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Article

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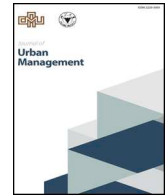
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Research Article

Assessment and modelling of urban road networks using Integrated Graph of Natural Road Network (a GIS-based approach)

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ABSTRACT

Road networks are one of the useful indicators through which sustainability of urban sprawl from an existing urban area and for a proposed new urban development area can be measured. Therefore, it is necessary for transportation engineers and urban planners to conduct various studies in this regard. In this paper, road networks are modelled and assessed using a method called “Integrated Graph of Natural Road Network (IGNRN)” in which the road networks are evaluated and patterned considering the importance of both nodes and road segments, simultaneously. However, the primal graph and the dual graph, by contrast, considers the importance of junctions and road segments, respectively, which are not sufficiently effective ways as far as all the aspects are concerned. For this study, a GIS-based method has been established. The method contains three major steps; 1) Data preparation 2) Modelling/Generation of IGNRN, and; 3) Measuring three classes of centrality, namely, closeness, betweenness and straightness. Finally, for validation and evaluation of methodology the case study of Kandahar City road network is carried out. The outcome of the results show that the method is accurate, helpful, and worth applying to get useful findings.

1. Introduction

In recent years, road transport has increased tremendously in developing countries in many different ways due to several reasons. The most vital reasons include, the high rising levels of private car ownership, rapid economic growth, the expansion of urban areas (urbanization), population boost, and an escalation in the availability of different modes of traffic and their productions. In road transport, road network in urban areas is the back bone of the cities, especially in those countries where other transportation facilities are either not available or limited. Thus, transportation engineers and urban planners tend to improve the efficiency of road networks in every aspect through numerous ways. Spatial modelling of Road network should accurately be performed so that the assessment can give us positive results in terms of travel cost (Jun-qiang, Jing, Qian-wen, & Lin, 2017), sustainability and environment (Rao, Zhang, Xu, & Wang, 2018; Singh, Vinay Shankar Prasad Sinha, & Pahuja, 2018).

In recent years, one of the useful methods through which road networks of an existing urban area and of proposed new urban

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development area is modelled and assessed is graph theory. Graphs not only represent the spatial road transport networks but also all types of transport networks such as land (highway networks and transit networks), air, and water are diagrammatically represented; which have helpful attributes including, speed, travel times, number of lanes, route fares, schedules, headways, etc. Graphs of different forms can be either weighted or unweighted. Weighted graphs represent edges and links along with various corresponding attributes of edges and links attached in them. In contrast, unweighted graphs are only the diagrammatic representation of distinct networks. The weights may correspond to any of the following: geometric-based weights (number of lanes, lane width, cross section elements, speeds, etc.), costs (fuel, toll, etc.), surface condition, weights in regards to the safety, and so on (Aldous & Wilson, 2004; Thomson & Ricardson, 1995).

Traditionally, road networks are modelled with two methods, namely: 1) primal graph, and; 2) dual graph, where in primal graph junctions are illustrated in the form of nodes, and in dual graph roads are illustrated in the form of links. However; in this study the author attempts to model and assess road networks using entirely different methodology called Integrated Graph of Natural Road Network (IGNRN) in which the road networks are evaluated and patterned considering the importance of both nodes and road segments, simultaneously.

In addition, the study proposes three important classes of centrality measurements operate on IGNN and PGNN (Primal Graph of Natural Road Network) that assess and characterize the importance of nodes and edges, and evaluate similarities, differences, and critical locations across the large road networks, as a result of centrality analysis and with the help of GIS-based approach the layouts of the road networks will qualitatively and quantitatively be measured with spatial and statistical illustrations (Dempsey et al., 2010; Porta, Crucitti, & Latora, 2006).

The study contains seven major sections, namely, 1) *introduction*, which has already taken place, 2) *literature review* provides brief literature in regards to the fundamentals of proposed study, 3) *objectives* of the research, 4) *methodology*, which is the most important part of the research that explains all important steps to be carried out to get an accurate output, 5) *case study*, in this section the methodology is validated and evaluated using a case example of Kandahar City Road Network, 6) *results and discussion* explain both the outcome of proposed methodology and findings within the case study, and finally; 7) *conclusion and further research*. All the sections are explored in details as below.

2. Literature review

2.1. Representation of spatial road network by graph theory

A topological spatial structure of a network, most of the times, is represented by a graph which is composed of lines and points, where lines can also be termed as links or edges and points as nodes or vertices (Aldous & Wilson, 2004). Essentially, a graph $G = (V, L)$ is a combination of two sets; a set V of N nodes and a set L of E links connecting the corresponding nodes. The adjacency matrix A ($N \times N$) is the first important part to be considered prior analysis and calculations in which $a_{ij} = 1$. If there is a link between vertices i and j , otherwise, $a_{ij} = 0$. However, if the weighted graph is to be considered then $a_{ij} = w_{ij}$ in which w_{ij} represents any quantity that flows between i and j (Barthelemy, 2018). In modelling spatial road networks, in addition to nodes and edges, the edges are usually qualified by adding weights that encode information like the length of the road segment that the edge denotes. Connectivity and shortest paths in spatial networks have extensively been studied using graphs (Gröger & George, 2012). Though, truthfully a road network is formed under natural conditions, social conditions and local construction conditions in order to meet the various requirements of transportation; it has no uniform format of representation (Hohai & Watanabe, 2015). Similarly, a route or path is a sequence of connected edges sharing a vertex. A graph is connected if a path can be found linking any pair of its vertices. A cycle is a path which leads from a vertex to the same vertex. Clearly, graphs can represent the topology and spatial structure of a road networks in a natural way; with vertices denote intersections, dead-ends and locations of interest on the roads such as settlements, and edges corresponding to road segments between such points (Thomson & Ricardson, 1995). Two vertices/nodes representing a link or edge may or may not be distinct. In case the nodes are the same defining a link, then this link is called a loop and is denoted by (i, i) , or if the nodes are distinct such as i and j defining a link, then the link is denoted by (i, j) (Potts & Oliver, 1972).

It is important to note that a transport network represent either a permanent track, for instance, roads, rails, and canals, or a scheduled service (e.g. transit, train, airline). The connectivity and arrangement of a network is known as its topology. Thus, road transport networks have various specific topologies denoting their structures in terms of edges, vertices, paths, and cycles (Rodrigue, Comtois, & Slack, 2006).

Traditionally, in most of the literatures road networks are represented and modelled with two methods, such as primal graph (Crucitti, Latora, & Porta, 2006) and dual graph method (Demsar, Spatenkova, & Virrantaus, 2008). Where in primal graph junctions are illustrated by nodes and roads are illustrated by edges, in contrast, in dual graph modelling roads are represented by nodes and junctions are represented by edges. Furthermore, in a research study by Jiang, Zhao, and Yin (2008); analyses of road networks' various topologies were carried out to both urban and nationwide extent. The study used Annual Average Daily Traffic (AADT) and Global Positioning System (GPS) data to figure out the differences between line-based and point-based approaches of road networks.

2.2. Centrality

Centrality measurements play an important role in modelling and evaluating of various types of networks. The significance of nodes and links is effectively determined with centrality in both directed and undirected graphs of road networks. It is important to note that in a directed graph, in addition to nodes and links, the direction of route is also indicated. On the other hand, in an

undirected graph G ; nodes and links denote junctions and road segments, respectively, where $G = (V, L)$, in which V is a set of vertices $\{v_1, v_2, \dots, v_n\}$, and L is a collection of lines $\{l_1, l_2, \dots, l_m\}$, see (Hohai & Watanabe, 2015) for further details with regards to directed and undirected graphs.

Centrality measures are most likely used to determine the significance of nodes within a network and are studied in two forms: 1) local centrality, and; 2) global centrality. Local centrality, as the name suggests clearly, is a local measure for a particular network considering neighbors of given node within a given radius. Global centrality, on the other hand, is a general measure which considers all nodes connected by paths. In other words, local centrality uses a limited radius for measurement, whereas, global centrality takes under account the entire road network of a given region for the purpose of capturing information in a global manner (Yu, 2017; Adali, Lu, & Magdon-Ismail, 2014). In this study, closeness, betweenness, and straightness centralities are used which are briefly explained as follows:

Closeness Centrality quantifies how close a node i is to all other nodes within a network as means of shortest paths., Or one can say if a node appears to be in the middle and not too far from the center, it results a high value of closeness centrality, and its normalized value is defined as the inverse of the average length of the shortest paths, see (Ghanbari, Jalili, & Yu, 2017; Lin & Ban, 2017) Both non-normalized and normalized values are computed with the following equations:

$$C_i^c = \frac{1}{\sum_{j=1, j \neq i}^N d_{ij}} \quad (\text{Non - normalized}) \tag{1}$$

$$C_i^c = \frac{N-1}{\sum_{j=1, j \neq i}^N d_{ij}} \quad (\text{Normalized}) \tag{2}$$

Where, C_i^c is closeness centrality of node i , N is the total number of nodes in the network, and d_{ij} is the shortest path distance between i and j .

Betweenness Centrality, C^B , is another important measure based on the shortest paths. Basically, in a connected graph of a road network, one can observe several pairs of origins and destinations within the network which has at least one shortest path between each pair. Hence, betweenness centrality of a node quantifies the number of shortest paths the node is part of and pass through this node (Yu, 2017; Adali et al., 2014; Sevtsuk & Mekonnen, 2012). The different forms can be computed with following mathematical equations:

$$C_i^B = \sum_{j=1, k=1, j \neq k \neq i}^N \frac{n_{jk}(i)}{n_{jk}} \quad (\text{Non - normalized}) \tag{3}$$

$$C_i^B = \frac{1}{(N-1)(N-2)} \sum_{j=1, k=1, j \neq k \neq i}^N \frac{n_{jk}(i)}{n_{jk}} \quad (\text{normalized for directed graph}) \tag{4}$$

$$C_i^B = \frac{2}{(N-1)(N-2)} \sum_{j=1, k=1, j \neq k \neq i}^N \frac{n_{jk}(i)}{n_{jk}} \quad (\text{normalized for undirected graph}) \tag{5}$$

Where, n_{jk} represents the number of network shortest paths connecting nodes j and k , respectively, and $n_{jk}(i)$ represents the number of shortest paths that pass-through node i .

Straightness centrality, C^S , of node i measures how much closer are the network shortest paths between node i and other nodes to the Euclidean distances (straight distances of lines) between the same nodes within a network. This means that the deviation of the shortest paths from Euclidean distances between node i and all the other nodes within a network is calculated (Crucitti et al., 2006). The equation used for calculation is as below:

$$C_i^s = \sum_{j=1, j \neq i}^N \frac{d_{ij}^{Eucl}}{d_{ij}} \quad (\text{non - normalized}) \tag{6}$$

$$C_i^s = \frac{1}{N-1} \sum_{j=1, j \neq i}^N \frac{d_{ij}^{Eucl}}{d_{ij}} \quad (\text{normalized}) \tag{7}$$

Where, d_{ij}^{Eucl} is Euclidean distance (straight-line distance) between node i and j , d_{ij} is the shortest path distance of the same nodes. As shown in equations $\frac{1}{N-1}$ it is used to adopting normalization (Vragović, Louis, & Díaz-Guilera, 2005).

The literatures revealed that there is a lack of research-based methodology through which the natural road networks can be evaluated considering the importance of both nodes (Junctions) and links (road segments) at the same time. Besides, in this study an attempt is made to measure centralities of undirected graphs by taking geometric edge-based weight into consideration.

3. Objectives

The main objectives of this study are listed below:

1. Assessing the efficiency of road network based on centrality measures with respect to both PGNRN and IGNRN, and performing

statistical and spatial comparison of centrality measures between them.

2. Comparing the obtained results of the centrality measurements with the attribute data of the roads' functional classification, and inferring whether centrality measurements provide some relevant information pertaining to the functional classification of roads.
3. Identifying the critical locations based on IGNRN and PGNRN with respect to the various centrality highest measures, and making suggestions based on the findings for creating new policies.

4. Methodology

4.1. Data collection, capture, and preparation

Although the graph modelling and generation has been performed in a plethora of ways, the methodology documented for this study is entirely different from them. Before the generation and displaying the graph at the zonal and city level road networks it is imperative to collect, capture and prepare some data that would be necessitous for the study. The first dataset needed for the integrated graph modelling should be in the form of shapefiles of natural road networks (Sevtsuk & Mekonnen, 2012). The shapefiles must contain georeferenced centreline features of road network. Shapefile for the area of interest can be either manually digitized (Docan, 2016; Bajjali, 2018; Ormsby, Napoleon, Burke, Groessl, & Feaster, 2010; Toms, 2015) or obtained in form of OpenStreetMap (OSM) data depending upon the level of study. In order to research in a disaggregate manner however, it is always recommended to collect data based on manual digitizing. Although it is a time-consuming process, by doing so, each and every single link of assorted kinds of streets/roads can be captured.

Capturing and digitizing data based on most recent high-resolution satellite and/or aerial imageries is preferred. Using Google Earth images for digitizing is also an option but keeping in mind that the possibility of the imageries acquired from Google Earth may not be the most recent or updated satellite images for some regions especially from a few developing countries. The flowchart of the methodology for data collection, capture and preparation is shown in the figure below.

4.2. Primal Graph Modelling/Generation

The methodology proposed in this paper for the generation and modelling of PGNRN (Primal Graph of Natural Road Network) is based on ArcGIS Desktop applications including ArcMap, ArcToolbox, ArcCatalog, ArcGIS Network Analyst Extension. The first step for modelling a primal graph is to getting the most recent natural road network into a shapefile based on centreline features using the methodology explained in Fig. 1. After fixing digitizing errors and finalizing both features and attribute data of relevant road network shapefile, the second step is taken. In the second step, network datasets using shapefile created in step one need to be crafted, see (Bajjali, 2018; Toms, 2015). It is worth mentioning that while using ArcGIS Network Analyst Extension; shapefile which has the line feature has to be imported to feature dataset of geodatabase in order to enable creating network datasets. The created network dataset consists of three distinct files namely 1) network dataset file of point features (junctions) 2) network dataset file of edges (links), and; 3) original file of line features having all captured attribute data. The PGNRN represents junctions as nodes and links or roads as edges, hence in the third step, network dataset feature file of junctions should be converted to shapefile using conversion tools of ArcGIS, see (Docan, 2016; Bajjali, 2018; Ormsby et al., 2010; Toms, 2015). As a result, the PGNRN is modelled for further analysis.

4.3. Integrated Graph Modelling/Generation

In graph theory, centralities of various types are measured based on vertices (nodes). Consequently, it depends on what the researchers intend to represent as nodes in the graph. For instance, in PGNRN; nodes represent junctions (cross roads), and edges represent segments of roads within a network. In other words, only the weight of junctions is considered for measuring centrality. On

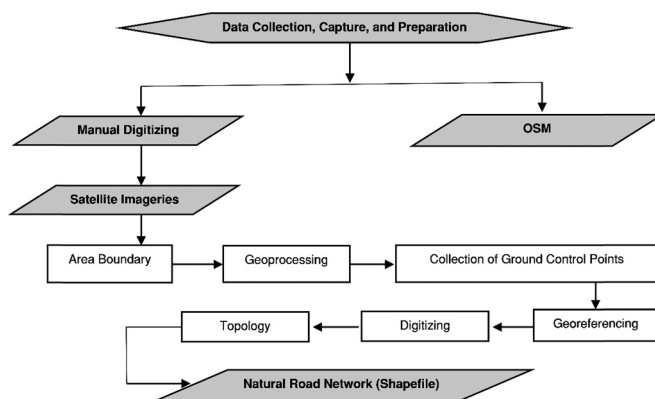


Fig. 1. Flowchart of methodology for data collection.



Fig. 2. Different ways of representing road transport network (a) the natural road network map (b) Primal Graph of Natural Road network (c) the Integrated Graph of Natural Road Network.

the other hand, in a dual graph of road network nodes illustrate roads and edges illustrate junctions as a means of giving importance to roads' segments. However, a different approach of graph theory is required to simultaneously assess the importance of both roads and junctions within a network. In this work, a method that incorporates the importance of roads and junctions to model a graph named "Integrated Graph of Natural Road Network" is proposed. The IGNRN integrates three major features as follows:

1. Nodes feature representing junctions.
2. Nodes feature representing road segments.
3. Network dataset file of edges in which lines represent centerline of roads.

A series of processes for creating each of the aforementioned feature is executed. In the first step the Network Analyst Extension of ArcGIS has been used in order to get; "nodes feature representing junctions" and "network dataset file of edges in which lines represent centerline of roads". In the second step, "nodes feature representing road segments" are generated. This feature is created using "feature to point" tool of ArcToolbox. In the third step, the file named "nodes feature representing junctions" which is a feature dataset is required to be converted to shapefile which has a point feature using "feature class to shapefile" conversion tool of ArcToolbox.

In the final step, shapefiles obtained in step two and three are merged to get a single file of point feature, where some nodes represent junctions and other represent links of road network segments (Figs. 2 and 4).

4.4. Centrality measures

In our research we study three centrality indices both on the global and the local level, including 1) closeness centrality, 2) betweenness centrality, and; 3) straightness centrality. Most of the previously conducted researches did not take the geometric weights of node and links into account, however, for further accuracy, it is important to consider the geometric weights of either links or nodes or both in calculation.

4.4.1. Geometric edge-based weights

An attempt is made to take the weights of links into consideration. In edge-based geometric weight the following attributes are considered:

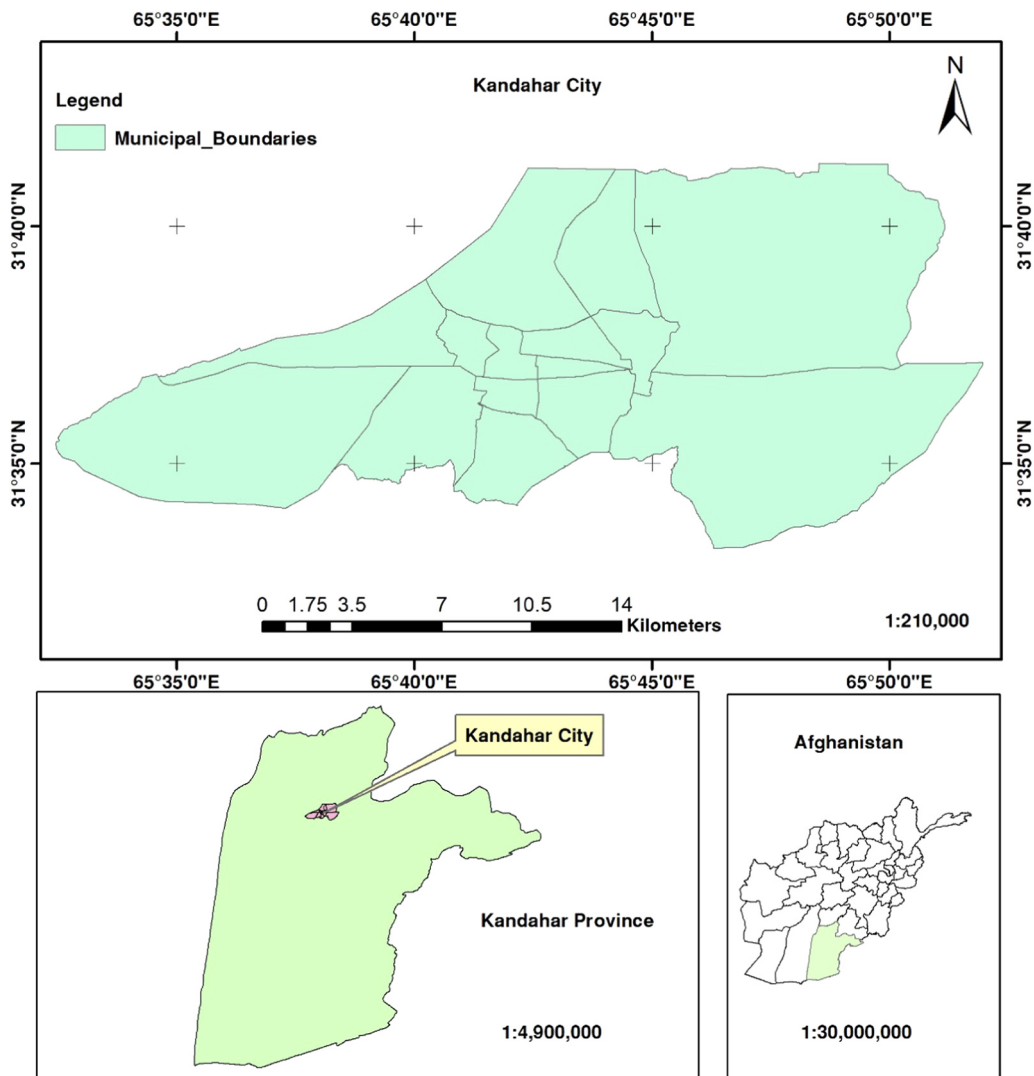


Fig. 3. Study area.

1. Speed limit of road segment with respect to the functional classification.
2. Width of roads with respect to number of lanes and average width of each lane.

For instance, a road segment is in the category of a main road which has two lanes. The weight of the link is calculated as follows:

$$Weight = \frac{Speed\ limit \times 5}{18} + (Number\ of\ lanes \times land\ width)Weight = \frac{70 \times 5}{18} + (2 \times 3.5) = 26.44 \tag{8}$$

In Eq. 8, speed is in kmph (km/h), the fraction 5/18 is taken for the purpose of changing kmph to m/s, and the standard lane width is 3.5 m on an average basis. As a result, high values of weights indicate most important road segments within the road network which have high speed limits and wide carriageways. Taking weights of the nodes (nodes that represent road segments) into consideration, the equations of centrality indices used for normalized measures are explained as follows (Liu, Wei, Jiao, & Wang, 2015).

4.4.2. Closeness centrality

The weighted normalized closeness centrality is computed by the following equation:

$$C_i^c = \frac{\sum_{j=1, j \neq i}^N [W(j) - 1]}{\sum_{j=1, j \neq i}^N [d_{ij} \times W(j)]} \tag{9}$$

Where, C_i^c is closeness centrality of node i , N is the total number of nodes in the network, and d_{ij} is the shortest path distance between

i and j , $W(j)$ is weight of the node that represents the corresponding link.

4.4.3. *Betweenness centrality*

The weighted normalized betweenness centrality for the directed graph is computed by the following equation:

$$C_i^B = \frac{1}{\left[\sum_{j=1, j \neq i}^N W(j) - 1 \right] \left[\sum_{j=1, j \neq i}^N W(j) - 2 \right]} \sum_{j=1, k=1, j \neq k \neq i}^N \left[\frac{n_{jk}(i)}{n_{jk}} \times W(j) \right] \tag{10}$$

And for the undirected graph:

$$C_i^B = \frac{2}{\left[\sum_{j=1, j \neq i}^N W(j) - 1 \right] \left[\sum_{j=1, j \neq i}^N W(j) - 2 \right]} \sum_{j=1, k=1, j \neq k \neq i}^N \left[\frac{n_{jk}(i)}{n_{jk}} \times W(j) \right] \tag{11}$$

Where, n_{jk} represents the number of network shortest paths connecting nodes j and k , respectively, and $n_{jk}(i)$ represents the number of shortest paths that pass-through node i , $W(j)$ is weight of the node that represents the corresponding link.

4.4.4. *Straightness centrality*

The weighted normalized betweenness centrality is computed by the following equation:

$$C_i^S = \frac{1}{\left[\sum_{j=1, j \neq i}^N W(j) - 1 \right]} \sum_{j=1, k=1, j \neq k \neq i}^N \left[\frac{d_{ij}^{Eucl}}{d_{ij}} \times W(j) \right] \tag{12}$$

Where, d_{ij}^{Eucl} is Euclidean distance (straight-line distance) between node i and j , d_{ij} is shortest path distance of the same nodes. The list of global and local centrality indices that are measured in this work both based on PGNRN and IGNRN is given in Table 1. It is important to note that the Urban Network Analysis (UNA) a toolbox of ArcGIS 10 created by Sevtsuk and Mekonnen (2012) is used, and the results are spatially illustrated using ArcGIS software program.

5. Case study

The purpose of this experimental case study is to validate the methodology proposed for assessing and modelling of road networks based on IGNRN (*Integrated Graph of Natural Road Network*). Thus, the case of Kandahar’s city road map which includes all types of official roads (excluding substandard traditional unpaved narrow streets) have been considered for this study. Kandahar is the second largest city in Afghanistan with the GPS coordinates of 31° 36’ 47.9520’’ N and 65° 42’ 36.4680’’ E. The city is located in the southern region of Afghanistan approximately 457 km away from capital city of Kabul, which is spread over 226 km² area. The road network of the study area is digitized based on the flowchart of the methodology shown in Fig. 1. The total length of the official natural road network is 1393 km which has 9142 links and 6662 junctions, as shown in the Fig. 4 (b).

After the digitizing of the centerline feature of the road network, the second step is to generate the primal graph and the integrated graph of the natural road network as per the methodology explained in section 4.2 and 4.3, respectively. The PGNRN contains 9142 links and 6662 junctions, as shown in Fig. 4 (b). Whereas, the IGNRN consists of 15,805 nodes in which 6662 green nodes represent junctions and 9142 red nodes represent the links of road segments as shown in Fig. 4 (a).

Table 1
List of the Centrality Measures (a) Integrated Graph Centralities (b) Primal Graph Centralities.

(a) Integrated Graph		Local Centrality	
Global Centrality			
Measure	Name	Measure	Name
ccc_i	City level Closeness Centrality based on Integrated Graph	dcc_i	District level Closeness Centrality based on Integrated Graph
cbc_i	City level Betweenness Centrality based on Integrated Graph	dbc_i	District level Betweenness Centrality based on Integrated Graph
csc_i	City level Straightness Centrality based on Integrated Graph	dsc_i	District level Straightness Centrality based on Integrated Graph
(b) Primal Graph		Local Centrality	
Global Centrality			
Measure	Name	Measure	Name
ccc_p	City level Closeness Centrality based on Primal Graph	dcc_p	District level Closeness Centrality based on Primal Graph
cbc_p	City level Betweenness Centrality based on Primal Graph	dbc_p	District level Betweenness Centrality based on Primal Graph
csc_p	City level Straightness Centrality based on Primal Graph	dsc_p	District level Straightness Centrality based on Primal Graph

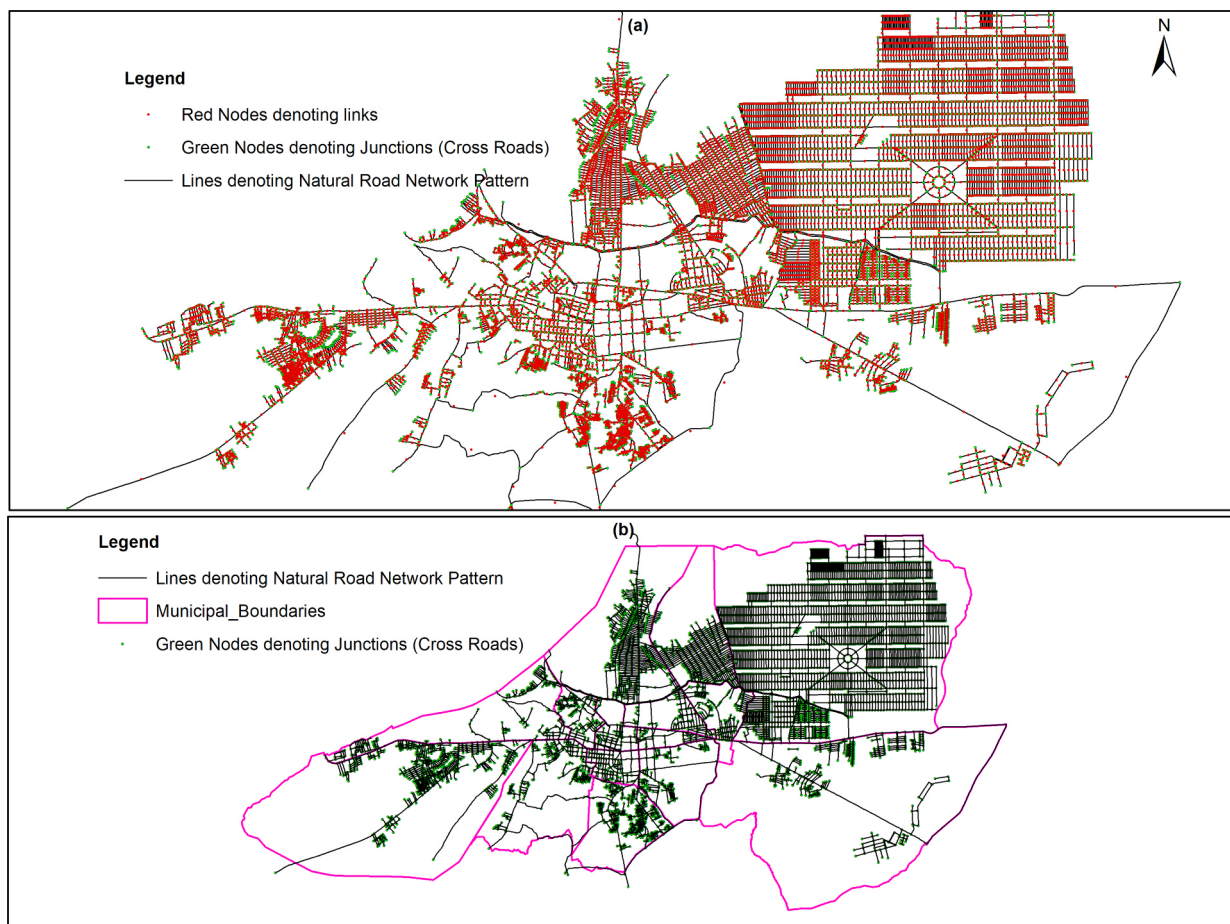


Fig. 4. Road Network models of Kandahar City (a) Integrated Graph model of Natural Road Network (b) Primal Graph Model of Natural Road Network.

5.1. Spatial distribution of centralities based on IGNRN

As shown in Table 1, the author attempts to measure the three major centralities in turn; closeness centrality, betweenness centrality and straightness centrality with respect to both global level (city level) and local level (municipal district level). In the global manner the centralities are measured considering the entire road network of the city as a single road network (see Fig. 5), whereas, at the local level the centralities are individually measured with respect to the municipal districts of the city, which means the road network of the city is divided into 15 subnetworks of 15 different zones where centralities of each zone are separately measured (see Fig. 6). As discussed earlier, with IGNRN method, this study attempts to take the geometric edge-based weights in consideration based on Eq. 8 while computing centralities.

5.2. Spatial distribution of centralities based on PGNRN

In this work, the author also takes global centrality measures based on PGNRN in order to spatially and statistically compare the results between IGNRN and PGNRN. In the primal graph method, similar to the IGNRN; the centralities are measured using the real metric distances between nodes. However, only the significance of junctions (cross roads) has been considered, thus, the importance of road segments and their geometric based weights are neglected in the primal graph centrality calculations, see Fig. 7 for spatial illustration of various centralities based on Primal Graph of Natural Road Network (PGNRN). The edge-based illustration cannot be directly applied in PGNRN, since centrality measures only consider junctions. So, in this work, the start and the end point of the corresponding edge is spatially joined allowing edges as a target feature. Afterwards, edges are illustrated based on the average centrality scores of the start and end points.

6. Results and discussion

The global closeness centrality statistical and spatial distribution IGNRN-based reveals the most and least accessible areas within

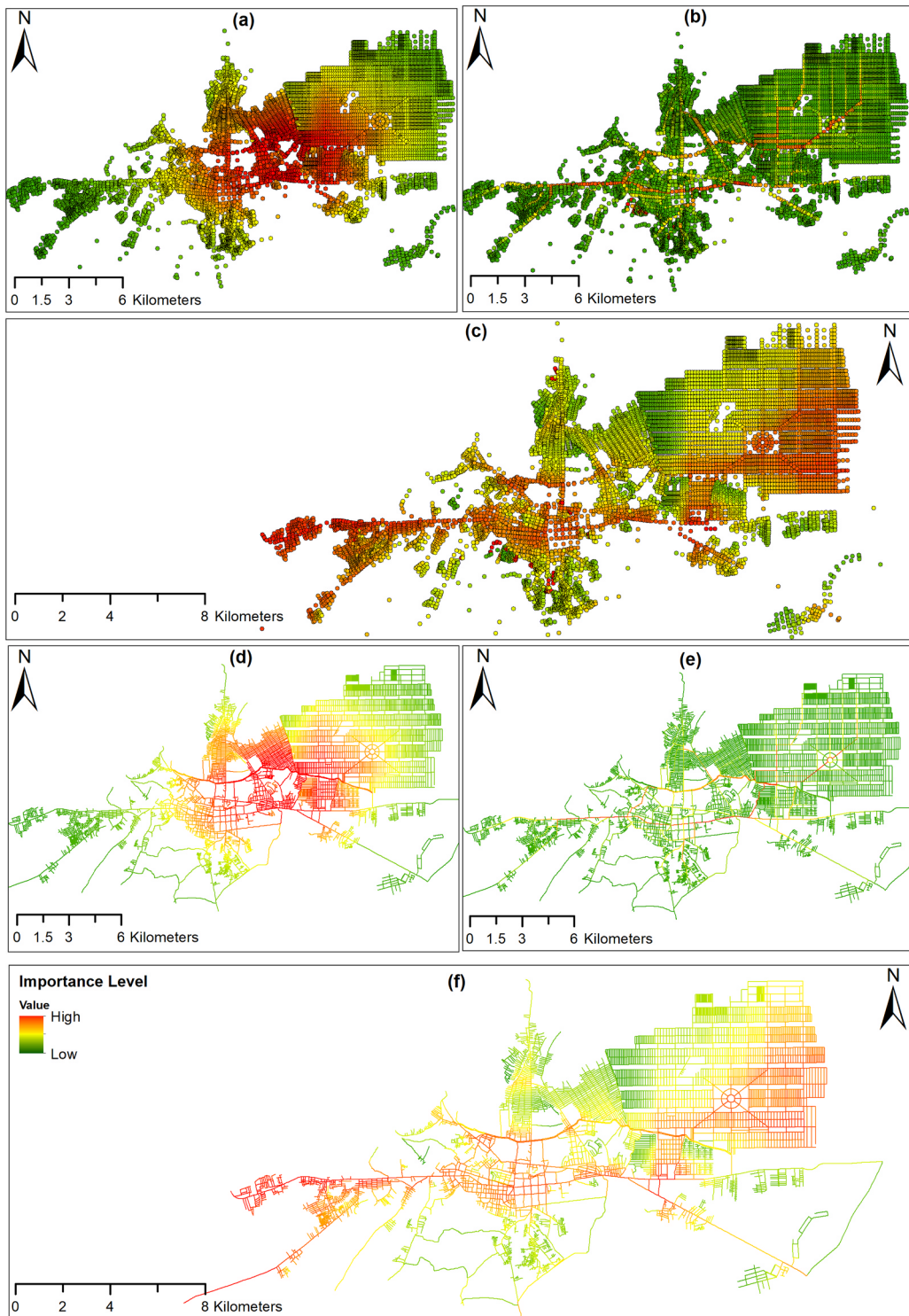


Fig. 5. Spatial illustration of Global Centrality measures based on Integrated Graph of Natural Road Network (a) ccc , node-based (b) cbc , node-based (c) csc , node-based (d) ccc , edge-based (e) cbc , edge-based (f) csc , edge-based (Refer to Table 1 for the details of abbreviations).

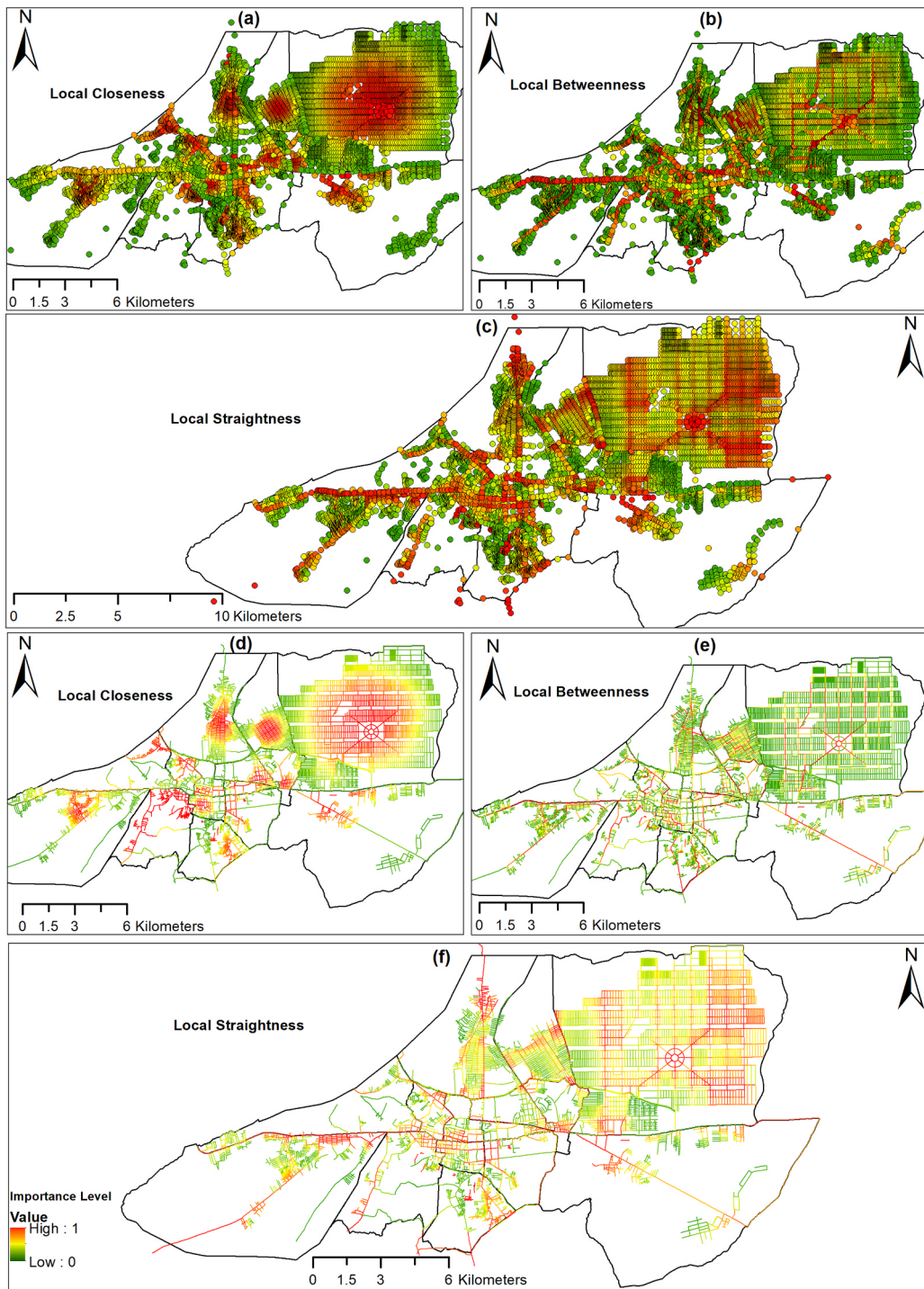


Fig. 6. Spatial illustration of Local Centrality measures (municipal district level centralities) based on Integrated Graph of Natural Road Network (a) dcc_i node-based (b) dbc_i node-based (c) dsc_i node-based (d) dcc_i edge-based (e) dbc_i edge-based (f) dsc_i edge-based (Refer to Table 1 for the details of abbreviations).

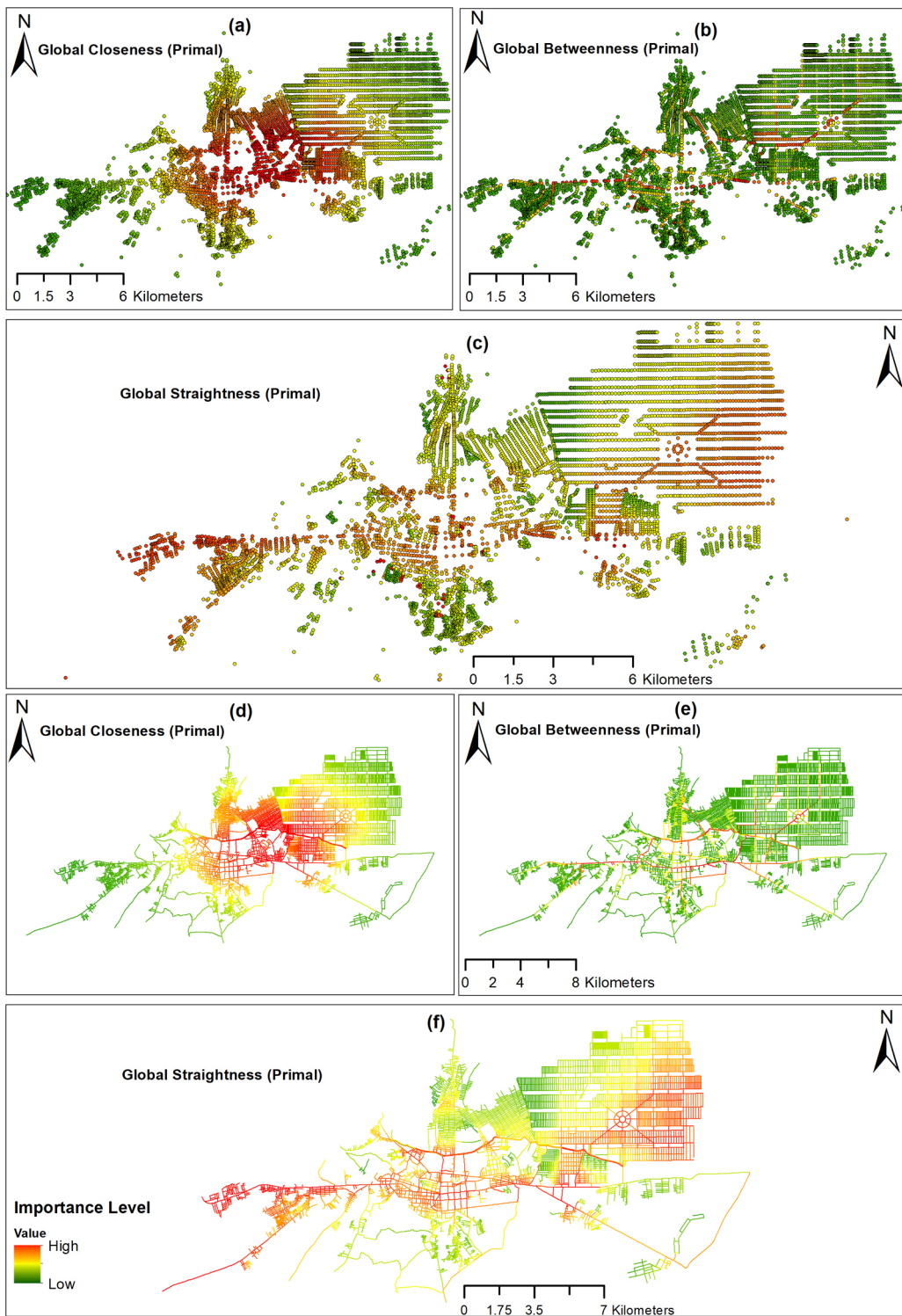


Fig. 7. Spatial illustration of Global Centrality measures based on Primal Graph of Natural Road Network (a) ccc_p node-based (b) cbc_p node-based (c) csc_p node-based (d) ccc_p edge-based (e) cbc_p edge-based (f) csc_p edge-based (Refer to Table 1 for the details of abbreviations).

Table 2
Mean and Standard Deviations of various global centrality measures.

Measure	IGNRN ^a		PGNRN		Weighted Edge-Based	
	Mean	SD	Mean	SD	Mean	SD
ccc ($\times 10^{-5}$)	10.007	1.965	9.839	1.902	9.898	2.262
cbc ($\times 10^{-4}$)	87.799	258.019	105.302	285.229	129.104	327.581
csc ^b	0.759	0.045	0.753	0.044	0.790	0.022

^a IGNRN = Integrated Graph of Natural Road Network, PGNRN = Primal Graph of Natural Road Network.

^b Refer to Table 1 for the further details of abbreviations listed in this table.

Table 3
Mean and SDs of local centrality measures based on IGNRN.

Measure	dcc ($\times 10^{-5}$)		dcc ($\times 10^{-4}$)		dsc	
	Mean	SD	Mean	SD	Mean	SD
District 1	130.649	551.895	667.973	850.228	0.679	0.082
District 2	93.795	18.249	484.831	510.372	0.752	0.056
District 3	133.483	480.815	747.432	1,231.635	0.637	0.085
District 4	69.797	9.101	905.036	914.908	0.808	0.077
District 5	18.670	3.611	438.684	931.011	0.594	0.089
District 6	81.437	74.951	666.462	994.546	0.671	0.075
District 7	35.847	9.412	340.489	506.701	0.729	0.062
District 8	43.718	36.402	1234.693	1702.837	0.803	0.104
District 9	47.588	47.619	382.430	553.834	0.734	0.097
District 10	48.625	6.450	661.998	763.551	0.650	0.081
District 11	19.823	3.170	126.633	224.208	0.782	0.044
District 12	59.472	12.135	303.591	325.563	0.786	0.035
District 13	56.736	10.286	614.299	951.319	0.578	0.088
District 14	61.579	11.825	634.154	566.543	0.790	0.078
District 15	56.263	116.816	407.668	818.489	0.529	0.104

the city with respect to the official urban road network considering the importance of junctions (cross roads), importance of road segments and their relevant geometric-based weights. From mean value (10×10^{-5}), standard deviation (1.965×10^{-5}), and highest value (13.784×10^{-5}) of global closeness centrality of the Kandahar City; it can be inferred that the city presents even distribution in terms of global closeness. Thus, the road network of the city can be called satisfactory in a global manner, as most of the highly important facilities are located within the red zone of spatial distribution (see Fig. 5 a and d). Similarly, on an average basis, the spatial and statistical distribution of local level closeness centrality values within various municipal districts of Kandahar City indicates an even distribution (Fig. 6 a and d), although some high variations between means, standard deviations and highest values have been noticed (see Table 3).

The results obtained from betweenness centrality measures based on IGNRN have revealed a few interesting facts in the road network of the Kandahar City. Especially for the road segments including geometric-based weights for the roads of the whole network, as most of the highest betweenness values are observed alongside the most important avenue of the city passing directly to the city center that contains dual carriageway and has four traffic lanes per each carriageway. In spatial distribution the dark red color mostly indicates main roads that contains dual carriageways, light red to yellow colors indicate main road of having single carriageway, light yellow to light green colors indicate secondary main roads, and light green to dark green colors indicate residential streets within the road network (see Fig. 5 b and e). It is worth mentioning that global betweenness is a helpful measure of centrality in identification of the major roads, such as arterials, national highways, sub arterials, etc. However, local betweenness measures can better identify secondary main roads, collectors and residential streets as illustrated in Fig. 6(b) and (e). Nevertheless, further research on a detailed modified methodology is needed to functionally classify the roads based on IGNRN (Integrated Graph of Natural Road Network). Apart from this, there are some substantial official unpaved roads in the network which play important bridging roles in terms of betweenness, hence, the municipality and Ministry of Public Works should put them all on high priority to be paved.

The straightness centrality from the perspective of road network originates from the idea that how straight the network shortest paths between origins and destinations are in comparison to the Euclidean distance. Consequently, it can be proven as a comprehensive indicator for determining the road network efficiency. The detailed spatial and statistical results both in the local and the global manner show that Kandahar City official road network can be called an efficient network in terms of straightness centrality, as global straightness centrality normalized values vary from 0.860 to 0.543 having 0.759 mean value and 0.045 standard deviation value. It is important to note that the road network considered as a case study for this paper contains official road network of the city, whereas, old cultural substandard unpaved narrow streets, most of which are used for residential purpose have irregular forms and are erased from the network, means, the road network of Kandahar City can substantially be enhanced in terms of sustainable development if the old cultural substandard unpaved narrow streets existing in the city are removed (as shown in Fig. 8).

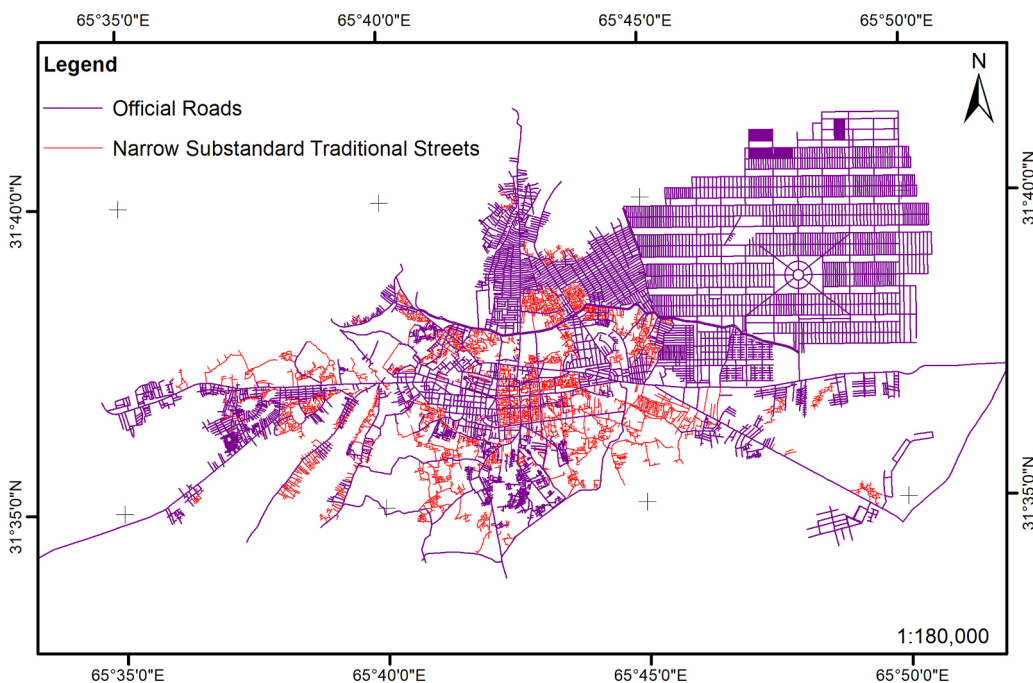


Fig. 8. Illustration of official vs narrow substandard roads in Kandahar City.

More importantly, after modelling road networks based on PGNRN and IGNRN, the following findings were noticed:

- The detailed statistical results obtained from PGNRN and IGNRN show that normalized values of centralities (especially for junctions) in both graphs are quite close to each other as shown in Tables 2–6.
- The nonnormalized values are entirely different from each other, which means, values based on IGNRN are higher than the values based on PGNRN. It is recommended to take the IGNRN in consideration while determining the critical locations alongside the road segments, and use weighted PGNRN (node-based weights) to determine the critical junctions within a road network. The weights of the nodes can be calculated by adding the weights of all links/edges that are directly connected to them as computed in Liu et al. (2015).
- Essentially if the weights of either links or roads are neglected, the normalized values of centrality measures computed based on the integrated graph used could be lower compared with the values obtained from a primal graph. Since the number of nodes in an integrated graph is greater than the number of nodes in a primal graph, as values in centrality measures are normalized based on node number. However, this phenomenon is not applicable when weights of edges are considered and the centralities values would highly be dependent on the weights of the links/nodes.

7. Conclusion and further research

7.1. Conclusion

In this work, the author concludes that centralities results obtained from the IGNRN have provided comprehensive statistical and spatial information regarding the important classes of centralities measures by which road network can significantly be modelled and evaluated. All in all, the following conclusions are noticed:

1. One of the crucial steps considered in this study is that in addition to the importance of road junctions, the importance of road segments and their geometric-based weights have also been taken into account. Hence, identification of critical locations and importance of road segments and junctions based on IGNRN with respect to the various centrality measures would be more accurate compared with a primal or a dual graph, as a primal graph considers only the importance of junctions (cross roads) and a dual graph emphasizes on only the importance of road segments.
2. A road network assessment and modelling based on IGNRN may lead us to accurate and descriptive information because of which we can make necessary plans and decisions. The results revealed that the weight of the edges is very beneficial for the betweenness and straightness centralities. On the other hand, the weights of nodes indicating junctions and specific locations can be of more significance for the accuracy of closeness centrality.
3. The study revealed that the method can be used as a helpful tool in identification of road network functional hierarchy where global betweenness is a helpful measure of centrality in identification of the major roads, such as arterials, national highways, sub

Table 4
Highest values of Centralities and identification of their locations in IGNRN.

Measure	IGNRN	Relevant other centralities		Location
		Closeness ($\times 10^{-5}$)	Betweenness ($\times 10^{-4}$)	
Highest ecc ($\times 10^{-5}$)	13.784	13.784	1064.160	The point indicates junctions (Cross road) located at the share Boundary of District 10 and 12.
Highest cbc ($\times 10^{-4}$)	2670.880	13.609	2670.880	The point is junction, indicating exactly the intersection point of four Municipal districts, including District 3, District 4, District 10, and District 14.
Highest csc	0.860	5.614	7.104	The point indicates road segment alongside Kandahar-Herat Highway near to "Bagh-e-Pool" located at the shared boundary of District 7 and District 8.

Table 5
Highest values of Centralities and identification of their location in PGNRN.

Measure	PGNRN	Relevant other centralities			Location
		Closeness ($\times 10^{-5}$)	Betweenness ($\times 10^{-4}$)	Straightness	
Highest ecc ($\times 10^{-5}$)	13.609	13.609	1208.838	0.802	The point is junction, indicating exactly the intersection point of four Municipal districts, including District 9, District 10, District 12, and District 14.
Highest ebc ($\times 10^{-4}$)	2806.367	13.557	2806.367	0.819	The point is junction, indicating exactly the intersection point of four Municipal districts, including District 3, District 4, District 10, and District 14.
Highest esc	0.853	5.721	6.148	0.853	The point indicates junction alongside Kandahar-Herat Highway near to “Bagh-e-Pool” located at the shared boundary of District 7 and District 8.

Table 6
Highest values of Centralities and identification of their locations in Weighted edges.

Measure	Weighted Edges		Relevant other centralities		Location
	Closeness ($\times 10^{-5}$)	Betweenness ($\times 10^{-4}$)	Closeness ($\times 10^{-5}$)	Straightness	
Highest ccc ($\times 10^{-5}$)	13.779	268.636	13.779	0.782	The point indicates road segment of main road located at the share Boundary of District 10 and 12.
Highest cbc ($\times 10^{-4}$)	2,666.583	2666.583	13.607	0.820	The point indicates road segment of Ahmadshahe Avenue consists of dual carriageway and having four lanes per each carriageway. The segment is located exactly at the intersection point of four Municipal districts, including District 3, District 4, District 10, and District 14.
Highest csc	0.860	7.104	5.614	0.860	The point indicates road segment alongside Kandahar-Herat Highway near to “Bagh-e-Pool” located at the shared boundary of District 7 and District 8.

arterials, etc. and local betweenness measures can better identify secondary main roads, collectors and residential streets as illustrated in Fig. 6(b) and (e).

- Another important point that is concluded from the experimental case study is that Kandahar official urban road network (excluding old cultural substandard unpaved narrow intra-community streets) is an efficient and a well-connected network. Hence, it is suggested for the government to create policies for eliminating the existing 450.188 km old substandard unpaved narrow streets, most of which are used for residential purposes; have irregular forms and avoid expansion and construction of the same in the future.

7.2. Further research

For further studies the following are suggested:

- Further research on a detailed modified methodology in integrated manner with some preliminary attribute data regarding road geometrics and traffic is needed to functionally classify the roads based on IGNRN (Integrated Graph of Natural Road Network).
- The methodology used in this work is applied on undirected graph of natural road network and lacks sufficient traffic data. For further research one can also use the same method with required modification for a directed graph of natural road network. Besides, more accurate and realistic results can be obtained if further attribute data with regards to road segments and junctions are provided while modelling both directed and undirected road network based on IGNRN computing importance of junctions and road segments simultaneously. The edge-based weights are, but not limited to; road geometrics, traffic data, climate factors, road grades, surface conditions, etc. The node-based weights include; the relevant weights of road segments connected to them, types of junction (signalized or unsignalized), surrounded land use type, etc.
- For further studies, it is recommended to use the IGNRN method for integration of road network and land use within urban area through which the sustainability of urban planning for the proposed layouts and existing urban sprawl layouts can be assessed and sustainable urban development policies can be suggested to government and nongovernment entities.

Appendix A. Supporting information

Supplementary data associated with this article can be found in the online version at [doi:10.1016/j.jum.2018.11.001](https://doi.org/10.1016/j.jum.2018.11.001).

References

- Adali, S., Lu, X., & Magdon-Ismael, M. (2014). *Local community and global centrality methods for analyzing*. Springer.
- Aldous, J. M., & Wilson, R. J. (2004). *Graphs and applications: An introductory approach*. London: Springer.
- Bajjali, W. (2018). *ArcGIS for environmental and water issues*. Springer International Publishing.
- Barthelemy, M. (2018). *Morphogenesis of spatial networks*. Paris: Springer.
- Crucitti, P., Latora, V., & Porta, S. (2006). *Centrality in networks of urban streets*. American Institute of Physics.
- Dempsey, N., Brown, C., Raman, S., Porta, S., Jenks, M., Jones, C., & Bramley, G. (2010). Elements of urban form. *Dimensions of the sustainable city* (pp. 21–51). London New York: Springer.
- Demsar, U., Spatenkova, O., & Virrantaus, K. (2008). Identifying critical locations in a spatial network with graph theory. *Transactions in GIS*, 61–82.
- Docan, D.C. (2016). *Learning ArcGIS for Desktop*. Birmingham-Mumbai: Packt Publishing.
- Ghanbari, R., Jalili, M., & Yu, X. (2017). Correlation of cascade failures and centrality measures in complex networks. *Future Generation Computer Systems*.
- Gröger, G., & George, B. (2012). Geometry and topology. In David M. Danko, & Wolfgang Kresse (Eds.). *Springer handbook of geographic information* (pp. 303–322). London New York: Springer.
- Hohai, J. F., & Watanabe, T. (2015). *Index and query methods in road networks*. Switzerland: Springer.
- Jiang, B., Zhao, S., & Yin, J. (2008). Self-organized natural roads for predicting traffic flow: A sensitivity study. *Journal of Statistical Mechanics: Theory and Experiment*.
- Jun-qiang, L., Jing, Z., Qian-wen, L., & Lin, Z. (2017). Construction of Road Network Vulnerability Evaluation Index based on general travel cost. *Physica A: Statistical Mechanics and its Applications*, 493, 421–429 (Elsevier).
- Lin, J., & Ban, Y. (2017). Comparative analysis on topological structures of urban street networks. *International Journal of Geo-Information*.
- Liu, Y., Wei, X., Jiao, L., & Wang, H. (2015). Relationships between street centrality and land use intensity in Wuhan, China. *Journal of Urban Planning and Development, ASCE*, 142(1).
- Ormsby, T., Napoleon, E., Burke, R., Groessl, C., & Feaster, L. (2010). *Getting to know ArcGIS Desktop*. New York: ESRI Press.
- Porta, S., Crucitti, P., & Latora, V. (2006). The network analysis of urban streets: A dual approach. *Physica A*, 369, 853–866.
- Potts, R. B., & Oliver, R. M. (1972). *Flows in transportation networks*. New York: Academic Press, Inc.
- Rao, Y., Zhang, J., Xu, Q., & Wang, S. (2018). Sustainability assessment of road networks: A new perspective based on service ability and landscape connectivity. *Sustainable Cities and Society*, 40, 471–483.
- Rodrigue, J.-P., Comtois, C., & Slack, B. (2006). *The geography of transport systems*. London and New York: Routledge.
- Sevtsuk, A., & Mekonnen, M. (2012). Urban network analysis. *Revue internationale de géomatique*, 22, 287–305.
- Singh, P., Vinay Shankar Prasad Sinha, A. V., & Pahuja, N. (2018). Vulnerability assessment of urban road network from urban flood. *International Journal of Disaster Risk Reduction*, 28, 237–250.
- Thomson, R.C., & Ricardson, D.E. (1995). A graph theory approach to road network generalization. In: Proceedings of the 16th international cartographic conference. Barcelona: International Cartographic Association (ICA).
- Toms, S. (2015). *ArcPy and ArcGIS – geospatial analysis with Python*. Birmingham: Packt Publishing Ltd.
- Vragović, I., Louis, E., & Díaz-Guilera, A. (2005). Efficiency of informational transfer in regular and complex networks. *Physical Review E*, 71(3).
- Yu, W. (2017). Assessing the implications of the recent community opening policy on the street centrality in China: A GIS-based method and case study. *Applied Geography*, 89, 61–76.