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DESIGN OPTIMAL RURAL ROAD NETWORK USING GIS

Anil Modinpuroju[1], CSRK Prasad[2]

[1,2] National Institute of Technology Warangal, Department of Civil Engineering, Warangal, India

[1]e-mail: anilmodin@yahoo.com
[2]e-mail: csrk@nitw.ac.in

Abstract: *To have an effective development among the isolated, remote areas, rural transportation is recognized as a key factor. Efficient rural transportation depends largely on a well-knit road network to provide accessibility and mobility in rural areas. This work affords an applied method for the development of rural road networks in rural areas of developing countries. The proposed methodology enables to determine nodal points in the rural road network based on the facility index of the settlements. The rural road network is generated by connecting the nodal points by minimum travel time path in Geographical Information System (GIS). Spatial analysis is carried out in the study area to identify the Desirable Coverage Distance of the Facility(DCDF). The Village Facility Index (VFI) is calculated by considering the desirable coverage distance. The suggested methodology is simple and practical, hence, highly applicable to real-world scenarios, as demonstrated in the definition of the road network for the rural areas.*

Key words: *rural roads, optimal road network, minimum travel time path, facility index, GIS.*

1. Introduction

Rural Roads play a vital role in the development of any emergent country. In India, rural roads share more than 85% of the road network of the country. A well-planned road network in rural areas is one of the most important infrastructure elements which improves rural accessibility and contributes to the rural development as a whole. Planning the road network in rural areas is crucial, not only in terms of network efficiency (concerning accessibility), but also regarding construction and operation costs, as limited funding is available.

There are different planning methodologies for the definition of rural road networks. Swaminathan et al. (1982) have developed a system approach to developing a rural road network. Principles from the graph theory and weights are used in determining the optimal linkage. Mahendru et al. (1983) have suggested a linkage pattern in rural road network by taking concepts of total link length, total route length, settlement interaction. Bhatia (1988) have developed a methodology an optimization of initial cost of construction and long run operational cost and developed optimal network. Raji (1996) has attempted to develop cluster algorithm to suit the rural road network development. Makarachi (1991) suggested a methodology an identification of link choice with considering minimization of travel and construction cost. Kumar et al. (1999) developed a methodology to generate a minimum accessibility to all villages with a service center. Rao et al. (2007) developed an information system for rural road network planning for Rupauli block of Purina District, Bihar, India. The optimum rural road network was developed and road maintenance management system helps in understanding the sustainability of existing roads for a longer time with minimal efforts. Durai et al. (2004) explained applications of GIS for Planning and Management of rural roads and developed a GIS-based database for the preparation of rural road plan and core network plan, including detailed project report information for Simdega Block of Jharkhand State, India. Using the network and routing tools of the GIS software the core network was prepared and GIS map can be utilized for effective on-line project monitoring activities. Mishra and Naresh (2009) explained the use of geo-informatics for the development of rural roads under Pradhan Mantri Gram Sadak Yojana (PMGSY). They developed a spatial and non-spatial rural road database which can be viewed by the common man to get the interactive and exciting way on the map with related attributes. Praveen et al. (2013) demonstrated the use of network analysis, in determining the optimal route between two or more destinations based on a specific travel expense.

This paper primarily focuses on the identify the nodal points in the network by considering the desirable distance for the facility. The optimal rural road of the network is generated by connecting the minimum travel time paths.

2. Methodology

2.1. General assumption

The proposed methodology can be separated into two main phases. The first phase is focused on identifying the nodal points in the rural areas, while the second phase focuses on generating the rural road network connecting the nodal points previously identified. The methodology process of defining the rural road network can be explained step by step procedure as follows.

- A collection of data, in the form of a map for the study area from SOI toposheet.
- Observed the travel time data on each road from field surveys.
- Development of a spatial database for the study area.
- Identify the DCDF values by carrying the buffer analysis of various facilities.
- Define nodal points for rural road network using VFI values.
- Performing network analysis to find the minimum travel path between the nodal points.
- Generate the rural road network by connecting the nodal points through minimum travel path.
- Develop the optimal rural road network .

2.2. Study area and data collection

Warangal district in Telangana state, India has been selected as a study area. The district was situated between 78° 49' and 80° 43'E, of the eastern longitudes and 17° 19' and 18° 36'N, of northern latitudes and it is shown in figure 1.

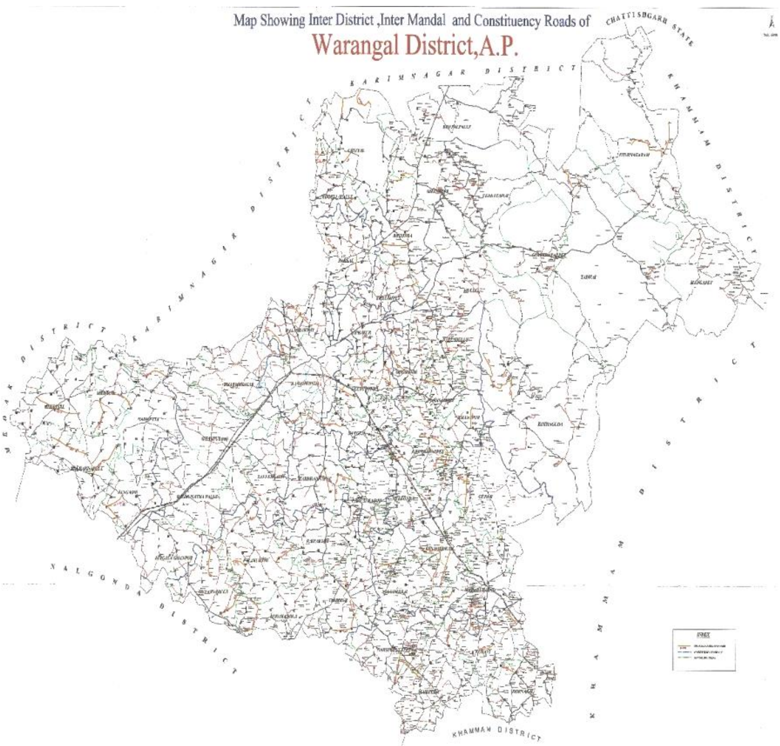

Fig. 1. Map showing the habitation location with connectivity of study area

In the present study average travel time on each link was collected from the field. The field surveys were conducted by traveling on each road twice in a year i.e., before and after the rainy season in both the direction and car was used as a design vehicle. Hand held GPS instrument was used to collect the location of facilities and settlements in the study area. Secondary data like toposheet, habitation details as well as road information data and other ancillary data were collected from Panchayath Raj department of Warangal district. Survey of India (SOI) topographic sheet of 1:50,000 scales used to prepare different layers of the study area.

2.3. Preparation of the spatial database

Spatial data refers to geographic areas or features. Features occupy a location. Spatial data stores geometric locations of geographic features along with attribute information describing what these features represent. In order to prepare the spatial database, preliminary, SOI map of scale 1: 50,000 of the study area has been collected from the data source; Panchayath Raj Department of Warangal District. The map has been scanned and entered to the GIS environment for registration purpose. After Geo-referencing was done, different features of the study area were digitized as different layers.

These layers are created on Arc Catalog environment according to the feature type; point layer for a location of habitations and polygon for a Mandal boundary and for determination of how many habitations covered in for selected distance. The shape files are created for various layers with the same coordinate system. The scanned toposheet has been defined to this coordinate system before Geo-referencing was done. Once the required shape files of different layers are created, digitization of features have been done. Digitization is the process of converting the geographic features on an analog map into digital format. In this process, the x, y coordinates of these features are automatically recorded and stored as spatial data. The spatial data has been created in Arc Map environment and the total spatial database organization involved in the process identifying the content of spatial data and the actual process of creating the database in Arc Catalog.

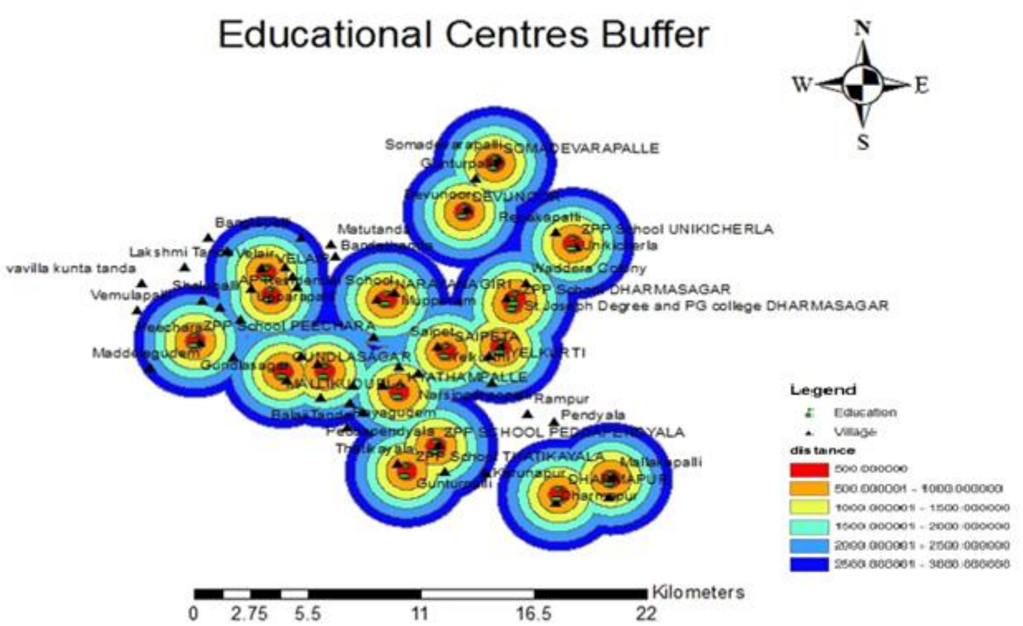

Fig. 2. Accessibility levels from the high school facility

3. Estimation of VFI and Identify the Nodal Points

3.1. Identify the desirable coverage distance to the facility

In this study, the DCDF values are identified based on the availability of the infrastructure and at what desired distance the facility covers the more habitations. Fixing a coverage service distance is a strategic decision. The maximum coverage distance is fixed in the ranges from 0.5 km to 5 km. The value corresponds to the average human walking speed which is 5 km/hour (Shrestha, 2003). Relaxing the service distance allows covering much more habitations, but the difficulty to achieve facility rises accordingly, which is not desirable.

To identify the DCDF, buffer/spatial analysis was carried out for each facility. The buffer analysis carried out for 10 blocks in the Warangal district ArcGIS software. For example, figure 2 shows the accessibility levels of the habitation from the high school. From this analysis, numbers of habitations and population covered from a facility at different distance levels are noticed.

The buffer analysis carried out for the facilities available in the 10 blocks and the average value is considering for the analysis. The facilities considered for the analysis is given below.

i. Education facilities: it includes a primary school, middle school, high school, an intermediate college, Degree College.
ii. Medical facilities: it includes sub-centers, maternity, child welfare centers, primary health centers (PHC) and hospitals.
iii. Economic activity centers: it includes markets, petrol bunks, retail shops, cold storages.
iv. Transport and communication facilities: it includes bus stand, railway station, post office, banks, electrical substations etc.

For example, the results obtained from the buffer analysis of high school is shown in figure 3.

From the figure 2, it was observed that the coverage percentage rapidly increases up to 3 km with nearly 80% and then increase with lower increments.

The desirable coverage distance identified from the analysis for middle school is 3 km. Similarly, the analysis is carried to all the facilities and coverage distances are identified as shown in Table 1.

Table 1. DCDF values for each facility by habitation and population covering approach

S. no.	Name of facility	DCDF by habitation approach (m)
1	Primary school	1000
2	Middle school	2000
3	High school	2000
4	Pre-university	8000
5	Anm center	2000
6	PHC	5000
7	Child welfare	8000
8	Veterinary hospital	5000
9	Bus stand	1500
10	Post office	4000
11	Petrol outlet	8000
12	Ware house	6000

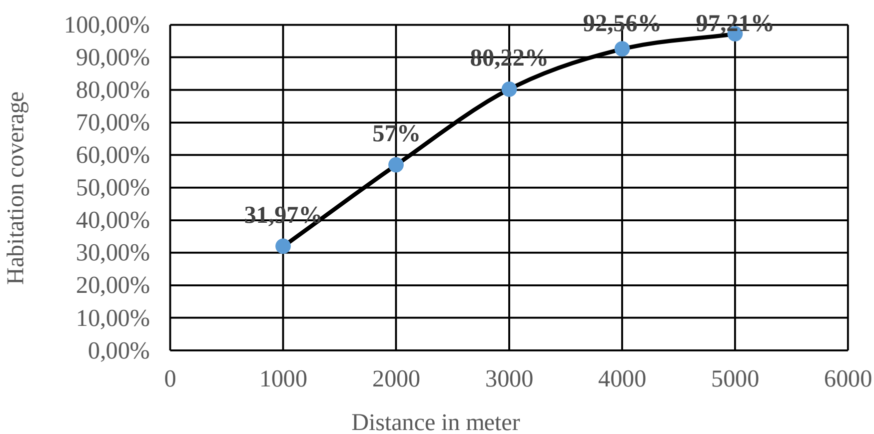

Fig. 3. Percentage of habitation coverage in service distance from a middle school

3.2. Estimation of village facility index

For each major facility, most popular and widely accepted approach is to find cumulative weight by assigning weights to each parameter under that major facility. Garg (2008), if is the index of particular facility "*f*" of *i*-th habitation, then the facility index is estimated using equation 1:

$$I_i = \sum_j \binom{n}{1} W_j X_j \qquad (1)$$

where:

$W_j = w_j \cdot d_j$ is a weight of *j*-th sub-facility:

w_j = (Total number of villages in block)/(villages having *j*-th sub-facility)

d_j is a distance factor, values are considering as 1, 0.5, 0.0 if these facilities are available only at a distance of less than 0.5 km, in between 0.5 km and maximum coverage distance of the facility, more than maximum coverage distance of the facility respectively.

Xj is a value or availability of *j*-th sub facility in *i*-th habitation.

n is a number of sub facility available in *i*-th habitation.

The Village Facility Index (VFI) value is obtained by cumulates the all the major facility indices are shown in equation 2.

$$VFI = EFI+MFI+ECOFI+TFI+CFI \qquad (2)$$

where:

EFI - Educational Facility Index,
MFI - Medical Facility Index,
ECOFFI - Economic activity Facility Index,
TFI - Transportation Facility Index,
CFI - Communication Facility Index.

3.3. Identification of nodal point

The nodal point in the network is a place which having the highest facility index value and it connected with more than one through route (PMGSY, 2013). Roads catering to large populations by connecting populations over a large area and which act as collectors of traffic from smaller roads would be treated as Through routes. Based on the VFI value and connectivity with through routes the nodal points are identified from the study area are mentioned in the following table 2.

Table 2. Identified nodal points from the blocks in the study area

S. No	Block Name	Nodal Point
1	Atmakur	Atmakur
2	Bachannapet	Bachannapet
3	Bhupalapally	Bhupalapally
4	Cheriyal	Cheriyal
5	Chennaraopet	Chennaraopet
6	Devurupala	Devurupala
7	Dharmasagar	Dharmasagar
8	Duggondi	Duggondi
9	St Ghanpur	St Ghanpur
10	Mulugu Gahanapur	Mulugu Gahanapur
11	Hasanprthy	Bhemaram
12	Kesamudram	Kesamudram
13	Khanapur	Khanapur
14	Kodakandla	Kodakandla
15	Kuravi	Kuravi
16	Maddur	Maddur
17	Mahabubabad	Mahabubabad
18	Maripeda	Maripeda
19	Mogullapalle	Mogullapalle
20	Nalaballe	Nalaballe
21	Narshimulapet	Pedda Mupparam
22	Narsampet	Narsampet
23	Nellikudur	Nellikudur
24	Palakurthy	Palakurthy
25	Parkal	Parkal
26	Parvathagiri	Parvathagiri
27	Raiparthy	Raiparthy
28	Regonda	Regonda
29	Sangem	Sangem
30	Shayampet	Shayampet
31	Wardanapet	Wardanapet
32	Eturu Nagaram	Eturu Nagaram
33	Tadvai	Tadvai
34	Govindaraopet	Govindaraopet
35	Gudur	Gudur
36	Kothaguda	Kothaguda
37	Lingala Ghanpur	Lingala Ghanpur
38	Narmetta	Narmetta
39	Mangapet	Kamalapur
40	Mulugu	Mulugu
41	Nekkonda	Nekkonda
42	Dornakal	Dornakal
43	Thorur	Thorur
44	Ragunath Pally	Ragunath Pally
45	Zaffergadh	Zaffergadh
46	Warangal	Warangal
47	Geesukonda	Dharmaram

4. Generate rural road network using minimum travel path analysis

There are many types of shortest path problems. For example, the most economic path or fastest path or minimum fuel consumption path from one specified node to another in a network. To conduct network analysis, this study focused on determining the optimal route between two or more destinations based on a specific travel expense. For the purposes of this study, those expenses of travel would be based on the length of time required traveling from origin to any destination point by visiting certain locations. The analysis was done by using the extension Network Analyst extension of Arc GIS software on the whole study area to locate some best routes. Network Analyst calculates the optimal route by means of Dijkstra's Algorithm. In particular, ArcGIS Network Analyst's route solver attempts to find a way through the set of stops with minimum cost.

To develop the database for the road network, mainly four types of attribute data were collected. First are descriptor attributes, which gives the description like name of the road, road class, and speed. Second are the cost attributes, which play the essential role in the analysis of road network to find the best route which has the cost of the length of road in meters and cost of drive time in minutes. Third are the restriction attributes, which also have the main role accompanying with cost attributes. This attribute data includes restriction value like one-way, U-turns and others. And fourth are hierarchy attributes which identify the type of roads and give their hierarchy from primary to local roads to perform network analysis by using a hierarchy. These attributes are collected directly from a field as well as from secondary sources. In the present study, the average speed of each link was determined by field survey.

Attributes of Road_network

Shape	ROAD_	ROAD_NET	FNODE_	TNODE_	HASANPAR	ROAD_NAME	SPEED_KMPH	SPEED_MPS	FT_MINUTES	TF_MINUTES	ROAD_CLASS	HIERARCHY	F_ELEV	T_ELEV	Shape_Leng
Polyline M	1	1	95	94	1	Filterbed to Unikicherla limits	15	4.16667	5.80785	5.80785	Local	1	0	0	1451.962894
Polyline M	2	2	95	93	2	Filterbed to Unikicherla limits	15	4.16667	2.12076	2.12076	Local	1	0	0	530.189792
Polyline M	3	3	91	96	4	PR Road Nirupnagar to Subbaiahpalli	25	6.94444	3.98749	3.98749	Local	1	0	0	1661.452393
Polyline M	4	4	91	92	5	Filterbed to Unikicherla limits	15	4.16667	4.25953	4.25953	Local	1	0	0	1064.882101
Polyline M	5	5	90	91	6	Filterbed to Unikicherla limits	15	4.16667	4.63569	4.63569	Local	1	0	0	1158.921857
Polyline M	6	6	89	90	7	Filterbed to Unikicherla limits	15	4.16667	2.6118	2.6118	Local	1	0	0	652.948861
Polyline M	7	7	92	88	8	Filterbed to Komatipaly via Banjara colony	25	6.94444	1.65094	1.65094	Local	1	0	0	687.892789
Polyline M	8	8	95	88	9	Parimala colony to Komatipaly via Banjara colony	25	6.94444	4.60365	4.60365	Local	1	0	0	1918.188852
Polyline M	9	9	85	86	10	Unikicherla Road to Devannapet road via Maduthand	15	4.16667	1.12112	1.12112	Local	1	0	0	280.279817
Polyline M	10	10	85	90	11	Unikicherla Road to Devannapet via Madu thanda	15	4.16667	5.90379	5.90379	Local	1	0	0	1475.947375
Polyline M	11	11	88	84	12	IMVR04 X to Komatipaly via Banjara colony	25	6.94444	4.35262	4.35262	Local	1	0	0	1813.590079
Polyline M	12	12	87	84	13	Devannapet to Hanamkonda via Kapri Thanda	25	6.94444	4.6562	4.6562	Local	1	0	0	1940.083836
Polyline M	13	13	83	85	14	Unikicherla Road to Devannapet road via Maduthand	25	6.94444	1.43008	1.43008	Local	1	0	0	595.865873
Polyline M	14	14	84	83	15	Devannapet to Hanamkonda via Kapri Thanda	25	6.94444	6.87669	6.87669	Local	1	0	0	2865.286836
Polyline M	15	15	81	80	16	Rayapatnam to Kodad	35	9.72222	0.147916	0.147916	Secondary	2	0	0	86.284554
Polyline M	16	16	83	78	17	Devannapet to Madipally	15	4.16667	1.79097	1.79097	Local	1	0	0	447.742211
Polyline M	17	17	84	74	18	Chinthagattu to Komatipally	15	4.16667	10.593	10.593	Local	1	0	0	2648.258083
Polyline M	18	18	74	80	19	PWD Road Bheemaram to Anathasagar via Munipally	25	6.94444	6.95984	6.95984	Local	1	0	0	2899.932278
Polyline M	19	19	78	72	20	Devannapet to Munipally	15	4.16667	8.16409	8.16409	Local	1	0	0	2041.021754
Polyline M	20	21	82	71	22	Arepally to Kantatmakur road KM0/0 to 16/085	35	9.72222	3.49703	3.49703	Local	1	0	0	2039.932738
Polyline M	21	22	74	70	23	Chinthagattu to SH7@125/2	25	6.94444	2.81407	2.81407	Local	1	0	0	1172.52919
Polyline M	22	23	80	70	24	Rayapatnam to Kodad	35	9.72222	3.55011	3.55011	Secondary	2	0	0	2070.897563
Polyline M	23	24	71	69	25	Arepally to Kantatmakur road KM0/0 to 16/085	35	9.72222	0.254638	0.254638	Local	1	0	0	148.538982
Polyline M	24	25	68	77	26	Madipally to Repaka X road	25	6.94444	4.43718	4.43718	Local	1	0	0	1848.826922
Polyline M	25	26	78	68	27	Devannapet to Madipally	15	4.16667	16.4368	16.4368	Local	1	0	0	4109.19783
Polyline M	26	28	66	72	29	PWD Road Bheemaram to Anathasagar via Munipally	25	6.94444	2.30504	2.30504	Local	1	0	0	960.434202
Polyline M	27	29	65	74	30	PWD Road Bheemaram to Anathasagar via Munipally	25	6.94444	3.32538	3.32538	Local	1	0	0	1385.575181
Polyline M	28	30	72	65	31	PWD Road Bheemaram to Anathasagar via Munipally	25	6.94444	3.91146	3.91146	Local	1	0	0	1629.775855
Polyline M	29	31	70	64	32	Rayapatnam to Kodad	35	9.72222	1.08597	1.08597	Secondary	2	0	0	633.484593
Polyline M	30	32	63	68	33	Madipally to Repaka X road	25	6.94444	2.38707	2.38707	Local	1	0	0	994.614098
Polyline M	31	33	79	63	34	SH7 to Madipally via Ananthasagar	25	6.94444	6.11208	6.11208	Local	1	0	0	2546.701672
Polyline M	32	34	75	62	35	KUC Road to Pegadipally X	25	6.94444	2.85067	2.85067	Local	1	0	0	1187.780991
Polyline M	33	35	69	61	36	Arepally to Kantatmakur road KM0/0 to 16/085	35	9.72222	1.90371	1.90371	Local	1	0	0	1110.49821
Polyline M	34	36	76	61	37	PWD Road to Vangapahad X via Reddipuram	15	4.16667	9.77528	9.77528	Local	1	0	0	4857.200205
Polyline M	35	37	63	60	38	SH7 to Madipally via Ananthasagar	25	6.94444	1.3082	1.3082	Local	1	0	0	545.0846
Polyline M	36	38	64	59	39	Parkal to Erragattugutta	35	9.72222	1.46613	1.46613	Local	1	0	0	855.240397
Polyline M	37	39	67	58	40	University to Mucherla Nagaram Km 0/0 to 9/900	35	9.72222	2.87656	2.87656	Local	1	0	0	1677.991647
Polyline M	38	40	60	57	41	Jayagiri to Madipalle	15	4.16667	10.5092	10.5092	Local	1	0	0	2627.28722
Polyline M	39	41	73	57	42	Balramthanda to Jayagiri	15	4.16667	9.64414	9.64414	Local	1	0	0	3683.986494
Polyline M	40	42	56	66	43	PWD Road Bheemaram to Anathasagar via Munipally	25	6.94444	4.88053	4.88053	Local	1	0	0	2033.554564

Record: 1 Show: All Selected Records (0 out of 117 Selected) Options

Fig. 4. Data set for network analysis for study area

To achieve the task of the optimal route in terms of time, real travel time was needed to insert in the database to instruct the analyzing system. In the present study, travel time was calculated from average speed and length of each link. In a place where the terrain is not flat and the level difference between the two origin-destination points is very high, travel time should be considered in both directions. In this study, since the terrain is plain, the travel time in both direction is assumed to be same. From field survey, it is found that there is no one-way and U-turn restricted link in the study area.

The overall attributes used for network analysis in this study are displayed in figure 4 above. The attributes include total length of the link, nodes, connectivity (F _Node and T_Node), road name, average speed in miles for second, travel time in both directions (FT_Minutes and TF_Minutes), road classification or category, hierarchy, elevation at each node. In the present study, the elevation of each node is taken as zero (0) because the surface is plain. The network analysis carried out in the warangal district between the nodal points and obtained rural road network shown in figure 5.

5. Development of optimal rural road network

The optimal road network is obtained using prim's algorithm. A brief description of the Prim's Algorithm (Prim, 1957) is described below.

At first a peak is chosen in random order, which for simplicity we accept it as V (1). This way two sets of pointers are initialized, the O= {1} and P= {2...n}. The O set will always contain the pointers of those peaks which are terminally attached in the T tree. The V (1) peak has already been attached in the T tree. The P set contains the rest of the pointers for the peaks, P= {1...n}-O which are those pointers who have not been terminally connected with a node of T, that means they are not attached in the tree.

In every execution of the Prim Algorithm, a new peak will be connected to the T tree, not always with their numbering order, for example the V (4) peak can be connected to the tree before the V (2) peak. The corresponding pointer of the newly connected peak will be deleted from P set and will be inserted to the O set. When all peaks are connected there will be O= {1,…, n} and P=0. This means the end of the algorithm.

The new peak every time will be chosen by using greedy method, among all sides of G which connect peaks already inserted in the T (pointers in the O set) tree with the rest of the peaks (pointers in the P set), we choose one with minimum cost. If the chosen one is e(ij) then i belongs in the O set, V(i) peak is already in the T tree, j belongs in the P set, and V(j) peak has not been attached in the T tree yet. We put V(j) in the T tree, we change the O set by putting the j pointer, and we also change the P set by removing the j pointer.

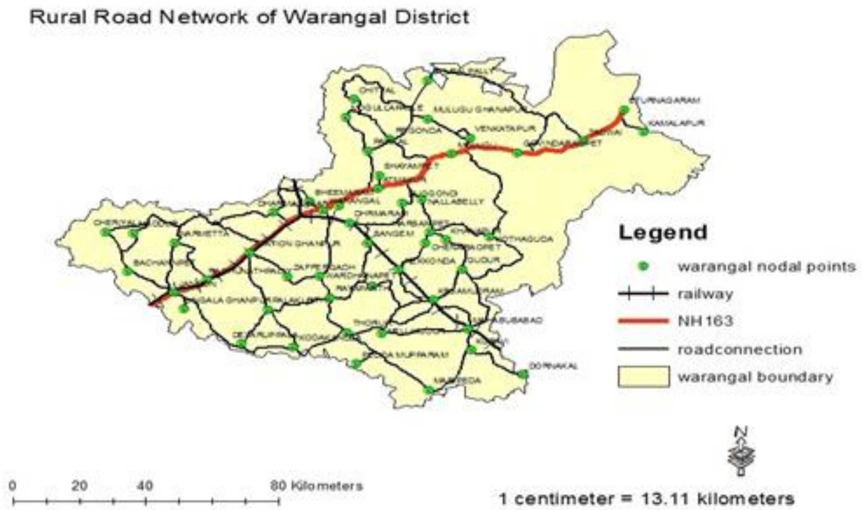

Fig. 5. Minimum travel rural road network of the study area

The pseudo code of the algorithm is as follows.

INPUT: n,c[e(ij)],i,j belonging to {1,...,n}.
OUTPUT: p(j) j=2,….,n (pointer of peaks j father in the T tree).

Steps:

1 . (initializations).
O= {1} (V (1) root of the T tree).
P={2,…,n}
For every j belonging to P: e(j): =c[e(j1)], p(j)=1 (all peaks connected to the root. By definition of the cost function: e(j)=infinite when V(j) does not connect to V(1).).

2. Choose a k for which e(k)<=e(j) for every j belonging to P. In case of tight choose the smaller one. Exchange the O set with the set produced by the union of the O set and {k} . Exchange the P set with the set produced by the difference of the P set and {k}. (P<-P-{k}) If P=0 then stop.

3. For every j belonging to P compare e(j) with c[e(kj)].
If e(j) >c[e(kj)] exchange e(j) <-c(e(kj)). Go back to Step 1.

This algorithm will give a MST connecting each nodal point in the region; hence can be used to define the rural road network in the of rural areas. The obtained MST of the network for the region is shown in figure 6.

5. Discussion

In order to define a minimum travel time rural road network, a methodology composed of two phases is proposed in this paper. The covering approach was found to be useful to identify the nodal points which cover the habitations from the facilities with in desirable distance. The nodal points taken as the habitation having the high VFI value in block level. From the buffer analysis of the existing infrastructure in the study area, it is observed that facilities like primary school, Middle school, High school, ANM center, and Post office cover the maximum habitations with in the 5 KM distance. It shows the accessible levels of these facilities are good in the study area. There is a need to identify the suitable location for providing the public facilities like PHC, cold storage, community health centers, and banks. The definition of linkages to the nodal points in the second phase can form a basic rural road network by connecting the nodal points with minimum travel time path using the network analyst in ArcGIS software. The proposed methodology can be a practical and realistic approach for identifying obligatory points and forming rural road networks in rural areas.

Fig. 6. Optimal rural road network of the study area.

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