & Villas Boas, 2007). A graph, meaning network constitutes a set of vertices (nodes) and a set of edges (links)(Lin & Ban, 2017). This concept is known as Graph theory; an essential method for evaluating the properties and characteristics of real world transport network (Derrible & Kennedy, 2011; Xie & Levinson, 2007; Xu & Sui, 2007).There are two distinct means of representing road networks, that is, the primal and dual methods. The primal representation is a natural and intuitional style, which denotes road segments as edges (links), and road intersections as vertices (nodes) (Lin & Ban, 2017). Urban road network is mostly studied in terms of primal space (Gross & Yellen, 2004). This is because such approach portray the geometric patterns and geographical properties like locations and lengths of road network (Ben-Joseph & Southworth, 2003; Gudmundsson & Mohajeri, 2013; Marshall, 2004). Additionally, the method has established conventions across diverse fields, and as well maintains the natural visual association(Rana & Batty, 2004).

In contrast, dual graph representation is an alternative approach in which roads represent the vertices in a graph, and the intersections denote edges(Marshall, 2015; Zhang et al., 2011). This method focuses on linear elements, constituted of lines between intersections and portrays continuity of lines through intersections (Marshall, 2015). Although it provides more detailed insights about the actual traffic flow (i.e., possible movement directions) compared with the primal graph representation, it could introduce subjectivity. Hence primal method was adopted in this study in order to provide a more objective picture of road network. It is also more appropriate to get clearer understanding of geometric properties of roads in Abuja city. Since in graph theory, a planar graph indicates a network which has all edges intersecting only at their endpoints(Lin & Ban, 2017). Vertices of graph in this study represent intersections and dead-end of roads. Edges are the road fragments connecting the intersections. All category of roads comprising expressways, arterial roads, sub-arterials, collector roads and local streets were mapped as single segment to represent the surface transportation system, a typical planar network in the city.

3.3 Evaluation of Road Network Topology

Road network topology is the spatial arrangement or configuration of roads in a given place (Rodrigue, Comtois, & Slack, 2016). It is conventionally evaluated by the measures of gridness, treeness, ringness, webness, Shannon entropy (Barthélemy, 2011; Buhl et al., 2006; Gudmundsson & Mohajeri, 2013; Xie & Levinson, 2007) and typology (Louf & Barthelemy, 2014). Recent development in topology, graph theories and increase in computational capacity paved way for more advanced methods for quantitative analysis of road network pattern (Bavelas, 1948; Cardillo, Scellato, Latora, & Porta, 2006; Jiang & Claramunt, 2004). Accordingly, topologic metrics are used to measure the coherence and connectivity of network(Zhang et al., 2011).

The two basic structures commonly observed in planar transport network include tree-like network and grid-like network (Levinson, 2012; Xie & Levinson, 2007). In this regard, Noda (1996) introduced the grid-tree-proportion index (GTP index) as a new mathematical measure uniting alpha and gamma indices used to jointly evaluate the grid pattern, tree pattern, and general road network patterns that do not belong to either of the two categories (Usui & Asami, 2011). The approach is as well used to quantify the formation, coherence and connectivity of road network pattern (Gogoi; Usui & Asami, 2011; X. Wang, You, & Wang, 2017). Additionally, it is used to determine effectiveness of traffic flow or movement in a road network. GTP index range from the lower value of 0 to the highest value of 1. The coefficient of GTP index is computed by substituting the following formula.

$$\text{GTP} = \frac{e - V + 1}{(\sqrt{V} - 1)^2}$$

Where:
GTP = Grid Tree Pattern
e = Total number of edges (Links)
V = Total number of vertex (Nodes)

4. Results and Discussion

The form and appearance of road network influences urban transport performance(J. Wang, 2015), traffic safety (Grammenos, Pogharian, & Tasker-Brown, 2002; S. Rifaat & Tay, 2009; Sun & Lovegrove, 2013), land use efficiency(Wegener & Fürst, 2004), and liveability (Grammenos et al., 2002) of urban dwellers. Hence the types of road network pattern is a vital and key step in the planning and evaluating land use and transport systems(P. Wang, Hunter, Bayen, Schechtner, & González, 2012; Xie & Levinson, 2007). The most common approach used to categorize road network pattern is visual examination(X. Wang et al., 2017). For instance, Southworth and Ben-Joseph (Ben-Joseph & Southworth, 2003) used this method to divide road networks into five broadly accepted patterns: lollipops, loops & lollipops, warped parallel, fragmented parallel and gridiron. S. M. Rifaat, Tay, and De Barros (2011) and P. Wang et al. (2012) outline additional two patterns: mixed and sparse patterns. Some authors, based on typologies, classified network into three patterns: grid, radial, linear and grid(Marshall, 2004). The foregoing grouping systems proposed by scholars was adopted as a base for road network pattern classification in this study which is explained hereafter.

4.1 Graphical Taxonomy of Road Network Pattern

Result of graphical analysis in current study reveals that Abuja city is generally characterized by grid road network pattern. This type of network has simple and straight form; which offers selections of routes, and disperses traffic over various ways. Conversely, grid network has many road crossings. Also, it predominantly encourages the use of motorised transportation system. From the map extracts, five distinct grid road network types have been identified in Abuja city. These comprise curvilinear, irregular, rectilinear, hybrid and broken grid-Iron road patterns as illustrated in Table 1. Examples of communities in each of the five categories are represented in Figures 1 – 5.

Table 1: Types of Road Network Pattern in Abuja City

Road Pattern	Number of Districts	Percent (%)
Curvilinear	12	30
Irregular	11	27.5
Rectilinear	11	27.5
Hybrid	5	12.5
Broken Gridiron	1	2.5
Total	40	100

Curvilinear Grid Network Pattern

Majority (30%) of districts in Abuja city have curvilinear grid road networks as represented in Table 1. This type of network exists in the central region, particularly Asokoro, Apo, Durumi, Gudu, Guzape, Wuse 1 and Wuse 11 districts. It also occur in North Western region comprising Bunkoro, Jabi, Kafe and Wupe districts. Curvilinear network pattern offers less connection and access due to loops and lollipops design (S. M. Rifaat et al., 2011). However, it has curved hierarchical thoroughfares running parallel to the topography to accommodate moderately sloppy terrain. The curved ways create visual attraction while the lanes on both sides enable efficient infrastructure development (Albemarle, 2015). Additionally, the combination of cul- de-sacs and loop facets has positive effect on traffic calming. Figure 3 is a typical curvilinear grid network in Abuja city.

Irregular Grid Network Pattern

The second majority (27.5%) of districts in Abuja city have irregular grid road network as revealed in Table 1. This pattern is well spread over the regions in the municipality; commonly found in Dakibiu, Gwarimpa I, Garki II, Jabi, Kabusa, Katampe, Kukwaba, Mabushi, Maitama and Utako districts. The irregular road network has a mix pattern developed in conformity with the rough terrain. Other possible reasons for development of irregular road pattern in the city could be haphazard response to urban growth or the intension of planning for aesthetic beauty

(GlobalSecurity, 2016). The network pattern is applauded for creating aesthetic appeal, less intersection and congestion (Salat, Bourdic, & Labbe, 2014). Notwithstanding, it encourages travel long distances, ease to get lost and difficult to extend additional ways(Albemarle, 2015). Figure 1 illustrates typical irregular road network pattern in Abuja city.

Rectilinear Grid Network Pattern

More than one quarter (27.5%) of districts in Abuja city have rectilinear grid road network as shown in Table 1. This is mostly found in the newly developed districts especially south central region of the city. Such include Duboyi, Dakwo, Dutse, Galadima, Gaduwa, Lokogoma and Wumba districts. The network pattern is also found in the North West region including Dape, Gwarimpa II and Nbora districts and Institutions & Research district in the south western region.

Rectilinear system is a classic grid network with maximum connections and hierarchical roads (Snellen et al., 2002). The network pattern is characterized by park spaces interspersed at regular intervals. It has variety of allowances with easily managed choices and thoroughfares. Most of the ways terminate at T-intersections, having lanes on both sides for efficient infrastructure development. Rectilinear road pattern is suitable for rolling topography unlike in steeply sloping landscape. The visual instance of rectilinear pattern in Abuja city is illustrated in Figure 2.

Hybrid Grid Network Pattern

Almost one tenth (12.5%) of districts in Abuja municipality have hybrid road network pattern as depicted in Table 1. The term hybrid here refers to combination of two or more elements of pattern; it is well-known as ‘bastard offspring’(Marshall, 2004). Although hybrid network provides a well-connected vehicular network (Girling & Kellett, 2005), it also favour walkability and cycling which reduces reliance on automobile transportation. Such type of road network is portrayed in few areas comprising Industrial Area II, Kado, Kaura and Salini districts. An example of community with hybrid road network in Abuja is illustrated in Figure 4.

Broken Gridiron Network Pattern

Only negligible (2.5%), that is, the Central Business District (CBD) portray Broken Gridiron pattern in Abuja Metropolis as exposed in Table 1. The network pattern reflects a simple lay out with series of ways at right angles, creating either square or rectangular blocks (Munsoncity, 2013). The networks are broken in the sense that roads are not completely netted together but fragmented at some intervals. Existence of gridiron pattern in the city centre is consistent with most cities globally(Snellen et al., 2002). Gridiron pattern is essential for easy navigation and further extension of ways. However, the frequent intersection may generate traffic crash, congestion, pollutant, road frustration and insensitivity to ecology such as streams and wood lots (Easymapwork, 2011). Figure 5 clearly illustrates the Broken Gridiron pattern in Abuja City.

Figure 2: Irregular Grid Pattern
Community: Maitama District

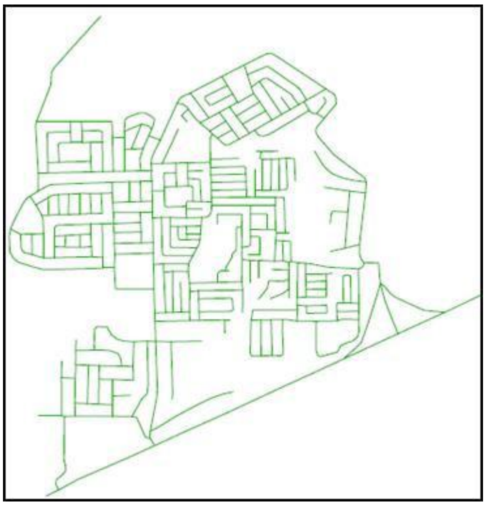

Figure 3: Rectilinear Grid Pattern
Community: Institutions & Research Area

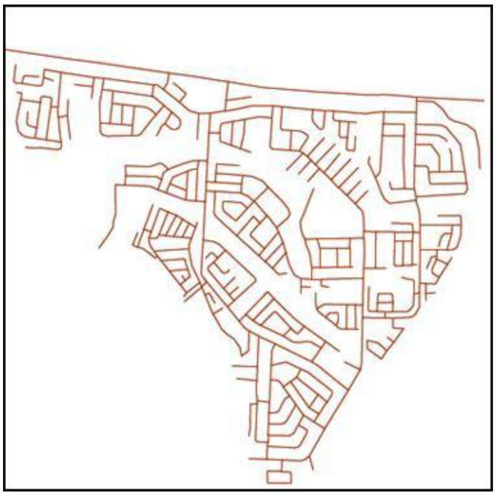

Figure 4: Curvilinear Grid Pattern
Community: Bunkoro District

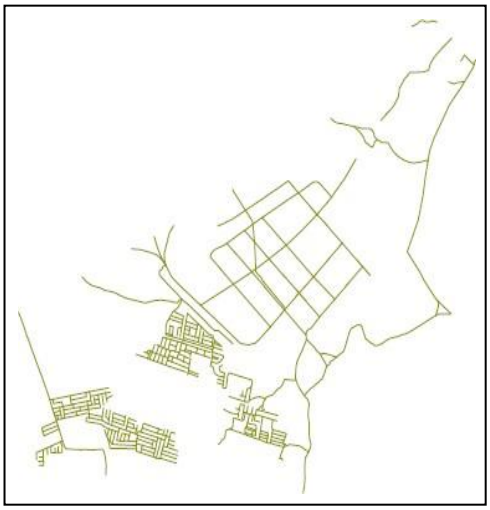

Figure 5: Hybrid Grid Pattern
Community: Industrial Area II

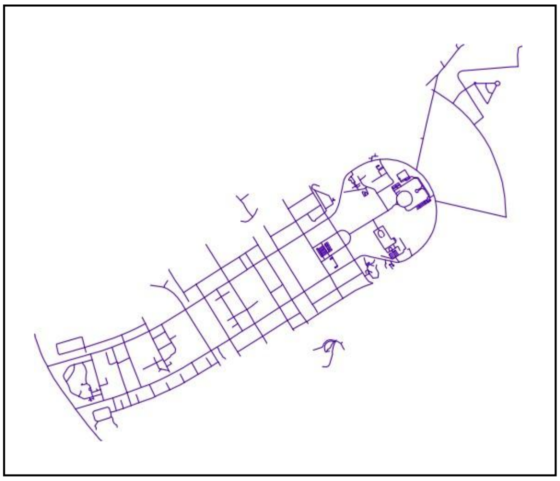

Figure 6: Broken Gridiron Pattern
Community: Central Business District

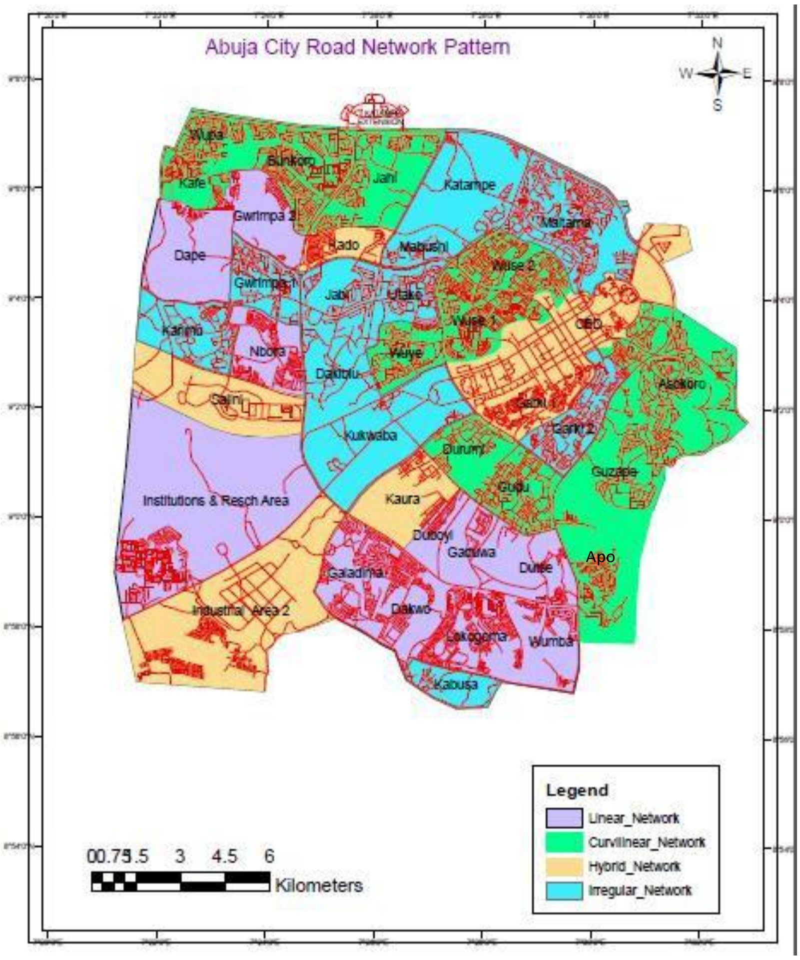

Figure 7: Spatial Distribution of Road Network Pattern in Abuja City

Figure 6 shows the spatial distribution of road network pattern in Abuja city. It clearly denotes that rectilinear network is found in the north western and southern regions as earlier stated. This exists in government layouts such as Federal housing development areas and institutional areas. Curvilinear network covers the greater share of the metropolis specifically located in the extreme north, north central and south eastern regions. Rugged and rolling terrain is supposed to have instigated the development of curvilinear network in most parts of Abuja metropolis. Hybrid network occur in limited areas of newly developed districts. On the map, Broken Gridiron network is merged with hybrid network. This is due to the slight traces of other network patterns observed in the CBD region. Irregular network covers more than one quarter of districts in Abuja city. Physical factors such as hills/streams and planning policy seem to be the main factors that influenced growth of irregular network in the concerned districts.

Road Network Topological Formation

Road network topology is essentially examined so as to understand the extent to which the network achieves transportation function. A well-designed road network helps immensely in providing efficient transport system (X. Wang et al., 2017). GTP index is a recently introduced graph theory measure for detecting whether the formation of a road network is well organized or not (Usui & Asami, 2011). Thus the approach was adopted in this study to ascertain the topological coherence of road network in Abuja city.

Applying the formula as described in section 3.3, GTP index of the forty districts in Abuja municipality were individually calculated. The results obtained is categorized into less, lesser and moderate GTP index values. More than half (52.5%) of the districts have less (0.08 – 0.29) GTP index as shown in Figure 7. Roughly above one third (35%) districts possess lesser (0.3 – 0.39) values of GTP index as indicated in Figure 8. Almost one tenth (12.5%) districts have moderate (0.4 – 0.52) GTP index values as represented in Figure 9.

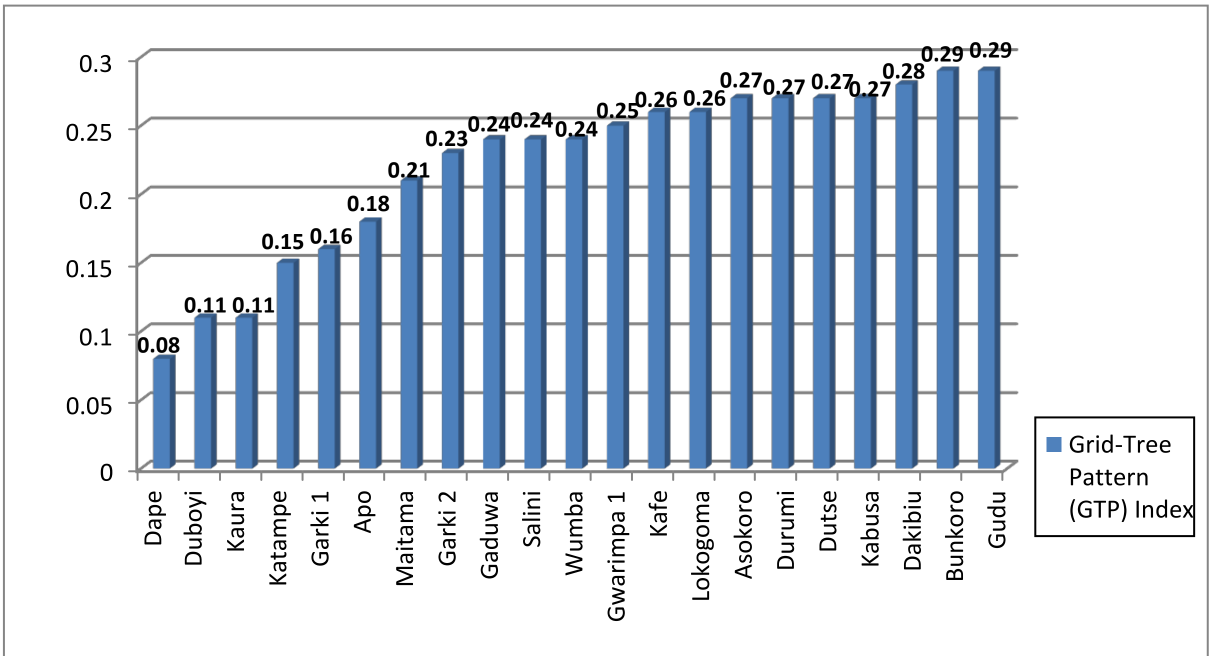

Figure 8: Lowest GTP Score (0.08 – 0.29) Districts

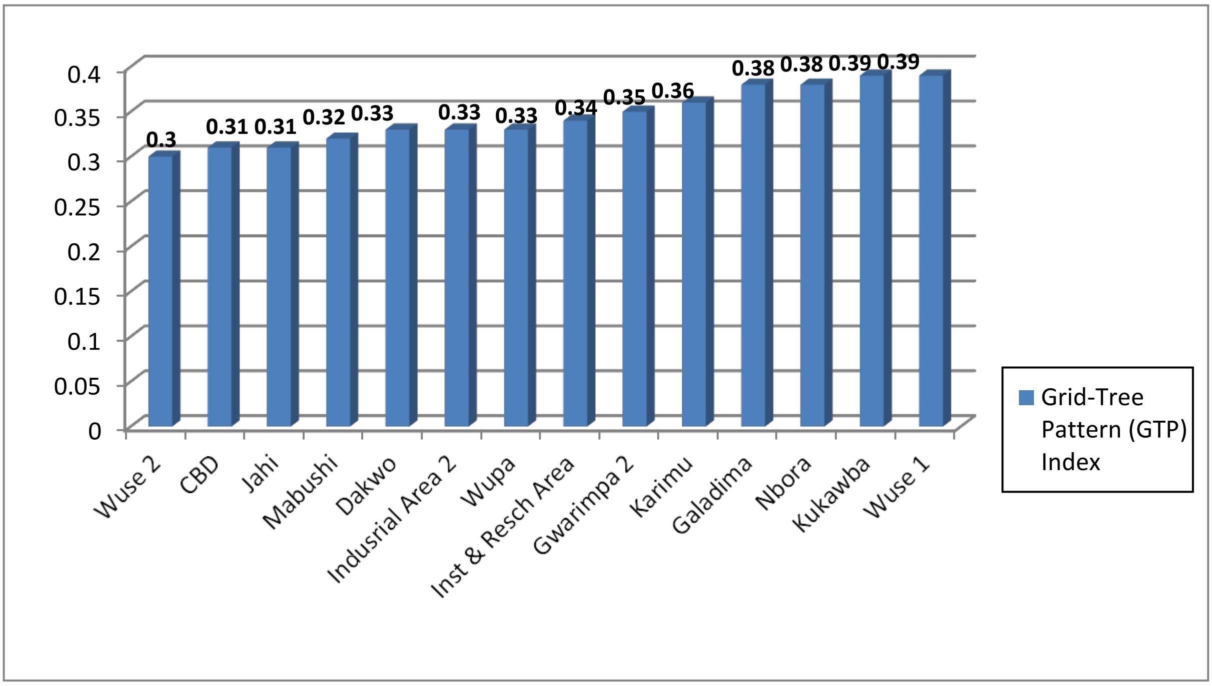

Figure 9: Lower Index Score (0.3 – 0.39) Districts

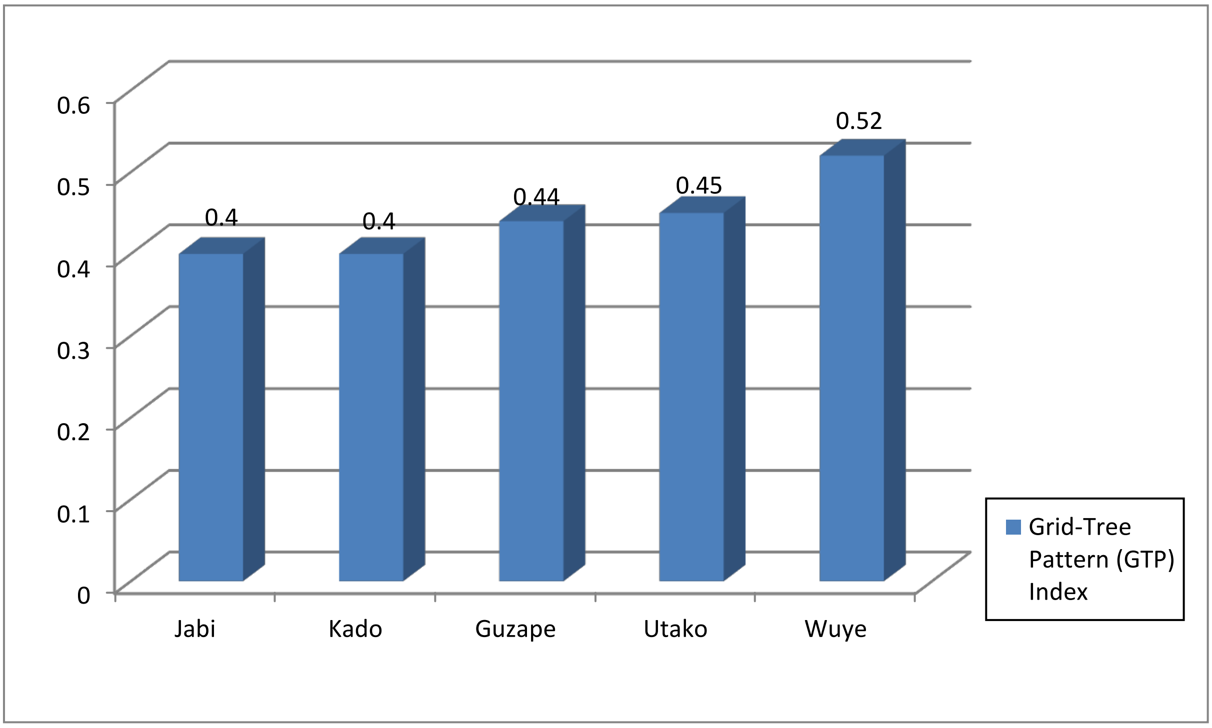

Figure 10: Moderate GTP Index Score (0.4 – 0.52) Districts

The outcome in figures 7, 8 and 9 reveal that the topological coherence of road networks in Abuja municipality range from minimal to moderate standards. Generally, about 38 (95%) of the districts have less than average GTP index values. Only few 2(5%) of the districts have average (0.5) GTP index values. Furthermore, the relationship between graphical pattern and topological coherence of road network was assessed and the result is shown in Figure 10.

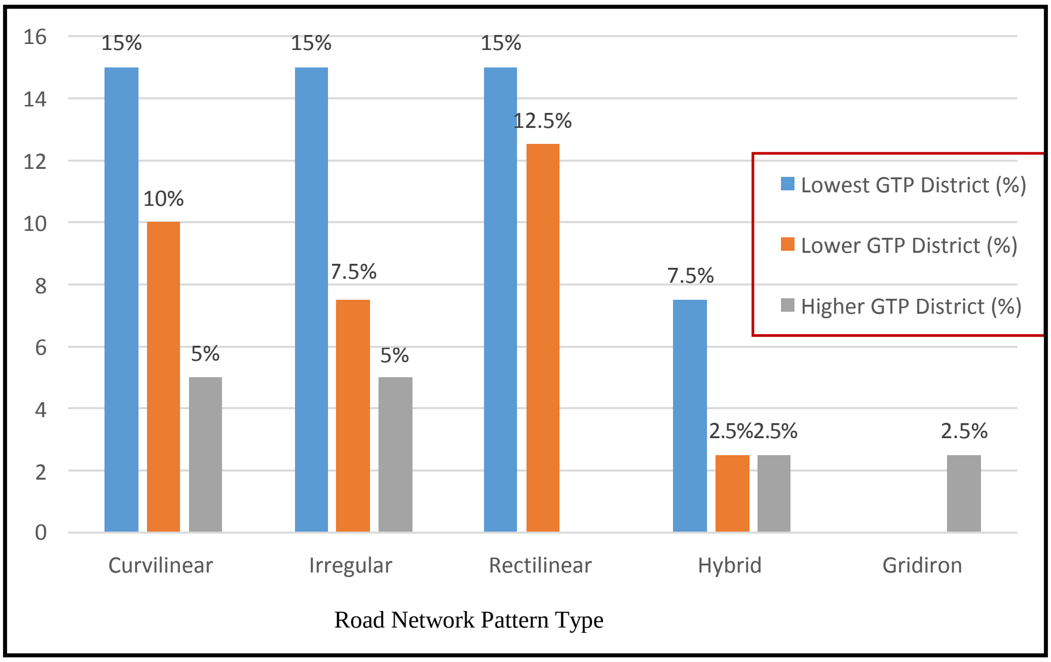

Figure 11: Relationship between Road Network Graphical Pattern and Topological Coherence

The result in Figure 10 reveals that the percentage of districts with least GTP index value is high for curvilinear, irregular and rectilinear network patterns. While the percentage of districts with moderate GTP index values is minimal for all the types of road network patterns. Since higher value of GTP index signifies better arrangement of road network patterns(Usui & Asami, 2011), it implies that the road network pattern in most districts of Abuja Municipality are inadequately coherent. This in turn could be an obstruction for efficient transportation system in the study areas.

4 Conclusion

Road network topology has tremendous influence on the performance of transport system and societal lifestyle in city. Thus, understanding the pattern and characteristics of road networks is a sure means of facilitating better plan for movement of people, goods, and activity-location in urban community. It also provides guidance for decision by developers, planners and policy makers which might result to proficient realization of overall city growth. This stimulated need to analyse road network pattern in the current study. Graphical technique was used to classify road network patterns. It was found that more than two-third districts have pure network pattern types; while the rest of the districts have combination of two or more patterns.

Curvilinear pattern is the most predominant network design in Abuja municipality. The topological coherence of road networks in Abuja municipality range from minimal to moderate standards. The relationship between graphical patterns and topological characteristics show that most of the pattern types have low GTP values, implying inadequate consistency in the network patterns.

Conclusively, the distribution of GTP proportion can be perceived as a useful way to measure the efficiency of road network pattern at city level. Hence this research offers proper insights in the road network design which can guide planners and policy makers in decision for future planning and development of roads in the city. However, the study only treated roads as planar network of real-world setting to understand the relation between graphical pattern and topological coherence, but there lies much more allied subjects to cover. The complexity of road networks could be a better and exciting issue for further discussion. Another fascinating subject for consideration is urban road network evolutional perception. Furthermore, the logical relations between road network measures and city attributes is an essential topic for additional exploration.

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