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Network evaluation and prioritisation of rural roads using vulnerability analysis

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The extent of a country's rural road network (RRN) is a major determinant of its economic activity and level of poverty. Connectivity to the rural population and the rest of the network are major tasks in the development of RRNs. This study envisages the consolidation of an existing RRN to improve its overall efficiency as a provider of transportation services for people, goods and services. Funding for rural road construction/upgrade is usually a major constraint in developing countries. Hence, the available resources should be effectively used and, for this, a prioritisation method is necessary. Different RRN models for the prioritisation of links for new construction and upgrading works were explored in this study. It is proposed that prioritisation can be achieved, using realistic and practical criteria, by considering two parameters – the population and the vulnerability of a link. Different patterns of road investment were investigated and compared in order to keep total transportation costs to a minimum while keeping within an investment budget constraint.

Notation

A_i	accessibility index of location i
B	fund available to improve road condition
B_j	attractiveness of location j
C_{ij}^S	cost per unit flow
c_{ij}^S	operating cost per unit flow
d_{ij}	distance
$f(c_{ij})$	impedance function
I_{ij}^S	total cost for road upgrading work
L	set of village nodes
O_{ij}^S	operating cost on link
S	surface type
W_{ij}	weight of road link
x_{ij}^S	travel time
z	total transportation cost

1. Introduction

The growth and development of economic activity and major sectors such as health and education depend on the availability of good transport infrastructure. Rural roads are the lifeline of India, with 68.8% of the population living in rural areas, according to the 2011 census. Proper infrastructure planning helps to mitigate poverty, create more employment opportunities and improve people's quality of living. The primary objective of a rural road network (RRN) is to open up access to land, meet individual transport requirements and connect to growth points.

To improve rural road connectivity in India, in 2000 the government of India, under the Ministry of Rural Development, launched a nationwide programme – the *Pradhan Mantri Gram Sadak Yojna-I* (PMGSY-I). The primary objective of PMGSY-I was to provide connectivity, by all-weather roads, to unconnected habitations. In May 2013, with the aim of consolidating the entire RRN, PMGSY-II was launched for the upgrading of existing selected through routes and main rural links. The selection of roads was based on their economic potential and their role in facilitating the growth of rural market centres and rural hubs.

In developing countries, a limited budget is allocated for the construction and maintenance of rural roads, which is usually a major constraint. Hence, a prioritisation method is necessary for effective utilisation of the available resources. Rural road construction is an intervention that raises living standards in deprived rural areas (Gannon and Liu, 1997). The development of infrastructure such as public facilities and road networks has been extensively studied in the past, mostly independently of each other.

Models developed for urban regions are often not suitable for rural areas (Shrestha, 2003) as the socio-economic characteristics, availability of facilities, traffic and other parameters differ. A study on the planning of rural roads and public facility locations in an integrated manner, targeting optimised budget allocation, was thus the main objective of this study.

The vulnerability of a transportation network, a performance measure of a system or component, plays an essential role in the evaluation of a transport network and efficient allocation of resources. Disconnection after a natural disaster is the most severe problem, which has been relatively less addressed in the literature. With a failure in connectivity, many villages, cities or towns can become isolated. There then arise difficulties in rescue, evacuation and post-disaster support. In addition, transportation costs are increased, with economic loss. The severity of weakness in a network will differ from location to location. Identification of the weakest position and critical links in a system in order to prioritise them for improvement projects was the aim of this evaluation.

To address this specific problem, a study on the planning of rural roads targeting optimised budget allocation was conducted. In this paper, an RRN decision model is proposed for the solution of RRN problems with different road surface options considering budget constraints for improvement of the road links to achieve minimum transportation costs.

2. Literature review

There are several methods for prioritisation of road links in the literature. They are generally based on economic returns from the road linkages and social factors. Kumar and Tillotson (1985) considered both construction costs and travel costs, as the total cost is considered to be proportional to the factor person-km.

Haboian (1988) developed a priority system based approach, where direct-access locations were connected to the surrounding arterial system. The method recommended was the identification of service centres by considering geographical area and employment activity. Makarachi and Tillotson (1991) suggested a methodology for the identification of link choice by considering minimising travel and construction costs. Airey and Taylor (1999) suggested a dual-index approach. The first index considered costs per head and the second considered traffic and degree of access change. The highest rank for the link was that with the lowest costs per head link. In this method, the difficultly is estimating the number of trips associated with each connection.

Kumar and Kumar (1999) prioritised road links based on the population served by the link. Sarkar (2003) used the integrated rural accessibility planning (IRAP) methodology was used to collect data for planning works in small areas. The accessibility index can be a valuable tool for prioritisation of road links. The IRAP method is suitable for village-level transport planning based on household information. However, this technique requires a massive volume of data, which is time consuming and costly to gather.

Shrestha (2003) and Jung *et al.* (2008) proposed prioritisation based on traffic flow on the link, estimated using a gravity model. Garg (2008) explained the importance of geographic information systems (GIS) in infrastructure planning, with rural areas prioritised using the weighted index method. In other work, cost efficiency analysis was introduced to prioritise new transport linkages, with the centrality index and the per-kilometre cost of upgrading considered as parameters (Dolidar, 2010).

Taylor *et al.* (2006) suggested that the evaluation index should be based on the accessibility of a node. In that work, the accessibility index of a node was calculated for two different scenarios – under normal conditions and the likely failure of each link, one at a time. The critical link is the link with higher variation in accessibility in a locality at the time of the failure assumption.

Jenelius *et al.* (2006) introduced the concept of a vital link, with the primary decision factor based on a change in total travel cost between link failure and normal conditions. Scott *et al.* (2006) proposed a methodology based on the network robustness index to identify the critical link in a road network. This index was determined by calculating the total change in travel cost after removing a link in the network; higher the value, the higher the criticality.

Kumar (2011) suggested planning rural roads based on upgrading of the rural road, using GIS. The upgrading of rural roads included providing closest facility routes for every village and providing new facilities wherever necessary.

According to Rahman (2018), the planning and prioritisation of rural roads in Bangladesh has two major components. The first component follows a network approach to rural road planning, focusing on access and connectivity; the second component involves prioritisation of road development based on the outcomes of cost–benefit analysis and multi-criteria analysis.

In this study, the prioritisation process was conducted in two phases. Critical links from the network were identified in the first stage. Based on the evaluation indicators, the second stage involved prioritisation of roads and budget allocation for those roads.

3. Method and study area

The process involved in the identification of critical links and the prioritisation of links is shown in Figure 1. The study are was Nellikudur, a *mandal* (sub-district) in the Warangal district of Telangana state, India. It is situated between 79°42′22″E to 79°55′42″E and 17°42′25″N to 17°31′8″N. The total population of Nellikudur *mandal* is 57 384, living in 12 581 houses, spread across 110 villages and 22 *panchayat* (village councils). The connectivity level of Nellikudur (i.e. the percentage of habitations connected to a road) is 54.62%. Photographs of data collection in the field are shown in Figures 2 and 3.

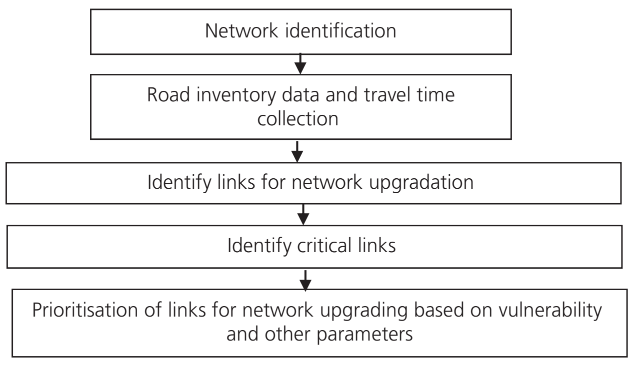

Figure 1. Method

Figure 2. Identification of critical links and missing links from villagers' information

Figure 3. Discussion with Panchayat Raj engineers regarding the road network

4. Identifying the links for network upgrading

The Survey of India toposheet at the scale of 1:50 000 and the PMGSY road network map prepared by Panchayat Raj engineering department were used to collect spatial information of rural roads in the study area. Road inventory details, pavement details, existing cross-drainage structure details and photographs were collected during field observations. Details about missing links were discussed with the villagers and the Panchayat Raj engineers. Links for network connections and upgrading works were identified from both the maps and field data. Details of the network links for upgrading works observed from the field survey are shown in Figure 4.

In the present study, the comfortable speeds of vehicles were observed during field surveys by travelling on each road twice in a year (i.e. before and after the rainy season) in both directions. The pavement condition index (PCI) of the road was calculated according to the PMGSY guidelines (Government of India, 2013). Assessment of the PCI, based on comfortable normal driving speed, as per the PMGSY, is shown in Table 1. The details of links identified for upgrading work as observed from field surveys are presented in Table 2.

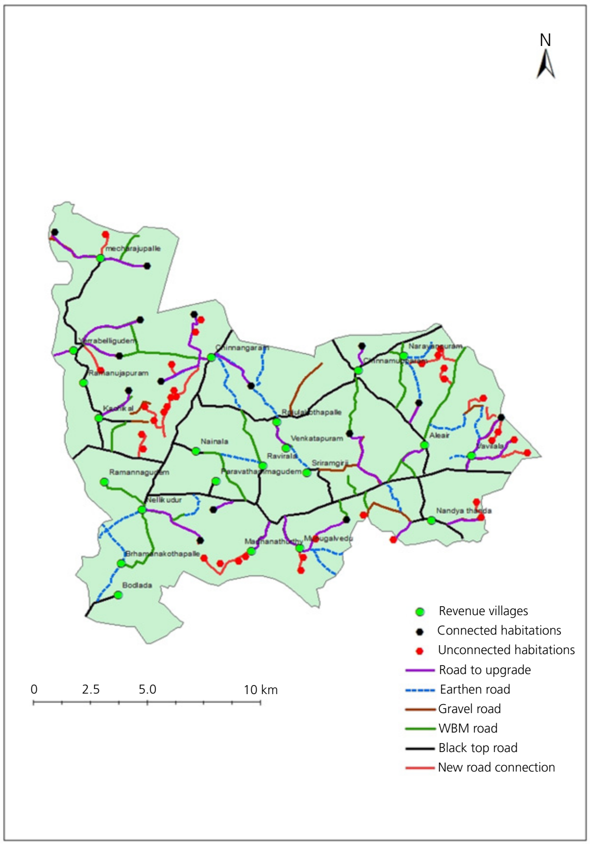

Figure 4. Connectivity level of the study area. WBM, water-bound macadam

Table 1. Assessment of PCI based on comfortable normal driving speed of vehicles

PCI	Normal driving speed: km/h	Road condition
5	Over 40	Very Good
4	30–40	Good
3	20–30	Fair
2	10–20	Poor
1	<10	Very Poor

5. RRN model

The mathematical formulation considers different road surfaces (e.g. water-bound macadam (WBM) and asphalt) in the upgrading of links. The model also allows investigation of public resource allocation to attain the minimum total cost.

5.1 RRN model: upgrading the network

With a constraint on investment budget, the intention of this study was to design infrastructure by keeping total transportation costs to a minimum. Roads identified for upgrading works were identified from the field survey based on the PCI of the road. It was found that the network in the study area generally consists of existing road links that need upgrading to a better surface level.

Table 2. Links identified for upgrading work (1 lakh = 100 000 INR ≈ £100)

Link	Road name	Total population served	Existing surface	Length of road: km	Cost of construction: lakhs
L053	Erraballigudem to Varam Banda thanda	603	Earthen	2	60.0
L055	Kachikal to Thimma thanda	309	WBM	2	100.0
L027	Narsimhulagudem to Dharavath Bheemala thanda	267	Earthen	2.5	75.0
L028	Narsimhulagudem to Nandya thanda	173	Black top	2	36.0
L049	Panchayat Raj (PR) road to Badavath Lakpathi thanda	512	Earthen	3	90.0
L023	PR road to Goplapuram	92	Earthen	2	60.0
L050	PR road to Kothur thanda	393	WBM	2	100.0
L021	PR road to Narayanapuram	736	WBM	1.5	75.0
L044	PR road to Suryanayak thanda thanda	124	Earthen	2	60.0
L043	PR road to Tulasya thanda	232	Earthen	1	30.0
L041	Public Works Department (PWD) road to Hemala thanda	351	Earthen	2	60.0
L061	PWD road to Bojya thanda	380	WBM	1	50.0
L039	PWD road to Laxmipuram	323	WBM	3	150.0
L063	PWD road to Metya thanda	198	Earthen	2	60.0
L060	Rathiram thanda to Nalla Gutta thanda	476	Earthen	2	60.0
L057	Chinnanagaram to Seetharampuram	786	WBM	2.6	130.0
L062	Chinnanagaram to Jama thanda	943	Earthen	2.5	75.0
L022	Rajulakothapally to Venkatapuram	384	WBM	2.5	125.0
L034	PWD road to Bojya Peenya thanda	154	Earthen	2	60.0
L031	PWD road to Panthulu thanda via Munigalaveedu	2913	WBM	4	200.0
L051	PR road to Baduva thanda	287	Earthen	3	90.0
L046	Vavilala to Rajya thanda	552	Earthen	2.5	75.0
L047	PR road to Hemla thanda	80	Earthen	2	60.0
L032	PWD road to Madanthurty	1609	WBM	2	100.0

Table 3. Surface options with approximate costs (1 lakh = 100 000 INR ≈ £100)

Existing surface type	Upgraded surface type	Pipe culvert: lakhs per unit	Causeway: lakhs per unit	Approximate construction cost excluding cross drainage works: lakhs/km
WBM	New black top	2.0	30.0	50.0
Black top	Upgraded black top	2.0	30.0	18.0
Gravel	New WBM	2.0	30.0	15.0
Earthen	New WBM	2.0	30.0	30.0

The model was formed based on the capacitated facility location/network design problem (Melkote and Daskin, 2001), which seeks to minimise the total transportation costs of the population subject to budget and spatial constraints. The model was formulated as follows (Heng *et al.*, 2006).

Minimise

1. $$z = \sum_{S=1}^{4} \sum_{(i,j)\in L} C_{ij}^{S} x_{ij}^{S}$$

The objective function of the model can be rewritten to consider the operating cost with weights assigned to the links (Shrestha *et al.*, 2013):

2. $$z = \sum_{S=1}^{4} \sum_{(i,j)\in L} W_{ij} O_{ij}^{S} x_{ij}^{S}$$

subject to

3. $$\sum_{S=1}^{4} \sum_{(i,j)\in L} I_{ij}^{S} x_{ij}^{S} \leq B$$

4. $$\sum_{S=1}^{4} x_{ij}^{S} = 1 \qquad \forall (i,j) \in L, \quad \forall s \in S$$

5. $$x_{ij}^{S} \in \{0,\ 1\} \qquad \forall (i,j) \in L \quad \forall s \in S$$

where S represents the surface option for the upgrading work, W_{ij} is the weight of the road link between i and j (i, j), C_{ij}^{S} is the cost per unit flow over surface type S, d_{ij} is the distance between i and j, c_{ij}^{S} is the operating cost per unit flow of

Table 4. Weights considered for upgrading work on road links

Link	Total population served, P_1	Total population served-km, P_2	Population served/km, P_3	Proportion of population served: %	Proportion of cumulative person-km: %	Proportion of population served/km: %
L053	603	1206	301.50	4.68	3.63	5.34
L055	309	618	154.50	2.40	1.86	2.74
L027	267	667.5	106.80	2.07	2.01	1.89
L028	173	346	86.50	1.34	1.04	1.53
L049	512	1536	170.67	3.98	4.62	3.02
L023	92	184	46.00	0.71	0.55	0.81
L050	393	786	196.50	3.05	2.36	3.48
L021	736	1104	490.67	5.72	3.32	8.69
L044	124	248	62.00	0.96	0.75	1.10
L043	232	232	232.00	1.80	0.70	4.11
L041	351	702	175.50	2.73	2.11	3.11
L061	380	380	380.00	2.95	1.14	6.73
L039	323	969	107.67	2.51	2.91	1.91
L063	198	396	99.00	1.54	1.19	1.75
L060	476	952	238.00	3.70	2.86	4.21
L057	786	2043.6	302.31	6.10	6.14	5.35
L062	943	2357.5	377.20	7.32	7.09	6.68
L022	384	960	153.60	2.98	2.89	2.72
L034	154	308	77.00	1.20	0.93	1.36
L031	2913	11652	728.25	22.62	35.03	12.90
L051	287	861	95.67	2.23	2.59	1.69
L046	552	1380	220.80	4.29	4.15	3.91
L047	80	160	40.00	0.62	0.48	0.71
L032	1609	3218	804.50	12.50	9.67	14.25

travelling over surface type S on link (i, j), O_{ij}^S is the operating cost on link (i, j) over surface type S ($O_{ij}^S = d_{ij}c_{ij}^S$), B is the fund available to improve the road condition and I_{ij}^S is the total cost for the upgrading work of road (i, j) with a specific surface type. The decision variables in this model are $x_{ij} = 1$ if link (i, j) is to be built with surface type S and 0 otherwise.

Roads upgraded with different surface options and the construction costs of upgrading work per kilometre are presented in Table 3.

The construction cost of an earthen road for new connections is approximately 10 lakhs/km (1 lakh = 100 000 INR ≈ £100). The construction cost per kilometre was calculated from the line estimation from standard bidding document 2016–17 and from the online management, monitoring and accounting system for PMGSY (NRRDA, 2015).

5.2 Indicators for rural road evaluation

Road links are generally prioritised based on economic analysis. The RRN model uses a simple parameter – the population served with unit investment – for the prioritisation of rural roads. As mentioned earlier in the paper, accessibility to people is considered a benefit of the investment in rural roads.

In this study, planning for the prioritisation of links was achieved by considering two different approaches – the population considered as a proxy and vulnerability analysis.

Table 5. Priority list for upgrading work

	Ranking according to			
Link	Population served by link, P_1	Person-km served, P_2	Population served/km, P_3	Vulnerability analysis, P_4
L053	6	8	6	17
L055	12	13	8	5
L027	17	16	19	14
L028	16	17	17	2
L049	10	6	14	8
L023	22	22	23	22
L050	7	10	7	6
L021	5	12	5	21
L044	20	19	20	7
L043	24	24	21	11
L041	14	14	13	24
L061	18	21	10	16
L039	9	5	12	3
L063	21	20	22	10
L060	15	15	15	11
L057	3	3	4	4
L062	4	4	3	23
L022	8	7	9	19
L034	19	18	18	20
L031	1	1	1	9
L051	13	11	16	15
L046	11	9	11	13
L047	23	23	24	18
L032	2	2	2	1

Table 6. Interventions in network links at different budget levels based on P_1 (1 lakh = 100 000 INR ≈ £100). P = possible within budget for upgrading work; N = not possible within budget for upgrading work

Budget available: lakhs	Link																							
	L31	L32	L57	L62	L21	L53	L50	L22	L39	L49	L46	L55	L51	L41	L60	L28	L27	L061	L34	L044	L063	L023	L047	L043
200	P	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N
400	P	P	N	P	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N
600	P	P	P	P	P	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N
800	P	P	P	P	P	P	P	N	N	N	N	N	N	N	N	N	N	P	N	N	N	N	N	N
1000	P	P	P	P	P	P	P	P	N	P	N	N	N	N	N	N	N	N	N	N	N	N	N	P
1200	P	P	P	P	P	P	P	P	P	P	P	N	N	N	N	N	N	N	N	N	N	N	N	N
1400	P	P	P	P	P	P	P	P	P	P	P	P	P	N	N	N	N	N	N	N	N	N	N	N
1600	P	P	P	P	P	P	P	P	P	P	P	P	P	P	P	P	N	N	N	N	N	N	N	P
1800	P	P	P	P	P	P	P	P	P	P	P	P	P	P	P	P	P	P	P	N	N	N	N	P
2000	P	P	P	P	P	P	P	P	P	P	P	P	P	P	P	P	P	P	P	P	P	P	P	N
2200	P	P	P	P	P	P	P	P	P	P	P	P	P	P	P	P	P	P	P	P	P	P	P	P

Table 7. Interventions in network links at different budget levels based on P_2 (1 lakh = 100 000 INR ≈ £100). P = possible within budget for upgrading work; N = not possible within budget for upgrading work

Budget available: lakhs	Link																							
	L31	L32	L057	L062	L021	L053	L050	L022	L039	L049	L046	L055	L051	L041	L060	L028	L027	L061	L034	L044	L063	L023	L047	L043
200	P	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N
400	P	P	N	P	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N
600	P	P	P	P	N	P	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N
800	P	P	P	P	P	P	N	N	N	N	N	N	N	N	N	N	N	N	N	N	P	N	N	N
1000	P	P	P	P	P	P	P	P	N	N	N	N	N	P	N	N	N	N	N	N	N	N	N	N
1200	P	P	P	P	P	P	P	P	P	P	N	P	N	N	N	N	N	N	N	N	N	N	N	N
1400	P	P	P	P	P	P	P	P	P	P	P	P	P	N	N	N	N	N	N	N	N	N	N	N
1600	P	P	P	P	P	P	P	P	P	P	P	P	P	P	P	P	N	N	N	N	N	N	N	N
1800	P	P	P	P	P	P	P	P	P	P	P	P	P	P	P	P	P	P	P	N	N	N	N	P
2000	P	P	P	P	P	P	P	P	P	P	P	P	P	P	P	P	P	P	P	P	P	P	P	N
2200	P	P	P	P	P	P	P	P	P	P	P	P	P	P	P	P	P	P	P	P	P	P	P	P

Table 8. Interventions in network links at different budget levels based on P_3 (1 lakh = 100 000 INR ≈ £100). P = possible within budget for upgrading work; N = not possible within budget for upgrading work

Budget available: lakhs	Link																							
	L031	L032	L062	L057	L021	L053	L050	L055	L022	L061	L046	L039	L041	L049	L060	L051	L028	L034	L027	L044	L043	L063	L023	L047
200	P	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N
400	P	P	P	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N
600	P	P	P	P	P	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N
800	P	P	P	P	P	P	P	N	N	P	N	N	N	N	N	N	N	N	N	N	N	N	N	N
1000	P	P	P	P	P	P	P	P	P	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N
1200	P	P	P	P	P	P	P	P	P	P	P	N	P	N	N	N	P	N	N	N	N	N	N	N
1400	P	P	P	P	P	P	P	P	P	P	P	P	P	P	N	N	N	N	N	N	N	N	N	N
1600	P	P	P	P	P	P	P	P	P	P	P	P	P	P	P	P	P	N	N	N	N	N	N	N
1800	P	P	P	P	P	P	P	P	P	P	P	P	P	P	P	P	P	P	P	P	N	N	N	N
2000	P	P	P	P	P	P	P	P	P	P	P	P	P	P	P	P	P	P	P	P	P	P	P	P

Table 9. Interventions in network links at different budget levels based on link vulnerability (P_4) (1 lakh = 100 000 INR ≈ £100). P = possible within budget for upgrading work; N = not possible within budget for upgrading work

Budget available: lakhs	Link																							
	L031	L032	L057	L062	L021	L053	L050	L022	L039	L049	L046	L055	L051	L041	L060	L028	L027	L061	L034	L044	L063	L023	L047	L043
200	P	P	N	N	N	N	P	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N
400	P	P	P	N	P	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N
600	P	P	P	P	P	N	P	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N
800	P	P	P	P	P	P	P	P	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N
1000	P	P	P	P	P	P	P	P	P	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N
1200	P	P	P	P	P	P	P	P	P	P	P	P	P	N	N	N	N	N	N	N	N	N	N	N
1400	P	P	P	P	P	P	P	P	P	P	P	P	P	P	P	N	N	N	N	N	N	N	N	N
1600	P	P	P	P	P	P	P	P	P	P	P	P	P	P	P	P	P	P	N	P	N	N	N	N
1800	P	P	P	P	P	P	P	P	P	P	P	P	P	P	P	P	P	P	P	P	P	N	N	N
2000	P	P	P	P	P	P	P	P	P	P	P	P	P	P	P	P	P	P	P	P	P	P	P	P

5.2.1 Population considered as a proxy

Prioritisation of links is necessary to implement a connection in a network for both types of links – either new links or upgraded links of the existing network. The parameters considered in this approach are

- population served by the link (P_1)
- person-km (P_2)
- population served/km (P_3).

The weights calculated from the above parameters for upgrading links are presented in Table 4.

5.2.2 Vulnerability of link (P_4)

In this study, the vulnerability of each link was determined based on the accessibility index. Thus, the vulnerability of a link was determined by the reduction in accessibility of the network, as measured by a standard index of accessibility (Taylor and D'Este, 2004), if the link is removed from the network.

The Hansen integral accessibility index (Hansen, 1959) provides an overall measure of the accessibility of one location to a set of other locations. This index is useful in assessing accessibility between locations. The Hansen integral accessibility index is given by:

6. $$A_i = \sum_{j=1} B_j f\,(c_{ij})$$

where A_i is the accessibility index for location (village) i, B_j is the attractiveness of location (village) j (in this research B_j was taken as the facility index of village j) and $f(c_{ij})$ is an impedance function, calculated as the reciprocal of the travel time between i and j ($1/x_{ij}$).

The accessibility index of a node was calculated for two different scenarios – under normal conditions and with the possible failure of each link, one at a time. For each condition, the travel time was observed from field studies. The vulnerability was calculated by the change in accessibility after failure of a link. The critical link was defined as the link with the higher vulnerability value.

6. Model application and validation

As already noted, Nellikudur *mandal* was considered as a case study for this analysis. This sub-district has a 54.6% connectivity level – the lowest connectivity of road networks in the Warangal district. From the calculated link weights, the priority list for new connections and upgrading work is presented in Table 5.

Different methods for prioritisation were applied in the model. The interventions for the network links with different budget levels are shown in Tables 6–9. The percentages of roads upgraded within the available budget based on the different methods are shown in Table 10.

Table 10. Percentage of roads upgraded using different methods (1 lakh = 100 000 INR ≈ £100)

Budget available: lakhs	Percentage of roads upgraded within the available budget based on			
	P_1	P_2	P_3	P_4
200	4	4	4	8
400	13	13	13	17
600	21	21	21	25
800	33	29	33	33
1000	42	38	38	38
1200	46	46	54	54
1400	54	54	58	63
1600	71	67	71	79
1800	83	83	79	88
2000	96	96	100	100
2200	100	100	—	—

7. Conclusions

The priority lists of roads requiring upgrading work based on parameters P_1, P_2 and P_3 were similar. All of these methods considered the population served as the key parameter. The results show that a greater percentage of roads would be upgraded with the same available budget when the priority list is instead based on the vulnerability of the link (P_4). The model proposed in this paper provides a portfolio of suggested links for road network improvements and offers solutions for different budget levels, optimising transportation costs in an RRN with different types of road surface considered for upgrading. The proposed decision model is thus a practical and realistic decision support tool for the study and development of road networks in rural areas. Using this method, it is easier for authorities or decision makers to select the most appropriate set of links for intervention within the available budget.

REFERENCES

Airey T and Taylor G (1999) Prioritization procedure for improvement of very low-volume roads. *Transportation Research Record* **1652**: 175–180.

Dolidar (Department of Local Infrastructure Development and Agricultural Roads) (2010) *Rural Roads Record*. Dolidar, Kathmandu, Nepal.

Gannon C and Liu Z (1997) *Poverty and Transport*. World Bank, Washington, DC, USA, Transportation, Water and Urban Development discussion paper series no. TWU 30, p. 65

Garg PK (2008) Spatial planning of infrastructural facilities in rural areas around Roorkee, Uttarakhand, India. *Integrating Generations FIG Working Week 2008 Stockholm, Sweden*, pp. 14–19.

Government of India (2013) *Pradhan Mantri Gran Sadak Yojana (PMGSY) Programme Guidelines (PMGSY-II), August 2013*. Government of India, New Delhi, India. See http://ommas.nic.in (accessed 30/04/2021).

Haboian KA (1988) Planning guidelines for transit way access. *Transportation Research Record* **1202**: 9–15.

Hansen WG (1959) How accessibility shapes land use. *Journal of the American Institute of Planners* **25**: 73–76.

Heng S, Hirobata Y and Nakanishi H (2006) An integrated model of rural road network design and multi public facility locations in developing countries. *The 34th Conference of Infrastructure Planning, Japan Society of Civil Engineers, Takamatsu, Japan.*

Jenelius E, Petersen T and Mattsson LG (2006) Importance and exposure in road network vulnerability analysis. *Transportation Research Part A: Policy and Practice* **40(7)**: 537–560.

Jung WS, Wang F and Stanley HE (2008) Gravity model in the Korean highway. *EPL (Europhysics Letters)* **81(4)**: 48005.

Kumar A and Kumar P (1999) User-friendly model for planning rural road. *Transportation Research Record* **1652**: 31–39.

Kumar A and Tillotson HT (1985) A planning model for rural roads in India. *Proceedings of Seminar on Roads and Road Transport in Rural Areas, New Delhi, India*.

Kumar P (2011) Upgradation planning of rural roads using GIS and GPS. *Indian Highways* 3**9(8)**: 33–46.

Makarachi AK and Tillotson HT (1991) Road planning in rural areas of developing countries. *Europian Journal of Operational Research* **53(3)**: 279–287.

Melkote S and Daskin MS (2001) Capacitated facility location-network design problems. *European Journal of Operational Research* **129(3)**: 481–495.

NRRDA (National Rural Roads Development Agency) (2015) *Standard Bidding Document For Pradhan Mantri Gram Sadak Yojana (PMGSY), Construction & Maintenance*. National Rural Roads Development Agency, Ministry of Rural Development, Government of India, New Delhi, India.

Rahman M (2018) *Planning and Prioritisation of Rural Roads in Bangladesh*. Department of Urban and Regional Planning (DURP), ReCAP Project Management Unit Cardno Emerging Market (UK) Ltd, London, UK.

Sarkar AK (2003) Application of IRAP in Rajasthan-India. In *Asist Asia Pacific Mainstreaming Poverty Reduction Strategies, Integrated Rural Accessibility Planning (IRAP)*. International Labour Organization, Bangkok, Thailand, pp. 126–159.

Scott DM, Novak DC, Aultman-Hall L and Guo F (2006) Network robustness Index: a new method for identifying critical links and evaluating the performance of transportation networks. *Journal of Transport Geography* **14(3)**: 215–227.

Shrestha CB (2003) Developing a computer-aided methodology for district road network planning and prioritization in Nepal. *International Journal of Transport Management* **1(3)**: 157–174.

Shrestha JK, Benta A, Lopes RB and Lopes N (2013) A methodology for definition of road networks in rural areas of Nepal. *World Academy of Science, Engineering and Technology: International Journal of Civil and Environmental Engineering* **7(6)**: 422–426.

Taylor MAP and D'Este GM (2004) Critical infrastructure and transport network vulnerability: developing a method for diagnosis and assessment. *Proceedings of the Second International Symposium on Transportation Network Reliability (INSTR04), Christchurch, New Zealand*, pp. 96–102.

Taylor MAP, Sekhar SVC and D'Este GM (2006) Application of accessibility based methods for vulnerability analysis of strategic road networks. *Networks and Spatial Economics* **6(3–4)**: 267–291.

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