An Integrated Model of Rural Road Network Design and Public Facility Location in Developing Countries

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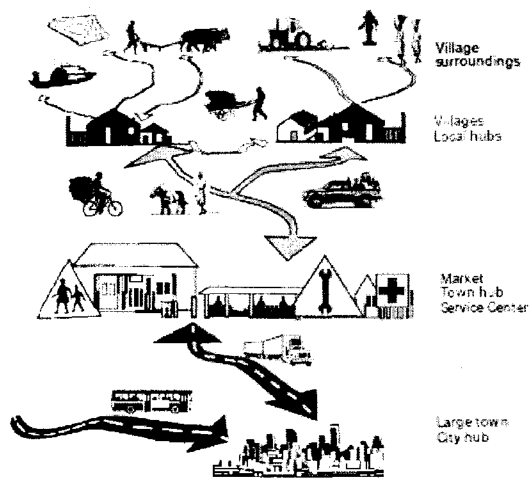
1. Introduction

In developing countries, rural transport infrastructure network is the lowest level of the physical transport chain that connects the rural population, and therefore the majority of the poor, to their farms, local markets, and social services, such as schools and health centers as shown in Figure 1. Poor geographical accessibility has made rural residents isolated from opportunities to improve quality of life. Under this background, claims have been made that by reducing isolation, better roads and facility locations reduce vulnerability and dampen income variability. It is vital to determine the network design and facility locations simultaneously as there is significant interaction of the network with facility locations [1], [2]. It would assist decision makers on how to effectively make a choice between using limited funds to build a school, expand a hospital, or improve a road link [1]. Therefore, this study develops a model to economically optimize the rural transport network configuration through concurrently allocating additional rural public facilities and upgrading the rural road link to the existing network.



Source: International Focus Group on Rural Road Engineering

Figure 1: A Rural Transport System

2. Problem Definition

In Figure 2, road links with dotted lines are existing tracks or roads in poor condition; and are considered as candidate links for improvement with options of road surface types (earth, gravel or asphalt). Each village nodes are taken into account as candidate sites for allocating more facilities (markets, schools and health centers). Within a national budget constraint, this model aims to minimize the total travel cost of the rural population. Furthermore, the model deals with access to the nearest main roads, and access to the nearest public facilities. Moreover, in the rural areas of developing countries traffic flows are low and congestion may be assumed to have no effect on travel time. Consequently, this study differs from much of previous work on transport network optimization in two major respects: a) congestion and the effect of traffic volume have not been considered, even though this is one of the main concerns in developed countries; b) the specific objective is to connect all villages to the network regardless of their sizes. Additionally, the model assumes each village demand is restrictively assigned to a single coresponding facility.

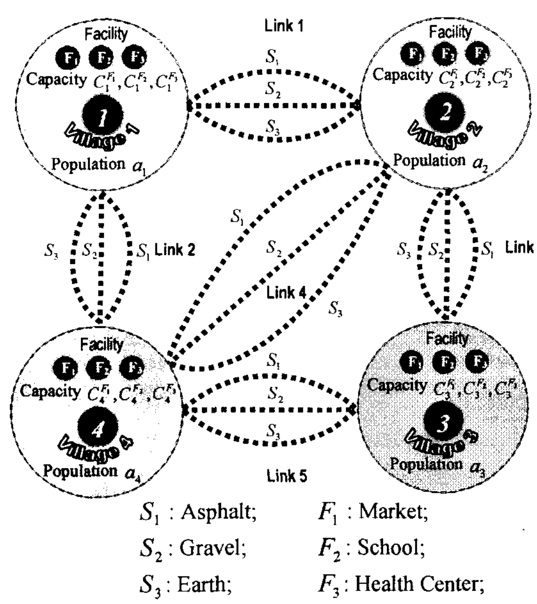


Figure 2: Rural Road Network Design and Facility Locations

3. Model Formulation

The model formulation in this study begins with an examination of the interacting process between the road network and facility locations, which is illustrated in Figure 3 below.

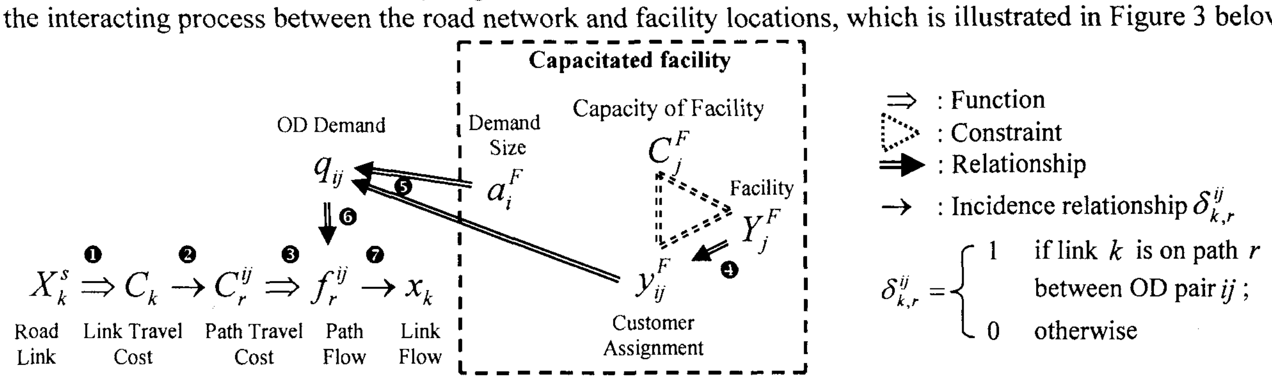


Figure 3: Interaction of the Network with Facility Locations

❶: $C_k = \sum_{s=1}^{3} d_k.c_k^s.X_k^s$, where C_k - Travel cost per unit flow on link k; c_k^s - Travel cost per unit flow and distance of traveling over surface type s ($s = 1, 2, 3$ for asphalt, gravel and earth) on link k; d_k - Distance of link k from the i^{th} node to j^{th} node;

❷: $C_r^{ij} = \sum_{k\in L} \delta_{k,r}^{ij}.C_k$, C_r^{ij} - Travel cost on path r connecting OD pair ij; L- Set of links in the network;

❸: Network user's travel behavior (minimum cost path with all-or-nothing traffic assignments);

❹: Demands assigned to the nearest selected facility;

❺: $q_{ij}^F = y_{ij}^F.a_i^F$, q_{ij}^F - Trip rate between node i and j for facility F; a_i^F -Size of demand at node i for facility F;

❻: $\sum_{r\in K_{ij}} f_r^{ij} = q_{ij}$, f_r^{ij} - Flow on path r connecting OD pair ij; K_{ij} - Set of paths connecting OD pair ij;

❼: $x_k = \sum_{i,j\in O,D} \sum_{r\in K_{ij}} f_r^{ij}\delta_{k,r}^{ij}$, x_k - Flow on link k; O, D- Set of origin and destination nodes respectively.

The decision variables are:

$$Y_j^F = \begin{cases} 1 & \text{if a facility type } F \text{ is located at node } j; \\ 0 & \text{otherwise} \end{cases} \quad X_k^s = \begin{cases} 1 & \text{if a link } k \text{ is constructed with surface type } s; \\ 0 & \text{otherwise} \end{cases} \quad y_{ij}^F = \begin{cases} 1 & \text{if demand at node } i \text{ is assigned to a facility } F \text{ located at node } j. \\ 0 & \text{otherwise} \end{cases}$$

The network design problem which seeks to minimize total transportation costs subject to budget and spatial constraints can be formulated as follows:

$$\text{Minimize} \sum_{k\in L} C_k.x_k \quad (1)$$

Subject to main constraints as follows:

$$\sum_{F=1}^{3}\sum_{j\in N} AC_j^F.Y_j^F + \sum_{s=1}^{3}\sum_{k\in L} CC_k^s.X_k^s \le B \quad (2) \qquad \sum_{i\in N} a_i^F.y_{ij}^F - C_j^F.Y_j^F \le 0 \quad (3)$$

$$y_{ij}^F - Y_j^F \le 0 \quad (4) \qquad \sum_{k=1}^{m} y_{i[k]_i}^F - Y_{[m]_i}^F \ge 0, m = 1,..., N-1 \quad (5)$$

$$\sum_{s=1}^{3} X_k^s = 1 \quad (6) \qquad \sum_{j\in N} y_{ij}^F = 1 \quad (7)$$

$$y_{ij}^F \le y_{jj}^F \quad (8) \qquad y_{ij}^F \in \{0,1\}; Y_j^F \in \{0,1\}; X_k^S \in \{0,1\} \quad (9)$$

Where x_k - Flow on link k; C_k - Travel cost per unit flow on link k; AC_j^F - Fixed allocation cost of a facility F at node j; CC_k^s - Cost of network improvement link k with surface type s; C_j^F - Capacity of a facility F at node j; a_i^F - Demand size at node i for facility F; B - Total investment budget; L, N- Set of links and nodes respectively.

The objective function minimizes total transportation cost. Eq. (2) is a budget constraint. (3) restricts that the total demand assigned to a facility must not exceed the capacity of the facility. (4) states that demands can only be assigned to open facilities. (5) ensures that demands are assigned to the nearest selected facility; $[k]_i$ - Index of the k^{th} farthest candidate location from demand node i. Hence, this constraint states that if the m^{th} closest facility to demand node i is opened then demand node i must be assigned to that facility or to a closer facility. (6) defines that one link can be paved with only one type of surface. (7) requires that each demand node be assigned to exactly one facility. (8) Eliminates the possibility of cross haulage by restricting assignments to only communities which assign to themselves: $y_{ij}^F + \sum_{k=1, k\neq j}^{n} y_{jk}^F \le 1$. If village i is assigned to a central facility in village j ($y_{ij}^F = 1$), then village j cannot reassign the people to village k ($y_{jk}^F \le 0$ for the people to village k) $\Rightarrow y_{ij}^F \le y_{jj}^F$. (9) are integrality and non-negative constraints.

4. Conclusion

The research model coping with the improvement of road network, along with provision of other public facilities, is expected to be a useful approach to invest the restricted public resources efficiently to achieve economic goals in the developing nations. The result from this work will be presented during the presentation.

References

[1] Daskin, M.S., Owen, S.H., 1999. Location Models in Transportation. In: Hall, R.W. (Eds.), Handbook of Transportation Science. Kluwer Academic Publishers, Norwell, MA, ch.10, pp. 311-360.

[2] Melkote, S., Daskin, M.S., 2001. An integrated model of facility location and transportation network design. Transportation Research Part A 35, 515-538.