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A METHODOLOGY FOR A COMPREHENSIVE EVALUATION OF AN URBAN TRANSPORT NETWORK STRUCTURE USING GEOGRAPHICAL INFORMATION SYSTEMS (GIS)

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Abstract

The transportation network is the most important component of an urban infrastructure. The efficiency of a region's transportation system can be understood by the effectiveness of its transport network arrangement. The current study employs Geographical Information Systems (GIS) to assess the structure of a transport network in various clusters of the Hyderabad Metropolitan Area (HMA). The study focuses on a thorough assessment of the transport (or) road network structure in terms of various criteria such as connectivity, accessibility, maturity, and development. The study also categorizes each Transport Network Structural Evaluation Criteria (TNSEC) level as "very low, low, medium, high, or very high". The goal of this research is to create a Road Network Structural Performance Index (RNSPI), which is usually used to measure the efficiency of a study area's transportation network structure. The study's findings serve as a foundation for city transportation planners to put efforts in the planning to enhance network facilities in the study region. The study also investigates the utility of Arc GIS software in assessing the structure of an urban transport network.

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Key words

- Comprehensive;
- Evaluation;
- Transport network;
- RNSPI;
- GIS.

1 INTRODUCTION

Urban road networks are described as the supporting structures for our society and economy (Shang, 2017). Urban road networks can be described as typically complex networked systems as there are many spatial components with complicated structures and interactions between different components (Goh et al., 2016). An excellent urban road network can be chiefly defined by four significant criteria: connectivity, accessibility, maturity, and development (Sreelekha et al., 2020).

An evaluation of a road network is necessary to understand the situation of an existing road network. The Road networks can be evaluated concerning their topological spatial structure and performance characteristics. Topological characteristics can be represented by the spatial structure of the networks, whereas performance characteristics are related to the operational issues in a network (Mohammadi, 2013). Road networks have different structural characteristics that exhibit geometrical and topological variations.

"Topology" is defined as "the arrangement and connectivity of nodes and links" in the road network (Xie and Levinson, 2007). The topological structure of networks can be evaluated concerning their accessibility, "connectivity", hierarchy, and morphology (Mohamamdi, 2013). An evaluation of connectivity is based upon indices extracted from a graph of a road network analysis (Kansky, 1963; Marshall, 2005). The hierarchy of road networks is the classification of roads in a network based on the function of the roads (Xie and Levinson, 2007). The "hierarchy" of a road network can be classified into a functional hierarchy and an operational hierarchy. Generally, link-

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based measures evaluate the operational and functional hierarchies of road networks by using the concept of entropy (Xie and Levinson, 2005). Generally, "accessibility" is evaluated concerning the attractiveness component (usually measured as having several opportunities at destinations) or an impedance function (usually measured in terms of distance or travel time) (Ingram, 1971). The "morphology" of a road network which is represented with the shape or pattern of the network, is generally evaluated and analyzed using fractal geometry or fractal dimension analysis (Rodin and Rodina, 2000).

Road network performance characteristics are evaluated based on the dynamic and functional characteristics of the network. The most critical measures to evaluate the functional characteristics of road networks are the road index (which is a function of a road's density, length, condition, population coverage, and traffic load) and the inter-nodal distance index (Santosa and Basuki, 2005), commercial speed and frequency (Gattuso and Miriello, 2005), capacity-volume ratio (Dhenadayalu et al., 2004), vehicle-kilometres (Scot et al., 2005) and robustness index of the network (function of the capacity, flows and topology) (Scot et al., 2006). The performance of road networks can also be measured in terms of their reliability, criticality, efficiency and vulnerability (Mohammadi, 2013). An evaluation of a road network provides a clear insight as to the situation of an existing road network which gives an understanding of the measures to be taken to improve it. The evaluation of a road network with respect to multi-dimensional criteria provides a base to balance a road network's structural growth in a city to improve the transportation system's efficiency.

Urban roads are a fundamental infrastructure that allows city dwellers to access various urban emergency, education, infrastructure, and recreational services. To reap significant benefits from urban areas, there must be a satisfactory level of accessibility, which includes the connectivity of various roads to various urban services. There is a need to address various issues in urban transportation and improve modernization to meet people's increasing demands. Inadequate network planning causes problems with connectivity, accessibility, mobility, and safety on the transport network. To enhance the quality of a transportation framework, it is necessary to make better use of the existing infrastructure. In the current scenario, an evaluation of a transport network is becoming increasingly important for planning an effective and efficient transportation system. An evaluation of a transport network may assist transportation planning authorities in implementing better planning practices to improve the network, develop its functional efficiency, make better use of existing infrastructure, and reduce network disparities. The current study is aimed as providing a detailed methodology for evaluating the structure of a transport network in terms of its connectivity, accessibility, maturity, and development. The present study also aims to show the quality of the study area's road network structure.

2 LITERATURE REVIEW

The problems in the connectivity, accessibility, mobility, and safety of a road network are caused due to the improper planning of networks. In order to enhance the efficiency of a transportation system, there is a need to use the existing infrastructure efficiently. The evaluation and modelling of a road network are becoming more prominent for planning an effective and efficient transportation system. An evaluation of a road network may help transportation planning authorities implement better planning practices to improve the network, develop its functional efficiency, effectively use the existing infrastructure, and decrease any network disparities.

There are several criteria and methods available in the literature to evaluate the structure of a road network. Some of them are direct empirical methods, while some are indirect methods. The direct empirical methods are generally estimated using nodes and links in the transportation network. The indirect methods are quantified using various components such as land use, time, distance, length and area. The study's have identified that a road network's connectivity, accessibility, maturity, and development are the essential criteria to be evaluated to understand the performance of a road network's structure. Some of the studies related to the methods used to evaluate a road network's connectivity, accessibility, maturity and development are reviewed in a detailed manner.

Connectivity refers to the density of connections in path or road networks and the directness of any links. A well-connected network has many short links, numerous intersections, and minimal dead ends (cul-de-sacs). As connectivity increases, travel distances decrease, and route options increase, allowing for more direct travel between destinationsand thereby creating a more accessible and resilient system (Victoria Transport Policy Institute, 2017). The interconnectedness of a road in a transportation network could be evaluated in terms of a connectivity index. Generally, a connectivity index is obtained by dividing the number of links by the number of nodes (Ewing, 1996). Graph theory measures are most commonly used in measuring road network connectivity (Hanson, 1986). There are three primary connectivity measures: alpha, beta, and gamma indices, which are based on the graph theory. These indices were computed concerning the number of nodes and links present in a road network. They are used to describe the structural connectivity of the road network. However, they are also applicable for explaining the changing structure of networks (Kansky, 1963). Generally, the connectivity indices are expressed on a scale of 0.0 to 1.0. An index over 0.75 is desirable and shows a greater degree of connectivity (Hanson, 1986). Other connectivity measures such as a street network's density (miles per square mile.), connected-node ratio, intersection density, and link-node ratio were subsequently evaluated for increasing bicycling and walking.

Preliminary results have been presented by applying such connectivity measures to the Portland, Oregon region. The connectivity measures were positively correlated but showed inconsistencies in assigning the same level of connectivity for a tract. The alpha index increased connectivity by providing multiple and alternative routes (Dill, 2004). Researchers have described some more connectivity measures along with graph theory measures to evaluate the overall network connectivity of China's railway network. The alpha index, beta index, gamma index, Cyclomatic number, distance matrix, and nodal accessibility coefficient were measured to analyse the expansion of the railway network. The greater the value of the above indices, the better a network is connected. An expansion in the railway network indicates a perfect correlation with the economic and urban development of a region (Wang et al., 2009).

The Aggregate Transportation Score (ATS), which is simply the summation of the Cyclomatic number and the alpha, beta and gamma indices, describes a road network's overall connectivity. A higher value of ATS indicates better road network connectivity (Ghosh, 2016).

Accessibility can be explained in many ways, including "the potential opportunities for interaction" (Hansen, 1959), "the ease with which any land use activity can be reached from a location using a particular transportation system" (Dalvi and Martin, 1976), "the freedom of individuals to decide whether or not to participate in different activities" (Burns, 1979), and "the benefits provided by a transportation or land use system" (Ben- Avika and Lerman, 1977). Accessibility may be chiefly classified in two ways: 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 the other points on the same surface." Ameasure based on the normal or Gaussian curve is the most suitable form for determining the integral accessibility at a given point (Ingram, 1971). There are different types of accessibility measures. The authors have tried to classify accessibility measures into three classes: 'infrastructure-based measures,' which focus on features of an infrastructure such as a road network's density, speeds on roads, 'opportunity-based measures' which are concerned with the opportunities for working, shopping, recreation, etc., and 'mixed measures', which integrate both network measures and opportunity measures (Wee et al., 2001). Accessibility can be estimated as the cost of moving people or goods from one place to another. Distance and travel time are two aspects considered in the measurement of accessibility. The centre of an urban area is where the highest degree of accessibility exists because of the convergence of different routes and systems (Lean and Goodall, 1977). Different studies have modelled accessibility in different ways such as a 'utility-based measure' (Ben-Avika and Lerman, 1977), a 'topological measure' (Mackiwicz et al., 1996), a 'gravity measure' (Hansen, 1959), an 'cumulative opportunity measure' (Ahmad Geneiddy and David Levinson, 2006), and a 'constraint based measure' (Wu and Miller, 2002).

An ***accessibility*** measure broadly integrates land use and transportation components. The quantification of accessibility has several uses, such as understanding the existing situation of a transportation system to examine the changes caused by inaccessibility because of the diversions in routes (or) changes in land use. The quantification and analysis of accessibility help policymakers take specific measures to improve the accessibility to different locations based on the results obtained from different accessibility indices. The addition of attractions accounts for the land-use aspect of an accessibility measure. Accessibility measures must include a behavioural component to be analysed. Accessibility can also be evaluated by other means such as the degree of a node, an associated number, and Shimbel's accessibility measure. Accessibility measures such as cumulative opportunities, gravity, and utility measures can measure accessibility to the maximum possible extent. A cumulative opportunity measure considers the distance and purpose of a trip to quantify its accessibility. It specifies a particular travel time or distance and uses the number of essential activities within that distance or time as the accessibility for that point. A gravity measure considers an attraction factor and separation factor continuously to examine the accessibility of different locations. The gravity model has an attraction factor weighted by the travel time or distance raised to some exponent. These models consider all the individuals as the same, which is the major limitation. A utility measure considers an individual's perceived utility for different travel choices. The time-space measure is a new dimension of accessibility that considers the individuals' time constraints travelling to a particular location. It is necessary to include all the dimensions such as the mode, time of day, type of activity, and spatial detail to measure the accessibility more precisely (Chandra Bhatt et al., 2000). A new planning paradigm necessitates a more thorough accessibility assessment. As transportation and land use planners develop better tools for quantifying accessibility impacts, such as multi-modal level-of-service indicators and models that measure the travel distances, time, and costs required by various types of transport system users to access various types of services and activities, the ability to evaluate accessibility is improved (Litman, 2021).

The ***maturity*** of road networks is analysed using fractal dimensions (Mohammadi et al., 2013). The term 'fractal' was first used by Mandelbrot (1975). Fractal geometry is applied in much of the literature to analyse the spatial pattern or morphology of a road network. A road network is one of the spatial phenomena which are complex in their nature and orientation. Many authors have stated that 'fractal geometry' is an efficient method to define the complexity of road networks. It is used to analyse the dissimilarities of networks which are utterly confused in nature (Frankhauser, 1992; Batty and Longley, 1994; Battylf, 1996; Falconer, 2004; Mandelbrot, 1977, 1982, 1967; Pietgen and Saupe, 1988; Shen, 1997; Mandelbrot, 1983; Falconer, 1986; De Cola and Lam, 1993; Hastings and Sugihara, 1993). Hausdorff's method (1918), which is specifically called fractal dimension, calculates a road network's coverage index, analyses the calculation results, and suggests optimising the road network. The geometry of urban residential development was fractal. Estimating fractal dimensions is based on the varying size of cities and the scale on which their form is identified. Space-filling was computed concerning the "size" and "scale." The increase in the radius or distance increases the size of the object measured. The required parameters are estimated using the least-squares regression method. The analysis of a size to the scaling relations was done only for the CBD area. The study indicated that this kind of analysis might be helpful to classify cities concerning their shape and density.Batty and Xie, (1996) tried to explain that when these parameters were integrated with economic and behaviour patterns, the functioning of the cities could be analysed in a much better way, which is essential for good planning. A transport network in a city exhibits fractal characteristics such as irregularity, self-similarity, and scale invariance. Thus, fractal analyses could be an efficient method for assessing and characterising a road network (Rodin and Rodina, 2000). The fractal aspect of urban transportation networks is generally analysed using the box-counting method (Sreelekha et al., 2017) and the mass-radius fractal method (Mohammadi et al., 2013). Later, a distributive continuous fractal analysis to evaluate a road network was introduced. There is a need to examine the fractal properties of cities on both "macro" and "micro" scales. A city is considered a continuous space, and fractal analysis is applied to every section of the city.

A new algorithm has been proposed for the box-counting fractal dimension method to continuously compute the fractal

dimension values on each section of a city. The mesh formed from the rectangular box dimension method is moved to the required place with a specified distance, and thus, fractal dimension values were calculated for different city sections. The conventional method could not describe the relationship between the fractal dimension and the city's geography, whereas the modified method can explain that relationship. Higher fractal dimension values indicate a better transportation network and a more developed economy (Sun et al., 2007). The complexity of road networks is concerned with the development of built-up areas and the network. A high fractal dimension value indicates the higher maturity of the transportation network in that area and vice-versa (Mohamamdi et al., 2013). The capability of using fractal dimensions as a method of "quantifying the qualitative" in terms of urban character helps find novel and innovative development techniques for a street network (Copper and Watkinson, 2010). The fractal characteristics of urban forms and road networks provide useful information for urban planning (Wee et al., 2017).

The ***development*** of a road network is evaluated using "coverage measures." Coverage measures describe the density aspect of the elements of a network, i.e; intersections and links. The higher the value, the more the network is developed. The growth of the transport network is described based on the network's length (Levinson, 2012) and density (Bento et al., 2003). A network's density and intersection density are attributable to its coverage in an area. A pattern analysis of the developemnt of a road network provides an empirical guide for planning and policy issues of urban development (Sreelekha et al., 2017). The compactness ratio, also known as a road network density, is the most widely accepted method for analysing urban sprawl (Purevtseren et al., 2018).

In recent years, GIS has been widely used as a powerful tool for road network analysis. GIS is the most efficient tool in solving various road network problems with promptness and accuracy (Adwani et al., 2005). GIS is used to maintain the road network data, integrate the data with other attributes, and visualise the results (Nijagunappa et al., 2007). The transport network analysis performed using GIS provides resilient and reliable results, which can be used as a base for transportation departments to enhance their techniques and analysis system (Arora and Kumar, 2011). ArcGIS-based network analysis provides solutions for different road network problems such as finding the most efficient travel route, generating travel directions, locating the closest facility, and defining service areas based on the travel time and distance covered (Kumar and Kumar, 2016). The merits and demerits of an existing transportation system can be evaluated using GIS. The need to improve the existing road network can be recognized with the help of a GIS-based road network analysis (Nalawade et al., 2015). A study was conducted to discuss the conditions of Slovakia for the common use of traffic engineering and urban planning. The main issue is the need for the preparation and rehabilitation of local urban roads and public spaces in cities in a complex 3D design. The study explained the integration of GIS and BIM. The integrated results would help in fulfilling the requirements of "sustainable mobility" and "smart cities" (Schlosser et al., 2022).

This section reviewed the literature on road network evaluation criteria and its methods. Road network analysis in different parts of the world help improve the road network facilities in those areas. The evaluation of road networks was limited only to small regions or small parts of the cities. There is a need to evaluate a road network in multi-dimensional aspects such as connectivity, accessibility, maturity, development, safety, and mobility. A city-level comprehensive transport network analysis in multi-dimensional aspects is necessary to understand the efficiency and performance of a network structure in an entire city.

3 DETAILED METHODOLOGY

The present study has been carried out in four phases. The first phase involves identification of the study area; the second phase focuses on evaluation of a transport network structure with respect to connectivity, accessibility, maturity and development; the third phase deals with the categorization of clusters in the study area with respect to the level of the structural evaluation criterion of the transport network and the fourth phase describes the development of a Road Network Structural Performance Index (RNSPI). The methodology adapted in the study is presented in Figure 1. The description of each phase of the study is explained in the following sections.

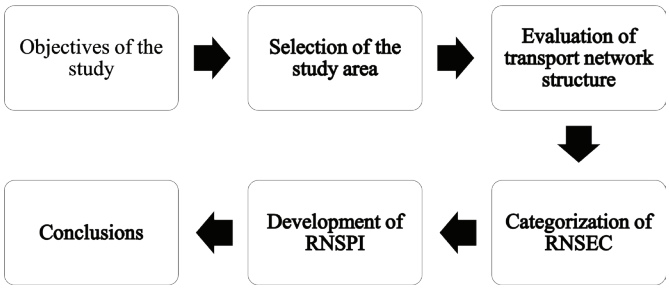


Fig.1 *Methodology adapted in the study*

3.1. Description of Study Area

Hyderabad, the capital of the state Telangana in India, was selected as the study location. The Hyderabad Metropolitan Area (HMA) is one of India's fastest-growing metropolises. With 9.5 million people, it is the country's sixth-largest metropolitan region (as per the 2011 census). The study area has a transport network that spans 5400 kilometres and covers an area of 7200 square kilometres. Figure 2 depicts the location of the study area.

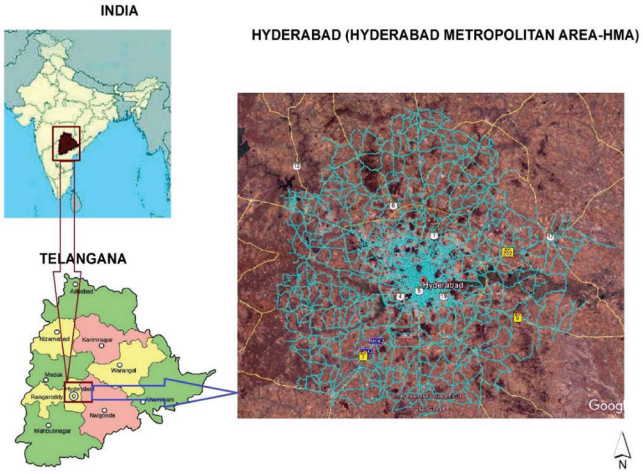


Fig. 2 *Location of the Study Area*

The transport network in 21 clusters of HMA was chosen for analysis. The clusters along with the transport network are shown in Figure 3. The classification of the clusters was considered from the Draft Final Report of the Comprehensive Transportation Study (CTS) for HMA, 2013.

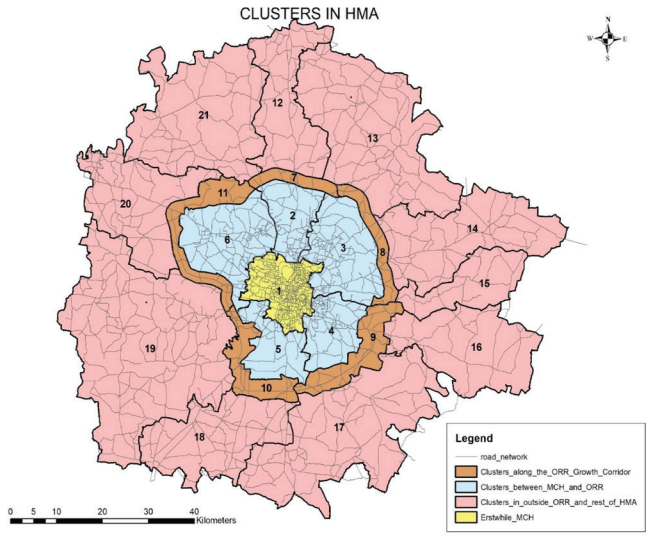


Fig. 3 *Map showing the transport network in different clusters of HMA*

3.2 Structural Evaluation Criteria of the Transport Network

Four key criteria are used to evaluate the transport network structure in the study area: connectivity, accessibility, maturity, and development of the network. Arc GIS 10.1 software was used to extract the features needed for the study, such as the number of nodes, the number of links, the length of the transport network, the size of the transport network, the built-up area, the number of utilities (or) urban services, and the distances. The methods for quantifying each of these criteria are given in detail below.

3.2.1 Connectivity of the Transport Network

To analyse the connectivity of the transport network, the study employs graph theory measures such as alpha, beta, gamma, Cyclomatic, and Aggregate Transportation Score (ATS). The greater the value of the indices, the better the transport network's connectivity. The alpha index, beta index, gamma index, and Cyclomatic Number were added together to form the ATS. As a result, the ATS can interpret the overall transport network's connectivity in a cluster. The empirical equations used to calculate the different connectivity measures are given in Eqs. (1) to Eq. (5).

$$\text{Alpha Index } (\alpha) = (e\text{-}v+1)/(2v\text{-}5) \quad (1)$$

$$\text{Beta Index } (\beta) = e/v \quad (2)$$

$$\text{Gamma Index } (\gamma) = e/3(v\text{-}2) \quad (3)$$

$$\text{Cyclomatic number } (\mu) = e\text{-}v+1 \quad (4)$$

$$\text{Aggregate Transportation Score } (ATS) = \beta+\alpha+\gamma+\mu \quad (5)$$

Where, e= number of edges / links, v= number of nodes / vertices

3.2.2 Accessibility of the Transport Network

The Accessibility Index (AI) is used to evaluate the accessibility of a study area's transport network. The number of utilities or urban services such as schools, colleges, ATMs, banks, hospitals, police stations, petrol stations, bus stops, parks, and theatres are computed in different clusters. The Weighted Scoring Model (WSM) was used to assign weights to various utilities. Different weights were assigned to the utilities, with an emergency receiving the highest priority, education coming in second, infrastructure coming in third, and recreation coming in fourth [9]. The accessibility index for different locations and clusters was computed using Eq. 6. The weights assigned to the different utilities are given in Figure 4.

$$\text{Accessibility Index } (AI) = \Sigma (W_i * N_{ir}) \quad (6)$$

Where,
W_i= Weights assigned to i^{th} utility (or) urban service and
N_{ir} = number of i^{th} opportunity at r^{th} radius

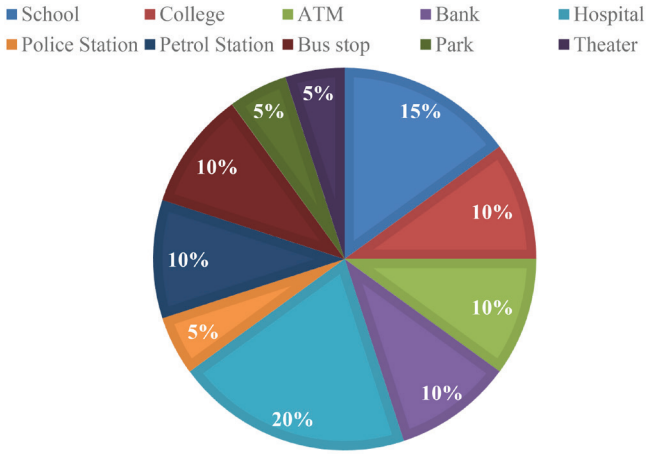


Fig. 4 *Weights Assigned to Different Utilities*

3.2.3 Maturity of Transport Network

Using fractal geometry, the maturity of the existing transportation network was quantified. The Box-Dimension method was used to calculate the fractal dimension. To evaluate the fractal dimensions in Arc GIS, a mesh with a grid size of 1km is created using Arc GIS's fishnet tool. Then, the transport network map within each cluster, was overlaid by this mesh, and the number of boxes covering the network was calculated. The same holds true for grid sizes of 2km, 3km, 4km, and 5km. The grid size and box count were calculated. As a linear plot, a double logarithmic plot of an inverse grid size and box count was created, yielding the box fractal dimension. The fractal dimensions (FD) of the 21 clusters were computed.

3.2.4 Development of the Transport Network

The density of a transport network is used to quantify its development. The length and area of a transport network in

Tab. 1 *Descriptive statistics of the road network parameters*

Cluster	Number of Nodes	Number of Links	Built-up area (sq. km)	Road network length (km)	Area of the cluster (sq.km)	Weighted accessibility index
1	1135	1709	591	118	175	4954
2	153	238	49	591	146	625
3	525	555	92	425	277	2267
4	176	257	57	332	161	1784
5	98	144	44	200	169	457
6	270	382	84	164	287	1510
7	19	32	2	331	48	54
8	36	60	3	56	73	84
9	47	81	10	93	140	153
10	37	67	9	155	113	151
11	36	64	6	124	135	99
12	84	129	22	142	353	227
13	94	155	20	326	743	272
14	76	118	32	467	483	518
15	22	37	8	319	215	47
16	46	68	35	129	419	397
17	127	184	41	193	740	425
18	91	146	57	447	405	385
19	211	305	44	337	1112	463
20	76	129	38	701	400	307
21	72	111	17	285	693	222

different clusters must be calculated. The Transport Network Density (TND) is used to calculate the development of a cluster's transport network. The higher density values indicate a higher development of a network. The transport network's density was calculated using Eq. 7.

TND = *Transport Network's Length (km) / Area (sq.km)* (7)

The descriptive statistics of the parameters required to compute the transport network's connectivity, accessibility, maturity, and development are given in Table 1.

3.3 Categorization of the Structural Evaluation Criteria of the Transport Network (TNSEC)

The values are normalized to a scale of 0 to 10 after the computation of various structural evaluation criteria of the transport network for different clusters. There are five categories of the transport network's connectivity, accessibility, maturity, and development. The clusters are then classified based on the categorization proposed in Table 2 based on their levels of the transport network's connectivity, accessibility, maturity, and development.

Tab. 2 *Categorization for the Level of the Structural Evaluation Criteria of the Transport Network*

Range of ATS, AI, FD and TND	Level of connectivity, accessibility, maturity, and development
0.00 – 2.00	Very Low
2.01 - 4.00	Low
4.01 – 6.00	Medium
6.01 - 8.00	High
8.01 – 10.00	Very High

3.4 Development of the Structural Performance Index of the Road Network (RNSPI)

The present study proposed a Road Network Structural Performance Index (RNSPI) in order to identify the quality of the transport networks in the HMA. RNSPI is the sum of all the normalized values of the Aggregate Transportation Score (ATS), Accessibility Index (AI), Fractal Dimension (FD) and Transport Network Density (TND). A higher value of the RNSPI indicates the excellent performance of the transport network in the HMA. The RNSPI of different clusters in the HMA is computed using Eq. 3.12.

$$RNSPI = ATS + AI + FD + TND \quad (8)$$

The RNSPI values indicate the performance standards of the transport network in each cluster of the HMA. The transport network's structural performance in the HMA is classified into five categories: very *weak, weak, average, good* and *very good* based on the RNSPI values; the ranges are presented in Table 3. These values help identify the clusters with weak

transport networks so that measures can be taken to implement better planning practices to improve the network's performance.

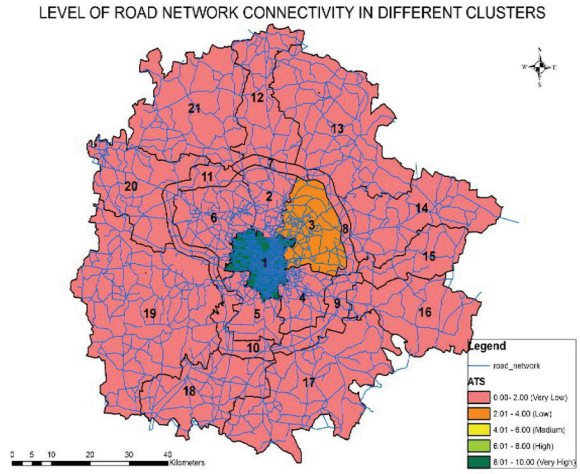
Tab. 3 *Categorisation of the Level of the Road Network's Structural Performance*

RNSPI Range	Level of performance
0-8	Very Weak
9-16	Weak
17-24	Average
25-32	Good
33-40	Very Good

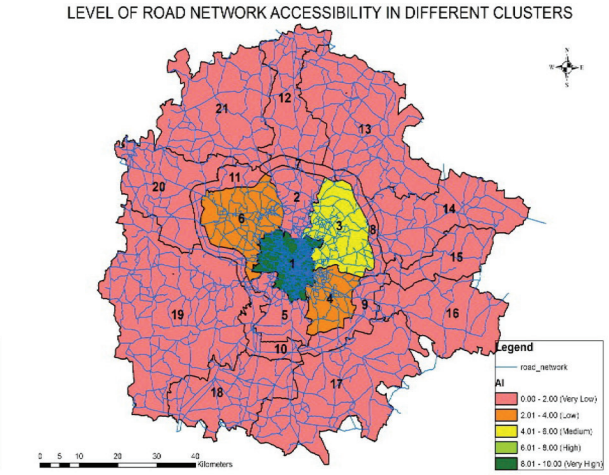
4 RESULTS AND DISCUSSIONS

According to the empirical procedures described in the previous section, the transport network in different clusters of the study area was evaluated with respect to different RNSEC. The transport network structure in the clusters was classified into five categories based on connectivity, accessibility, maturity, and development: *very low, low, medium, high, and very high*. Figure 5 depicts the level of the transport network's connectivity, accessibility, maturity, and development in various HMA clusters.

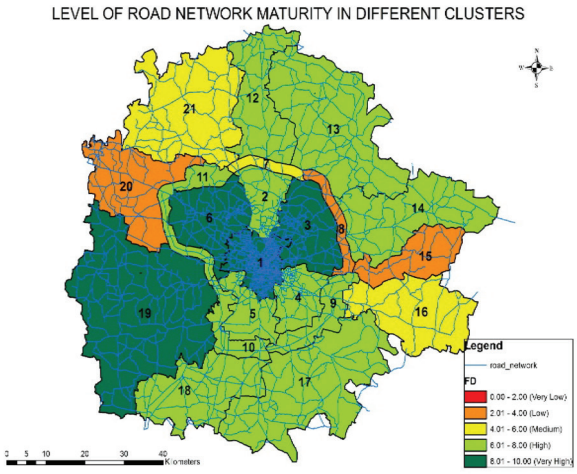
The highest values of the ATS, accessibility index, fractal dimensions, and density values are noted in Cluster 1. The transport network in Clusters 7 and 15 have very low degrees of connectivity and accessibility. The transport network in Cluster 8 has very low maturity. The transport network's density values are very low in Clusters 16 and 21. The lower connectivity values are due to smaller links available in a particular cluster. If there are fewer links, the direct route options to the users decrease, which lowers the network's connectivity. The very high accessibility index in a particular cluster is due to the higher availability of utilities like hospitals and schools, which are given more weightage. The transport network's maturity is higher in clusters with more coverage of the transport network. The transport network's development is less in clusters having very low transport network density values, there by indicating the lack of compactness of the transport network.



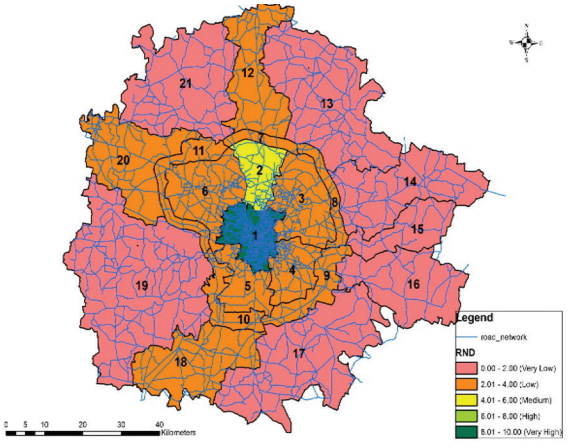
(a) *Level of road network's connectivity*



(b) *Level of road network's accessibility*



(c) *Level of road network's maturity*



(d) *Level of road network's development*

Fig. 5 *Level of road network's structure (a) connectivity, (b) accessibility, (c) maturity and (d) development*

4.1 Structural Performance Index of the Road Network (RNSPI)

The HMA urban transport network structure was evaluated for different aspects such as its connectivity, accessibility, maturity, and development in the previous sections. The evaluation of the transport network results indicates that the transport network in some locations and clusters has low connectivity and high accessibility, very high maturity and average development, very low maturity, and high accessibility. That is due to different structural evaluation criteria which were based on different transport network structural components. Therefore, to understand the overall performance standards of the transport network in a particular location or cluster, a Road Network Structural Performance Index (RNSPI) has been developed. RNSPI is an integrated measure of four structural evaluation criteria of an urban transport network. The higher value of RNSPI indicates the excellent performance of the transport network in the study area. The transport network's structural performance level of each cluster is evaluated based on the categorization of the RNSPI values provided in Table 2 and is presented in Figure 6.

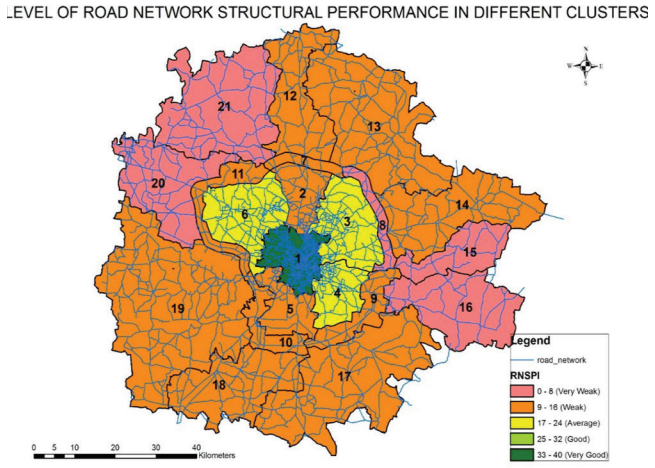


Fig. 6 *Level of road network's structural performance in different clusters*

Figure 6 presents the clusters in different colors falling under five different ranges of RNSPI values. The clusters are shown based on their levels of the transport network's structural performance. It also indicate that RNSPI values are higher for the clusters present in the central region of the city, when compared to the clusters away from the center of the city.

5 CONCLUSIONS

The following are the methodological conclusions drawn from the present study:

1. The study proposed a methodology for a comprehensive analysis of the road network structure in a city that involves the evaluation and modelling of different variables with reference to a specific case study of the Hyderabad Metropolitan Area (HMA). The methodology is applicable to similar cities.
2. The clusters occupying the central region of the city have high road network connectivity, accessibility, maturity and development versus the locations and clusters away from the central part of the city. The development authority, can promote the optimization of the different structural evaluation criteria of the road network by adding links and locating different types of opportunities wherever necessary. This improves the uniformity of the road network's structural growth in the entire city. The balance in the growth of the development in the city has many benefits, like reducing congestion on major arterials, trip lengths, travel time, and environmental degradation.
3. The categorisation of the road network's structural evaluation criteria proposed in the study is useful for interpreting the level of road network's connectivity, accessibility, maturity and development in a city. This categorization provides a base for the development authorities in understanding the locations where there is a need for improvement with respect to each criterion.
4. The Road Network Structural Performance Index (RNSPI), developed in the study is an analytical measure for comprehending the overall road network's structural performance. This index presents the locations where there is a need for the improvement in the network's structure to the development authorities.

The following are the case-specific conclusions drawn from the study:

1. According to the study, the transport network in Cluster 1 has higher levels of connectivity, accessibility, maturity, development, and structural performance for the overall transport network. According to the study, all of the transport network's structural evaluation criteria are high in clusters occupying the city's central region when compared to the peripheral clusters.
2. According to the study, the network facilities are concentrated in clusters located in the city center and decrease as one moves away from the center of the city. It demonstrates the non-uniformity in the development of the transportation network's structural facilities throughout the city, which may be due to a lack of proper planning during the early stages of the city's development. The road network in the city of Hyderabad requires a balance between the availability of direct routes, urban services, built-up areas and a dense road network to optimise the growth of the transport network in the city.
3. The study also demonstrated the utility of Arc GIS software in assessing the structure of an urban transport network with regard to connectivity, accessibility, maturity, and development.

The present study is limited to an analysis of the existing structure of the road network in the study area; the operational features of the network were not considered. The study is also limited to an analysis of the clusters of the city of Hyderabad. Future studies can be carried out in cities with similar road network characteristics by adapting the methodology proposed in the present study. The dynamic features of the road networks' such as traffic flow, speed, capacity, etc., should be considered in future studies and structural measures to provide an overall understanding of the road network conditions in a study area.

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