

URBAN ROAD NETWORK STRUCTURAL ANALYSIS AND ITS RELATION WITH HUMAN SETTLEMENTS USING GEOGRAPHICAL INFORMATION SYSTEMS

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Abstract

Infrastructure like roads has a major role in the development of any urban form. Efficient road network structure is necessary for a sustainable transportation system. The present study attempts to examine the performance of existing city-level road network structure using Geographical Information Systems (GIS). The criteria for evaluating the effectiveness of the road network structure considered in the study are connectivity, accessibility, spatial pattern and development. The study focuses on proposing a “Road Network Structural Performance Index” (RNSPI) which indicates the efficiency of the road network structure at different locations in the city. The study also attempts to establish a relationship between urban road network structural evaluation criteria and human settlements. The results of the study indicated that the locations with deficient road network have to be looked up for network enhancement by planning professionals in order to optimize the road network in the city. The positive correlation between population density (PD) and RNSPI also seems to be an interesting outcome of the study. Emerging technology namely Arc GIS software has been used for location finding, buffer analysis, feature extraction and data representation. Implementation of GIS in road network structural evaluation made the analysis more feasible and accurate.

Keywords: Road network, structure, evaluation. population density, modeling, GIS

Introduction

An efficient transport network structure is responsible for a region's economic growth. The engineer's adherence towards a region can be understood by analyzing the efficiency of the transport network structure. A well-arranged and well-organized transportation network structure is very important for the development of a region. Good transportation network structure improves the accessibility thereby decreasing the travel time and travel cost. In an urban road network, the real

difficulty lies in analyzing the effect of implemented policies on it. In the course of time, the changes that are made to the existing road network system influence the land use pattern and also travel demand in that particular region. The evaluation and analysis of basic structural criteria like connectivity, accessibility, spatial pattern (or) morphology (or) similarity (or) fractal dimension and density of the transport network system are on focus in the study. The categorization and recognizing of locations

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with vulnerable road network is addressed in the study. Nowadays specific integrated system like GIS is being availed in urban road network planning to enhance the performance and quality of the transport structure. The present study implemented various tasks such as location finding, multiple ring buffer analysis, data extraction, data analysis using a GIS platform. The present work also explored the potentials of GIS in data capture, processing, and analysis in evaluating the structural parameters of urban road networks. The ease of travel to desired destinations is facilitated in a well-connected street structure. Different modes of transport, different speeds, and volumes of vehicles are facilitated in a well-organized hierarchical road structure. The higher values of connectivity indicators represent a satisfactory interconnectedness of roads (Obafemi *et al.*, 2011). There are three important indicators measuring connectivity like Alpha, Beta, and Gamma. With the help of these indicators, the transport structure performance based on the connectivity of roads can be explained easily (Kansky, 1963). 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. The growth of the transport network is described based on the network length (Levinson, 2012) and network density (Bento *et al.*, 2003). Network density and intersection density attribute network coverage in an area. Accessibility is majorly defined as “the potential of opportunities for interaction” (Hansen, 1959). Accessibility may be classified into relative and integral accessibility. Relative accessibility is defined as “the degree to which two places or points on the same surface are connected” and integral accessibility as “the degree of interconnection with all other points on the same surface” (Ingram, 1971). A facility-based planning methodology for rural roads has been proposed using spatial techniques. The accessibility for different facilities is quantified and analyzed in terms of Village Facility Index (VFI). A GIS-based rural road database was developed to improve the accessibility for different facilities from habitations and expand the infrastructure for current and future requirement (Modinpuroju *et al.*, 2016). Fractal geometry is an efficient approach to explain the complexity of the spatial objects. It is used to characterize irregularity and to quantify forms that are seemingly chaotic (Falconer, 1986). Road network in a city shows the fractal properties including irregularity, self-similarity, and scale-invariant. Thus, the fractal analysis will be an effective approach for evaluation and representation (Benguigui and Daoud, 1991). The relationships

between fractal dimension, urbanized areas, and urban population are explored to examine the fractal dimension of urban forms based on urbanized forms (Shen, 2002). A city is to be treated as distributive continuous space and the fractal analysis should be deployed on every piece of space on a GIS platform. A new method named Distributive Continuous Fractal analysis is introduced to evaluate the road networks (Sun *et al.*, 2007). Fractal modeling is a mathematical tool applied to analyze network, functionality and built-up areas with a relational view and policy view for urban planning to generate a sustainable level of service of traffic, environment, and uniform road utility (Mohamamdi *et al.*, 2013). The fractal dimension of transport network can be determined by a number of methods like the structured walk/divider method, equipaced polygon method, cell count method, mass-radius method, hybrid walk method, calliper method, pixel-dilation method, and box-counting method. A simple statistical model was derived to indicate the space-filling efficiency of the transport system applying box dimension considering Calicut city as the study area (Sreeleka *et al.*, 2017). A city-level road network accessibility evaluation has been done based on the number of opportunities (or) urban services with respect to the distance using Arc GIS software. The level of accessibility has been categorized and the different locations of the study area were evaluated according to it (Sahitya and Prasad, 2020). The urban road network structure of Calicut city, India was analyzed and evaluated to examine the interdependency of network structure with road network centrality. The results of the study indicated that the road network in the central part of the city was densely connected and was inversely proportional to the distance from the central zone of the city (Sreeleka *et al.*, 2020).

The present study aims to evaluate the city-level existing road network structure based on different evaluation criteria. A Road Network Structural performance Index (RNSPI) was established in order to indicate the level of road network structural performance in different locations of the city. The present work also focused on comprehending the relationship between urban road network structural evaluation criteria and human settlements.

Methodology

The methodology of the study can be divided into four phases. The collection and extraction of required data comes under the first phase, while the evaluation of road network structure was done in the second phase, where as third phase deals with the development of RNSPI and the fourth phase

includes developing models to establish relationship between population density and road network structural evaluation criterion.

In the first phase, Hyderabad city, capital of Telangana state, India was chosen as study area. The geo-referenced road network map of the study area was procured from Hyderabad Metropolitan Development Authority (HMDA) office. The map obtained was used as the base map for further analysis. The base map was imported to Arc GIS 10.1 software. The total road network length 5,400 km and a road network area of 7,200 sq.km. The location of the study area is shown in Figure 1. Thirty-six places, one for each 200 sq.km of road network area are selected covering the entire city in all directions. The points selected for this study are Abids (AB), Kukatpally (KP), Mehadiapatnam (MP), Dilshuknagar (DN), Secundrabad (SC), Panjagutta (PG), Jeedimetla (JM), Sikenderguda (SG), Nadergul (NG), Kothapet (KT), Ameerpet (AT), Banjara Hills (BH), Gandhi Nagar (GN), LB Nagar (LN), Malkajgiri (MJ), Hitech city (HC), Bhuvanagiri (BG), Ghatkesar (GS), Bhanur (BR), Moinabad (MB), Rama Chandra Puram (RCP), Shivampet (SP), Sangareddy (SR), Wargal (WL), Domara Pocham Pally (DPP), Sitharampuram (SM), Kothur (KR), Golconda Khurd (GK), Thummaloore (TR) Ibrahimpatnam (IBM), Ramalingapally (RL), Jagathpally (JP), Chevella (CV), Shahabad (SH), Kallakal (KL) and Yellammaguda (YL). The classification of the locations in the central (CBD) and non-central (non-CBD) region of the city is shown in Table 1. Buffer analysis has been carried out to draw multiple buffers for every 1 km radius up to 5 km from the center of each point. The road network structural components such as nodes, links, opportunities (or) urban services, built-up area, network length and area were extracted from the base map using Arc GIS software. The places identified for the analysis are shown in Figure 2. The multiple ring buffers drawn for each point is presented in Figure 3.

In the second phase, the road network structure was evaluated in terms of connectivity, accessibility, similarity and development. The road network connectivity in terms of Aggregate Transportation

Score (ATS), accessibility in terms of accessibility index, road network similarity in terms of fractal

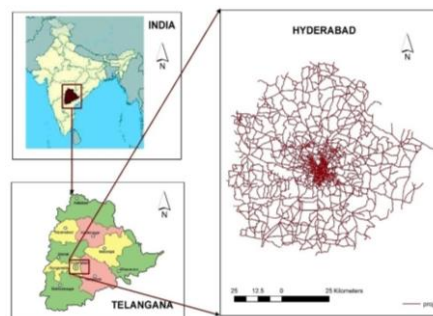


Figure 1. Location of the study area



Figure 2. Places identified for analysis

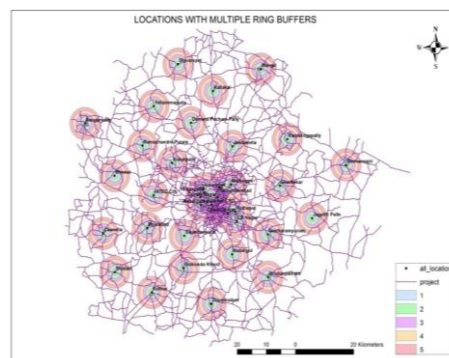


Figure 3. Multiple Ring Buffers of places

Table 1. Classification of locations in central and non-central region of the city

Region	Locations
Central	Mehadiapatnam (MP), Dilshuknagar (DN), Secundrabad (SC), Jeedimetla (JM), Sikenderguda (SG), Ameerpet (AT), Banjara Hills (BH), Gandhi Nagar (GN), L.B. Nagar (LN), Hitech City (HC), Abids (AB), Kukatpally (KP), Panjagutta (PG), Kothapet (KT), Malkajgiri (MJ).
Non-Central	Ghatkesar (GS), Ramalingapally (RL), Jagathpally (JP), Bhanur (BR), Moinabad (MB), Rama Chandra Pram (RCP), Shivampet (SP), Sangareddy (SR), Shahbad (SH), Kallakal (KL), Sitharampuram (SM), Kothur (KR), Golkonda Khurd (GK), Ibrahimpatnam (IBM), Nadergul (NG), Bhuvanagiri (BG), Chevella (CV), Wargal (WL), Yellammaguda (YM), Domara Pocham Pally (DPP), Thummaloore (TM).

Table 2. Description of road network structural evaluation criterion

S. No	Evaluation criteria	Equations and Description
1	Connectivity	Alpha index (α) = $(e-v+1)/2v-5$ Beta index (β) = e/v Gamma index (γ) = $e/3(v-2)$ Cyclomatic number (μ) = $e-v+1$ Aggregate Transportation Score (ATS) = $\beta+\alpha+\gamma+\mu$ e = number of edges/links, v = number of nodes/ vertices
2	Accessibility	Accessibility Index (A_i) = $\sum(W_i * N_{ir})$ W_i = Weights assigned to i^{th} opportunity (or) urban service, N_{ir} = Number of i^{th} opportunity at r^{th} radius
3	Fractal Dimension	$D_i = \log [X(R_i)/X(R_{i-1})]/\log [R_i/R_{i-1}]$ R_i = radius at scale i , X = built-up area at scale i , R_{i-1} = is the radius of scale $i-1$, $X(R_{i-1})$ = built-up area at the scale of $i-1$, D_i = fractal dimension of built-up area at scale i
4	Road network density	$RND = L/A$ L = Road network length (km), A = Area of the zone (sq.km)

Table 3. Categorization of different structural evaluation criterion

Connectivity	Accessibility	Similarity	Development	Categorization
0-38	0-10	0.5-0.95	0-2.0	Minimum (Min)
39-77	11-20	0.96-1.39	2.1-4.0	Moderate (Mod)
78-114	21-30	1.4-1.8	4.1-6.0	Maximum (Max)

dimension and road network development in terms of density were computed for each point at different radius using equations given in Table 2.

The values of road network connectivity, accessibility, fractal dimension and density were computed for different radii at each point. Then the mean values of each criterion for every point were acquired. The acquired average values of each criterion were classified into three categories based on the range of values obtained. The categorization of the different evaluation criterion proposed in the study is presented in Table 3. The road network of the places analyzed was classified based on the categorization provided. Then the locations with minimum or moderate or maximum road network connectivity, accessibility, similarity and development were identified.

In the third phase, an equation for Road Network Structural Performance Index (RNSPI) was proposed based on the road network structural evaluation criteria. RNSPI has been proposed to identify the performance of road network at different locations in the study area based on different structural evaluation criterion. RNSPI is the sum of average values of connectivity (C_m), accessibility (A_m), fractal dimension (D_m) and density (ND_m) of the road network obtained for each location. As these values are of different ranges, the values of the entire criterion are normalized to the scale of 0 to 10. The equation used to compute RNSPI for each location is presented in Equation 1.

$$RNSPI = C_m + A_m + D_m + ND_m \quad (1)$$

The higher value of RNSPI indicates good performance of the road network in the study area. RNSPI determines the performance standards of road network in each location of the study area. The road network performance in the locations of study area are classified into four categories such as weak, fair, average and good networks based on the range of RNSPI values obtained. The categorization of RNSPI values is shown in Table 4.

Table 4. Categorization of road network performance based on RNSPI values

RNSPI range	Level of Performance
0-10	Weak
11-20	Fair
21-30	Average
31-40	Good

In the fourth phase of the study, the human settlements in different locations of the city were determined in terms of population density (PD). The population of different locations was obtained from the statistics of Greater Hyderabad Municipal Corporation (GHMC) population census and a data compilation and statistics report of Comprehensive Transportation Study (CTS) conducted at different locations of Hyderabad city. The relationship between population density and urban road network structural evaluation criteria was analyzed using MLR and ANN methods. The models were validated for their accuracy. The correlation between PD and RNSPI was also analyzed using regression analysis. The equation used to compute population density is given in Equation 2.

$$\text{Population Density (PD) (in thousands/km}^2\text{)} = \frac{\text{Population}}{\text{Area}} \quad (2)$$

Results and Discussion

Evaluation of Road Network Structure

The locations with minimum, moderate and maximum road network connectivity, accessibility, similarity and development are identified based on the values given in Table 3. The results of different road network structural evaluation criterion are plotted in Figures 4 to 7. The locations are marked with the notations 'min', 'mod' and 'max' representing the levels of connectivity, accessibility, similarity and development.

Road Network Structural Performance Index (RNSPI)

The overall performance of road network structure at different locations in the city was analyzed using RNSPI value. The locations with

good, average, fair and weak road network structure are recognized. The need for improvement of different road network structural components such as nodes, links, built-up area, opportunities, road length and area could be analyzed using the RNSPI values. The map showing locations with different categories of RNSPI values is presented in Figure 8.

Population Density (PD)

The population density values for different locations of the city were obtained using Equation (2). The PD values for different locations of the city are shown in Figure 9.

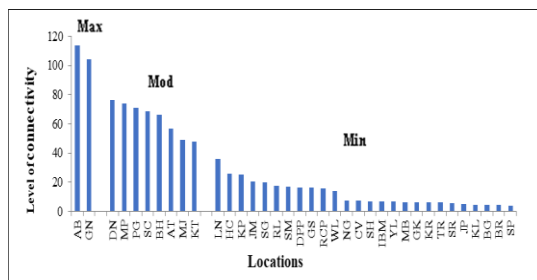


Figure 4. Level of connectivity at different locations

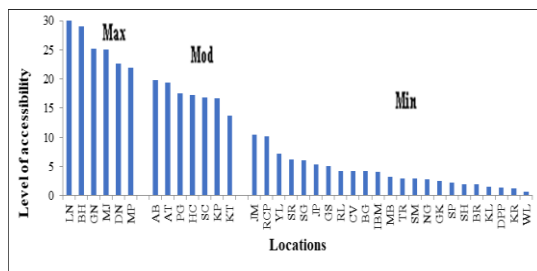


Figure 5. Level of accessibility at different locations



Figure 6. Level of similarity at different locations

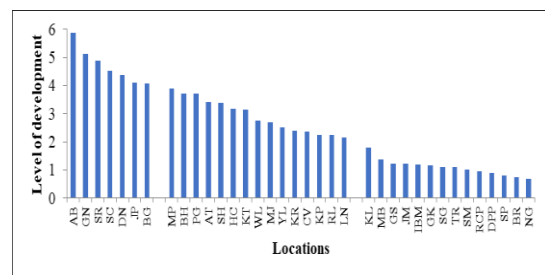


Figure 7. Level of development at different locations

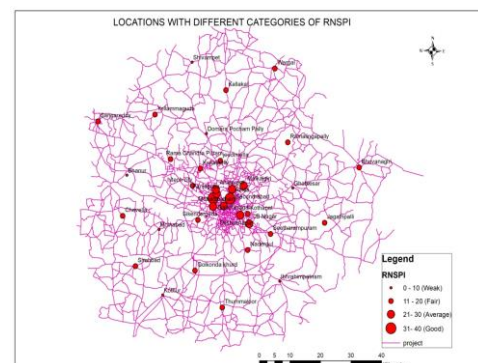


Figure 8. Level of road network structural performance at different locations

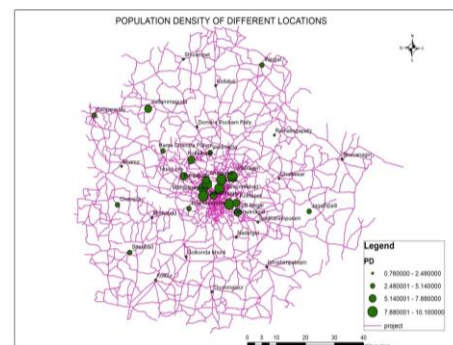


Figure 9. Population density values for different locations

Relationship Between Population Density and Road Network Structure

The study focused on analyzing the association between population density and road network structural evaluation criteria such as connectivity, accessibility, fractal dimension and density. Two different models were developed to establish the relationship between urban road network structure and population density using MLR and ANN methods.

Multiple Linear Regression (MLR) Modeling and Validation

MLR method was used to develop an equation in order to estimate and predict the population density with respect to road network structure. Out of 36 locations, data obtained from 24 locations (MP, DN, SC, JM, SG, AT, BH, NG, LN, HC, GS, RL, JP, BR, MB, RCP, SP, SR, SH, KL, SM, KR, GK, IBM) was used for model development. Here, PD is considered as dependent variable and C_m , A_m , D_m and ND_m are taken as explanatory variables. The MLR model developed in the study is given in Equation 3.

$$PD = 0.95 + 0.015 \times C_m + 0.177 \times A_m + 1.04 \times D_m + 0.788 \times ND_m \quad (3)$$

Where; PD= Population density (thousands/km²), A_m = accessibility index, ND_m = road network density (km/sq.km), C_m = connectivity in terms of ATS, D_m = fractal dimension. All the explanatory variables considered have shown significant relationship with the dependent variables. All the variables obtained a P-value less than 0.05 and t-stat value greater than 1.96. Hence, all the variables are included in the model. The regression outputs are presented in Table 5.

Table 5. Regression Outputs

Variable	P-value	t-stat value
Intercept	0.006	1.98
Connectivity	0.00001	5.86
Accessibility	0.00002	5.53
Fractal Dimension	0.003	2.36
Network Density	0.009	2.86

The MLR model developed was validated for its accuracy. The data of 12 locations (AB, KP, PG, NG, KT, MJ, BG, CV, WL, YL, DPP, and TR) was considered for model validation. The model validation as shown in Figure 10 indicated that there is no significant difference between the measured and modeled PD values. The model validation is successful, as it showed an Root Mean Square Error (RMSE) value of 0.00019 (which is less than 20%), Mean Absolute Percentage Error (MAPE) value of 4.08% (which is less than 10%) and a P-value of

1.04 (which is greater than 0.05). The validation plot is shown in Figure 10.

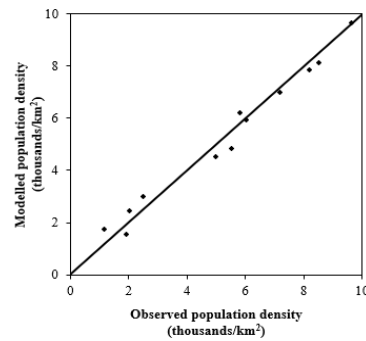


Figure 10. Measured PD v/s modeled PD

Artificial Neural Network (ANN) Modeling

The present study also developed an ANN model to predict population density. Multi-layered feed-forward ANN is used in the present study for analysis. The study availed MATLAB for ANN modelling. ANN comprises three layers namely the input layer, hidden layer for calculating input weights and output layers. In this study, PD is given as output layer and C_m , A_m , D_m and ND_m are given as input layers. ANN is developed in three steps. The first step is network training, the second step is the selection of optimal network structure and the third step is testing. ANN utilizes 70% of the data for training, 15% for testing and 15% for validation. The number of hidden layers and neurons are decided based on the trial and method iterations. The network structure with less error between the measured and ANN modelled values is chosen to be the optimal structure. In this study, the network structure for predicting the population density is optimized at 2 hidden layers and 10 neurons. The output of ANN modelling is presented in Figure 11(a). The plot of measured and ANN modelled MWAI values for all locations are presented in Figure 11(b).

The model validation presented that there is no significant difference between the measured and ANN modelled PD values. The model validation is successful, as it showed an Root Mean Square Error (RMSE) value of 0.000011 (which is less than 20%), Mean Absolute Percentage Error (MAPE) value of 1.08% (which is less than 10%) and a P-value of 1.09 (which is greater than 0.05).

Association between RNSPI and PD

The study was found much interesting when the relationship between RNSPI values and PD values was observed. The two variables RNSPI and PD were found to be significantly influencing each

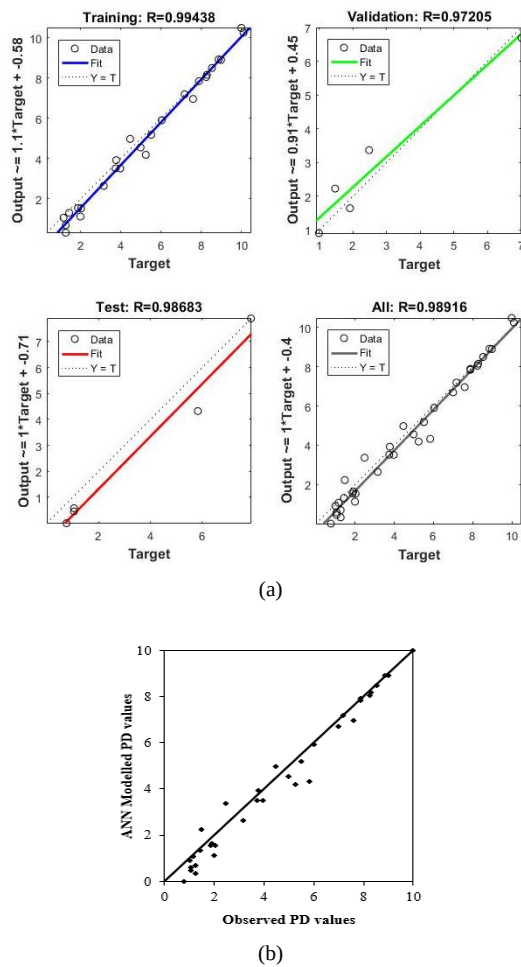


Figure 11. (a) Output of ANN model, (b) Observed PD v/s ANN modelled PD values

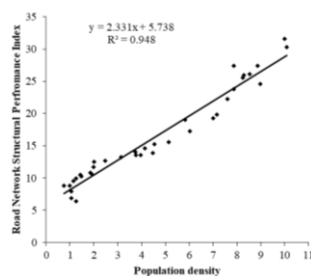


Figure 12. Association between RNSPI and PD values

other with a linear positive correlation in regression analysis. As the PD values are increasing the RNSPI values are also increasing and vice-versa. This indicates that the human settlement is high at the locations with good road network structural performance. The plot representing the association between the two variables is presented in Figure 12.

Conclusions

The study proposed a methodology for analyzing and evaluating the performance of city-level road network structure using Arc GIS software. The road network structure at different locations in the city was evaluated using different criteria such as connectivity, accessibility, fractal dimension and density. Each criterion has been categorized into three levels indicating the locations with minimum, moderate and maximum road network connectivity, accessibility, similarity and development. Road Network Structural Performance Index (RNSPI) has been proposed to analyze the overall performance of road network structure. The RNSPI values depicts that the there is efficient road network structure in the Central Business District (CBD) region of the city when compared to the sub-urban zones of the city. There is a necessity to improve the efficiency of the road network in all aspects with respect to number of nodes, number of links, opportunities (or) urban services, built-up area and road network length at the locations with weak performance. The evaluation of city-level road network structure is helpful in the further improvement of network in the city. The transportation planners can look up to the locations with minimum connectivity, accessibility, similarity, development and low RNSPI values for the necessary improvement of network. The focus on network enhancement in these locations will optimize the overall road network performance in the city. The level of categorization proposed for each structural evaluation criterion is useful in the decision-making process of the urban transportation planners. The relationship between population density and urban road network structural evaluation criteria was modeled using MLR and ANN methods. The model development was successful with R^2 values of 0.83 and 0.94 for MLR and ANN models respectively. The study also tried to describe that the ANN model is more efficient in explaining the relationship between population density and road network structure rather than MLR model. The validation statistics of the models depict that the models were successful and can be used for estimating the population density at any location in Hyderabad city. The results obtained from association of PD and RNSPI seemed to be note-worthy indicating that the human settlements are higher at the locations with good road network structure. The study also depicted that, like RNSPI values, the population density values were also found to be higher in CBD region when compared to the sub-urban zones of the city. The methodology

proposed in the study can be extended to other cities with large road network to analyze the situation of road network structure. This study also proved the efficiency of Arc GIS software in evaluating and analyzing the road network structure. The integration of Arc GIS in urban transportation planning process improves the decision-making capability of the planners.

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