

Optimal Design of Bus Routes and Frequencies for Ahmedabad

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ABSTRACT

A method is developed to simultaneously select routes and assign frequencies for a bus transit system. The method is intended (a) to concentrate the flow of passengers on the road network in such a way that the sum of passenger riding-time cost and operation cost is minimized, (b) to generate a large set of possible bus routes that satisfy certain constraints, and (c) to simultaneously select the routes and their frequencies so that the number of transfers saved in the network is maximized. Heuristics are used for the concentration of flow and generation of routes, and linear programming is used to select routes and their frequencies. The model was applied to the design of a bus transit system for the city of Ahmedabad. Four alternative networks with 514, 492, 426, and 402 links, respectively, were evaluated for the concentration of passenger flows, and the minimum cost (riding-time cost plus operation cost) was obtained for the network of 426 links. This network was used to generate 457 feasible routes. A total of 421 turning movements for the network was identified. The optimal routes and their frequencies were obtained by the linear programming model for three different operating fleet sizes of 670, 750, and 790 buses, respectively.

Ahmedabad, population 2.1 million, is the sixth largest metropolis in India and is the largest industrial city in the state of Gujarat. The city is accessible by seven major highways and five major rail links, both broad and meter gauge, from different parts of the state and the country. Because of its great accessibility, the city has grown concentrically (1). The bus transit system in the city is operated by Ahmedabad Municipal Transport Service (AMTS). AMTS operates 191 bus routes with an operating fleet of 670 buses. Approximately 0.85 million passengers per day are served by 10,600 scheduled bus trips. Average route length is 8 km (1). The transit network consists of 134 important nodes. Transit network expansion has largely been the result of sociopolitical demands in the absence of a well-defined route location policy (1,2). Increases in routes inconsistent with the fleet size have resulted in parallel operations, low load factors, and low frequencies. As a result nearly one-third of the existing routes are uneconomical.

A study of the literature on the various models of bus transit planning (3-8) indicates that the generation of routes and scheduling of vehicles are generally done sequentially. On the basis of the given desired travel matrix, the routes are first generated one at a time. Routes are evaluated without considering the routes already accepted for the

network. This neglects, to a great extent, the interactions between the transit routes. The scheduling of vehicles on the routes is done after all the routes in the network have been determined.

This study has developed a method whereby the selection of routes and the assignment of frequencies are done simultaneously for the bus transit system. The method is a combination of heuristic search and programming models and has been applied in the optimal design of the bus transit network for Ahmedabad (9). The model structure is shown in Figure 1.

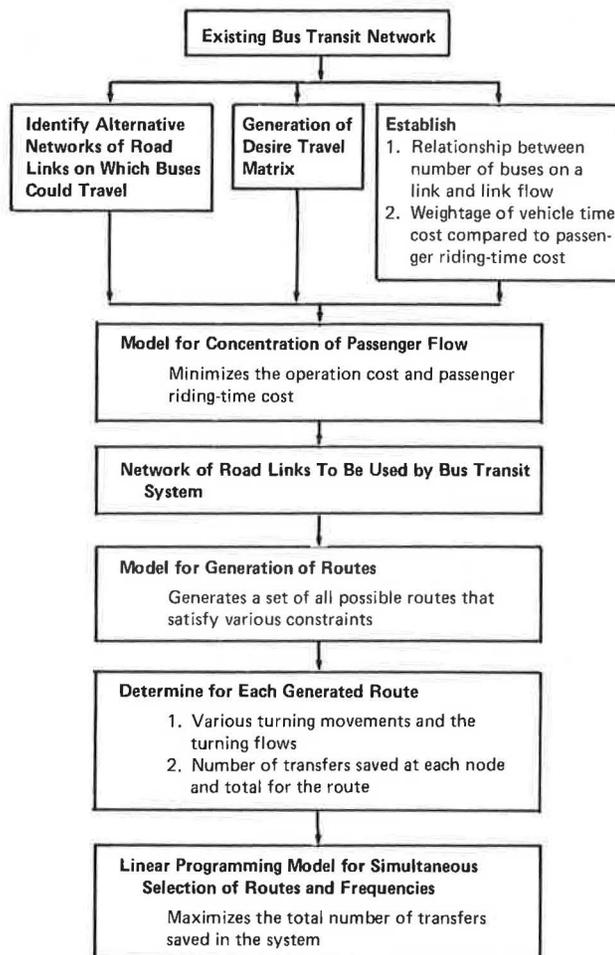


FIGURE 1 Structure of the model.

MODEL FOR CONCENTRATION OF PASSENGER FLOW

The model estimates where the passengers are expected to travel in the optimal route system. If all the passengers travel along their shortest paths, this would imply an extremely dispersed route network with low vehicle use and many vehicle hours. On

the other hand if the vehicles are filled to capacity, the implication is that passengers are concentrated in large flows and thus have to make substantial detours from their shortest paths, resulting in increased riding time. To reach a reasonable compromise between these two extremes, the sum of operation cost and passenger riding-time cost is minimized for the fixed desired origin-destination (O-D) matrix.

Let RT_i be the riding time on link i and $LKFLOW_i$ the passenger flow in unit time on link i . Then the total riding time for all the passengers is $\sum_i RT_i \cdot LKFLOW_i$ and the total vehicle time for the network is $\sum_i RT_i \cdot NOBUS_i$ where $NOBUS_i$ is the number of bus trips to be made in a unit time on link i . The objective function is

$$\text{Minimize } Z_1 = \sum_i RT_i \cdot LKFLOW_i + \sum_i RT_i \cdot NOBUS_i \cdot W \quad (1)$$

subject to satisfaction of given travel demand, where W is the value of vehicle time compared to the riding time of passengers.

The number of trips to be made in a unit time on a link $NOBUS_i$ depends on the passenger flow on that link, $LKFLOW_i$. Some studies (8,10,11) indicate that $NOBUS_i$ is directly proportional to the square root of passengers on a link. In the absence of any such relationship for Indian cities, the average link flow of passengers on a route for all the 191 routes is related to the existing number of bus trips on that route as

$$NOBUS_i = 0.137LKFLOW_i^{0.795} \quad R^2 = 0.88 \quad (2)$$

where $NOBUS_i$ is the number of bus trips to be made in a unit time on link i and $LKFLOW_i$ is the flow of passengers in unit time on link i .

Next, to rationalize the relationship between the value of vehicle time and that of the riding time of passengers, the following equation is developed:

$$W = BUSKMH \cdot KMCOST/VT \quad (3)$$

where

- W = value of vehicle time relative to that of passenger riding time,
- $BUSKMH$ = average kilometers traveled by the bus in an hour,
- $KMCOST$ = operating cost of a bus per kilometer, and
- VT = value of the riding-time hours of the riders.

The operating cost ($KMCOST$) per bus kilometer is found by considering salaries, allowances, fuel and oil consumptions, repair and spare parts plus other overhead charges, depreciation, and so forth. The value of a riding-time hour (VT) of the passenger is found by estimating the average income of captive users. The average bus-kilometers traveled per hour ($BUSKMH$) is obtained from the existing data on bus speeds on various links of the network. The mean value of W as estimated as 15.

The objective function (Equation 1) can be written as

$$Z_1 = \sum_i RT_i \cdot LKFLOW_i + \sum_i RT_i \cdot 0.137LKFLOW_i^{0.795} W \quad (4)$$

After substituting the values of $NOBUS_i$ and W from Equations 2 and 3, respectively, the objective function is

$$\begin{aligned} \text{Minimize } Z_1 &= \sum_i LKFLOW_i \cdot RT_i [1 \\ &\quad + (2.055/LKFLOW_i^{0.205})] \\ &= \sum_i LKFLOW_i \cdot T_i^* \end{aligned} \quad (5)$$

where

$$T_i^* = RT_i [1 + (2.055/LKFLOW_i^{0.205})] \quad (6)$$

To obtain the minimum value of the nonlinear objective function a heuristic algorithm is used. A backward approach (i.e., deleting links from a fine-meshed network) appears to give better results than a forward approach (i.e., adding links to the minimal spanning tree). Initially, all of the 514 unidirectional links on which buses can travel are taken and then the number is reduced to that of the coarse-meshed network (402 links). For this study, four networks are tested. The heuristic algorithm used for each of the four different networks to obtain total cost in terms of time is as follows:

1. The shortest paths for all the O-D pairs are obtained. In the first iteration, only riding time (RT_i) is considered, but in subsequent iterations the sum of riding and vehicle time (as revised in the subsequent steps; i.e., T_i^*) is used. Using the shortest paths, all the link flows ($LKFLOW_i$) are estimated for the given O-D matrix.

2. The time to traverse link i (T_i) is revised (T_i^*) based on the link flow ($LKFLOW_i$) using the following relationship:

$$T_i^* = (RT)_i [1 + (2.055/LKFLOW_i^{0.205})]$$

3. The revised time (T_i^*) obtained in Step 2 is used to find the shortest paths for all the O-D pairs, and a revised value of the link flow ($LKFLOW_i^*$) is obtained.

4. The total link time (i.e., $LT_i = T_i^* \cdot LKFLOW_i^*$) and total time for the network (i.e., $TLT = \sum_i T_i^* \cdot LKFLOW_i^*$) are computed.

5. If any link time (i.e., LT_i) or total link time (TLT) gets changed in Step 4, the procedure is repeated starting with Step 2; otherwise it is stopped.

This procedure is repeated for all four networks. It is observed that generally about four iterations need to be performed for each network to obtain the convergence of the total link time. The results (Table 1) indicate that by deleting some links from the starting network of 514 links, the total time is reduced until a certain stage is reached and then total time starts increasing. The minimum time is for the network with 426 links. This network is considered in the further analysis.

MODEL FOR GENERATION OF ROUTES

This model generates a large set of all possible routes through a heuristic algorithm that considers the following constraints to avoid the possibility of generating some unfeasible routes:

1. The length of the route should not be less than 2.0 km.
2. The path of the route between two terminating stations should not meander excessively from the shortest path. The length of the path of a route

TABLE 1 Concentration of Passenger Flows in Alternative Networks

Network No.	No. of Links in Network	Iteration			
		1 (total riding time in min)	2 (total riding + vehicle time in min)	3 (total riding + vehicle time in min)	4 (total riding + vehicle time in min)
1	514	11,897,919	13,704,568	13,718,200	13,720,158
2	492	11,898,220	13,705,189	13,718,554	13,720,282
3	426	11,903,306	13,723,576	13,717,526	13,717,565
4	402	11,954,794	13,773,298	13,767,130	13,773,238

should not be greater than twice the shortest distance between the termini.

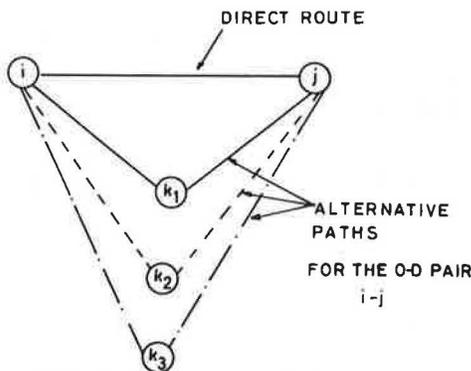
3. There should not be any backtracking on the route.

In cases where there are a number of intermediate stations on the shortest path between two termini, there may be an extremely large number of alternative paths that may be formulated. It is desirable that the nodes inserted be selected rationally without leaving the combinations that satisfy the basic requirements.

The network consists of 134 nodes and there are 8,911 different O-D pairs that are to be served by the routes. To determine the terminating stations, it is desirable that the routes run through the major generators. Routes are also generated from other stations to satisfy the entire O-D matrix. In some studies (3,5,7) the routes between the major generators are fixed first, but the difficulty is that of satisfying the various requirements of a route in an optimal way. In this method the paths of the routes between closer terminals are first determined and then expanded for the distant ones. The already developed paths are of great significance in the location of the paths of the routes between the distant termini.

This is a four-step procedure:

1. All the O-D pairs that have direct links between them are first selected for route generation. Let *i* and *j* be the nodes directly connected by link *i-j*. Alternative paths for this route between *i* and *j* can be found by inserting the intermediate nodes (e.g., *k*) such that path *i-k-j* satisfies the requirements; namely, the length of the path *i-k-j* is less than twice the shortest distance between nodes *i* and *j* (Figure 2). In this way all possible intermediate nodes *k* (*k*₁, *k*₂, . . .) that can be inserted are analyzed.

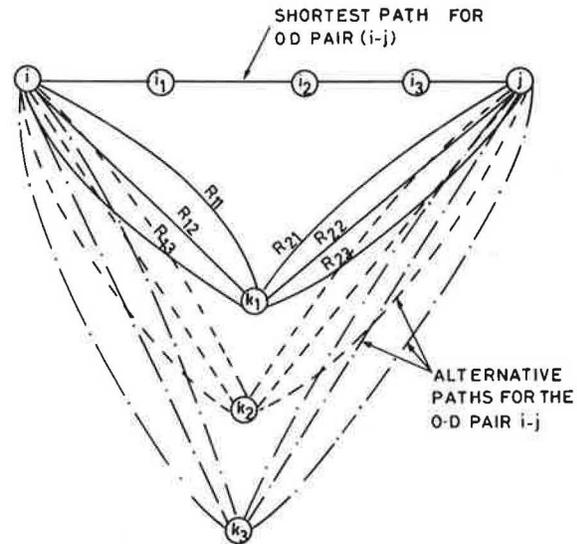


IF $SD(i,k)+SD(k,j) \geq 2.0 * SD(i,j)$
 THEN NODE $k(k=k_1, k_2, k_3, \dots)$ IS
 INSERTED OTHERWISE NOT.

FIGURE 2 Alternative paths for directly connected O-D pair.

2. The O-D pairs, not directly connected, are divided into various groups according to the shortest distance through them. In this study, the O-D pairs are divided into nine different groups starting with 1.5 to 20 km. The generation of the routes is first done for the closer O-D pairs and then expanded by using information on previously generated routes.

3. For a given group of O-D pairs the alternative paths of the route are generated as follows: Let *i-j* be the O-D pair having stops *i*₁, *i*₂, *i*₃, . . . on the shortest path between them. Let *k*₁ be the node to be inserted such that the shortest path between *i* and *j* via *k* [i.e., $SD(i,k_1) + SD(k_1,j)$] is less than 1.5 times the shortest distance between *i* and *j* [$SD(i,j)$]. All the previously established routes between *i* and *k*₁ (i.e., *R*₁₁, *R*₁₂, *R*₁₃, . . .) and between *k*₁ and *j* (i.e., *R*₂₁, *R*₂₂, *R*₂₃, . . .) are considered (Figure 3). All the combinations of the routes between *i* and *k*₁ and *k*₁ and *j* are analyzed so that the total length of the selected path between *i* and *j* does not exceed twice the shortest distance between *i* and *j*.



IF $SD(i,k)+SD(k,j) \geq 1.5 * SD(i,j)$
 THEN NODE $k(k=k_1, k_2, k_3, \dots)$ IS
 INSERTED OTHERWISE NOT.

FIGURE 3 Alternative paths for O-D pair not directly connected.

The procedure is repeated for all the possible intermediate nodes (i.e., *k*₁, *k*₂, *k*₃, . . .) to be inserted, and all the feasible routes are stored.

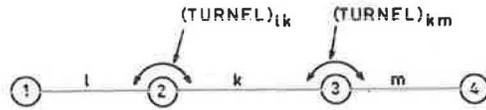
4. Step 3 is repeated for all the O-D pairs of a group.

This heuristic procedure generated 457 possible routes for the Ahmedabad network.

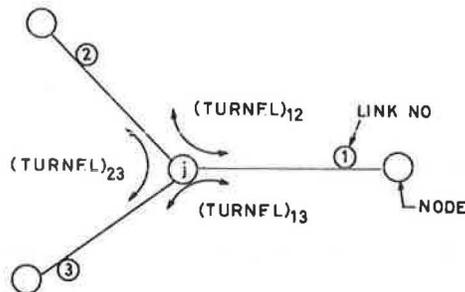
TRANSFERS SAVED

When a route diverts or terminates at a node, the passengers destined for a node not lying on the route have to transfer.

Let the path of a route be represented by nodes 1, 2, 3, and 4 and links 1, k, and m as shown in Figure 4(a). Let $(TURNFL)_{1k}$ be the number of passengers going directly from link 1 to link k and vice versa. The various turning movements on a small network are shown in Figure 4(b). The estimated num-



(a) TURNING MOVEMENTS ALONG A ROUTE



(b) TURNING MOVEMENTS AT A NODE j IN A PART OF A NETWORK

FIGURE 4 Number of transfers saved on a route.

ber of bus trips per day is $NOBUS_1$ on link 1. If a route goes directly from link 1 to link k, the number of transfers saved per route trip for this route and this turning flow is estimated by the following relationship:

$$NOTRAN_{pr} = [TURNFL_{1k} / \text{Minimum}(NOBUS_1, NOBUS_k)] \quad (7)$$

where

$NOTRAN_{pr}$ = number of transfers saved for pth turning flow of route r,

$TURNFL_{1k}$ = number of passengers traveling from link 1 to link k and vice versa, and

$\text{Minimum}(NOBUS_1, NOBUS_k)$ = minimum value of the number of bus trips on the two links 1 and k.

The procedure for calculating the number of transfers saved by a route trip is as follows:

1. All turning flows along the route are found using the O-D matrix.
2. The number of bus trips on each link is estimated using the relationship (Equation 2) between link flow and the number of bus trips. The link flow is found by using the O-D matrix.
3. The number of transfers saved for each turning flow per route trip is found by Equation 7.
4. The total number of transfers saved by a

route $TTRAN_r$ is found by summing the transfers saved for each turning movement along the route.

This procedure was used for the case study network, and the number of transfers saved by each of the 457 routes was obtained. For each route, the transfers saved were calculated along the route and added to get the total number of transfers saved. Then all turning movements on the network were identified. The different values of the various turning movements were obtained for various routes. From these the maximum value of a turning movement was found.

For the Ahmedabad network, 421 turning movements were identified and the maximum value of each turning flow was determined.

SIMULTANEOUS CHOICE OF ROUTES AND FREQUENCIES

In the preceding phases passengers were assigned paths on the basis of passenger riding-time cost and operation cost. A set of intersecting routes (457) was generated. In this phase an optimal set of routes and frequencies is obtained such that as many transfers as possible are avoided. The problem is formulated and solved as a linear programming (LP) problem.

The objective function is

$$\text{Maximize } Z = \sum_{r=1}^{NR} TTRAN_r \cdot \text{FREQ}_r \quad (8)$$

subject to four sets of constraints

$$\sum_{i=1}^{NR} NOTRAN_{pr} \cdot \text{FREQ}_r \leq \text{MAXTFL}_p \cdot \psi_p \quad (9)$$

$$\sum_{i=1}^{NR} \text{RTIME}_r \cdot \text{FREQ}_r \leq \text{OT} \cdot \text{OPF} \quad (10)$$

$$0 \leq \text{FREQ}_r \leq \text{MAXFRE}_r \cdot \psi_r \quad (11)$$

$$NOTRAN_p \geq 0 \cdot \psi_p \quad (12)$$

where

$NOTRAN_{pr}$ = number of transfers saved for pth turning flow of route r,

FREQ_r = frequency on route r,

$TTRAN_r$ = total number of transfers saved by route r,

NR = number of routes in a network,

MAXTFL_p = maximum value of the turning flow for the pth turning movement,

RTIME_r = round-trip time on route r,

MAXFRE_r = maximum frequency of route r,

$NOTRAN_p$ = number of transfers saved for pth turning flow,

OPF = operating fleet size, and

OT = operating time in hours.

The first constraint set (Equation 9) contains TTF equations where TTF is the total number of turning moments in the network. The different values of the pth turning movement are obtained for various routes. From these, the maximum value of the pth turning movement (MAXTFL_p) is found and no more than this number of transfers can be saved. The second constraint set (Equation 10) takes into consideration the operating fleet size. The third constraint set (Equation 11) takes into consideration

the upper boundary on frequency for every route. The fourth constraint set (Equation 12) considers the non-negativity requirements of the number of transfers saved for the pth turning movement.

ANALYSIS OF RESULTS

For the fixed O-D matrix of Ahmedabad, the model generates 426 links on the network on which the passenger flow can be concentrated to minimize the total cost (riding-time cost plus vehicle operation cost). The network consisting of these 426 links (213 links in each direction) and 134 nodes is used to generate the feasible routes that satisfy the basic requirements of the routes and meet the demand. A total of 457 routes is generated and 421 turning movements are identified. The optimal routes and their frequencies are obtained for seven different zones and for the entire network using three different operating fleets of 670, 750, and 790 buses. A summary of the outputs is given in Tables 2 and 3. The results indicate that the number of

TABLE 2 Summary of Outputs for the Different Zones

Zone No.	Part of Network	Fleet Size	No. of Optimal Routes	Maximum Frequency per Day	No. of Transfers Saved
1	Central	52	8	340	235,777
		69	14	340	288,417
		88	23	333	323,074
2	West	102	35	120	316,841
		114	35	120	316,841
		117	35	120	316,841
3	North	154	34	111	334,631
		166	34	111	334,631
		172	34	111	334,631
4	Southeast	99	35	224	354,924
		110	43	223	358,692
		114	43	223	358,692
5	East	64	16	141	200,665
		72	30	123	230,307
		74	30	123	230,307
6	Northeast	114	32	170	339,228
		125	32	170	339,228
		129	32	170	339,228
7	South and southwest	85	26	192	269,310
		94	28	192	270,043
		96	28	192	270,043

TABLE 3 Summary of Outputs for the Network

	Total Fleet Size		
	670	750	790
No. of optimal routes	160	191	207
Average route length (km)	6.625	6.11	5.8
No. of transfers saved (10 ³)	2,052	2,138	2,173

routes in the optimal solution, the number of transfers saved, and the average route length are affected by the size of the operating fleet for the network. Figure 5 shows that as the size of the operating fleet for the network increases, the number of routes in the optimal solution also increases. This happens because increased numbers of vehicles help run more routes and thus maximize the number of transfers saved. Figure 6 shows that more transfers are saved with increased numbers of routes or increased size of the operating fleet.

As the number of routes in the optimal solution

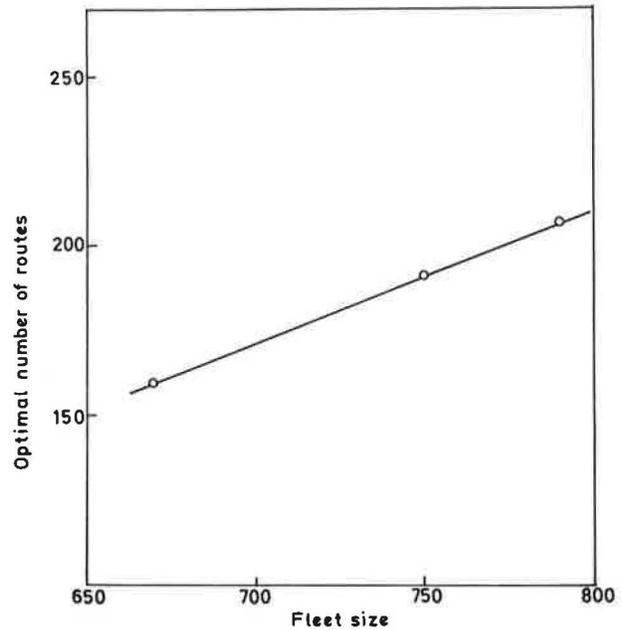


FIGURE 5 Relationship between optimal number of routes and fleet size for the network.

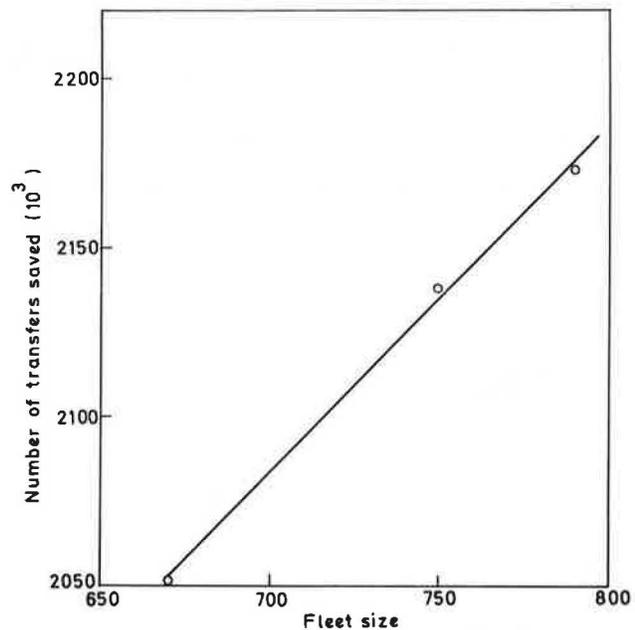


FIGURE 6 Relationship between number of transfers saved and fleet size for the network.

increases, the tendency is to have shorter routes. Figure 7 shows that the average length of the route decreases with fleet size. The length of routes varies between 2.0 and 20.0 km with a mean of 6.625 km for an operating fleet of 670.

The data given in Table 2 indicate that the effect of operating fleet size on the routing system for a zone depends on the size, the traffic demand, and the land-use pattern of the zone. The central zone, which is quite small in area compared to other zones, has been found to be quite sensitive to changes in fleet size compared to other zones. The optimal routes with their paths obtained for the central zone for a fleet of 88 buses are shown in

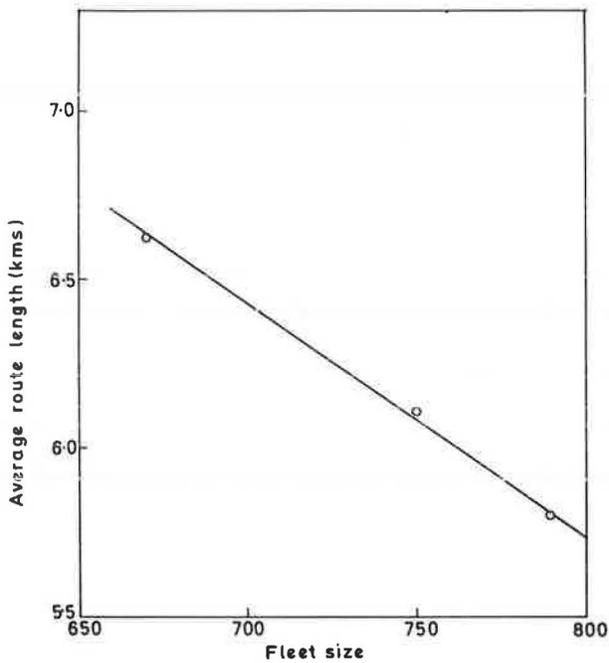


FIGURE 7 Relationship between average route length and fleet size for the network.

Figure 8. When the fleet size is changed from 52 to 88 vehicles, the number of routes in the optimal solution increases from 8 to 23. The maximum frequency of a route in a zone depends on travel demand. The data in Table 2 indicate that the maximum frequency is insensitive to the range of the operating fleet sizes considered in this experiment.

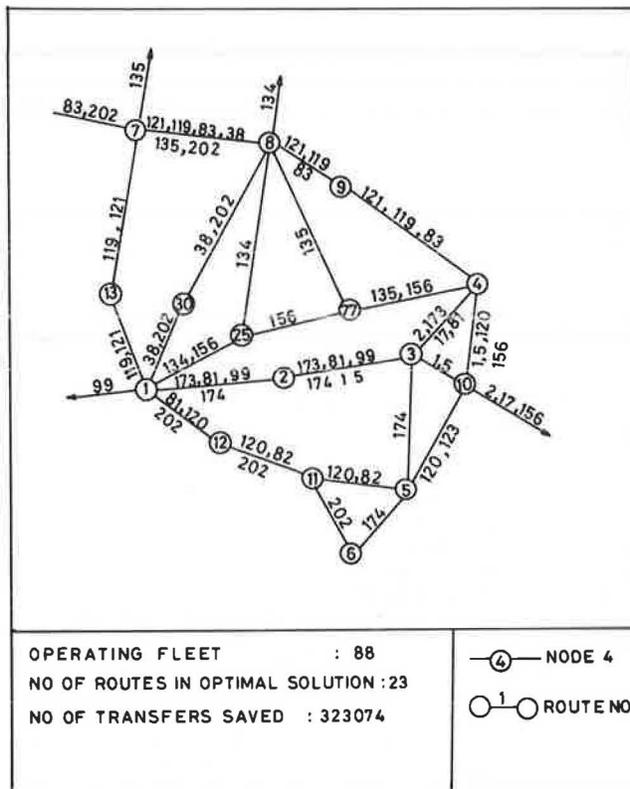


FIGURE 8 Route network for Central Zone (operating fleet = 88).

CONCLUSIONS

The proposed method is a valuable tool for simultaneous selection of optimal routes and frequencies for a bus transit network. It can be used by the planner to structure routes in a rational and systematic way for the given spatial distribution of travel demand, and to find the number of buses and frequencies on each route and the operating fleet size for the system.

On the basis of the application of the model to the city of Ahmedabad, the following conclusions can be drawn:

1. The number of bus trips (Y) on a link for a day varies with the passenger flow (X) on the link. The relationship has been established for the city of Ahmedabad and is of the form $Y = ax^b$.
2. For a given spatial distribution of travel demand, the optimal total cost (passenger riding-time cost plus operation cost) can be obtained from the algorithm that concentrates the flow on the links.
3. The method first distributes the passengers on the links in the network and then generates routes that follow the passengers. This method is computationally efficient compared with other methods that repeatedly distribute the passengers on trial networks.
4. The route-generating procedure developed in this study is a systematic and rational algorithm that generates a large set of all possible routes that satisfy the various requirements.
5. Selection of the optimal set of routes and frequencies is made through a linear programming formulation that maximizes the number of transfers saved on the network. This method is realistic because the interaction of various routes is taken into consideration.
6. The application of the model to the city of Ahmedabad indicates that the model can be successfully applied to large transit networks, and the results are quite encouraging.
7. The results indicate that the number of routes in the optimal solution and the number of transfers saved increase linearly with an increase in operating fleet size. However, the average length of the route decreases with an increase in operating fleet size.

Future work may include consideration of the following aspects of the problem: (a) The structuring of routes and the assignment of frequencies is done for a given desired trip matrix. Further refinement of the suggested model may consider stochastic variations in travel demand. (b) The frequencies assigned are for the entire day. The variation of headways during the day needs to be investigated. (c) Operation cost and passenger riding-time cost have been considered in terms of time by estimating their weights. The analysis can be made more realistic by considering actual costs.

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Reducing the Energy Requirements of Suburban Transit Services by Route and Schedule Redesign

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ABSTRACT

Reducing energy consumption has become an increasingly important concern of transit planners and managers in recent years. Energy consumption may be reduced by improved scheduling of vehicles, reduced deadheading, and laying out more efficient routes. This paper investigates several ways of redesigning an existing transit service to reduce its energy requirements without reducing service quality substantially. Bellevue, a suburban area within King County, Washington, is used as the study area in this investigation. A 13-route existing transit service in Bellevue is simulated and then redesigned to reduce its energy requirements while still providing a comparable level of service. The generation and evaluation of seven alternate designs was accomplished with an interactive graphic computer program called the Transit Network Optimization Program. Results from the "best" design indicate that the energy requirements of the existing system could be reduced by about 56 percent without a substantial reduction of the level and quality of service in the study area.

ernmental aid to meet many of their operating costs. Consequently, cost reduction techniques, particularly those that relate to energy costs, are receiving more attention. In recent years energy costs have become a fast-growing and large component of operating costs. Because of fluctuating prices and uncertainty about availability, reducing energy consumption has become an important concern of both planners and managers of transit systems. Energy consumption may be reduced by improving the scheduling of vehicles, reducing deadheading, and laying out more efficient routes. The optimal scheduling of vehicles is constrained by minimum headway requirements and deadheading by the location of bus bases. Transit routes may often be shifted to some limited extent to save energy. The objective of this study is to determine how much energy might be saved by designing more energy-efficient route structures and schedules. An interactive graphic computer program, the Transit Network Optimization Program (TNOP), is used to generate and evaluate alternative designs quickly and easily.

TNOP can be used to design and evaluate the performance of alternative fixed-route, fixed-schedule bus and rail transit systems. Through interactive computing, TNOP helps transit planners generate and evaluate a wide range of design alternatives and to compare their performance characteristics. Typically, planners are able to find higher performance designs by providing transit services that more closely match actual origin-destination travel patterns. Seattle Metro Transit decided to explore the applicability of TNOP to this question and this study was designed to evaluate TNOP's usefulness as

Most transit agencies are currently under substantial financial pressure and depend heavily on gov-