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Interaction between Road Network Connectivity and Spatial Pattern

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Abstract

Road network is considered to be one of the keys to regional development of a region. The huge developmental cost of the road network demands effective utilisation, which can be attained only when there is proper connectivity and orientation. But the road network in many urban areas develop in an organic growth pattern. Hence a great emphasis needs to be given to the connectivity pattern of the road network. Urban road network has less theoretical research. Only some developed countries have carried out the evaluation of urban road network and hence it has great potential for development and application prospects.

In this study an attempt has been made to analyse the road network connectivity and spatial pattern existing in Calicut city in India, and hence to determine if the network connectivity can explain significant variance in the spatial pattern of the network structure. Analysis reveals that transport network fractality is directly varying with respect to connectivity and coverage of the study area. Network density could better predict fractality of the road network than any other connectivity indicators. This means that there is significant relationship between the level of road network development and the network spatial structure within the study area.

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1. Introduction

Road transport network is primarily designed to connect local resources and people to distant markets and population centres. Thus it provide support to urban system development. An efficient transport network is essential for maintaining and improving the quality of life within cities and ensuring sustainable development. Because of the huge developmental cost of the road transport network, effective utilisation is essential, which can be attained only when there is proper connectivity and orientation. Hence, a great emphasis needs to be given to layout and pattern of the urban road transport network. Urban road transport network evaluation have less theoretical research, and relative project cases are also not enough. Only some developed countries have carried out urban road network evaluation and hence it has great potential for development and application prospects.

Extraction of the basic connectivity indices, which provide fundamental information to delineate a given network character had been the focus of many studies. Very few studies concentrated on finding the spatial pattern of the network and to understand its structural attribute. Interaction between network connectivity and the structural attribute of the road network is not clearly understood. To increase the understanding of this interaction we explore the concepts of Connectivity and Development. Also Fractality, which help in characterising and understanding the spatial pattern of road network is focussed. Hence the main idea of this study is to determine if the road characteristic variables indicating connectivity can explain significant variance in the spatial pattern of the network structure. Calicut city region has been chosen as the study area for preparing the road network basemap across the zonal tracts and hence for road network characterisation using ArcGIS 9.3 software.

2. Literature review

A network is a framework of links, connected within nodes. Several network based indicators have been developed to analyse the transport network since 1960 and these indicators can be classified as connectivity, cyclic property, efficiency measures. [4, 6] developed graph theory measures to quantify the spatial structure of road network and to verify their relationship with regional economic characteristics. Traditional interest in understanding network structure has been limited to geographers who view the spatial nature of the road network as a vital input to regional development [11]. In recent years, there has been considerable interest to understand the topology of transport networks that connects points in geographic space [17, 5]. [18] investigated the potential application of proposed network measures namely, heterogeneity, connection patterns and continuity, in quantifying the structure of road networks. The proposed network measures were later applied to trace the changes in network characteristics over time [3]. In short, various spatial metrics provide quantitative information for urban transport network analysis.

3. Objectives

1. To understand the existing road network of the city in terms of connectivity and development.
2. To characterise the spatial structure of the road network in terms of fractal dimension.

4. Characteristics of road network

Road network display both topologic and geometric variations in their structure. There are a variety of indices, proposed in earlier studies applicable for evaluating road network properties. These measures find further application in planning and transportation practice. Selected measures used in this paper are discussed below.

4.1. Connectivity

Connectivity measures evaluate the intensity of connections between road segments**.** Connectivity refers to directness of travel between destinations. A well-connected network has many short links, numerous intersections, and minimal dead-ends providing continuous, direct routes to destinations. Several types of connectivity indicesare developed in the past. Various indices used for evaluating connectivity pattern of road transport network are Alpha Index, Beta Index, Gamma Index, Eta Index [6] and Grid Tree Pattern Index [9].

Alpha index (α) is the ratio of actual number of circuits to the maximum number of circuits in the network. Itrange from 0 (no circuits) to 1 (completely interconnected network).

$$\alpha = \frac{e-v+p}{2v-5} \quad (1)$$

where *e* - number of edges in the network
v - number of vertices in the network
p - number of subgraphs.

Beta index (β) is the number of links per node. Greater the value of β, greater the connectivity. As transport networks develop and become more efficient, the value of β should rise.

$$\beta = e/v \quad (2)$$

Gamma index (γ) is actual number of edges to maximum possible number of edges. It ranges from 0 (no connections between nodes) to 1 (the maximum number of connections, with direct links between all the nodes).

$$\gamma = \frac{e}{3(v-2)} \quad (3)$$

Eta index(η) indicates average length per link. Adding new nodes will cause a decrease of *eta index* as the average length per link declines.

$$\eta = M/e \quad (4)$$

where *M* - total network length in km

Grid Tree Pattern (GTP) index is a measure for identifying the pattern of the network, varying from 0 in case of tree pattern to 1 in case of grid pattern.

$$GTP\ index = \frac{e-v+p}{(\sqrt{v}-1)^2} \quad (5)$$

[19] studied the associations between connectivity and pedestrian-bicyclist accidents and determined that higher connectivity relate to fewer crashes for non-motorized road users. [13] made an attempt to explore the spatial variation of the road network structure of West Bengal with the help of graph connectivity measures along with road density. [7, 8 and 16] are some other Indian studies which applied GIS technology for the assessment of transportation network using connectivity indices.

4.2. Coverage

Coverage measures describe the density aspect of the elements of a network, as intersections and links. Coverage measures are useful in determining compactness and development. Higher the value, more the network is developed. Network Density and Intersection Density attribute road network coverage in an area. [13] made an attempt to explore the existing pattern of the road network of West Bengal using structural measures including road density.

4.3. Spatial pattern

This measure is used to capture the spatial pattern, which describe the structural attribute including compactness, shape, fragmentation and irregularity of the network. Fractal dimension indicates to what extent the street segments are more or less uniformly distributed and fill the space in the study area when zoomed to finer scales. Fractal dimension can be determined in number of ways as cell count method, box counting method, mass radius method etc. In this study, box counting method has been used for evaluating the fractal dimension. Box fractal dimension (D) is a measure to quantify the spatial pattern of road network [1].

$$D = -\frac{\ln N_i/N_{i-1}}{\ln L_i/L_{i-1}} \quad (6)$$

where L_i - grid size at scale I, N_i - number of cells covered by road at scale I, L_{i-1} - grid size at scale i-1, N_{i-1} - number of cells covered by road at scale of i-1.

[14] applied distributive continuous fractal analysis to get spatial distribution of transport network of Dalian city. [10,20] applied fractal theory in urban analysis for characterising the structure of the road network. [13] and[2] are some studies which tried to link the fractal properties of transportation networks with cities' properties and functions.

5. Methodology

The methodology involves application of GIS for evaluating the road network of the study area. Urban road network evaluation based on GIS involves collecting the data resources, digitizing the network, building road network database, extracting the network structure etc..Calicut corporation road network was taken from Google map and the zone wise corporation boundary from the Autocad drawing obtained from Calicut Corporation office. ArcGIS 9.3 was used for characterising the network based on various indicators and hence to identify the variation in their pattern. All the roads including Arterial, Sub-arterial, Collector Streets and Local Streets were digitised from the Google base map. The Autocad ward map was converted into ESRI shape file format. Both the maps were geo-rectified in ArcGIS to geographic co-ordinates for which the ground control points were used. In ArcGIS, the ward boundary and roads were converted into polygon and polyline features respectively.

The ward boundaries were superimposed on Calicut city road network to extract the network within each zone and the various indicators were evaluated for studying their spatial pattern and performance. Regression analysis was done to develop models, to understand the interrelation between connectivity and spatial pattern of road network.

6. Study area and data collection

6.1. Study area

Calicut city is situated in the South-West corner of the district has been selected as the study area. It extends between 75º 47' 23" E and 76º 26' 40" E longitudes and 11º 30' 08" N and 11º 58' 40" N latitudes. Calicut city has an

Fig. 1. Zone map of Calicut city

Fig. 2. Digitised road map of Calicut city

of 118 sq km and has a population of 6.022 lakhs as per 2011 data with gross density of about 5104 persons per sq.km. Corporation area of the city, containing seventy five wards has been taken as the study area. Fig. 1. gives the zone map of the Calicut Corporation. Road density is 3.39 km per sq.km. Roads in the entire network can be broadly divided into categories based on their functions, namely, roads facilitating intercity trips and roads facilitating intra city trips. National Highways and State Highways are the major roads facilitating intercity trips. The city roads, which connect residential neighborhood with the major road or with the CBD and other work centres, are meant for intra city movements. Fig. 2. shows the digitised road network map of Calicut Corporation.

7. Data Preparation

First overlay of Traffic Analysis Zones with the existing road transport network of the city was performed so as to extract the road network within each zone. This network was evaluated based on connectivity, coverage and spatial pattern measures, so as to analyse the interdependence between them.

7.1. Network Connectivity

To generate connectivity indices as Alpha, Beta, Gamma, GTP and Eta, number of nodes and links within each zone were required. Network dataset analyst of ArcGIS 9.3 was used to generate nodes and edges, from which connectivity indices were evaluated for all zonal tracts. Descriptive statistics of various connectivity indices are listed in table 1.

Table 1. Descriptive Statistics of Connectivity Indices.

Index	Minimum	Maximum	Mean	Std. Deviation
Alpha	0.090	0.760	0.437	0.163
Beta	1.000	2.490	1.769	0.354
Gamma	0.430	0.840	0.633	0.104
Eta	0.050	0.340	0.140	0.071
GTP	0.150	0.870	0.570	0.181

7.2. Network Development

To obtain the network coverage and development, road length and area within each zone were obtained from the attribute table of road and zones respectively. Using these Network Density was calculated. Intersection Density, obtained from node count and zonal area. Descriptive statistics of various coverage indices are listed in table 2.

Table 2. Descriptive Statistics of Coverage Indices.

Index	Minimum	Maximum	Mean	Std. Deviation
Network Density	1.198	16.533	5.997	3.351
Intersection Density	4.520	126.64	32.734	27.397

7.3. Network Spatial Pattern

For evaluating Fractal Dimension using ArcGIS, mesh of grid size 1000 m was prepared using fishnet tool in ArcGIS. Then road network digital map within each zone was overlayed by this mesh using spatial join tool and the count of boxes covering network completely was obtained. Repeated for grid sizes 800m, 600m, 400m, 200m, 100m and 50m. Grid size and corresponding box count obtained. Double logarithmic plot of inverse of grid size and box count was prepared as a linear plot, slope of which gives the box fractal dimension. Following this procedure, fractal dimension of the 75 zones were obtained. Table 3. explains the descriptive statistics of the box fractal dimension.

Table 3. Descriptive Statistics of box fractal dimension.

Index	Minimum	Maximum	Mean	Std. Deviation
Fractal Dimension	1.004	1.542	1.188	0.138

8. Data Analysis

For examining the relationship between the fractal dimension of road network as dependent variable and each of the connectivity and coverage indices as explanatory variables, correlation and regression analysis were performed.

8.1. Correlation analysis

Preliminary analysis was performed to understand the correlation or association between the dependent variable and each of the predictor variables. The correlation can be negative or positive with varying strength. From the correlation analysis, it was identified that Fractal Dimension had the highest correlation with the Network Density, that is 0.877.

8.2. Scatter Plot Analysis

Scatter plots prepared separately for each connectivity and coverage indices, to identify their influence on spatial pattern measure. It was seen that fractal dimension of road network grows with connectivity and coverage. It was also noted that, in the scatter plots of Fractal Dimension against connectivity indices as Alpha, Beta, Gamma, GTP, Eta or Intersection Density, the data points were rather scattered. While that between Fractal Dimension and Network Density showed clustered pattern. Hence it was concluded that Network Density exhibits highest correlation, compared to other indices as Alpha, Beta, Gamma, GTP, Eta or Intersection Density. That is, there seems some relation between Fractal Dimension and Network Density.

8.3. Regression Analysis

Applying regression technique, relationship between fractal dimension and each of the connectivity and coverage indices were analysed. Curvilinear regressions were tested with several types of mathematical formulations as linear, logarithmic, exponential including polynomial forms as quadratic and cubic. R^2 the coefficient of determination, which gives the proportion of variation in the dependent variable that is attributed by the explanatory variable were obtained. The linear formulation showed the highest R^2 for most of the indices taken individually as the explanatory variables. Table 4. shows the parameter estimates when Network Density used for predicting Fractal Dimension for the different mathematical formulations as linear, logarithmic and exponential.

Table 4. Parameter estimates of Network Density as explanatory variable.

	Model Summary [Predictor variable: Fractal Dimension]			Parameter Estimates	
	R^2-value	F-value	Sign.	Constant	Coefficient
Linear	0.794	268.743	0.000	0.970	0.036
Logarithmic	0.754	223.302	0.000	0.845	0.210
Exponential	0.767	239.974	0.000	0.987	0.030
Inverse	0.523	80.030	0.000		

From table 4. R^2 is highest for linear relationship. This confirms the fact that data fits well for linear model than

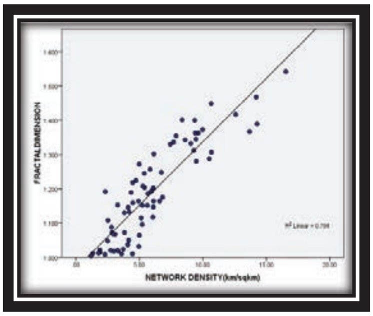

Fig. 3. Linear regression plot of Fractal Dimension with Network Density

nonlinear formulations. Parameter estimates as R^2, T statistic and RMSE values for linear models of each explanatory variable considered independently for predicting Fractal Dimension were arrived and R^2 showed strong correlation between Fractal Dimension and Network Coverage Index. Percentage Root Mean Square Error (PRMSE) values showed that Network Density is better suited to predict network Fractal Dimension. Linear and nonlinear plots were tried. Fig. 3. shows that the empirically observed relationship between Fractal Dimension and Network Density fits rather well to a linear model. Dispersion of the points around the fitted line is small, as compared to other non linear models. Again the coefficient of determination between the two variables showed the highest for the linear model. Even the polynomial models as cubic or quadratic, what usually requires more parameters to be estimated, showed no better correlation as compared to linear relationship. This justifies the linear relationship between Fractal Dimension and road Network Density.

8.4. Thematic map showing the variation of the network structure

Thematic maps [Fig. 4. and Fig. 5.] visualise how the variable varies across the geographical area. Fig. 4. ascertains

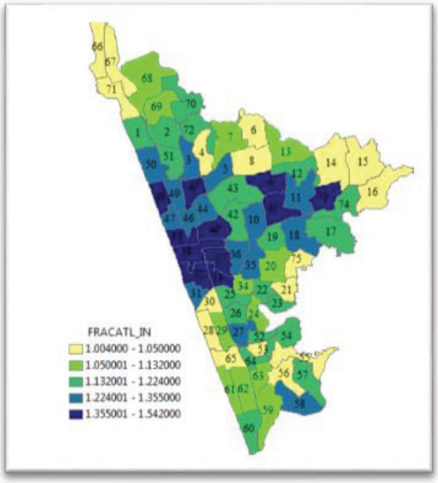

Fig. 4. Variation of fractal dimension

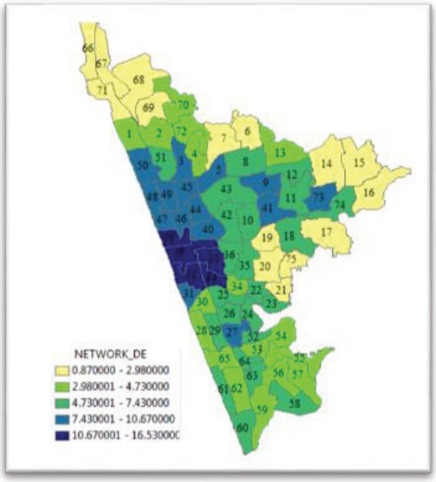

Fig. 5. Variation of network density

that network density is more towards CBD region and lesser towards outer suburban region of Calicut city. Again from Fig. 5. which shows the pattern of fractal dimension, values are highest near CBD area. Based on the maps prepared it can be observed that that is a correlation between Fractal dimension and Network Density.

9. Difference between Fractal Dimension and Network Density

Network Density is usually computed by dividing the mass length of road network by the surface on which this mass is located. Thus density only provides information about the mean occupation of the object by a mass; it doesnot take into account the spatial distribution of the mass under consideration. From a mathematical point of view, this is a rather rough interpretation of the notion of density. If fractal dimension was a simple synonym of road density, the correlation between the two variables evaluated for the same road network would be close to 1.0.

Fig. 6. gives examples of network pattern and corresponding D values along with road density. From this we can expect that, for a given road density, we can have different spatial arrangement of road, thus varying the Fractal Dimension. Again it is possible to have different road density pattern for the same fractal dimension. Hence the Fractal Dimension of road network is really far from being equal to Network Density.

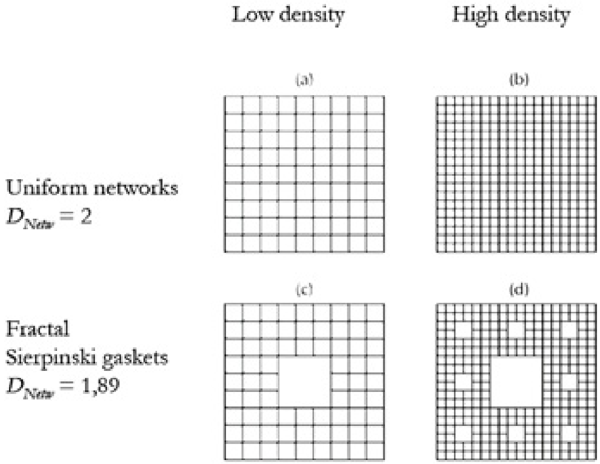

Fig. 6. Road network pattern and corresponding Dvalues along with network density
(Ref) Thomas I, Frankhauser P, "Fractal Dimension of Built-Up Footprints: Buildings Versus Roads, evidences from Antwerp", unpublished.

In a sense we can say that fractal dimension reflect the spatial pattern of transport network filling urban space, and the variation in spatial pattern of road network across the zonal tracts could be better explained by network density.

10. Conclusion

This study investigates road network characterisation of Calicut city based on various aspects as connectivity, coverage and spatial pattern and hence to quantify variation in the spatial structure of the network. A measure of connectivity evaluates network based on intensity of connections between the road segments while the spatial pattern measure describe the structural attributes of complicated road networks. Further, the study examines how road network characteristics as connectivity and development indices impacts the spatial pattern of the road network.

Analysis reveals that road network fractality is directly varying with respect to connectivity and coverage of the study area. Root Mean Square Error (RMSE) values showed that road network density is better suited to predict road network fractal dimension even though the data contain some amount of dispersion. This means that there is significant relationship between the level of road network development and the network spatial structure within the study area, suggesting that the road network development could explain the variation in the spatial pattern significantly. The indicators undertaken for measuring the spatial structure of road networks can be applied to identify its effect on the performance of the road transport system, as well as its subsequent effects on land use and urban form. The quantitative relationship identified between the spatial pattern and arrangement of urban road network and network density provides an empirical guide for the planning and policymaking of urban development and road construction.

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