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Transport and Urban Activity Systems

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Policy-Oriented Urban-Systems Model: Structure and Application

G.M. SAID AND B.G. HUTCHINSON

An urban-systems model developed for the Toronto region of Canada is described. The model operates in five-year time increments that allocate exogenously estimated regional employment and dwelling-unit totals to zones in terms of the conditions that existed at the beginning of the time period and the major public-policy decisions taken during the time period. The state of the urban system at any point in time is described by (a) the spatial distributions of households stratified by household type; (b) the spatial distributions of basic, semibasic, and population serving employment, stratified by income group; (c) the spatial distributions of land use by five types; and (d) the transportation flows and generalized travel costs on each transportation link. Ten basic submodels are imbedded in the model and the structure of each of these submodels is discussed. The calibration of the model to a 1966-1971 data base is described along with some sensitivity tests on the model. Although the model captured the principal regional development patterns, significant deviations existed for some zones, which indicated inadequacies in particular submodels, and these deficiencies are discussed.

Several activity-systems models with dynamic or longitudinal frameworks were reviewed, including those by Batty (1,2), Putman (3,4), Ayeni (5,6), and Mackett (7,8). The capabilities of each of these modeling approaches were reviewed against the modeling requirements established for the Toronto region, and it was concluded that none of the models fully satisfied these requirements. The principal deficiency of the models proposed by Batty and Ayeni is their inadequate treatment of the transportation sector. The Mackett model provides good representation of the transportation sector but it has little chance of being made operational with its current degree of disaggregation. Estimates of transportation corridor flows were required along with the impacts that differential levels of transportation service in different corridors might have on the spatial distributions of activities. Although the PLUM and IPLUM derivatives developed by Putman treat the transportation sector more fully, they operate with rather aggregate activity information and their dynamic specifications are inadequate. Although existing model frameworks were rejected, there were a number of characteristics of existing models that have been incorporated into the model framework described in this paper.

MODEL FRAMEWORK

Figure 1 provides a more detailed illustration of the sequence of operations within the model, which is structured into 10 submodels. These models vary widely in their complexities and consist of the following:

1. Basic employment,
2. Semibasic employment,
3. Residential location,
4. Housing stock,
5. Housing-stock use,
6. Labor force,
7. Service employment,
8. Job supply,
9. Transportation, and
10. Land accounting.

Each of these submodels is described in detail later in this paper.

The state of the urban system at any particular time is defined in terms of the variables listed in the table below, along with the volumes and generalized travel costs on each transportation link:

Variable	Class
Housing	
Households	ℓ = 1 one person
	2 two or three persons
	3 four or five persons
	4 six or more persons
Housing stock	k = 1 single, semidetached
	2 town houses, semiattached
	3 apartment
Employment	
Basic	One class
Semibasic	g = 1 manufacturing
	2 construction
	3 transportation
	4 wholesale
Service	s = 1 retail
	2 small businesses, banks, medical services
Jobs/labor force	w = 1 low income
	2 medium income
	3 high income
Land use	m = 1 industrial
	2 residential
	3 commercial
	4 utilities, transportation
	5 institutional
	6 unusable, open land
	7 vacant, agricultural
	8 total

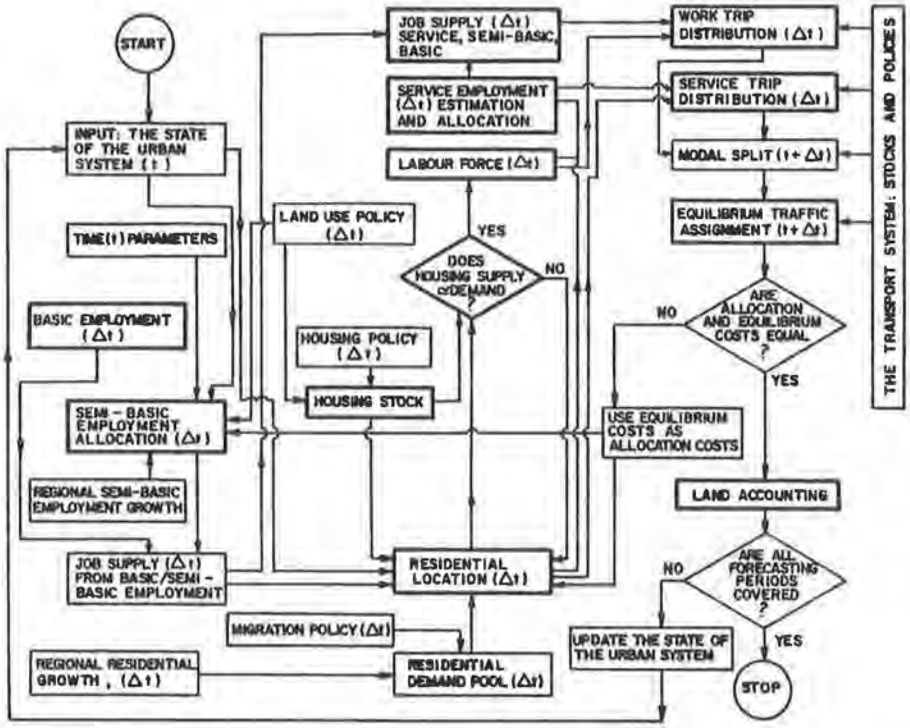
The model first calculates the spatial distribution of the expected growth in semibasic employment for each sector. The inputs to this submodel are designated vacant industrial land, the level of employment in each semibasic-employment sector at time t, and the regional total growth in Δt in each semibasic sector.

The spatial allocation of households by household type is then calculated by using as inputs the total employment in time t, the overseas migration rate, and the housing supply at time t and in time period Δt. In the first iteration of the residential-location submodel, a preliminary estimate of housing-stock supply is used that is estimated from the land available for each housing type during Δt and the relative accessibility of each land parcel to employment in time t.

The spatial allocation of housing stock is calculated by using as input the designated residential land, the supply of any public housing, and the output of the residential-location submodel. In general, there may be a spatial mismatch between the outputs of the residential-location and housing-stock submodels. In those zones with unacceptable differences between housing demand and supply in time period Δt, excess demand is reallocated to zones and available opportunities. This reallocation process is continued until a prespecified difference is no longer exceeded.

The output of the residential-location submodel that is obtained after the matching of demand and

Figure 1. Structure of urban-systems model.



supply is used to estimate the labor force resident in each zone stratified by income group. This is achieved simply by multiplying the number of households in each household type by the average number of workers in each income group in each household structure.

The output of the residential-location submodel is used to estimate the new demand for service employment in time period Δt, and this demand is then allocated to service centers in the service-employment submodel. This allocation is a function of the attractiveness of the different zones to service trips and the travel times between residential zones and the service-employment zones.

The total supply of jobs in each zone in Δt is estimated from the sum of the exogenously specified basic employment, the semibasic-employment allocations, and the service-employment allocations calculated in the previous step. The distributions of jobs by income group are calculated from the employment composition in each zone.

A trip-distribution model is used to estimate the new pattern of work trips in Δt stratified by income group and uses as input the spatial distributions of jobs and labor force and the travel-time matrix. Trips to services are estimated in the service-employment submodel and the proportions of these two trip types that occur in the peak period are used to estimate peak vehicle trips.

An equilibrium traffic-assignment model due to Florian and Nguyen (9) is used to estimate link volumes and travel times on the coded network. Link travel times produced in the traffic-assignment model are then used in a minimum path program to produce a new estimate of travel times. The new and old travel-time matrices are compared and the model is rerun until the differences between the two matrices are acceptable.

Once convergence is achieved between the two travel-time sets, a land-accounting procedure is performed. The inputs to the land use accounting submodel include the land uses in time t, the changes in all activities in time period Δt, and a specification of the activities that consume each land use type. The outputs of the land use accounting submodel are the increments in land use consumption of the different types and total land use consumptions at time t + Δt. The consumption of land use in each zone is subject to capacity constraints on each land use type.

There are two levels of iteration in the model. The first level of iteration is carried out within several of the submodels, and these are the housing-use, traffic-assignment, and land-accounting submodels. The second level of iteration involves the entire model, where the purpose is to ensure consistency between the travel-time matrix estimated from the equilibrium link traffic flows and the ones used to allocate the different activities whose interactions yield the link flows.

At the end of each time period a check is made to see if all forecasting periods are covered. If all forecasting periods are not covered, the results for the end of the current time period are used as input for the next period and the allocation process begins again.

DATA BASE

The urban-systems model has been calibrated for the 1966-1971 period. The 1966 household information was obtained from the 1966 Census of Canada and aggregated to the zone system used in this study. Employment data were not available for 1966 but only for the years 1964 and 1971, so the employment by sector in each zone was interpolated. Land use data were assembled from various planning department sources, and both the land use and employment vectors assembled for 1966 required some significant assumptions that are described by Said (10). The 1971 data base was a little easier to assemble since the 1971 Census of Canada included place-of-work questions. Transportation data were assembled from the 1964 Metropolitan Toronto and Region Transportation Study, the 1971 Census, and the data files of the various municipal transportation planning departments in the region.

Table 1. Summary of semibasic-employment calibration.

Semibasic-Employment Type	Equation Form	R^2
Manufacturing	$E_i^3(1966\text{-}1971) = 147.3 + \underset{(12.2)}{0.6122} \cdot DIL_i(1966) + \underset{(3.4)}{0.058} \cdot E_i^3(1966)$	0.87
Construction	$E_i^4(1966\text{-}1971) = 35.4 + \underset{(23.6)}{0.6097} \cdot DIL_i(1966) + \underset{(7.6)}{0.105} \cdot E_i^T(1966)$	0.96
Transportation	$E_i^5(1966\text{-}1971) = 139.4 + \underset{(4.6)}{0.1100} \cdot DIL_i(1966) + \underset{(9.1)}{0.006} \cdot E_i^T(1966)$	0.75
Wholesale	$E_i^6(1966\text{-}1971) = 38.3 + \underset{(13.3)}{0.2367} \cdot DIL_i(1966) + \underset{(8.0)}{0.251} \cdot E_i^6(1966)$	0.93

URBAN-SYSTEMS MODEL

Semibasic-Employment Submodel

Table 1 summarizes the allocation equations developed for the four semibasic-employment zones. These equations have been developed only for those zones that exhibited growth in employment during the 1966-1971 period and the designated industrial land measure includes only that land area that was serviced during the period. It should be noted from Table 1 that all equations incorporate the amount of designated industrial land in a zone and the level of employment in the same sector, or total employment. The coefficients of determination are quite good for all of the equations except for the transportation sector. The Student's t-magnitudes for each partial regression coefficient are shown in parentheses in Table 1 and are all significant at the 1 percent level. The largest deviations for the allocation equations were for the manufacturing-employment sector where the very large areas of designated industrial land in some of the fringe area municipalities created overestimation in about six zones. These large tracts of designated residential land also created overestimations in the transportation employment allocated to a number of the peripheral zones.

Inspection of the allocation equations in Table 1 shows that the designated industrial land had the largest impacts on the growth in manufacturing and construction employment while the existence of employment in the same sector in the base year was an important factor in the growth of wholesale employment. A number of independent variables were explored in the development of these allocation equations, including accessibility to households, distance to nearest major highway, accessibility to the same type of employment, and accessibility to total employment.

Residential Submodel

In the residential-location submodel, four types of residential growth and change are possible. These are as follows:

1. Transitions in household structure $[HS_*^\ell(\Delta t)]$,
2. Households that are newly formed from the population already resident in the area $[HN_*^\ell(\Delta t)]$,
3. Households due to migration from overseas $[HO_*^\ell(\Delta t)]$, and
4. Households due to migration from within Canada $[HC_*^\ell(\Delta t)]$.

The transitions in household structure and the newly formed households are calculated in the following way:

$$HS_*^\ell(\Delta t) = H_*^\ell(t)\,[SHF^{\ell'|\ell} - I] \tag{1}$$

and

$$HN_*^\ell(\Delta t) = \sum_\ell a^{\ell'|\ell} \times HS_i^\ell(t + \Delta t) \tag{2}$$

where

$H_*^\ell(t)$ = total number of households of type ℓ in the region at time t,
$SHF^{\ell'|\ell}$ = transition matrix that shows the probability that households of type ℓ will shift to households of type ℓ' during time period Δt,
$HS_*^\ell(\Delta t)$ = total number of shifted households of type ℓ in the region in time period Δt, and,
$a^{\ell'|\ell}$ = rate of household formation of type ℓ' households out of type ℓ households.

The regional total number of households of each type due to overseas migration is specified exogenously to the model, and the total number of households due to migration from within Canada is calculated from the following:

$$H_*^\ell(\Delta t) = HO_*^\ell(\Delta t) + HN_*^\ell(\Delta t) + HS_*^\ell(\Delta t) + HC_*^\ell(\Delta t) \tag{3}$$

The spatial allocation of households that migrate from overseas is calculated by using the following gravity-type allocation function:

$$HO_i^\ell(\Delta t) = HO_*(\Delta t) \cdot \left(\left\{H_i^*(t) \cdot [F_i^\ell(t)]^{\gamma^\ell} \cdot f(c_{ic})\right\} \div \left\{\sum_i H_i^*(t) \cdot [F_i^\ell(t)]^{\gamma^\ell} \cdot f(c_{ic})\right\}\right) \tag{4}$$

where

F_i^ℓ = proportion of households of structure ℓ in zone i at time t,
$H_i^*(t)$ = total number of households in zone i at time t, and
$f(c_{ic})$ = some function of the travel time between residential zone i and the center of the region.

The calibration approach matched the observed and estimated mean travel times between all zones and the center of the region. Because of the small numbers of overseas households of structure $\ell = 1$ and $\ell = 4$, the four household groups were grouped together with group 1 consisting of $\ell = 1$ and $\ell = 2$ and group 2 consisting of $\ell = 3$ and $\ell = 4$.

The table below summarizes the calibration results obtained for the two groups:

Household Group	α	γ	Mean Travel Time (min) $\bar{c}$	$\hat{c}$	R^2
1	0.0192	0.2	27.15	27.25	0.80
2	0.0164	1.0	28.32	28.45	0.83

The travel time to the center of the region has a relatively small influence on the location of households of overseas migrants. The proportions of households of a similar type have the most important influence, particularly for the larger-sized households.

Net migration from within Canada is also allocated by using a gravity-type allocation function of the following form:

$$HC_i^{\ell}(\Delta t) = HC_*^{\ell}(\Delta t) \cdot \left(\left\{ \left[\sum_k a^{\ell|k} \cdot DUO_i^k(\Delta t) \right]^{\gamma^{\ell}} \cdot ACCE_i(t) \right\} \div \left\{ \sum_i \left[\sum_k a^{\ell|k} \cdot DUO_i(\Delta t) \right]^{\gamma^{\ell}} \cdot ACCE_i(t) \right\} \right) \tag{5}$$

where

$a^{\ell|k}$ = probability that a dwelling unit of type k will be occupied by a household of structure ℓ,

$DUO_i^k(\Delta t)$ = number of dwelling-unit opportunities of type k in zone i in time period Δt, and

$ACCE_i(t)$ = accessibility of the households in zone i to the surrounding employment.

The accessibility of households is defined as follows:

$$ACCE_i(t) = \sum_j E_j(t) \exp(-\alpha^{\ell} c_{ij}) \tag{6}$$

where c_{ij} is the travel time between zones i and j, and α^{ℓ} is the parameter that reflects the sensitivity of travel time of type ℓ households in selecting residential locations. The calibration proceeded by identifying the set of parameters that maximized the magnitude of the simple correlation coefficient between the observed and estimated household vectors. The four household groups were aggregated into two groups for calibration purposes in the same way as the overseas migrant households.

The table below summarizes the results of the calibration process:

Household Group	α	γ	λ	R^2
1	0	0.8	1.6	0.81
2	0	1.2	1.0	0.83

It shows that the estimated α magnitude is 0 for both household groups, which indicates that accessibility to jobs as defined in Equation 6 had no influence on the locations of households migrating from within Canada. This is probably because the dwelling-unit opportunities term already reflects the accessibility of zones to jobs. The magnitude of γ for the two groups indicates that the availability of opportunities is of much greater importance to the larger household sizes, which indicates that larger household groups tend to locate in the newly developing areas. The λ-magnitudes illustrate that the existence of households of a similar structure in the base year have a much greater influence on the location decisions of the smaller-sized households.

The following regression equation has been developed for estimating potential nonmovers:

$$HNM_i^* = -32.1 + \underset{(23.4)}{0.604 X_1^*(1966)} + \underset{(14.9)}{0.437 X_2^*(1966)} \tag{7}$$

where $R^2 = 0.93$. The allocation function used for movers is as follows:

$$M_{ij}^*(1966\text{-}1971) = HMG_j^*(1966\text{-}1971) \cdot \left\{ [DUO_i^*(1966\text{-}1971) \cdot \exp(-\alpha^m c_{ij})] \div \left[\sum_i DUO_i^*(1966\text{-}1971) \cdot \exp(-\alpha^m c_{ij}) \right] \right\} \tag{8}$$

$$HMA_i^{\ell}(\Delta t) = \sum_j M_{ij}^* \tag{9}$$

where $DUO_i^*(1966\text{-}1971)$ includes the new dwelling units constructed during the period and the dwelling units vacated by movers. The term $HMG_j^*(1966\text{-}1971)$ represents the number of movers generated by zone j who are going to locate in the same region, and analyses of the 1971 census data showed that 85 percent of the movers in the Toronto region located within the region and 15 percent moved outside of the region. Calibration of α^m proceeded by matching the observed and estimated trip length frequency distributions of movers, where the observed distribution had been developed by Simmons (11).

The total change in residential growth in each zone may be estimated from the sum of the four growth components and the relocating households:

$$H_i^{\ell}(\Delta t) = HS_i^{\ell}(\Delta t) + HO_i^{\ell}(\Delta t) + HN_i^{\ell}(\Delta t) + HC_i^{\ell}(\Delta t) + HMA_i^{\ell}(\Delta t) - HMG_i^{\ell}(\Delta t) \tag{10}$$

Housing-Stock Submodel

The housing-stock submodel is calibrated as follows:

$$DUO_i^k(\Delta t) = DUO_*^k(\Delta t) \cdot \left(\left\{ ACCE_i^k(t) \cdot [DRL_i(t) \cdot DUO_i^k(t) \div L_i^{rk}(t)]^{\gamma^k} \right\} \div \left\{ \sum_i ACCE_i^k(t) \cdot [DRL_i(t) \cdot DUO_i^k(t) \div L_i^{rk}(t)]^{\gamma^k} \right\} \right) \tag{11}$$

where

$DUO_i^k(\Delta t)$ = number of dwelling units of type k allocated to zone i in time Δt,

$DUO_*^k(\Delta t)$ = regional total number of dwelling units of type k available in Δt,

$DRL_i(t)$ = amount of designated serviced residential land in zone i at the beginning of the time period, and

L_i^{rk} = amount of land available for type k dwelling units.

In the calibration, single detached units have been treated separately while attached units and apartments have been grouped together. The accessibility term is defined by the following:

$$ACCE_i^k = \sum_j E_j(t) \cdot \exp(-\alpha^k c_{ij}) \tag{12}$$

The table below summarizes the calibration results for that calibration run that maximized the correlation coefficient between the observed and estimated dwelling-unit vectors:

Dwelling-Unit Type	αk	γ	R^2
Single unit, k = 1	0.06	1.0	0.79
Attached units plus apartments, k = 2 + 3	0.09	1.0	0.81

The greater sensitivity of apartments and attached units to employment accessibility is illustrated.

Housing-Use Submodel

In the housing-use submodel, $H_i^{\ell}(\Delta t)$ is altered (if necessary) to achieve acceptable agreement between the spatial distributions of both the demand and supply for housing. Excess demand for houses is reallocated to zones with excess housing supply. This process is conducted iteratively and terminates when either a satisfactory matching has been achieved between demand and supply or the maximum number of iterations has been reached.

This iterative process begins by estimating the difference between supply and demand in Δt and $ERR_i^k(\Delta t)$. Zones are classified into three sets, where Z_1 contains zones with differences within the acceptable limit, Z_2 contains zones with excess demand, and Z_3 contains zones with excess housing supply. Excess demand in zones $j \epsilon Z_2$ is allocated to excess supply in zones $i \epsilon Z_3$ by using the following:

$$H_i^{\ell,m}(\Delta t) = \Sigma\, a^{\ell|k}\left[\sum_{j \epsilon Z_2^k} ERR_j(\Delta t)\right] \cdot \left\{[ERR_i^k(\Delta t) \cdot f(c_{ij})] \div \left[\sum_i ERR_i^k(\Delta t) \cdot f(c_{ij})\right]\right\} \qquad \text{all } i \epsilon Z_3^k \tag{13}$$

where $H_i^{\ell,m}(\Delta t)$ is the number of type ℓ households that are relocated to zone i in time period Δt in the mth iteration of the housing-use submodel, and Z_2^k and Z_3^k are, respectively, the sets of zones with excess demand and with excess supply partitioned into k housing types. Equation 12 allocates the excess demand to zones as a function of their excess supply and their spatial separations from the zone of excess demand.

Service-Employment Submodel

The service-employment-allocation submodel has the following form:

$$T_{ij}^{Ss}(\Delta t) = \left[\sum_{\ell} H_i^{\ell}(\Delta t) \cdot r^{Ss|\ell}\right] \cdot \left(\left\{[(FL_j^*/FL_*^s) + (E_j^*/E_*^*)]\gamma^s \cdot \exp(-\alpha^s c_{ij})\right\} \div \left\{\sum_j [(FL_j^s/FL_*^s) + (E_j^*/E_*^*)]\gamma^s \cdot \exp(-\alpha^s c_{ij})\right\}\right) \tag{14}$$

Three calibration subregions have been isolated, and these consist of the three census areas within the region. The parameters of Equation 13 have been estimated by matching the observed and estimated trip length frequency distributions. The calibration could only be undertaken for type 1 service employment, since appropriate trip length frequency information was not available for type 2 employment (banks, small businesses, etc.). The results of the calibration process are summarized in the table below for subregions 1 and 2. The parameters for subregion 3 are estimated subjectively, since this subregion consists of only three zones:

Calibration Subregion	α	γ	Mean Trip Length Observed	Mean Trip Length Estimated	Sum of Absolute Errors (%)
Toronto	0.20	0.52	11.38	11.13	18.6
Hamilton	0.23	0.39	9.37	9.12	16.2

There is only a marginal difference in the deterrence parameter magnitudes between the two subregions while γ decreased significantly for the Hamilton subregion. This is due to the use of only 9 zones in the Hamilton subregion, which resulted in almost 70 percent of the area retail activities being concentrated in two zones, and the lower γ magnitude decreases the influence of these zones. A similar effect may be noted for the Toronto calibration subregion since $\gamma << 1$, but the retail activities are more widely distributed.

Labor-Force and Jobs Submodels

The labor-force submodel calculates the growth in the spatial distribution of the labor force from the estimated growth in households $[H_i^{\ell}(\Delta t)]$ in the following way:

$$LF_i^w(\Delta t) = \Sigma\, a^{w|\ell} \cdot H^{\ell}(\Delta t) \tag{15}$$

where $LF_i^W(\Delta t)$ is the growth in the labor force in income group w in zone i in time period Δt, and $a^{w|\ell}$ is the probability of having a worker of income group w in household type ℓ.

The jobs submodel simply sums the employment growth estimated by each of the submodels and the exogenously specified basic employment:

$$J_i^w(\Delta t) = e^{w|b} \cdot E_i^b(\Delta t) + e^{w|sb} \cdot E_i^{sb}(\Delta t) + e^{w|s} \cdot E_i^s(\Delta t) \tag{16}$$

where E_i^b, E_i^{sb}, and E_i^s are basic, semibasic, and service employment, respectively, and $e^{w|b}$, $e^{w|sb}$, and $e^{w|s}$ are the probabilities of having workers in income group w who are employed in basic, semibasic, or service employment, respectively.

Transportation Submodel

Service trips are calculated in the service submodel and work trips are estimated by using the following doubly constrained model, which is calculated on the basis of location behavior within the incremental development period:

$$T_{ij}^w(\Delta t) = LF_i^w(\Delta t) \cdot \left\{[J_j^w(\Delta t) \cdot \exp(-\alpha^w c_{ij})] \div \left[\sum_j J_j^w(\Delta t) \cdot \exp(-\alpha^w c_{ij})\right]\right\} \tag{17}$$

where c_{ij} is the travel times between zones, and a^W is the sensitivity of workers in income group w to travel time in their joint selection of residential and work place locations. Because Equation 16 is a production-constrained form of the gravity model, an attraction trip-end balancing procedure is used to ensure the following:

$$\sum_i T_{ij}^w(\Delta t) = J_j^w(\Delta t) \tag{18}$$

Trips at the end of time period $t + \Delta t$ are estimated from the following:

$$T_{ij}^w(t + \Delta t) = \hat{T}_{ij}^w(t) + T_{ij}^w(\Delta t) \tag{19}$$

where $\hat{T}_{ij}(\Delta t)$ is an adjusted work-trip matrix at time t for workers in income group w to account for workers who change their place of residence during Δt.

$$\hat{T}_{ij}(t) = T_{ij}^w(t) - \left[\sum_{\ell} HMG_i^{\ell}(\Delta t) \cdot a^{w|\ell}/H_i^{\ell}(t)\right] T_{ij}^w(t) \tag{20}$$

Equation 19 adjusts the time t trip matrix by removing trips from the rows in proportion to the number of household movers from the residential zone represented by the row. Employment turnover is assumed not to influence the trip matrix.

The peak-hour car-trip matrix at $t + \Delta t$ is estimated by the following equation:

$$T_{ij}(t + \Delta t) = \sum_w T_{ij}^w(t + \Delta t) \cdot SP^w/OC^w + \sum_i T_{ij}^{Ss}(t + \Delta t) \cdot SP^s \cdot PK^s/OC^s \tag{21}$$

where

SP^W, SP^S = proportion of trip makers who use private automobiles for work and service trips, respectively;
OC^W, OC^S = average number of persons per car for

Table 2. Calibration results for work-trip transportation submodel.

Calibration Subregion	Deterrence Function Parameter α^w					
	Low, w = 1		Medium, w = 2		High, w = 3	
	Result	Percent[a]	Result	Percent[a]	Result	Percent[a]
Toronto	0.122	30.2	0.115	30.0	0.111	30.0
Hamilton	0.125	21.3	0.114	18.1	0.195	18.3

[a] Absolute percentage error of differences between the observed and estimated trip length frequency distributions.

work and service trips, respectively; and

PK^S = proportion of service trips that occur in the peak hour.

The calibration criterion used was the minimization of the absolute differences between the observed and estimated work-trip-length frequency distributions for each income class. Two calibration subregions were used for the work-trip model and these are the Toronto plus Oshawa census areas and the Hamilton census area. The results of the calibration process are summarized in Table 2. Within the Toronto calibration area the sensitivity to travel time decreases with increasing income while in the Hamilton area the sensitivity of the high-income group to travel time is the largest. The reason for this higher parameter magnitude appears to be the concentration of the higher-income groups in the Hamilton area in just two zones.

The traffic-assignment part of the transportation model uses an equilibrium assignment procedure developed by Florian and Nguyen (9). Transportation flows are assigned to the alternative paths between origin and destination pairs so that the travel times are equal for all paths that are used. The supply characteristics of transportation network links are represented through their travel-time and volume-capacity functions.

Land-Accounting Submodel

The land-accounting submodel simply updates the land use data at the end of each time period. The model distinguishes between the physical land use categories and the human activities that occupy the land. Following the ideas of both Seidman (12) and Wilson (13), incremental changes in land uses are estimated from the following:

$$L_i^u(\Delta t) = \eta_i^u(\Delta t) \cdot L_i^u(t) \cdot \left\{ \left[\sum_{Q \in u} AC_i^Q(\Delta t) \right] / \left[\sum_{Q \in u} AC_i^Q(t) \right] \right\} \tag{22}$$

where

$L_i^u(\Delta t)$ = change in land use type u in period Δt,

$AC_i^Q(\Delta t)$ = increase in activities in zone i that consume land use type u in time Δt, and

$\eta_i^u(\Delta t)$ = index between 0 and 1 that reflects the constraints on land use in zone i.

Equation 21 indicates that, when no constraints exist on land capacity and $\eta_i^u = 1$, the increase in land consumption is proportional to the ratio between land consumption and activities that existed in a zone at time t.

CAPABILITIES OF COMPLETE MODEL

Although most of the calibrations of the individual submodels have been shown to be quite reasonable, one important test of the integrity of the model is its performance when all submodels operate together. The entire model was run with the 1966 data as input and used to estimate 1971 conditions. Because all of the data required by the model were not immediately available for all parts of the regions, some assumptions had to be made and are detailed in Said (10).

A comparison of the observed and estimated semibasic-employment magnitudes for the four sectors demonstrated generally good agreement, but there were significant deviations for selected zones. Significant overestimations of manufacturing employment occurred in three very large industrial zones located on the fringe of the developing area. These zones contained very large tracts of designated industrial land but contained little employment at the beginning of the forecast period. Underestimations occurred for those zones with available industrial land that were well-established manufacturing employment zones at the beginning of the time increment. Although the manufacturing-employment allocation function captured the average effects of manufacturing-employment growth, the deviations between estimated and observed growths would suggest that a logistic-type allocation function would be more appropriate.

Similar deviations were detected for the other semibasic-employment sectors. There were some unusual deviations for the transportation sector, as several of the zones contained large concentrations of transportation employment, such as the zones containing the head offices of the Toronto Transit Commission and the railway freight yards. The other concentrations of transportation employment were largely in the peripheral zones where many trucking companies locate.

Although some of the residuals of the type highlighted in the previous paragraphs might be reduced by modifications of the allocation functions, it is clear that some of the residuals, particularly in the transportation sector, can only be removed by the exogenous allocation of employment growth. This approach is justified, since the locations of much of the transportation employment are not sensitive to changes in public policy of the type incorporated in the allocation functions.

The capabilities of the model in allocating retail employment could not be assessed properly, since reliable observations of retail-employment distributions were not available for the fringe-area municipalities adjacent to the boundaries of metropolitan Toronto. The limited evaluations of the predictive capabilities of the household and housing submodels showed that they had generally satisfactory capabilities but that some deviations could be detected that were related in part to the misallocation errors in the employment submodels.

Comparisons of the observed and model-estimated traffic volumes showed excellent agreement. This is not surprising, however, given that an equilibrium traffic-assignment procedure was used.

SENSITIVITY ANALYSES

Because the calibration approach that was adopted estimated the parameters of each submodel separately, the model was subjected to a sensitivity analysis to examine the extent to which relatively large changes in the parameters of particular submodels had impacts on the behavior of the other submodels. Table 3 summarizes the changes in calibration parameter magnitudes for the four model runs conducted where all of these changes are in the

Table 3. Changes in parameter magnitudes used in sensitivity analysis.

Run No.	Submodel	Parameter	Change of the Parameter Value (%)	Old Value	New Value
1	Transportation	α^w	+20	$\alpha^1 = 0.122$ $\alpha^2 = 0.115$ $\alpha^3 = 0.111$	$\alpha^1 = 0.146$ $\alpha^2 = 0.133$ $\alpha^3 = 0.133$
2	Housing stock	α^k	+20	$\alpha^1 = 0.060$ $\alpha^2 = 0.090$ $\alpha^3 = 0.090$	$\alpha^1 = 0.072$ $\alpha^2 = 0.108$ $\alpha^3 = 0.108$
3	Residential location (allocation of movers)	β^m	-20	$\beta^m = 0.245$[a]	$\beta^m = 0.195$[a]
4	Service employment	α^s γ^s	-20 +20	$\alpha^s = 0.210$ $\alpha^s = 0.490$	$\alpha^s = 0.175$ $\alpha^s = 0.590$

[a] All k.

Table 4. Effects on model performance of parameter changes.

Submodel	Parameters Changed (%)			
	α^w	α^k	β^m	α^s and γ^s
Semibasic employment	NC	NC	NC	NC
Residential location				
Overseas migration	±3	NC	NC	±2
From Canada migration	±3	±10	±1	±2
New households	±3	±5	±1	±2
Allocation of movers	±8	±5	±25	±2
Total	±5	±5	±15	±2
Housing	±10	±22	±3	±4
Service employment				
Zone attractiveness	NC	NC	NC	±50
Demand for service employment (origin)	±5	±15	±15	±4
Demand for service trips (origin)	±5	±15	±15	±4
Allocation of service employment	±15	±12	±15	±30
Service trips	±15	±15	±15	±30
Jobs	±7	±10	±5	±10
Labor force	±15	±20	±5	±5
Transportation: trip distribution				
Mean trip length				
w = 1	−15.2	−0.44	NC	+0.4
w = 2	−14.8	−0.40	NC	+0.05
w = 3	−14.2	−0.56	NC	+0.15
Traffic assignment objective function[a]	−31	−4.7	−7	NC
Objective function[b]	−35	−6.5	−4	−4.2
Vehicle hours	−27	−4.5	−1.9	−2.7
Vehicle kilometers	−18	−0.2	−1.3	+1.05
Avg speed	+12	+4.5	+0.6	+3.9
Overall convergence[c]				
Percentage of travel time difference[d]				
1 iteration				
Base run	38	38	38	38
New run	25.4	39.6	39.8	41.7
2 iterations				
Base run	12.6	12.6	12.6	12.6
New run	7.4	12.9	11.3	11.1

Note: NC = no change.

[a] All or nothing assignment.
[b] After 5 iterations.
[c] Number of iterations for both the base and new runs was 2.
[d] Percentage travel time difference is the aggregate absolute difference between allocation travel time matrix and equilibrium travel time matrix.

parameters of the deterrence functions imbedded in various allocation functions. These parameters were selected because of their impacts on the spatial allocations calculated by the model.

Table 4 summarizes the impacts of these parameter changes on the outputs of various submodels compared with the basic run. Inspection of Table 4 illustrates that most of the significant changes in submodel output are confined to the submodel in which the parameter change occurred. For example, the increases in the α^W parameters of the transportation submodel reduced the mean trip lengths by some 15 percent and through this increased the average speed of travel on the network. However, the impacts of these changes outside of the transportation model were quite small. A 20 percent increase in α^k of the housing-stock submodel had significant impacts on the allocation of housing stock and, because of this, had impacts on the distribution of households and service employment. It should be recalled that α^k is the deterrence function parameter of the accessibility to employment term of the housing-stock submodel.

The decrease in the mover-allocation parameter β^W had a strong impact on the spatial distribution of movers, as indicated in Table 4, which in turn had an impact on the spatial distribution of total households. These changes had impacts on the service-employment submodel as indicated in the table. The changes in the parameters of the service-employment submodel had very significant impacts on the output of the submodel, but the impacts on the other submodels were small, except of course for the jobs submodel.

These sensitivity tests illustrate that the calibration strategy adopted of independent calibration of each submodel is acceptable. These tests also suggested that the goodness of fit of the model might be improved by some additional adjustment to the parameter magnitudes. The parameters of the trip-distribution part of the transportation submodel are the most sensitive parameters, since they have important influences within the transportation submodel itself and, when the changes are large, on the results of the housing, service-employment, and labor-force submodels as well.

CONCLUSIONS

The allocation functions calibrated for the four semibasic-employment sectors showed that the spatial distribution of growth in semibasic employment was influenced mainly by the availability of serviced industrial land and the existence of employment in the district at the beginning of the period. Although the calibrated allocation functions have been shown to explain observed growth quite well, they had a tendency to overallocate growth to the large peripheral zones. This tendency might be corrected by using a logistic function for the allocation procedure.

The spatial distributions of the various components of household growth were influenced primarily by the availability of new dwelling-unit opportunities and the existence at the beginning of the period of housing stock with similar household characteristics. The spatial distributions of the growth in households of overseas origin were influenced primarily by the existence of households with a similar structure at the beginning of the period while households moving from within Canada tended to locate in newly developing residential areas. Accessibility to employment was not isolated as a significant factor in the household-allocation functions, although this effect is reflected in the allocation of the spatial distribution of dwelling-unit opportunities input to the household-allocation model. These dwelling-unit allocation functions showed that the locations of apartments were more sensitive to employment accessibility than those of the detached dwelling units. The household-allocation submodel also has a tendency to overallocate household growth to the peripheral locations, which is also a zone size effect.

The spatial distribution of the growth in service employment is influenced by the size of the retail shopping area and travel deterrence, the factors incorporated in most allocation functions.

The model described in this paper may be used to support strategic planning studies at the regional scale. It seems to be capable of capturing the major influences on development in growing areas. The allocation functions have plausible structures, and the response of the model to changes in parameter magnitudes suggests that the initial calibration strategy and internal structure of the model were satisfactory. The major deficiency of the model, as in all models of this type, is that it relies heavily on the exogenous input of many of the supply-related variables.

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Urban Transportation in Korea: Lesson for the World or a Passing Phase?

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Research into Korean urban transportation prospects conducted in 1979 and 1980 is summarized. This paper identifies unusually low automobile ownership during a period of rapid growth as the distinctive feature of Korean cities and traces the fiscal, financial, and utilitarian reasons for this phenomenon. It is argued that the low number of automobiles has benefited both existing automobile owners and users of public transportation. The public transportation system is described and evaluated. Future plans for Korean cities are based on the assumption that rapid motorization will occur. It is argued that the plans contain contradictory policies about decentralization and fail to consider viable alternatives. These consist of increasing the efficiency of the existing transportation system while retaining the full set of policies for constraining the growth of automobile ownership and use. It is suggested that this strategy would maintain the efficiency and equitability of the existing city while minimizing investment. If this alternative strategy is adopted, then Korean cities will become the scene for important experiments in urban transportation, comparable to the Singapore area licensing scheme. In this case, Korea might become a lesson to the world. However, if existing constraints on automobile ownership are relaxed, then the present system will prove only a passing phase and Korea will experience the problems of adjustment to the motorcar faced by European and Japanese cities in the past. Irrespective of which strategy is adopted, the achievements in holding down the growth of private cars is a lesson that might be considered in other developing countries.

Automobile ownership in South Korea has remained at an unusually low level during a period of rapid economic growth that spans more than 20 years. This paper presents a summary of research conducted in 1979 and 1980 into the results of restricting such an important variable in the urban transportation system and the prospects for the future (1-4). It is argued that the effect has been beneficial to the majority of urban Koreans, but that a combination of forces is now working to reverse past policies and accelerate the growth of automobile ownership. The short- and medium-term consequences of this growth will be to destroy the existing system. Alternatives exist that would allow sufficient time to experiment to preserve many of the beneficial fea-

Table 1. Major indicators of principal Korean cities.

Item	Seoul	Pusan	Daegu	Inchon	Kwangju	Daejon
Population, 1979 (000 000s)	8.1	3.0	1.57	1.04	0.73	0.61
Area (km^2)	627	436	178	200	213.4	87.5
Urban area[a]	252.6	132.4	64.8	66	34	33.7
Urban density	32 066	22 652	24 228	15 740	21 479	18 085
Private cars	77 008	14 126	8239	3135	2214	2025
Official cars	2131	377	288	110	226	209
Taxis	26 960	20 051	3297	1866	1360	1053
Buses	6411	1915	1712	679	1279	596
Minibuses	600	-	-	-	-	-
Trucks	50 688	18 838	12 849	5048	4323	3593
Total vehicles[b]	167 101	45 114	27 118	12 877	9734	7616
Cars per 1000 people	9.8	4.9	5.5	3.35	3.2	3.48
Bus companies	90	30	30	NA	4	14
Bus lines[c]	193	110	43	NA	NA	NA
Per capita income[d] (1975 $)	1099	900	883	NA	462	705

[a] Excluding mountain, agricultural land, rivers, and lakes; in several cities these act as parks and recreational areas.
[b] Including special vehicles, private buses, etc.
[c] Excluding minibus lines, seatbuses, etc.
[d] Calculated by RDRI and Korean Institute for Science and Technology from Bank of Korea data for 1978 at 1975 prices.

Table 2. Sample comparisons of national levels of automobile ownership.

Country	Year	GDP per Capita (1975 or 1976 U.S. dollars)	Cars per 1000 Inhabitants
Pakistan	1976	200	2.7
Thailand	1975	379	6.2
Philippines	1976	407	8.82
Colombia	1975	574	16.4
Ivory Coast	1976	610	12.8
Ecuador	1976	640	13.7
Paraguay	1976	640	9.9
Korea	1976	707	2.7
	1979	817[a]	6.8
Tunisia	1976	840	21.3
Turkey	1975	900	11.5
Brazil	1975	1158	46.1
Japan	1976	4937	164.0
West Germany	1976	7249	307.6
United States	1976	7912	504.0

Notes: GDP = gross domestic product.
The vagaries of national income calculations in different countries mean that GDP per capita figures cannot be precisely compared without specific country information.
[a] 1976 constant prices; all other figures current.

tures of the present system. If conducted, such experiments could be of great interest to Western planners, and the future progress of the Korean urban system should prove deserving of closer attention. Regardless of the future, the Korean experience offers a useful lesson to developing countries with lower per capita incomes.

THE KOREAN CITY

South Korea is the fourth most densely populated country in the world, with a 1978 average density of 364 persons/km^2, compared with 373 in the Netherlands, 361 in England (excluding Scotland), and 304 in Japan. Because 67 percent of the land area is mountainous, only 33 percent is available for agriculture, industry, and cities.

Accordingly, Korean cities are high-density cities, with severe topographical constraints and high land prices augmented by an aggressive green-belt policy adopted in the 1970s. Seoul, the capital, with 8 million inhabitants, is about the size of New York but occupies only one-third of New York's area. Pusan has 3 million inhabitants that are crammed into an awkward site, which is hemmed in by the mountains and the sea. Daegu, the third largest city, has 1.6 million inhabitants. Table 1 (5) lists the major indicators of six principal Korean cities.

As is well known, Korea is one of the world's fastest-growing economies, with an average annual gross national product (GNP) growth rate of 9.9 percent between 1963 and 1978. Population growth has also been rapid, although slowing from around 3 percent/year at the beginning of the 1960s to about 1.6 percent during much of the 1970s. Urban growth has been even faster. Most cities have grown by about 5-6 percent/year, but several cities around Seoul have experienced an annual growth rate of well over 10 percent. The basic ingredients of urban transportation demand--population and income--are therefore extremely dynamic, and the potential rapidity of change compounds the problem of appropriate action.

Koreans do not think their cities function well, but few outside observers can fail to be impressed by the way such high-density cities function. For example, average car journey speeds in 1978 in crosstown journeys at peak times were in the region of 29 km/h, nearly twice that of most large cities in the Western world. When it is remembered that the actual distances involved are short by European standards, and very short in American terms, it appears that the average Korean is spending much less time per day in traveling than his or her American or European counterpart (6; 7, pp. 21-22). Public transportation also has a high average speed.

That traffic and people move as well as they do in this situation is chiefly the result of Korean success at holding down the number of automobiles. As can be seen from Table 2 (8,9), Korea had until very recently a level of car ownership approximately four times lower than countries with comparable per capita incomes, and only 5 percent of households own motorcars at the present time. The consequences have been that the total transportation systems of Seoul, Pusan, and other cities function more smoothly. This is the result of the low number of cars that impede neither one another's progress nor that of public transportation.

CONSTRAINTS ON AUTOMOBILE OWNERSHIP

The motivation for government policies aimed at restricting car ownership does not stem purely from urban transportation considerations. There has been strong government concern to restrict luxuries and conspicuous consumption, to encourage savings, and to reduce social tension. Automobiles have been classified as luxuries, and this has influenced the types of cars available.

The constraints used may be divided into three types: fiscal (subdivided into taxes and bonds), financial, and utilitarian. The Korean tax system contains little that is unique. The various types of taxes are merely levied at high rates by international standards. These consist of a purchase tax, a defense tax (levied on luxuries and very high incomes), a value added tax, a gasoline tax, and an automobile-ownership tax.

In 1979 the annual automobile-ownership tax was set at 225 000 Won (U.S. $346) compared with $25-$30 in many states of the United States or $120 in the United Kingdom. The gasoline tax pushed up the price of petrol to levels 2-3 times those in Europe and therefore six times U.S. levels.

More unusual is the bond. All vehicle purchasers are required to buy an interestless bond (set at $1000 in 1979 in Seoul and at lower rates in other cities), repayable after five years. In Seoul and Pusan, the proceeds are used to finance subway construction, which provides about 15 percent of the funds required for the subway program. In other cities the bond is used to provide public housing.

The financial constraints include the nonavailability of credit, high insurance rates, competing demands on household income, and the pressures to employ a chauffeur. In Korea, there are no financial institutions that give credit facilities to private individuals. This reflects the deliberate government policy of directing all available funds into industrial investment. Even for housing there is only one institution that makes limited advances for mortgages. The private money market (known as the curb market) is disorganized and consists of moneylenders and brokers with interest rates that vary between 36 and 60 percent/year.

Insurance rates are extremely high because of a high accident level and the small market. Equally necessary, many Koreans would argue, is a chauffeur; perhaps 70 percent of car owners in Seoul employ chauffeurs. Accordingly, the urban system has evolved around this fact. Parking facilities tend to be provided on the assumption that the passenger will be driven door to door but the car may be parked at a different point.

As a result, a minimum of $400/month is required to own a car and perhaps $1200 if a chauffeur is employed, at a time when an upper-middle-class salary might amount to $1600 after taxes.

The utilitarian constraints on automobile ownership are those where alternative modes of transportation (chiefly taxis) are available, which provide the same, or similar, levels of service as car ownership. Tax rates are lower for business cars and most large firms own fleets of cars that work on a pool basis. These pools provide transportation to and from work. Family and firm connections usually permit access to a car for special occasions, weddings, family celebrations, trips to the airport, etc.

At the same time, the universal willingness of shops to deliver purchases to the home and the availability of yondal (taxi pick-up trucks) for larger consignments mean that the carriage-of-goods function of a car can be bypassed. Car-rental firms exist, but the low number of drivers and the preference for chauffeurs restricts their usefulness.

The combination of fiscal, financial, and utilitarian constraints has held the ownership of cars at a low level. The high cost of owning and operating a car appears to be more important than the initial high purchase price. This is demonstrated by the small scale of the second-hand car market and the prevailing low prices. With limited exceptions, if a household can afford to operate a car, it can afford to buy a new one. In 1978 only 2 percent of cars were over 10 years old (10). Although this might also be the result of the low number of cars in 1968 (only 13 percent of the 1978 total), the absence of pre-1974 production models on the streets and the common practice of breaking up cars only three years old suggest otherwise. [Many older vehicles are imported cars (such as Mercedes-Benz), which cannot be replaced legally.]

Mopeds and motorcycles, which play a prominent role in Bangkok and other Asian cities, are also absent. This is the product of strict import controls and centrally directed industrial investment. Productive capacity is increasing and the number of motorcycles rose by 80 percent in 1979 alone, although the growth was largely in rural areas and smaller cities. The growth of the number of two-wheeled vehicles, which in Japan preceded the family car, will in future years inject a further variable into Korean urban transportation.

Although in the past the combination of taxes, firm cars, taxis, alternate delivery systems, and the high cost of chauffeurs and insurance has been sufficient to hold the ownership of cars at a very low level, rising incomes and the failure to peg taxes to inflation in recent years have led to a rapid growth of car ownership, as Table 2 shows. Between 1976 and 1979, real per capita income rose only one-seventh but car ownership tripled.

If rapid economic growth resumes in the 1980s and the cost of owning a car falls in real terms, then a rapid growth of car ownership is to be expected, as occurred in Japan in the 1960s and Europe during the 1950s. Under such circumstances, the present favorable urban transportation system will deteriorate as journey times for all road users increase and the cost of public transportation rises.

PUBLIC TRANSPORTATION SYSTEM

In the 1970s, many urban planners dreamed of restricting the use of private cars to the point where the average vehicle speed could double. The opportunity to examine a number of cities in which general car ownership (rather than car use) has been restricted is therefore of great interest. How effectively are the needs of 96 percent of urban Koreans met who do not travel by car?

Tables 3 and 4 (3) show that between 20 and 30 percent of all trips in Korean cities are made on foot. Both income and urban density would lead one to expect this. Indeed, many walk trips go unrecorded because the corner shop is less than 1 km away. The average walk trip in Pusan in 1979 was 17 min. Without obstructions one might expect a distance of around 2 km. In fact, walking in all Korean cities is full of obstacles. Major streets have a sidewalk flow of 4000 pedestrians/h along sidewalks often only 3 m wide and with street furniture located without regard for pedestrians.

At most major intersections in Seoul, the pedestrian is forced to go over or under the road, and may have to do both to cross diagonally. This is an additional reason why the average vehicle speed in Seoul is high. Not in Tokyo; Washington, D.C.; New York; or in any comparable capital city in Europe is the pedestrian forced to take such long detours to avoid delaying traffic. The subjective feel of any walk trip is that it is much farther than a comparable distance in a European or American city. This has repercussions on the rest of the system, i.e., discouraging walk trips and encouraging the use of taxis for short trips. These short trips reduce the availability of taxis, although they increase the profitability of taxi operations.

More than 60 percent of all trips are made by bus. All buses are privately operated but routes and fares are strictly controlled by city governments. Seoul alone has 90 city bus companies that operate about 200 lines. Although the Korean public

Table 3. Modal split including walking.

	Modal Split (%)			
Mode	Seoul, 1977	Pusan, 1979	Kwangju, 1979	Daejon, 1978
Bus	56	50.8	45	54
Walking	17	30.1	27	34.5
Taxi	16	12.0	10	3.5
Passenger car	3	3.6	9	3.5
Subway	4	–	–	–
Other	4	3.5	9	4.5

Table 4. Modal split excluding walking.

	Modal Split (%)				
	Seoul				
Mode	1977	1979	Pusan, 1979	Daejon, 1978	Kwangju, 1979
Bus	67.0	66	72.6	83.2	61.6
Taxi	19.0	19	17.1	5.3	13.6
Subway	4.8	7	–	–	–
Passenger car	3.6	8	5.1	5.2	12.3
Other	4.8	–	5.0	6.8	12.3

despises their buses, the bus system is a highly efficient people mover that offers a service without public subsidy. Buses are frequent, running at an average of 3- or 4-min intervals and covering the city with a comprehensive network that serves all areas and offers through routes, so that all parts of the city can be reached with a single interchange. In short, they offer everything but comfort.

There is considerable tension between the necessity of operators to make a profit or to cease operations and the control that city halls and planners wish to exert. From an operator's point of view, the ideal route passes through the city center and out the other side. However, buses that carry nearly 70 percent of mechanized trips are widely regarded as holding up traffic. There are indeed problems in certain main arteries where streets have only two lanes in each direction and one lane may have a solid train of buses. The fact that bus trains form is a reflection of the high volume of passengers who move along a particular corridor rather than a defect in the bus network. However, the announced aim of Seoul planners is to prevent through bus routes and force passengers to change to special city-center buses.

Currently, buses have high speeds as well as high volumes compared with their Western counterparts. This is partly a by-product of general traffic conditions conducive to higher speeds but is equally the work of very efficient crews.

A third factor is the relatively long distances between bus stops. In the city center, bus stops are about twice as far apart as in European cities. This obviously encourages vehicle speed at the expense of passengers who may have to walk farther before boarding or alighting, which would be more acceptable if walking were easier.

Moreover, a Korean bus stop within the central business district (CBD) is probably the length of a subway station. At each stop a bus train forms with 30 vehicles that serve 10-20 routes, and each vehicle crawls along most of the length. This negates most of the benefits of long distances between stops and speedy unloading at outer-city stops. Experimentally, bus stops at certain points have now been segregated, thus reducing layover time.

In one city, Daejon, the bus operators have solved the problem of being forced to operate marginal routes by city officials. The 14 operators have formed a cooperative in which all companies form a pool that will cross-subsidize unprofitable routes. Clearly, this is only possible if the companies that hold the most profitable routes agree to participate.

In 1979, the seat bus--a direct bus from the city center to selected suburbs (mainly aimed at commuters)--was introduced. More important minibus lines were also created. Both have been an unqualified success. They are faster, and the minibuses are much more maneuverable in traffic. Stops are spaced even farther apart and fares are three times as high as those on ordinary city buses. By 1980 it was estimated that minibuses carried 3.5 percent of mechanized trips. On a number of routes, demand far outstripped supply. However, the city showed considerable reluctance to authorize more vehicles and one must hypothesize that powerful interests are opposed to more minibuses.

Because minibuses are operated by existing city bus companies, the one mode to clearly suffer from their competition was the taxi. Ordinary taxis carry about 19 percent of trips. In terms of passenger kilometers, Seoul taxis may perform as much as 25 percent of the total, and for the Korean middle classes the taxi is the normal mode of transportation.

In any rational calculation of modal choice, the high probability of catching a taxi within a short time is obviously important. In 1978, under the stimulus of 12 percent GNP growth, the demand for taxis far exceeded supply, so that a wait of 20 min at a Seoul taxi rank was quite possible. But with 10 000 more ordinary taxis and 1000 new call-taxis and minibuses, supply and demand balanced by mid-1979 and tipped heavily in the consumers' favor as the recession deepened.

In 1974 the first subway was opened in Seoul. This was a 7.8-km link between newly electrified suburban railways that link satellite cities to the south. A total of four further lines for Seoul and four for Pusan are planned. The first section of Seoul subway 2 opened in October 1980. As in Tokyo, private enterprise is involved in the promotion of subways; i.e., building and preparing to operate subways 3 and 4.

Visiting consultants usually express severe doubts about the wisdom of building subways. This has been partly the result of the failure of Bay Area Rapid Transit (BART) in San Francisco and the Washington, D.C., Metro to fulfill all their promises. Likewise, cost/benefit studies in the Netherlands and United Kingdom in the 1970s have suggested that projected subways are not justified, but they have been built nevertheless for political reasons. Is this also true of Korea?

In compact high-density cities with low automobile ownership, subways offer a significant alternative that does not compete with existing modes for space. Currently, subway 1 carries about 6 percent of mechanized trips in Seoul. The central corridor in Pusan under which subway 1 is to be built currently has an hourly flow of 36 000 passengers traveling in buses where there is no room between the mountains and docks for further road widening. Similar flows are recorded in the major corridors in Seoul. In terms of speed, subway 2 has reduced the journey time to the east of the city by half compared with buses.

Although cost/benefit studies of subways have been conducted in Korea, it cannot be claimed that a full range of alternatives such as bus-only roads was evaluated. In high-density cities, expensive engineering is the only way to increase capacity in the system, and subways may be justified. Nevertheless, the actual decision to construct them was based on political considerations without adequate data for a rational choice to be made.

ROAD NETWORKS AND TRANSPORTATION SYSTEM MANAGEMENT MEASURES

Despite the fact that major roads in downtown Seoul are often four or five lanes in each direction, the overall proportion of the city devoted to roads is low. Only about 14 percent of the urban area is devoted to roads, compared with 20-26 percent for most European cities and more than 30 percent for most U.S. cities. Even the 14 percent is misleading, since the CBD has a road ratio of more than 20 percent, which leaves proportionately less for the other areas.

Obviously, a high-density city can ill afford to progressively surrender land to the motorcar. Seoul city estimates that to add 0.5 percent to the road ratio would now consume its annual total budget. In response, Koreans have evolved what they term super blocks, which are eight-lane highways or on a wide-spaced grid, with each block enclosing a considerable area compared with the U.S. model. This speeds through traffic but leaves minimal street widths inside each block; indeed, at their smallest they are merely a meter wide. The problem then becomes, What happens when traffic wants to penetrate each block for access and in order to park? The answer is potential and often absolute chaos, with cars, handcarts, bicycles, and pedestrians fighting their way through confined spaces among parked vehicles.

Clearly, each incremental augmentation of motorcar traffic makes this particular problem worse. One might have expected transportation system management (TSM) measures such as one-way streets, pedestrian-only streets, parking restrictions, and so on to be systematically applied. However, by mid-1980 there were a few token one-way streets, more honored in the breach than the observance, one short stretch of a counter-flow bus lane, and one small area where the pedestrian was supposedly in a traffic-free zone.

The most strikingly successful measure is the total ban on heavy lorries in central areas except during the 12:00-4:00 a.m. curfew hours. At other times, goods are unloaded at peripheral depots and then brought in by small trucks.

FUTURE PLANS

Korea is a rapidly changing country, with cities and income growing fast and life-style changing rapidly. One might expect a cautious and experimental attitude to urban planning to prevail. This is not the case. It has been decreed by the Ministry of Home Affairs that by the end of 1981 every city in Korea shall have an unchangeable master plan that covers all urban details to the year 2000. This included a national set of guidelines that directed each city to have highways 50 m wide (14 lanes), running from north to south and east to west and meeting in the geographical center of the city. In draft plans this instruction had been obeyed literally so that all through traffic from every direction would pass through the very center of the CBD. There were no directions for ring roads or for even basic facilities such as bus stations (11).

The implicit assumptions were that automobile ownership and automobile use would continue to grow and that sufficient road space to keep the traffic flowing could be provided. Each plan envisages both an increase in the road ratio and an expansion of the city over a much larger area. Nowhere within the guidelines for planning procedures are there provisions for costing the plan or providing revenues to bring such a city into being. Correspondingly, there was no evaluation through cost/benefit analysis of various alternative schemes.

The present situation in Korean cities is an evolved rather than a planned situation. No planner ever sat down and drew up a set of guidelines to produce the largely favorable situation that exists, although attempts have been made to create master plans in the past. Today's Korean cities are largely the product of market forces with the additional ingredient of the restrictions on automobile ownership and use.

The main aim of Korean planning since the late 1960s has been decentralization. In general, it has been held that any decentralization is good, and there has been a marked tendency to fail to distinguish among the four main categories:

1. Removal of economic activity to another part of the country (e.g., industry or administration),
2. The creation of subcenters within cities,
3. The removal of economic or social activity from the center to the periphery of the existing city (e.g., relocation of industry, administration, social, and transportation facilities), and
4. The gradual evolution of suburban sprawl through a lowering of residential density and the growth of conglomerations as smaller settlements are absorbed.

Of the four types, only 1 and 2 are compatible with the existing types of cities. Types 3 and 4 are incompatible with profitable privately owned public transportation systems and, in particular, with the creation of a subway network that relies on the existence of high volumes of traffic between limited destinations. They encourage the use of automobiles and low-occupancy vehicles such as taxis, thereby placing penalties in the way of those who do not own cars and cannot afford taxi fares. They tend to increase passenger kilometers and normally increase the amount of time spent in traveling. Even in Tokyo, where the subcenter has evolved with relatively high levels of skill (i.e., building on an already existing rail network), the effect has been to double journey-to-work time.

Numerous examples of the problems caused by indiscriminate decentralization could be given (1-4, 12). In general, land use planning is being executed crudely without regard to the transportation implications. In particular, no consideration is being given to whether the type of city being created preserves the existing beneficial features of the city or whether it demands the use of private vehicles.

Quite apart from planned measures, the growth of private automobiles independently creates decentralization. Car owners can live farther from their work and beyond public transportation routes where land prices are lower. Services whose patrons are predominantly car owners can likewise be sited away from public transportation. In this manner, the city begins to segregate itself.

In American and European cities, the tendency has been for public transportation to deteriorate rapidly as the public system loses the marginal riders on whom the greatest profit is made while congestion from the increase in private vehicles raises operating costs (13). The deterioration and the rise in fares, if a realistic pricing policy is in operation, lead to an increased incentive to own a car. At this point the lower-income groups suffer from not only decreased accessibility but also higher travel costs per passenger kilometer.

POTENTIAL FOR IMPROVING EXISTING SYSTEM

The description of the existing urban transportation system indicated that there were considerable inefficiencies in the present system. Analyses of these inefficiencies suggest that with a minimum of investment the capacity and efficiency of the present system could be expanded while the attractiveness of nonmechanized and public transportation trips can be enhanced. This requires the application of the best practice in advanced countries to Korean cities.

Walking should be the starting point. As Thompson has observed, the short walk trip is the highest achievement of the transportation planners' art (7, p. 47). Each Korean city is a consumate example of the fact that there is no consideration of how walk trips can be encouraged and facilitated. The standardized macroplanning practiced in Korea discourages on-the-ground observation of what is actually happening in Korean cities. The lack of a pedestrian network is particularly unsatisfactory, although Koreans have begun to develop what could become a viable underground system. During 1979 and 1980 this was just beginning to offer one or two arterial routes. It has a special attraction to city governments in that each section paid for itself, since it was built as a shopping arcade in which the advance rentals paid for the construction. The chief problem is that there is no network design based on demand, and only selected stretches can be built when there is demand for shops; outside the CBD it is not economically viable.

Existing underground thoroughfares are already getting crowded and the notion of putting all pedestrians underground is impractical. It is essential that a systematic surface system of pedestrian-only streets be developed by using existing back streets, with appropriately controlled pedestrian crossings in main streets.

The possibility of bus and pedestrian-only malls is well worth considering. When Uljiro, one of the major east-west routes, was closed to all other traffic because of subway construction in 1980, bus times improved immediately, in some cases halving journey time. By segregating buses and other traffic, some of the tensions could be removed. At the same time the improvement of modal interchange--especially pedestrian, bus, and subway--needs to be made.

One of the greatest dangers about the new subways is that the interchange for pedestrian and bus will be ill-conceived. Existing interchanges are poor, even where space exists for improved systems to be effected very simply. Moreover, there is an assumption among city officials that the creation of a subway will automatically drain off all demand for buses.

This is far from the case along the existing subway 1. It will certainly take longer-distance traffic from the buses where the journey time is substantially shortened, as for instance in the case of the existing portion of subway 2 where the journey time is halved. However, subway fares are on a stage system. This means that the bus becomes cheaper with distance, since a flat-fare intracity rate applies.

The problem arises when a route rationalizer eliminates a through bus, which creates a journey that starts and ends on a bus but includes a subway stage. This triples the cost of the journey--no small consideration for at least 40 percent of the population. Indeed, it may be claimed that the present city system is highly equitable. There are no parts of the city not easily reached by one change of a bus. This will no longer be true of the city of the future.

At the other end of the scale, the design of new construction south of the Han River creates a disincentive to walk to a bus stop from new middle-class apartment areas. Indeed, the failure to plan these areas to minimize the desire to travel by taxi and ultimately by car is serious. The new areas remain very dense, although high-rise apartments are segregated from shops and public transportation by highways planned on the super-block concept.

Unless existing prejudices against buses are revised, there is a real danger of disaster when the subway system is regarded as complete. Unless buses and subway are allowed to compete and find their equilibrium, both public transportation operators and the public are likely to suffer. Ideally, the completion of the subway system should inaugurate a reduction in bureaucratic control on bus routes and permit negotiation for a variety of fare schemes between bus companies and subway operators. The alternative is likely to be large-scale bankruptcy, with the city governments being forced to operate loss-making routes.

Within the bus system there is plenty of room for improving the quality of the bus service, both through introducing a greater variety of types like express buses and minibuses and through improving existing designs of Korean city buses. The present design reflects its evolution from converted army lorries. The potential for making both smaller and larger vehicles is considerable.

When the economy picks up, the call-taxi must be encouraged. The old call-taxi could not be relied on to arrive when booked and thus failed in its basic advantage. But unless consumers are offered a door-to-door service that can be ordered by telephone, they will increasingly opt for their own cars. Likewise, one would hope to see something like the public light bus of Hong Kong authorized, which has proved highly popular in similar urban environments. This hybrid between a bus and a taxi could provide a further alternative mode in the dense-traffic conditions of Korean cities.

Assuming that cars do increase, if the number grows slowly enough, there is a potential for systematic application of TSM measures that can ease the flow of traffic. With a very selective construction program designed to fill in missing links and ease pinch points, particularly where through traffic can be diverted from downtown areas, TSM strategies ought to keep Korean traffic moving at close to its present speed for the next decade.

EQUITY, EFFICIENCY, AND LOW AUTOMOBILE OWNERSHIP

The evaluation of transportation plans is frequently couched in terms of pareto optimality, in which the optimum system is the one in which no change could produce a more satisfactory system for one individual without making it less satisfactory for another. Those who lose under the present system belong to the marginal group of households who would buy cars under a different fiscal regime, but only up to the point where an increase of cars would lead to general congestion. Once congestion grows, those who would gain would be heavily outnumbered by losses to all other transportation users.

Such an ideal evaluation is rarely approached in reality where financial considerations are paramount. It can be argued that the preservation of existing policies is more likely to produce a beneficial system, however evaluated, in the Korean context. There are two reasons for this point of view. The first is that the present system provides a good level of service for most citizens and the second is that there is only an illusion of choice for Korean cities. So-called full motorization is not practicable in the Korean context because of the high population density and unsuitable topography. Even if the residential density were to fall to one-third of current levels, the continued circulation of traffic would depend, as it does in most major European and Japanese cities today, on a majority of car owners commuting by public transportation. But it would be by public transportation that required a subsidy.

Korea has very little land to spare. It must import every barrel of oil, and pollution is already a serious problem from industrial and domestic sources without a rise in automobile emissions. The diversion of public expenditure into road construction merely to maintain the existing level of service would be at the expense of urgently needed sewers, water supply, housing, and public amenities, as was the case in Japan in the early 1960s.

At the same time it is equally unrealistic to suppose that car ownership will not grow in a country where incomes are rising. All that can be controlled is the rate of growth of car ownership and use and the improvement of the existing system to ensure that potential car buyers and car users have alternative modes available. Currently, it is a theoretical assertion that the rate of growth can be permanently slowed, since it has never been attempted in practice, and experts still disagree on the ingredients of the model for predicting the rate of growth of car ownership. [Note that the Singapore government managed to stabilize the car fleet at 62/1000 in 1973 and 1974 at approximately the same per capita income as Seoul now enjoys, and the fleet actually declined in 1976 (14).]

Only if this course of action is adopted will Korea produce any lessons for the developed world. Up to the present, the unique system that exists in Seoul and other major cities can justifiably be regarded as a passing phase produced by the temporary phenomenon of low automobile ownership. Currently, the only lesson is a mental exercise in imaginative transportation planning and implementation to produce a more satisfactory system in the future.

It has been argued in the previous section that the cities contain sufficient inefficiencies to permit improvements in the urban system that will be greatly enhanced if the policy of restraining automobile growth is continued. If certain courses are taken to their logical conclusion, then it is at this point that Korea will begin to produce lessons of great interest. The provision of an integrated pedestrian system on a citywide scale has rarely been attempted in an existing city, although occasionally it is provided in new towns.

A further case would be if Korea applies the area-licensing scheme as practiced in Singapore. The Singapore scheme covers only 5 km². Initial assessments for Seoul suggest that a minimum of 22 km² would have to be included. The implementation of such a scheme would therefore be of much more direct applicability to a number of major cities throughout the world.

It must be emphasized that only if measures to enhance alternative modes of transportation are taken can a policy of restricting use of automobiles be effective. This in turn requires that current urban planning practices are revised. Unless Korean urban planning techniques pay close attention to the existing land use and transportation patterns and to the consequences for urban transportation of major relocation decisions, transportation strategy and urban planning will pull in opposite directions. The beginnings of an integrated approach have been inaugurated but are grossly underfinanced and out of accord with planners who work on other aspects of city planning.

On the whole, Western planners have abandoned the integrated citywide transportation planning approach. If Korean cities are to evolve along the lines suggested, they will require techniques that may well offer considerable lessons to developing and developed countries.

CONCLUSION

No solution to urban transportation is ever definitive, for people do not travel to please transportation planners but instead travel as a by-product of their daily lives. As has been argued throughout this paper, the future of Korean cities is at a critical point. Internal forces within Korea may well produce pressures for expansion of the domestic automobile industry. If this is so, then the potential of Korea as a lesson will be lost, and the situation described above will be accounted for as merely a passing phase.

This does not alter the fact that for many developing countries the Korean experience remains of great interest. Much would depend on the willingness of governments to restrain the growth of automobile ownership, but the other features of the Korean system are also of considerable interest. Perhaps the country that might profit most would be mainland China.

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India's Transportation Energy Problem

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The transportation sector is the largest and fastest-growing imported oil consuming sector in India. This paper reviews the growth of the sector in recent decades and characterizes its current demand, supply, and energy consumption. Two analyses, one of the social, political, and physical infrastructure constraints on the sector and the other of the government's policies, plans, and five-year budget are summarized. The paper concludes that without good planning the transportation sector may hinder rather than support the country's development, not only because the cost of imported transportation fuels reduces the ability to import other goods needed for development but because the sector could become insufficient for the required internal distribution. Several suggestions for planning and research projects are presented.

The study of transportation in India is a study of contrasts: jumbo jets landing on handmade but smooth runways, a subway under construction in Calcutta, bullock-carts mixed in with motorized traffic on city streets and rural highways, vehicles produced by only two automobile and two highway truck manufacturers (each company with only one model), nearly 8000 steam railway locomotives in service, and 314 000 towns and villages not served by any road. Laborers sometime load coal from head baskets into railway hopper cars, yet India launches communication satellites that one day may replace some travel with telecommunications.

India has a population of nearly 700 million, three times that of the United States in 40 percent of the land area. Although only about 23 percent of the population is now urban, by 2000 the urban population is expected to increase by 85 percent and the rural population by 29 percent, assuming that the government's population-control program works reasonably well. All Indian resources appear to be limited in some way. For example, coal reserves are abundant but the coal is not efficiently extracted, distributed, or used and it has very high ash and moisture content. Labor is abundant and is used instead of machines as a matter of government policy but is becoming more organized, which results in many protracted strikes. The country is now feeding itself and in recent years even exporting grain. Lack of capital is the main drag on development.

Recent trends in fuel and energy use in India are shown in Table 1 (1). India now faces an energy crisis, the primary component of which is its reliance on imported oil; the Indian subcontinent imports two-thirds of the petroleum it uses. The problem is one of foreign exchange: India's imported oil bill is 85 percent of its export earnings. Although the percentage of oil demand met by imports remained stable during the 1970s (61-71 percent), both the oil-import bill as a percentage of export earnings and the amount of product imported have increased dramatically (tenand six-fold, respectively) (1). Because India is on the front side of its industrial revolution, it increases its commercial energy consumption 1.8 percent for every 1.0 percent increase in gross domestic product (GDP). For most Western countries this elasticity is less than 1 (2). The transportation sector consumes a third of India's commercial energy. It is the largest and fastest-growing consumer of petroleum-based fuels, mainly diesel fuel. This sector therefore is key in any long-term solution to India's energy crisis. No short-term solution seems possible.

OVERVIEW OF INDIAN TRANSPORTATION

India's demands on its transportation system are more like those of the United States than Europe, even though Indian transportation technology has an inherited European flavor. In Europe, cities are close together and the rail system is extremely well developed. In the United States and India, however, distances between activity centers are large (except in the northeastern United States). Even though the analogy to the United States holds better for freight shipments than for passenger travel, the historical trends of U.S. transportation, especially the trend toward highway transportation, are being replayed in India.

The Indian transportation system should be evaluated in terms of its ability to meet the country's current and future transportation needs, but there is no consensus among Indian transportation experts regarding the adequacy of the system. Transportation plays a critical role in the development of a nation like India. It links industry to its sources and markets and permits imports and exports. It carries fertilizer to the farmers and produce to the hungry. Advances in passenger transportation change the social fabric of the country because more people can interact more easily. Transportation brings the medicines and the agricultural extension workers to the villages. A rural road allows a once isolated, marginally self-sufficient village to participate in and, with irrigation water and fertilizer, contribute to the Indian economy.

Over a decade ago, Wilfred Owen wrote the following (3):

> In India a key factor in economic development is the rapid growth of the transport burden with rising levels of economic activity. Every increase in national product is accompanied by two to three times as great an increase in the movement of materials.

India's transportation system has no spare capacity as it is currently operated. Any increase in capacity created by more efficient operation would quickly be filled by passengers and goods. Indian business people today use trucks at an average cost six times the rail tariff to increase reliability and reduce inventories. People hang on the sides of buses and commuter trains and often sit on the roofs of intercity trains. Waiting in line to obtain a first-class booking on a train can take hours and must often be done days in advance for a chance for a seat. The national highways are obstacle courses for motorized vehicles, especially in towns that are seas of pedestrians, carts, and bicycles, with an inevitable one-lane bridge in the middle of each town. Trucks are small, not maintained, and apt to fail. Vehicles on the same road move at many different speeds. Sometimes 140 people have been counted in a bus designed for 50.

The Indian transportation engineer is well aware of all the operational techniques to increase energy efficiency: proper tire pressure, vehicle maintenance, channelized intersections, contraflow bus lanes, etc. (4). The Indian automotive engineer has studied Western advancements in vehicle technology, engines, transmission, and fuels. But the transportation problems of Indian are far different than those of the West.

Consider that Indian engine and vehicle technology is 15-20 years behind that in the West, and the engines wear rapidly because they are run on

Table 1. Distribution of energy consumption in India by fuel type.

Fiscal Year[a]	Coal Replacement (t 000 000s)						
	Commercial			Noncommercial (or traditional)			
	Coal[b]	Oil[b]	Electricity	Firewood	Animal Dung	Agricultural Waste	Total
1960-1961	40.4	43.9	16.9	94.6	21.8	29.1	246.7
1965-1966	51.8	64.6	30.6	103.8	23.9	31.9	306.6
1970-1971	51.4	97.2	48.7	122.0	25.8	34.4	369.5
1975-1976	70.1	115.7	66.0	126.5	29.2	38.9	446.4
1980-1981	72.3	159.6	90.9[c]	–[d]	–[d]	–[d]	–

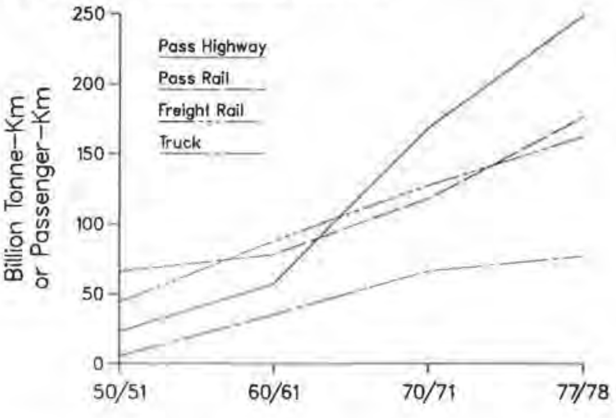
[a] Indian fiscal year begins April 1.
[b] Excludes electric power generation.
[c] Estimated electric power generation.
[d] No estimate given.

Table 2. Growth in Indian vehicle stocks.

Vehicle	Growth by Fiscal Year (000s)				Increase[a] (%)
	1950-1951	1960-1961	1970-1971	1977-1978	
Railway					
Locomotive					
Steam	8.1	10.3	9.3	8.2	–[b]
Diesel	0.02	0.2	1.2	2.0	990
Electric	0.07	0.1	0.6	0.9	118.6
Suburban electric multiple-unit coach	0.5	0.8	1.7	2.3	36
Conventional coach[c]	13.1	20.2	24.7	26.6	10.3
Freight car	205.6	307.9	384	400	94.6
Highway					
Car, jeep, and taxi	159	309	–[d]	846	423
Bus	34	57	–[d]	117	244
Truck	82	168	–[d]	368	349
Two- and three-wheelers	27	95	–[d]	1509	5489

[a] Covers period 1950-1951 to 1977-1978.
[b] None built after 1971.
[c] Excludes baggage and mail cars.
[d] Not reported in available sources.

Figure 1. Highway and rail activity, 1950-1978.



high-sulfur fuel (maximum allowable sulfur content is about four times the U.S. standard). In general, roads can barely be repaired with existing funds, much less improved. The pavement is not thick enough to carry today's loads. Because of low tire quality and overloads, truck tires last only 30 000 km. The side walls fail long before all the tread is used, and rubber is not cheap in terms of either rupees or energy.

Three historical trends are important to note. First, per capita use of transportation, especially passenger transportation, has increased tremendously since India's independence from the United Kingdom in 1947. As Figure 1 shows, highway transportation growth has outstripped rail transportation growth, and more passengers now travel by highway than by rail (5). This shift away from rail is consequential and is recognized as such by the government (5,6).

Second, India imported its first electric and diesel-electric locomotives; now it exports locomotives and coaches (and has stopped building steam locomotives). This is a good transportation example of the government's policy of self-sufficiency. All vehicles are now made in India. Table 2 (5,7) summarizes the growth in vehicle stocks. Although the number of railroad cars doubled between 1950-1951 and 1977-1978, the number of highway vehicles skyrocketed, especially the stock of small two- and three-wheeled vehicles.

Third, the direct correlation between investment in transportation and the economic growth of India is high. A regression analysis of gross capital formation in the transportation sector and GDP time-series data shows R^2 goodness-of-fit indicators of 0.95 or more (5).

CURRENT STATUS OF TRANSPORTATION

Concerning the railways, the Sixth Five-Year Plan (6) laments that, recently, "there have been frequent bottlenecks when even important commodities, particularly coal, fertilizers, cement, etc., have not moved adequately." These bottlenecks often have been due to shifts in traffic patterns; commodities once imported are now exported and traffic demands have shifted as different areas have developed various industries. The railways, however, are the fourth largest in the world (based on kilometers of track) and with 1.6 million employees may be the largest employer in the world (7).

Highway freight transportation and ports suffer from undercapacity. The supply of trucks is insufficient when rail cannot meet demands. Long waiting times at ports, particularly at Bombay, are common on many commodities. Traffic at ports has quadrupled since 1950-1951, and the government has developed minor ports to handle important commodities.

Inland-waterway transportation is limited by the small number of navigable rivers. Approximately 550 km of navigable inland waterways carry only about 10 million tons of goods each year (8). The Sixth Five-Year Plan sees the growth potential in this energy-efficient mode; it also notes the potential of coastal shipping, which is now plagued by port congestion and high transshipment costs and thus poor reliability.

There are an estimated 80 million work animals and 13 million bullock-carts in the country. Animal power is estimated to provide 10 billion t-km of freight transportation annually (6).

Of prime importance is the transportation of coal, India's main domestic source of commercial energy. The Indian transportation system carried 69.26 million t of coal an average distance of 673 km/t in 1977-1978. Of that, 92.2 percent moved an average of 691 km by rail and the rest moved an average of 408 km by truck. Coastal shipping carried 670 000 t of coal that year, but the average distance carried is not reported (5).

India, like the United States, has one dedicated unit-train system where the track, locomotives, and cars are owned and operated by a power company. Both of these systems are closed to all other traffic and not part of a local railroad. In the Indian system, 1 car/min, moving at about 1 km/h, is loaded from a pneumatic system in a silo. Bottom-discharge hopper cars are used; 40 percent of the bottom area opens electropneumatically. Each car carries about 60 t and the power plant is about 50 km from the mine. Trains are 30-40 cars long.

The normal rail shipment of coal is much different. Side-opening hopper cars and regular boxcars are used in nondedicated service (i.e., they also carry other commodities at other times). Loading and unloading methods are mechanical or manual. The cars can be shipped on regular freight trains in small groups or arrangements can be made to ship full train loads to avoid many switching delays. The latter arrangement, called a block train, is not a unit train since it is not made up of dedicated equipment and because some marshalling yards are not by-passed.

The public mass transportation modes are required to carry the masses because the per capita number of private motor vehicles is quite small, possibly about 0.01. Urban population was 44.15 million in 1951, is estimated at 150 million today, and is projected to be 278 million by 2001. Consider that Bombay's population during the 1970s increased by 2.5 million. The mass transit systems are extremely overcrowded and, except in Madras, Delhi, Bombay, and Calcutta, consist entirely of buses. These four cities have commuter rail systems that use mostly electric, multiple-coach trains.

The mass transit systems are most crowded during rush hours, when people literally hang onto the sides of the buses and commuter trains. Three-wheel auto-rickshaws (essentially motor scooters built like rickshaws) and automobile taxis are prevalent in most cities, but fares have been increasing regularly and ridership has declined. Table 3 (5) presents statistics on urban travel in India's four largest cities. A 16.4-km underground railway (subway), India's first, is being constructed in Calcutta.

Intercity passenger transportation is also quite crowded. Intercity trains offer few amenities. Ordinary second-class railway compartments have wooden walls and wooden seats. Fares for first-class accommodations, some of which are air-conditioned, are an order of magnitude higher than for second-class travel but cheap by Western standards. Domestic air transportation carries less than 1 percent of the passenger kilometers.

ENERGY CONSUMPTION

The Indian transportation system, especially the highway mode, is quite energy inefficient, primarily because of congestion, outdated engine technology, poor vehicle maintenance, vehicle underutilization, poor intermodal coordination, and limited infrastructure. Traffic congestion causes many accelerations, which are the most energy-intensive part of transportation. The effect on energy consumption of poorly maintained and outdated vehicles is obvious. Vehicles are underutilized because of delays due to congestion as well as ineffective system operation. This underutilization causes additional capital requirements for vehicles and facilities (since more are needed to perform the same tasks) and the concommitant energy expenditure to build the additional vehicles and facilities. There is a lack of intermodalism and thus a failure to conserve enrgy by using better combinations of modes to transport goods and passengers between origins and destinations. In freight, the lack of intermodalism stems mainly from the public and private split of the modes and the inability of the more energy-efficient railways to carry international containers and semitrailers. Infrastructure limitations, such as severe load limits on highways, constrain the use of larger, more energy-efficient trucks.

India's National Transportation Policy Committee has studied energy intensity and consumption by mode and submode. Table 4 (5) summarizes its findings. The relatively good efficiency of rail transportation is quite apparent from the table, and the electrification of more routes will decrease dependence on imported fuels. India is in an enviable transportation and energy position relative to the rest of the world, developing and industrialized countries alike, because it has a very large rail system. Clearly, the railways are central to any plan to conserve energy in the Indian transportation sector.

A recent major study of energy prospects for developing countries made the following observation (9):

> There is some evidence that energy intensity of freight (transport) varies with stage of economic development. At times of rapid industrializa-

Table 3. Indian urban transportation statistics.

Mode and Vehicle Use	Calcutta	Bombay	Delhi	Madras
Total daily trips[a]				
No. of trips (000 000s)	7.0	9.4	5.0	3.6
By mass transit (%)	80.0	75.0	43.5	65.0
Daily mass transit trips[a] (%)				
By rail	25.5	53.0	4.0	20.0
By bus	74.5[b]	47.0	96.0	80.0
Vehicles[c] (000s)				
Cars and jeeps	80.8	137.4	105.2	27.8
Two-wheelers	33.9	62.7	282.3	40.8
Auto-rickshaws[d]	-	0.7	17.9	1.5
Taxis	7.1	23.7	5.6	2.5
Urban buses[e]	4.1	3.5	6.9	1.8
Trucks[f]	25.8	35.5	31.1	5.9

[a] 1976-1977 estimate.
[b] Includes trams (36 percent of bus trips).
[c] 1978.
[d] Three-wheelers used as small delivery vehicles and taxis.
[e] Standard, school, and mini buses.
[f] Private-public carrier, tractor-trailers, and tempos-delivery vans (tempos are three-wheeled trucks with a capacity of about 0.5 t).

Table 4. Average energy intensities of various Indian submodes.

	Energy Intensity (Btu/vehicle km)		Average Total Energy Intensity[a,b]	
Submode	Propulsion (direct)	Total[a]	Btu per Passenger km	Btu per t-km
Rail[c]				
Diesel	121 055	129 820	160.2	255.5[d]
Steam	776 840	785 605	1460.8	3576.9
Electric	41 595	50 360		84.6
Suburban electric	21 935	30 700	64.6[e]	–
Bus				
Urban, diesel	9 178[f]	10 638	307.7	–
Regional, diesel	8 410	9 870	NA	–
Petrol	15 135	16 595	555.5	–
Petrol automobile	3 817[g]	5 512	NA	–
Scooter	625	865	NA	–
Barge	NA	NA	–	328.0
Pipeline	NA	NA	–	281.7
Coastal shipping[h]	NA	NA	–	155.0
Truck	NA	NA	–	1587.3

Notes: Btu = British thermal unit.
NA = not available.

[a] Includes indirect energy spent in maintenance, construction, and vehicle manufacture.

[b] Although it is not clear from the source how all these numbers were derived, and some must be estimates, at least for the railways it is the ratio of the net passenger kilometers or metric ton kilometers to fuel consumed over the three-year period 1974-1975 to 1976-1977.

[c] Main line rail, except suburban electric.

[d] Or about 374 Btu/ton mile; the U.S. value for 1977 was 670 Btu/ton mile.

[e] Average for electric rail and suburban electric rail.

[f] Or about 8.4 miles/gal, a typical value for a U.S. 40-ft urban bus is 3.7 miles/gal.

[g] Or about 20 miles/gal, which seems reasonable given the light weight of the cars.

[h] About 14 400 dead-weight-tonnage ship.

Table 5. Modal distribution of India's commercial energy, 1978-1979.

	Consumption (Btu trillions)				
Source	Railway	Highway	Air	Ship	Total
Coal	42.3	0	0	0	42.3
Oil	27.0	205.8	30.7	3.4	266.9
Electricity	8.9	0	0	0	8.9
Total	78.2	205.8	30.7	3.4	318.1

Note: About 4.5 percent of the energy used in transportation is animal power.

> tion, the number of ton-miles relative to GDP increases; indeed at some point this figure may become greater in developing than in industrial countries, whose typically more regionally balanced economic structures lead to even declining freight transport.

This observation does not bode well for India. Regional imbalances have plagued the Indian freight transportation system. The trend toward the more energy-intensive truck exacerbates the regional energy-intensity effect.

Table 5 (10) gives the distribution of commercial energy demand by energy type and mode. In short, transportation is dependent on diesel fuel (since there are relatively few cars) and thus susceptible to world oil prices and potential oil shortages. Although India is attempting to make itself more energy independent by using more domestic coal and oil, oil importation will continue for the foreseeable future, especially importation of middle distillates. Gasoline is highly taxed, as are automobiles, because automobile ownership and use are considered luxuries. Diesel is sold at about cost.

TARIFFS

All modes of transportation are subsidized in India; airports, ports, railway cars and facilities, and roads are built by the government. Urban mass transit is subsidized. The freight rates on some commodities are set to cross-subsidize the shipment of other commodities, and passengers who travel in the higher classes (e.g., intercity first-class air-conditioned rail) subsidize those in lower classes of accommodation. Because noncommuter rail passenger traffic accounts for only 50 percent of the total rail passenger trips and 80 percent of the total passenger miles (but 90 percent of the total passenger earnings), the intercity traveler is subsidizing the commuter (8).

A major scheme for cross-subsidization is freight equalization. Here short hauls subsidize long hauls of certain basic commodities through a pool to the extent that the charge for shipping the commodity between any two points in the country is the same. The rationale for the scheme was that location in the country should not be a factor for discrimination and that balanced regional growth would occur because of equalization.

Another scheme used in goods shipment involves telescoping rates. Here the cost for the first increment of distance is relatively high, the second increment costs less, the third even less, and so on. Like freight equalization, this scheme covers the total cost of all shipments of the commodity, but short hauls subsidize long hauls. The real cost of shipping is tapered with distance due to some fixed and initial switching costs, but not tapered as much as in telescoping rates (5,11).

CONSTRAINTS TO CHANGE

This section addresses constraints on the Indian transportation system that prevent rapid change, since a key question about India's transportation system is whether it is constraining the nation's economic and social development and whether its growth can at least match that of other sectors. The potential for a systematic evolution is there, but the constraints or barriers are substantial. They include national policy, continued shifts in demand patterns, capital availability, infrastructure inadequacies, management resistance, spatial location of industries, a decentralized population, size of vehicles, age of vehicle technology, lack of sufficient planning information, and energy availability and cost. Further research would undoubtedly uncover more. Some of this has already been mentioned and the most significant are discussed below.

Two national policies define the types of change that can take place in India; these policies state that all undertakings should be as labor intensive as possible and that all goods used in India should be made in India. Exceptions to these policies are possible but rare. Sophisticated electronic instrumentation may, for example, be imported. On the other hand, the railway managers are proud that almost every component of their diesel and electric locomotives is now made in their shops. The goal of self-sufficiency limits the types of technology that can be used in the transportation sector. Indian vehicles are simple and will remain simple. There is no infrastructure to maintain complex vehicles. The impact of the labor-intensiveness policy on the transportation sector is best seen in facility construction. Roads and runways are built by hand.

Since India gained independence, the demands placed on the transportation system have shifted continually; this situation also constrains the development of the system. Commodities once imported are now exported. New major industries have sprung up that require the shipment of new commodities, sometimes over long distances. Many of the resources of the transportation system, especially the railways, have been devoted to an attempt to meet this dynamic demand. As a result, attention to growth often has been distracted by the need to fix the latest bottleneck.

One of the major constraints on change in the transportation sector is lack of capital. The government, with its limited budget, must carefully choose its priorities. During the time since independence, feeding its people has been of prime importance to India, and it still is not an easy task. Irrigation projects therefore receive great emphasis. However, the transportation sector has not been neglected and its importance in development has been recognized. Now energy is a problem and the Sixth Five-Year Plan focuses on coal, conservation, and the large users of petroleum. The emphasis on the railways and the electrification of the railways is strong. Yet sufficient capital to move the railways ahead quickly is not forthcoming.

The social and political infrastructure of the transportation system often hinders change. The nine zonal railways act independently, which cuts into efficiency. The structure of the government of India, with its various bureaucracies, hinders intermodalism. The Railway Board is independent of the government. Most highway decisions are made at the state and local level. The government owns the railways; therefore no private investment can be attracted to stimulate growth. Trucks are privately owned.

The physical infrastructure is also a problem. The two-axle highway trucks are designed to haul 9-12 t with a 25 percent overload, but overloads beyond that are common. The highway network is limited both in the quality of the roads and the extent of coverage. Low weight capacity on bridges limits use of many routes. Only 29.3 percent of the villages are connected by all-weather roads, another 16.1 percent are connected only by fair-weather roads, and the remainder are not linked by any road. Clearances and overhead structures severely limit the size of railway shipments; this limitation is a critical problem on the narrow gauge and only slightly less of a problem on the meter gauge. The inability to carry international size containers (about the size of the box of a common U.S. semitruck trailer) causes much loading and unloading of containers at ports (12). Since there are two main track gauges and some narrow gauge, high cost transshipments also occur within the railway system.

The tariff structure often hinders transportation efficiency. Certain commodities and passengers do not cover their shipment cost. For example, firms tend to locate farther from their input sources because of freight equalization and too steep a taper on the telescoping rates, which generate extra ton kilometers.

INDIAN TRANSPORTATION POLICY

India's transportation policy, which is spelled out in Chapter 17 of the Sixth Five-Year Plan, addresses energy directly (6):

> As a long term goal, efforts will have to be made for the railways to develop the capacity to clear (i) all train load traffic for long, medium and short distances, and (ii) all nontrain load traffic (i.e., piecemeal traffic) for long and medium distances (except for certain commodities). This would broadly leave all short distance piecemeal traffic for the road transport. While capacity will need to be developed by the railways to do so, and while fiscal measures would be in keeping with the above objectives, the choice of transport mode will, to a great extent, be conditioned by the consumers preferences as a regulatory or legal measures will be difficult to implement, and could lead to misuse of the regulatory processes.

Some of the action items are to (a) accelerate the pace of railway electrification; (b) improve the fuel efficiency of diesel-based road vehicles through vigorous methods, including improved vehicle design and road conditions, speed control devices, and truck-trailer combinations on selected stretches of national highways; and (c) encourage other energy-efficient modes, including coastal and inland-waterway shipping, pipeline, bicycles, bullock-carts, and public transportation (including electrified commuter rail and trolley buses).

Like most plans, the Sixth Plan seems too ambitious in light of the available funds. The Sixth Plan budget shows transportation receiving 12.4 percent of the $115 billion plan. Although the emphasis of the plan's text is that the rail and water modes require renewed support for energy reasons, the budget does not appear to reflect this. Historically, the railways received an average of 51.4 percent of the national transportation expenditures for each five-year period. In the Sixth Plan they are targeted for 42.2 percent. Historically, the highways received a 38.4 percent average share; this plan pegs them at exactly that average, up from 33.5 percent in the Fifth Plan. In dollars, the highway mode will receive much more emphasis than the railways because of private investment in vehicles, repair facilities, and other infrastructure. The historical average budget share for the water modes is 5.4 percent, as compared with 6.9 percent in the Sixth Plan.

Owen (3) gives an interesting perspective as an observer of India in the late 1960s. The new technology with the potential of removing the isolation of most of India's population, of moving its goods, and of making the cities operate was the highway mode. From his perspective, development would get a great push from the modern car, truck, and bus on surfaced highways. The government's expenditure on highways as a percentage of transportation expenditure during the Fourth Plan (1969-1974) was 15.7 percentage points higher than under the Third Plan (1961-1966).

Then came the energy crisis of the mid to late 1970s, when a developing country could ill afford to pay the steeply rising cost of imported oil. Instead of being a springboard of development, the thirsty highway diesels became a drag on foreign exchange.

Although the Sixth Plan forecasts vigorous measures to improve the fuel efficiency of the highway mode, significant improvements seem impossible. Even if the 15-year-old engine technology could be immediately updated and other new vehicle improvements implemented, the fleet has a long average life and many older vehicles would remain in service for years to come. Reducing congestion on the Indian highways to a reasonable level will remain a dream, at least in this century, and congestion wastes energy. Maintaining vehicles also seems impossible, given the present vehicle-service infrastructure, the little real control the government seems to have over truckers and taxi drivers, and the quality of the maintenance of government-owned buses.

If there is any lesson India can learn from the United States, it is that every dollar spent on road, automobile, and truck improvements will reduce user cost relative to the user cost of trains and urban buses. The modal shift so apparent in the Indian transportation data will be fostered by the government's highway expenditures.

The average lead for trucks is too long, based on purely economic trade-offs between shipping a commodity via truck or rail (5). (Truck has the economic advantage for shorter distances, rail for longer. Currently, truck traffic goes far beyond the break-even point for most commodities.) As diesel fuel price increases, the break-even point moves toward shorter truck leads. Because trucks haul beyond the break-even point, "the diseconomies of moving goods by road beyond the economical distances are being borne by society, in fact, through increased oil import bills" (10). The "catch-22" is that the rail system has insufficient capacity growing at an insufficient rate. The only way for the economy to expand is to let trucking grow.

CONCLUSIONS

My discussions with transportation professionals throughout India have convinced me that much of what can generically be called systems analysis is required to rationally guide the Indian transportation system toward energy efficiency while making it a more effective tool of India's development. Systems analysis here means constructing alternative plans and evaluating each plan on several criteria, including at least total energy consumption and type of energy consumption, economic and political feasibility, and improvement in mobility.

The Indian transportation system offers many areas for research and analysis. The trade-offs between building synthetic liquid-fuel plants and improving transportation system energy efficiency to lower future demand should be examined. Research is needed to improve vehicle and vehicle-component testing techniques to increase reliability and life. Methods to improve engine efficiency and reduce the wear caused by the high-sulfur diesel fuel--such as lubricant additives, different engine materials, and different combustion chamber or fuel-injection configurations--should be explored. Many optimization studies of subsystem operations come to mind, as do cost-effectiveness and environmental impact studies. Since the Indian transportation system is so vulnerable to reduction or cut off of imported middle distillates, contingency planning to cope with shortfalls seems necessary.

Other studies should investigate better methods of direct combustion of coal in railroad locomotives. Because coal is India's main domestic commercial fuel, systems analysis aimed at increasing the economic and energy efficiency of coal distribution is quite important.

Although high technology has little place in Indian transportation, the potential substitution of telecommunications for travel deserves at least an initial appraisal. Even though much can be done to reduce lead imports by improving vehicle-starting batteries, the market potential and technical feasibility of battery-powered electric vehicles deserve study.

The Indian transportation infrastructure needs rationalization, a task that will require much planning. Intermodalism is an obvious energy-conservation measure, but strong arguments based on careful study are needed to bring about the required infrastructure changes. The transportation system should be moving processed and manufactured products the long distance to market and the raw (more weight-intensive) materials as little distance as possible. The current situation is far from this optimum. Rationalized tariffs will help, but a rigorous exercise in location theory would identify energy-saving opportunities.

India needs these and many other studies to provide a basis for internalizing the real cost of transportation and energy into individual and government decisionmaking. This real cost includes the full social and resource cost. Economic incentives and disincentives (taxes and subsidies) are often needed to accomplish this internalization for individuals.

Both long-term transportation energy system planning and subsystem analysis will be required to allow India's transportation system to keep pace with and fully support the nation's growth and development. For every barrel of diesel fuel India imports it cannot import something else needed for development. The challenge is great.

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The paper summarizes the analysis and field work performed for the U.S. Agency for International Development during the summer of 1981. The purpose was to design Indo-U.S. transportation energy projects for the agency. I acknowledge their support and direction. It was in traveling through India, observing its transportation system and talking to its transportation professionals, that I learned the meaning of India's transportation problems and plans. I greatly appreciate the assistance of the Indians who gave me their time and insights and hope this paper does some justice to what they tried to teach me.

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Regional Land Use and Transportation Development Optimization Model for Delhi Region of India

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Rapid industrialization has brought rapid population growth in major metropolitan areas in India. The rapid population growth rates in the Delhi metropolitan area (created by strong expansion of the economic base due to industrialization) have led to the adoption of decentralization policies for the region. A regional scale land use and transportation model is developed that may be used for the analysis of decentralization options. The model searches for regional development configurations that minimize the combined costs of providing urban infrastructure and intercity transportation costs. The objective function is a nonlinear function of the regional activity distribution, and a sequential search procedure is used to identify the least-cost alternative. The capabilities of this allocation-simulation model are demonstrated by several example analyses for the Delhi commuter region.

The largest population growth rates in India in recent years have been in the biggest metropolitan areas of Delhi, Bombay, Calcutta, and Madras. In 1971 the Delhi region had a population of 13.05 million, and this population is expected to grow to 16.18 million in 1981 and 19.74 million in 1991. Between 1961 and 1971 the annual rate of urban population growth was 5.1 percent while the rural growth rate was only 1.2 percent. In 1971 the Delhi metropolitan area had more than 70 percent of the urban population of the region within an 80-km radius of Delhi.

Expansion in government employment and the industrial base of the Delhi area have been the major stimuli to rural to urban migration in the Delhi region. A policy of decentralization of industrial growth away from the Delhi metropolitan area has been pursued in an attempt to reduce the rate of growth of Delhi. The state governments adjoining Delhi have provided infrastructure and other incentives in various urban centers within the region in order to attract industries. Industries have responded positively to these policies, and many large and medium-sized industries have located in smaller towns within a 30-km radius of Delhi.

The decentralization of industries, population, and other types of employment to these centers, however, has led to increasing problems of intercity commuting. Studies and analyses conducted by the Central Road Research Institute (1) of these intercity commuter flows showed that large investments in new intercity transportation facilities would be required if these commuter flows continued to grow. These findings suggested that any attempts to decentralize employment and population within the Delhi region should recognize explicitly the costs of handling the commuter flows generated by future development patterns.

This paper describes a technique for exploring the public investment cost implications of alternative regional development policies in the Delhi region.

OPTIMIZATION MODEL

The basic approach of the optimization model is to allocate urban population growth and employment opportunities among urban centers so as to minimize the costs of regional urbanization, including the provision of intercity transportation costs. Figure 1 shows the broad flow of activities involved in the regional development optimization model. The model is described in general terms in this section of the paper and subsequent sections describe the detailed structure of each of the modules in Figure 1 along with the mathematical structure.

The allocation process starts by allocating a hypothetical increment of population to each urban center, and then the basic and service employment required to support this population increment at each urban center are estimated. The intercity flows likely to be created by this increment of urban activity are then estimated. The total annual costs of the increased activity at each urban center are then calculated and the population increment is allocated to the minimum cost urban center, subject to any development constraints. The activity level, cost, transportation flow, and travel-time vectors are then updated and the process is repeated until all of the regional population growth has been allocated. This sequential approach to the problem is required, since the underlying relations are nonlinear.

DELHI REGIONAL SYSTEM

Figure 2 illustrates the zone system used for the analyses described in this paper and the principal components of the regional transportation system of the Delhi commuter region (DCR). The region has been divided into 22 zones; each zone focuses on one of the urban centers of the region. Each zone has a dominant urban center and a rural population distributed throughout the zone in small villages. The 1971 population distribution is also illustrated in Figure 2.

Figure 3 illustrates that the railway and highway networks are radial in character and converge on Delhi. Most of the urban communities have direct transportation links with Delhi by both the highway and railway networks. There are no cross-connections in the regional transportation system with the Yamuna River, which flows from north to south in the region and provides a major constraint in the development process. The regional transportation facilities are all part of the intercity road and railway systems that have developed over many years.

CHARACTERISTICS OF INTERCITY COMMUTER DEMAND

Data on intercity commuter flows were collected by use of traditional survey techniques. The overall sample size was about 33 percent for intercity trips by mass transportation and 25 percent for trips by means other than mass transportation (1,2). In the survey year of 1969 there were approximately 60 000 one-way commuter trips/day, with about two-thirds of these trips traveling from residences in the regional urban centers to Delhi and one-third traveling from residences in Delhi to the surrounding regional centers. Approximately 89 percent of the total intercity trips were for purposes of work and about 10 percent were for educational purposes.

Modal choice data showed that about 75 percent of the trips were carried by mass transportation, 7.5 percent by individual fast vehicles, and the remaining trips by slow vehicles, including bicycles. These data also showed that about 11 percent of the trips were by the high-income group, about 19 per-

Figure 1. Regional development optimization model.

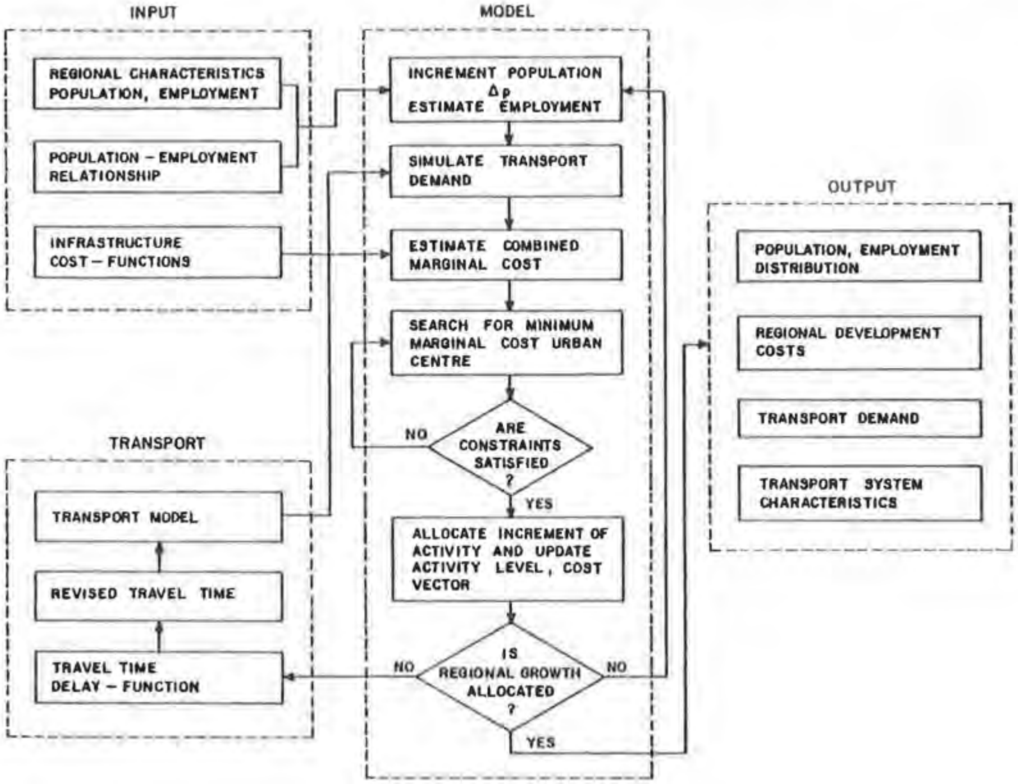
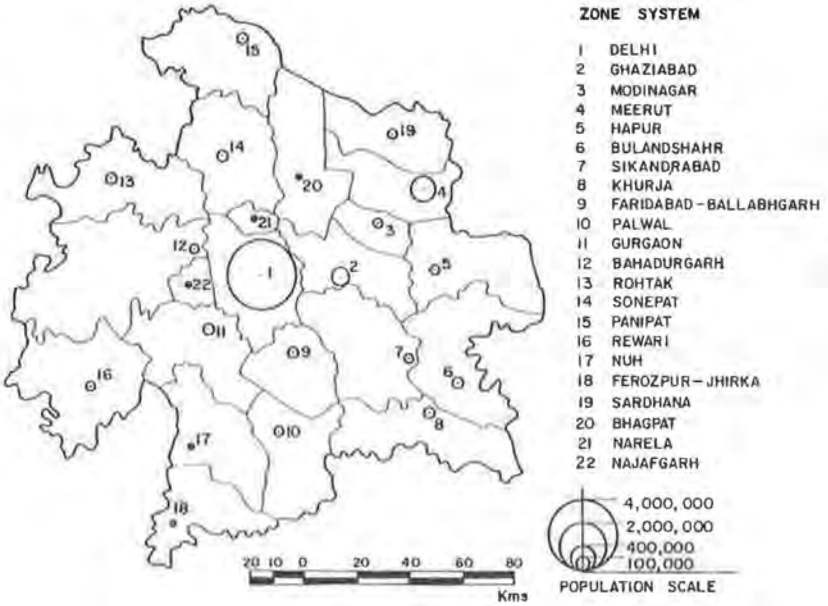


Figure 2. Zone system and urban population distribution in DCR.



cent by the middle-income group, and 70 percent by the low-income group.

A number of alternative equation structures for estimating intercity transportation flows were explored, and the following equations were selected from those considered:

$$T_{jd} = 192.8\, P_j^{-0.5129} \exp(-0.0213 t_{jd}) \quad (R^2 = 0.87) \tag{1}$$

and

$$T_{dj} = 404.9\, EB_j^{-0.2293} \exp(-0.025 t_{dj}) \quad (R^2 = 0.89) \tag{2}$$

where

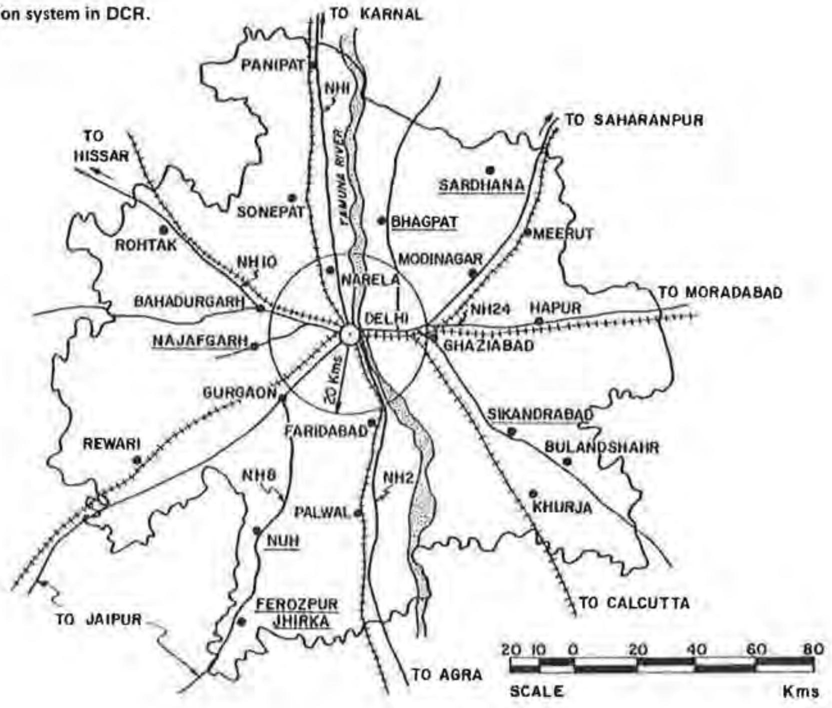
T_{jd} = number of person trips for purposes of work from urban center j to Delhi per 100 population of urban center j,

P_j = population of urban center j (in thousands),

t_{jd}, t_{dj} = travel time between urban center j and Delhi d and vice versa (in minutes),

T_{dj} = number of person trips for the purpose of work from Delhi to urban center j per 100 basic jobs at urban center j,

Figure 3. Regional transportation system in DCR.



EB_j = basic employment at urban center j (in hundreds), and

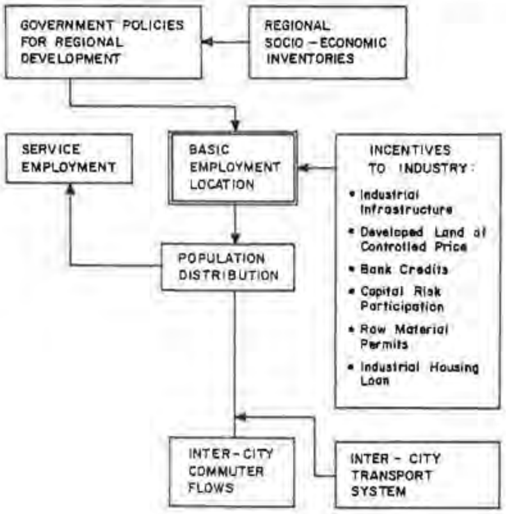
R^2 = coefficient of determination.

Although the above equations have been developed by regression analysis, they are both of the unconstrained-gravity type. Equation 1 shows that trip production from the urban centers that surround Delhi depends on the travel time to Delhi and the population of the urban center. The equation suggests that a continued supply of commuter transportation will continue to stimulate intercity commuting, whereas the negative exponent of the population term indicates increasing self-containment of the urban centers with increasing population size. Equation 2 has a similar structure to the trip-production equation. The commuting trip-attraction rate of the urban centers throughout the region decreases with increasing travel time from Delhi and with increasing basic employment in the urban centers. An inspection of the residuals of both equations suggested that other factors influence the intercity commuting patterns for some of the communities, but significant correlations could not be established. These equations also suffer from the traditional limitations of using any empirically derived equations for estimating future conditions. This does not mean that these equations are not stable for future trip estimations. However, it does mean that trip-generation equations can only be considered stable for future trip estimates if one assumes that the socioeconomic conditions remain the same over the forecast period. The structure of the trip-generation equations is quite logical.

REGIONAL POPULATION AND EMPLOYMENT CHARACTERISTICS

The regional activity system consists of three main activities: population, basic employment, and service employment. Among these activities, basic employment is the most important and is a driving force in the regional urban system. This is recognized by the India government as the basic approach to urbanization and regional development, as shown in Figure 4. Figure 4 illustrates that governments have a strong influence on the location decision of industries through a variety of programs and regulatory powers. These include the supply of industrial land at a regulated price, water supply, sewerage and electrical power connections, bank credits, risk participation in capital, raw materials permits, import-export licenses, and loans for industrial housing. These incentives and powers exert a very strong leverage in the Indian economy, where private capital is scarce and most of the basic infrastructure is absent in the majority of urban centers.

Figure 4. Role of basic employment in distribution of activities in region.



Analyses of population growth rates in the urban centers of the Delhi region have shown that these industrial incentives and other decentralization policies have been the primary reason for the differential rates of population growth that have occurred at the various urban centers. Employment has been partitioned into basic and nonbasic categories to reflect the growth processes that have occurred in the urban centers of the region. The basic category includes employment in government, industry, trade, and commerce. The nonbasic category includes employment in retail trade and personal services. Regression equations have been developed that capture the interrelations between the two employment categories and population. These equations are as follows:

$$\text{Basic employment rate} = 7.4030 + 0.5706 \cdot \ell n \quad \text{population} \qquad (3)$$

where $R^2 = 0.89$, and

$$\text{Service employment rate} = -0.3507 + 0.9784 \cdot \ell n \quad \text{population} \qquad (4)$$

where $R^2 = 0.99$. Equations 3 and 4 allow the basic and nonbasic employment required to support an increase in population at each urban center to be estimated, given an existing population level. The equations show that both the basic and nonbasic employment rates increase with population, but at a decreasing rate.

COMMUTER TRAVEL SUPPLY CHARACTERISTICS

The supply of commuter transportation facilities should be demand-oriented, but in India the transportation services are not supplied exclusively for intercity commuters. Intercity commuters share the regional and national transportation system with other users. The current transportation facilities in the DCR have a fixed capacity and are unlikely to be expanded dramatically because of limited resources.

A review of the supply and demand characteristics of the regional highway network indicated that some excess capacity existed that could accommodate future volume increases. The 1971 demand-capacity ratios ranged from a low of about 0.2 to a high of about 0.9; most links operated at ratios of 0.4-0.5. The railway links consist primarily of single lines with conventional signaling systems. Many of the lines were operating at capacity in 1971, although some residual capacity existed, particularly to the west of Delhi.

The marginal costs of handling additional public transportation passengers by bus and rail have been estimated for each link of the road and rail networks. The annual transportation supply costs per passenger per kilometer by the bus mode have been calculated to be 9.62 rupees and by the rail mode to be 5.74 rupees [$1 (1978) = 7.5 rupees] (3). These costs are for those facilities with available excess capacity and do not involve major new capital investments in capacity. The private costs incurred by road users are not included in these analyses, which focus only on public-sector costs.

The optimization process illustrated in Figure 1 also requires travel-time-delay functions for the road and railway networks in order to reflect the impacts that increased intercity commuting might have on travel times. The travel-time-delay functions for the highway and railway networks have been derived from some earlier work by the World Bank (4,5). Modification to these delay functions was carried out for inclusion in the optimization process. Details of the modification may be found in Gupta (3).

URBAN INFRASTRUCTURE COST FUNCTION

The marginal-cost concept was used in developing the urban infrastructure cost function. This concept will provide a tool or some objective means to planners and politicians for evaluating their decisions of investing public money.

The 22 urban centers in the Delhi region have been grouped into six categories on the basis of population size and geographic locations, and these groupings are shown in the table below:

Group	Urban Center	Constraints on Development
1	Delhi	Urban land, water supply
2	Meerut	Urban land
	Faridabad-Ballabhgarh	
	Najafgarh	
3	Ghaziabad	
	Modinagar	
	Hapur	
	Bulandshahr	
	Khurja	
	Palwal	
	Panipat	
	Narela	
4	Sikandrabad	Rail
	Sardhana	
	Bhagpat	
5	Gurgaon	Moderate water supply reserves
	Bahadurgarh	
	Rohtak	
	Sonepat	
	Rewari	
6	Nuh	Rail and poor water supply reserves
	Ferozpur-Jhirka	

Urban development cost functions have been estimated for each town group by calculating the infrastructure requirements for population magnitudes that range from 50 000 to 1 million. Equations have been fitted to the cost data in order to produce the marginal-cost functions summarized in Table 1. The cost functions in Table 1 for residential activities include the infrastructure costs required by the associated service employment.

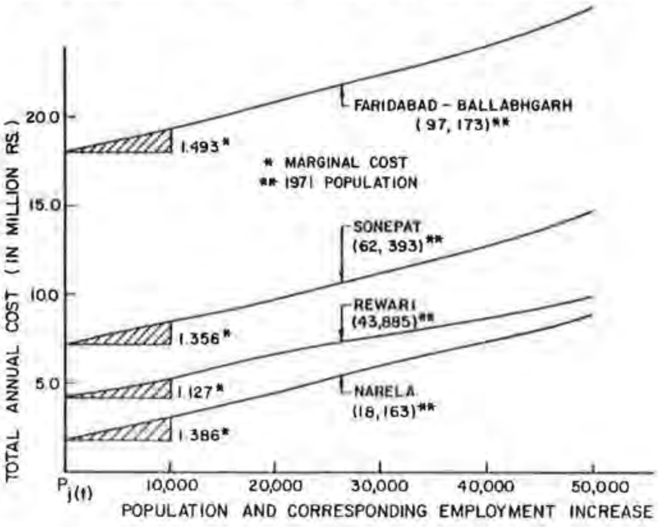
Figure 5 shows total annual cost curves and the marginal costs for a few urban centers of the Delhi

Table 1. Marginal infrastructure cost functions for residential and basic employment activities, by town group.

Town Group	Residential Activities		Basic Employment Activities	
	Equation	R^2	Equation	R^2
1	$MCP_{j(G)} = 16.9981\, P_{j(G)}^{0.1323}$	0.8950	$MCB_{j(G)} = 58.3465\, EB_{j(G)}^{0.1247}$	0.9197
2	$MCP_{j(G)} = 17.7290\, P_{j(G)}^{0.1282}$	0.9120	$MCB_{j(G)} = 57.9048\, EB_{j(G)}^{0.1349}$	0.9216
3	$MCP_{j(G)} = 18.0835\, P_{j(G)}^{0.1258}$	0.9044	$MCB_{j(G)} = 60.1956\, EB_{j(G)}^{0.1196}$	0.9197
4	$MCP_{j(G)} = 18.0835\, P_{j(G)}^{0.1258}$	0.9044	$MCB_{j(G)} = 60.1956\, EB_{j(G)}^{0.1196}$	0.9197
5	$MCP_{j(G)} = 19.0621\, P_{j(G)}^{0.1339}$	0.9158	$MCB_{j(G)} = 62.3273\, EB_{j(G)}^{0.1169}$	0.9139
6	$MCP_{j(G)} = 19.6642\, P_{j(G)}^{0.1234}$	0.9254	$MCB_{j(G)} = 64.3412\, EB_{j(G)}^{0.1147}$	0.9044

Note: $MCP_{j(G)}$ = marginal cost in rupees per increment of population in urban center j of town group G, $P_{j(G)}$ = population of urban center j in town group G, $MCB_{j(G)}$ = marginal cost in rupees per increment in basic employment in urban center j of town group G, and $EB_{j(G)}$ = basic employment of urban center j of town group G.

Figure 5. Application of marginal-cost concept in regional development process.



region. These costs include residential, service, and basic-employment infrastructure along with the intercity transportation costs. These curves indicate that total investment in the development of infrastructure and transportation increases with increasing population. The marginal cost is shown by the shaded area and indicates that there are significant differences in the marginal costs between urban centers.

ALLOCATION-SIMULATION MODEL STRUCTURE

The general form of the allocation-simulation process illustrated in Figure 1 may be expressed mathematically as follows:

$$Z = \sum_{j\epsilon G} \left\{ (1/2)\, K^{(1)}_{j\epsilon G} \left[P^{\gamma j\epsilon G}_{j\epsilon G(t+1)} + P^{\gamma j\epsilon G}_{j\epsilon G(t)} \right] * \left[P_{j\epsilon G(t+1)} - P_{j\epsilon G(t)} \right] \right\}$$

$$+ \sum_{j\epsilon G} \left\{ (1/2)\, K^{(2)}_{j\epsilon G} \left[EB^{\rho j\epsilon G}_{j\epsilon G(t+1)} + EB^{\rho j\epsilon G}_{j\epsilon G(t)} \right] * \left[EB_{j\epsilon G(t+1)} - EB_{j\epsilon G(t)} \right] \right\}$$

$$+ \sum_{j=2}^{n} (1/2)\, K^{P} \exp(-\alpha_1 t_{jd}) * C_{jd} \left[P^{-\beta_1}_{j(t+1)} + P^{-\beta_1}_{j(t)} \right] * \left[P_{j(t+1)} - P_{j(t)} \right] * R_{Pj}$$

$$+ \sum_{j=2}^{n} (1/2)\, K^{EB} \exp(-\alpha_2 t_{dj}) * C_{dj} \left[EB^{-\beta_2}_{j(t+1)} + EB^{-\beta_2}_{j(t)} \right] * \left[EB_{j(t+1)} - EB_{j(t)} \right] * R_{Aj} \tag{5}$$

subject to the following constraints:

$$\sum_{j=1}^{n} P_{j(t+1)} - P_{j(t)} = P^{u}_{(t+1)} \tag{6}$$

$$\sum_{j=1}^{n} EB_{j(t+1)} - EB_{j(t)} = EB^{u}_{(t+1)} \tag{7}$$

$$P_{j(t+1)} \geqslant P^{min}_{j(t)} \tag{8}$$

$$P_{j(t+1)} \leqslant P^{max}_{j} \tag{9}$$

$$EB_{j(t+1)} \geqslant EB_{j(t)} \tag{10}$$

$$T^{im}_{jd(t)} + T^{m}_{jd} \leqslant X^{im}_{jd} \tag{11}$$

$$T^{im}_{dj(t)} + T^{m}_{dj} \leqslant X^{ij}_{dj} \tag{12}$$

where

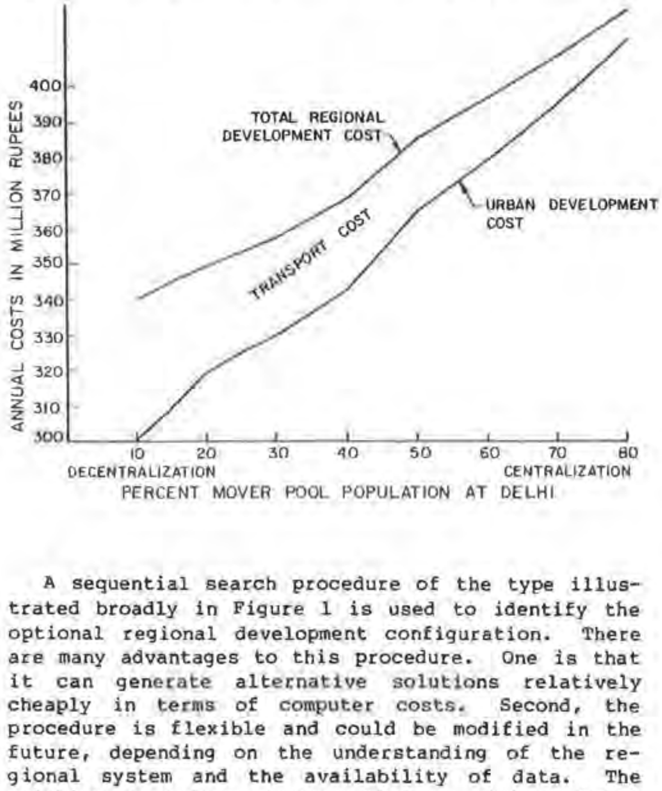
n = number of urban centers;
G = number of homogenous town groups;
$P_{j(t)}, EB_{j(t)}$ = level of population and basic employment, respectively, at urban center j for the base year time period t;
$P_{j(t+1)}, EB_{j(t+1)}$ = level of population and basic employment, respectively, at urban center j for the horizon year time period t+1;
$K_{j\epsilon G}^{(1)}, K_{j\epsilon G}^{(2)}$ = constants for population and basic-employment activities derived from the infrastructure cost function for urban center j of town group G;
$\gamma_{j\epsilon G}, \rho_{j\epsilon G}$ = parameter values associated with population and basic employment, respectively, in the infrastructure cost function for urban center j of town group G;
K^{P}, K^{EB} = constants associated with the trip-production and trip-attraction rates of the transportation models;
α_1, α_2 = parameter values associated with travel time in the trip-production and trip-attraction rates of the transportation models;
t_{jd}, t_{dj} = travel time (in minutes) between urban center j and the regional center Delhi, and vice versa;
C_{jd}, C_{dj} = transportation supply costs per trip from urban center j to the regional center Delhi, and vice versa;
β_1, β_2 = parameter values associated with trip-production and trip-attraction rates of the transportation models;
R_{Pj}, R_{Aj} = expansion factor for the trips produced and the trips attracted by urban center j for purposes other than work;
$P_{(t+1)}^{u}, EB_{(t+1)}^{u}$ = total urban population and basic-employment growth in the region at the horizon year;
T_{jd}^{m}, T_{dj}^{m} = peak-hour transportation flows from urban center j to the regional center, and vice versa, on transportation mode network m;
X_{jd}^{im}, X_{dj}^{m} = transportation capacity of link i for the transportation corridor that serves j to d, or vice versa, by transportation network m; and
T_{jd}^{im}, T_{dj}^{m} = existing peak-hour transportation flows on link i for the corridor that serves j to d, or vice versa, by transportation network mode m.

The objective function shown in Equation 5 is nonlinear in the decision variables. The basic problem in this formulation is to find the values of $P_{j(t+1)}$ that optimize the objective function. With each level of $P_{j(t+1)}$ there are associated jobs that are expressed by the second term $EB_{j(t+1)}$. The objective function estimates the total costs of development for total regional urban growth. There are many solution procedures to nonlinear optimization problems, but the efficiency of the procedure depends on the number of independent variables.

Table 2. 1991 population holding capacities and employment targets for urban centers of DCR.

Urban Center	Population (000s)	Employment (000s)		
		Basic	Service	Total
1	5200	843.8	768.6	1612.4
2	400	60	50	110
3	150	22	17	39
4	600	122	105	227
5	100	14	11	25
6	100	14	11	25
7	60	8.5	6.3	14.8
8	100	14	11	25
9	300	50	36	86
10	70	10	8	18
11	100	14	11	25
12	75	11	8	19
13	200	30	24	54
14	200	30	24	54
15	200	30	24	54
16	80	11.5	9	20.5
17	17	2.3	1.7	4
18	24	3.2	2.3	5.5
19	50	7	5.2	12.2
20	30	4	3	7
21	60	8.5	6.3	14.8
22	40	5.5	4.1	9.6
Total	8156	1315.3	1146.5	2461.8

Figure 6. Annual regional development costs versus degree of centralization.



A sequential search procedure of the type illustrated broadly in Figure 1 is used to identify the optional regional development configuration. There are many advantages to this procedure. One is that it can generate alternative solutions relatively cheaply in terms of computer costs. Second, the procedure is flexible and could be modified in the future, depending on the understanding of the regional system and the availability of data. The solution procedure ensures that a minimum total public investment for regional urban development is achieved.

MODEL APPLICATION TO HORIZON YEAR STRATEGIC REGIONAL PLANNING

Population and employment targets have been set for future time horizons for the Delhi region in the National Capital Regional Plan (6), and these targets are listed in Table 2 for the 22 urban centers. A number of alternative regional development policies have been prepared where these policies may be expressed in terms of deviations from the population and employment targets listed in Table 2. For each of the alternatives examined, the expected growth in regional population was allocated in two steps. The natural population growth expected in each urban center was allocated to the urban center in which it occurred while migrant population was allocated in the second step on the basis of the costs of development.

An issue of concern to governments involved with the management of urban growth is the extent to which urbanization should be decentralized. Figure 6 shows the annual costs of development for a range of development policies, which range from almost complete decentralization of rural-urban migrant growth to almost complete centralization of this growth. The diagram illustrates that the annual costs of development are about 80 million rupees/year, with the transportation cost component varying from 41 million rupees/year with heavy decentralization to about 8 million rupees/year with a policy that encourages the strong centralization of growth. Intercity transportation flows ranged from 19 000 to about 122 000 trips/day for the range of policy options.

Within this range of broad regional development strategies there is a large number of more specific policy issues, such as the efficacy of investments in water supply and transportation in various parts of the region. The table below lists seven alternative regional development strategies in terms of variations in the population holding capacities from the regional plan targets listed in Table 2:

	Variation Over Target Population (%)			
Alternative	Delhi	East of Delhi	Northwest Delhi	Southwest Delhi
1				
2		+10		
3		+20	+10	
4		+50	+20	+10
5		+20	+50	+50
6		+50	+50	+50
7	-10		+50	+50

Figure 7 shows the migrant population allocations to the various urban centers for four of the alternatives listed in the table above, including alternative 1, the regional plan population targets, and alternative 6 with the minimum total annual development costs. The information presented in Table 3 shows that the annual development costs may be reduced by some 28 million rupees from the development costs that would be required by the regional plan population distribution if alternative 6 was implemented. Growth would be directed into the corridors to the northwest of Delhi and to the outermost urban centers in some of the other corridors, particularly in the southeast.

Alternative development strategies that involve significant investments in water supply systems in the groundwater-deficient areas to the west and southwest of Delhi have also been analyzed. These alternatives were translated into increased population holding capacities for those areas that also have significant amounts of unused intercity transportation capacity. Population growth was directed toward these urban centers and there were significant changes from the regional plan population targets.

Several alternative policies that involve investments in new highway capacity were analyzed; these had little impact on regional development patterns but did incur a significant increase in transportation investment costs. Although two of the invest-

Figure 7. Migrant population allocation for four strategies.

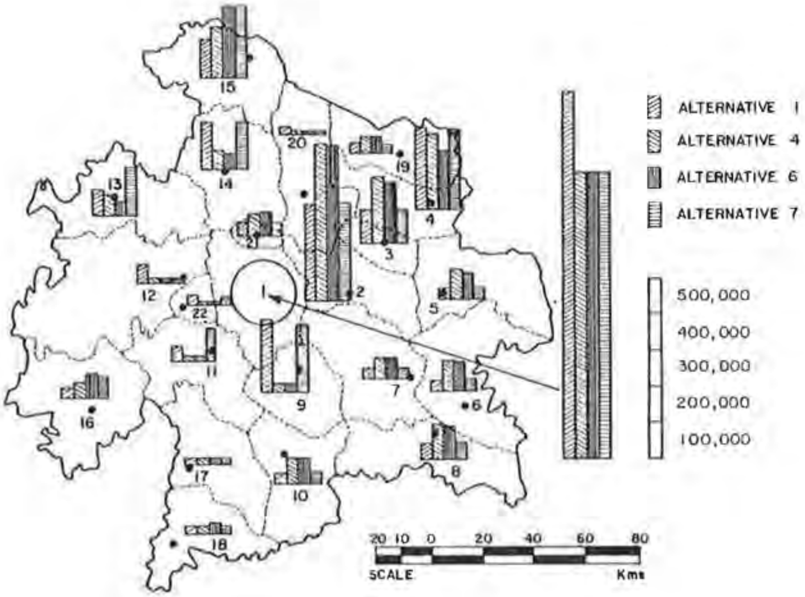


Table 3. Migrant population at Delhi, regional basic employment growth, and development costs for alternative regional development.

	Mover Pool Population at Delhi			Cost (rupee 000 000s)		
Alternative	No.	Percent	Basic Employment	Urban Development	Transportation	Total Regional Development
1	1 023 199	40.76	375 540	353.07	31.62	384.69
2	813 199	32.40	372 072	335.75	34.61	370.35
3	803 199	32.00	372 772	335.53	29.57	365.10
4	803 199	32.00	372 304	332.59	25.34	357.93
5	803 199	32.00	372 282	334.52	27.79	362.31
6	803 199	32.00	371 808	331.23	25.18	356.41
7	803 199	32.00	371 686	336.46	33.11	369.57

ment strategies reduced the annual development costs from the regional plan alternative, these changes were small and much greater than the minimum achieved under different development policies. Major investments in new railway capacity were not considered.

The examples of regional development policy analysis presented above provide an illustration of the types of policy analysis that may be performed quickly and cheaply in any developing region with the allocation-simulation model described in this paper.

CONCLUSIONS

The changing socioeconomic environment in developing countries, including the emphasis on industrialization, has resulted in more emphasis being placed on regional land use and transportation planning. The primary aim of many of these regional planning initiatives has been to achieve balanced development of a region and to have an equitable distribution of resources throughout the region. The Delhi region of India provides an excellent example of the planning and resource-allocation problems that face many countries with similar problems. Policies of regional decentralization have been pursued in many countries and simple policy analysis tools are required to highlight the costs and impacts of alternative regional development strategies.

A technique has been described that identifies regional development patterns that minimized development costs subject to a variety of constraints. Two major cost components are recognized: the costs of supporting activities at different urban places and the costs of supplying the intercity transportation demands likely to be created by a particular development strategy.

The search procedure operates by allocating a hypothetical increment of population growth to each urban center and then estimates the employment growth necessary to support this population increment along with the expected increase in intercity travel demands. The total costs of development are then estimated and the increment in population is allocated to the urban center with the minimum marginal costs subject to any constraints on population and employment holding capacities and on intercity transportation capacities. A simple sequential search procedure is used to identify the optimal allocation of activities. The combinatorial nature of the problem is greatly simplified by the radial structure of the Delhi region.

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Multimodal Logit Travel-Demand Model for Small and Medium-Sized Urban Areas

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The development and application of a one-step modal-split process that uses the logit approach and is oriented toward the needs and attributes of small and medium-sized urban areas are described. The essence of this study lies in the tailoring of commonly available aggregate (zonal) data for use in the disaggregate-based logit model, which is currently included in the Urban Transportation Planning System planning package. The development of work-trip and non-work-trip models is presented separately for the Flint urban area in Michigan. Each model studied the following five modes: (a) automobile, drive alone; (b) automobile, one passenger; (c) automobile, two passengers; (d) automobile, three or more passengers; and (e) transit, bus service. The results of the study indicate that the development of multimodal logit modal-split models is feasible by using aggregate data, and that the potential of applying this approach in other urban areas is quite high, although further calibration and validation efforts are needed before a more widespread application is practiced. The study also shows that, unlike traditional modal-split (diversion-curve-type) models, the resource requirements for these models are nominal and thus can be used for transportation planning purposes in small and medium-sized urban areas. The model is also sensitive to changes in transportation system attributes as well as in tripmaker characteristics and can be applied for testing air quality, energy, and other impacts of transportation strategies typical of smaller urban areas.

The increasing concern about traffic congestion, air pollution, and energy shortages in recent years has caused most urban areas in the United States to promote public transportation and ridesharing programs. Historically, the emphasis on such transit-related activities has been directed toward large urban areas. It is only during the past few years that small and medium-sized urban areas have been receiving significant attention on transit, ridesharing, and other transportation system management (TSM) programs.

Travel-demand forecasting constitutes the most critical element of the urban transportation planning process. The traditional approach to transit-demand analysis has been criticized as being oriented toward larger cities and being insensitive to the needs and attributes of small and medium-sized urban areas (1). Typically, travel-demand models are cross sectional in nature, as these are developed on the basis of data for a single time period (2,3). Empirical relations are developed from observed data on travel, land use, and demographic characteristics of the area that are used to forecast future travel desires. The data needs for these models are generally very high, and smaller urban areas are hard-pressed to commit the resources necessary for the collection and retrieval of such a data base. The process of allocating travel among a number of competing modes, commonly known as the modal-split process, has posed particularly significant problems to these small areas.

The recent emphasis on different types of ridesharing programs presents further problems to these smaller areas. Most of the available demand models can allocate travel between two modes at a time as opposed to many modes at the same time. When a multiple number of modes are involved, the analyst must take recourse to a submodal-split process that successively allocates travel between two modes at each step. This process of successive allocation can get complicated due to the need to calibrate the model at each step and to trace backward whenever the model output might not provide an acceptable match to observed data.

Obviously, any modeling error committed at a given step would be propagated to all successive steps by this submodal-split process. Thus, the overall reliability of such a model is likely to be questionable when a multiple number of modes are involved. This process becomes lengthy, involved, and costly, which makes it somewhat inappropriate for application to smaller areas.

The above-mentioned procedure, despite the complexities involved, has been successfully used in multimodal travel-demand forecasting for large urban areas (2). There is, however, a need to develop a simpler procedure for smaller urban areas, where resources are constrained and where transit options are quite limited and bus travel is the only feasible mode. This need becomes more evident when one considers the current emphasis on developing plans that involve different levels of automobile occupancy. For example, How does the transportation planner assess air quality, energy, and other impacts of a shift in automobile travel from a low occupancy level to higher occupancy level? What are the overall effects of such a shift in the total vehicle miles of travel generated in a medium-sized urban area?

The purpose of this paper is to describe the development and application of a one-step modal-split process designed specifically for small and medium-sized urban areas. This paper is the result of a study sponsored by the Michigan Department of Transportation (MDOT) that had the objective of developing a procedure for testing the demand consequences, air quality, and energy impact of alternate transportation strategies for medium-sized urban areas (4). The model developed with this study is multimodal in nature and does not require the lengthy step-by-step process of branching and submodal split. Further, the model is oriented toward the data base commonly available for small and medium-sized urban areas and is responsive to the needs of smaller urban areas. The model is developed around the Urban Transportation Planning System (UTPS) software framework by using the logit approach and lends itself to convenient calibration through the selective use of variables that are initially created in a calibration file. Unlike traditional modal-split (diversion-curve-type) models, the resource requirements for these models are nominal, and the models can be fine-tuned with minimal effort. Last, the model is sensitive to changes in transportation system attributes, as well as in tripmaker characteristics, and can be applied for testing air quality, energy, and other impacts of transportation strategies typical of smaller urban areas.

LOGIT MODEL

A logit model incorporates modal-choice decisions through the use of explanatory variables in a set of mathematical formulations. Probabilistic equations are developed to reflect characteristics based on the relative attractiveness of the candidate modes, as expressed below (5):

$$P(i-j/m) = \exp[-U(i-j/m)] / \sum_{m=1}^{N} \exp[-U(i-j/m)] \quad (1)$$

where $P(i - j/m)$ is the proportion of total person trips from zone i to zone j by using mode m, and N is the total number of travel modes (m). The modes are numbered consecutively 1 through N. Further, $U(i - j/m)$ is the utility or disutility value of a trip from i to j by using mode m, as described below:

$$U(i-j/m) = F_c(i-j/m) + F_t(i-j/m) + F_s(i-j/m) \quad (2)$$

where

$F_c(i - j/m)$ = function of the out-of-pocket cost in making the trip from i to j by mode m,
$F_t(i - j/m)$ = function of the travel time in making the trip from i to j by mode m, and
$F_s(i - j/m)$ = function of the socioeconomic characteristics of the tripmaker or land use characteristics associated with trips from i to j by mode m.

In addition, the following must hold true:

$$\sum_{m=1}^{N} P(i-j/m) = 1.00 \quad (3)$$

Each of the three utility or disutility functions (F_c, F_t, and F_s) can be developed as a linear or nonlinear combination of independent variables. A linear combination of the following form was used in this study:

$$F(i-j/m) = (\alpha_1 X_1 + \alpha_2 X_2 + \ldots + \alpha_n X_n) \quad (4)$$

where

$F(i - j/m)$ = impedance function (time, cost, distance, etc.) for trips from i to j by using mode m,
X_i = individual elements within the impedance function (e.g., in-vehicle time, waiting time, out-of-pocket cost, parking cost, etc.), and
α_i = coefficients to be derived as a part of the model calibration.

Model Attributes

The logit model described in this paper has the attributes described below:

1. Aggregate data base: The most important feature of the modeling process described in this paper is the use of data aggregated at the zonal level. Logit models are typically developed for household-level analysis to reflect individual tripmaker decisions; however, the time and cost involved in the use of disaggregate data have often precluded their use. A major emphasis in this modeling process was to investigate the traditional approach of using zonal data in a logit model without any significant loss of accuracy.
2. Multimodal: Logit models can apportion trips among several modes in a single step. This feature lends the model quite well to analyzing different levels of automobile occupancy and public transit modes as individual modes.
3. Multinomial: Logit models can use several independent variables to describe tripmaking characteristics. This feature increases the model's flexibility to include several factors that may affect modal-choice decisions.
4. Existing software: The models were calibrated by using the ULOGIT computer program from the UTPS modeling package (5). Other UTPS modules were also used in this study.
5. Flexibility of calibration: Once a model formulation is developed, the ULOGIT program can be used to selectively add, delete, or modify variables for calibration purposes. The ULOGIT module provides a series of statistical outputs to evaluate the model. This approach allows considerable flexibility in testing several different model formulations and results in a more thorough search for the best model.

Modeling Process

The process to develop and calibrate the logit modal-split models as described in this paper is shown in Figure 1. The process contains four main steps. The first step is to prepare the data for the calibration file. The data used include observed modal trip tables, trip interchange impedance data, and zonal socioeconomic and land use data.

When working with a large data base, it is preferable to calibrate the model by using a sample of trip data in order to reduce computing costs. The sampled trip records should be selected at random but should still maintain the same proportion of trips among different modes.

The second step involves developing a calibration file from a random sample of observed trips through the use of the UTPS program UMODEL. This file provides a specification of variable names, units, and all possible variables (mode, travel time and cost, socioeconomic data, etc.) that may be used in the ULOGIT computer runs.

The calibration file consists of a matrix in which the rows correspond to observed trip records (1 trip/record) and the columns correspond to trip information (variables). The aggregated data are converted into a disaggregated form in the calibration file (6). However, the data for each trip represent a zonal average of variables such as income, land use, etc. The dependent variable in the calibration file relates to the mode of travel and assumes a binary form. Each trip in the file is asso-

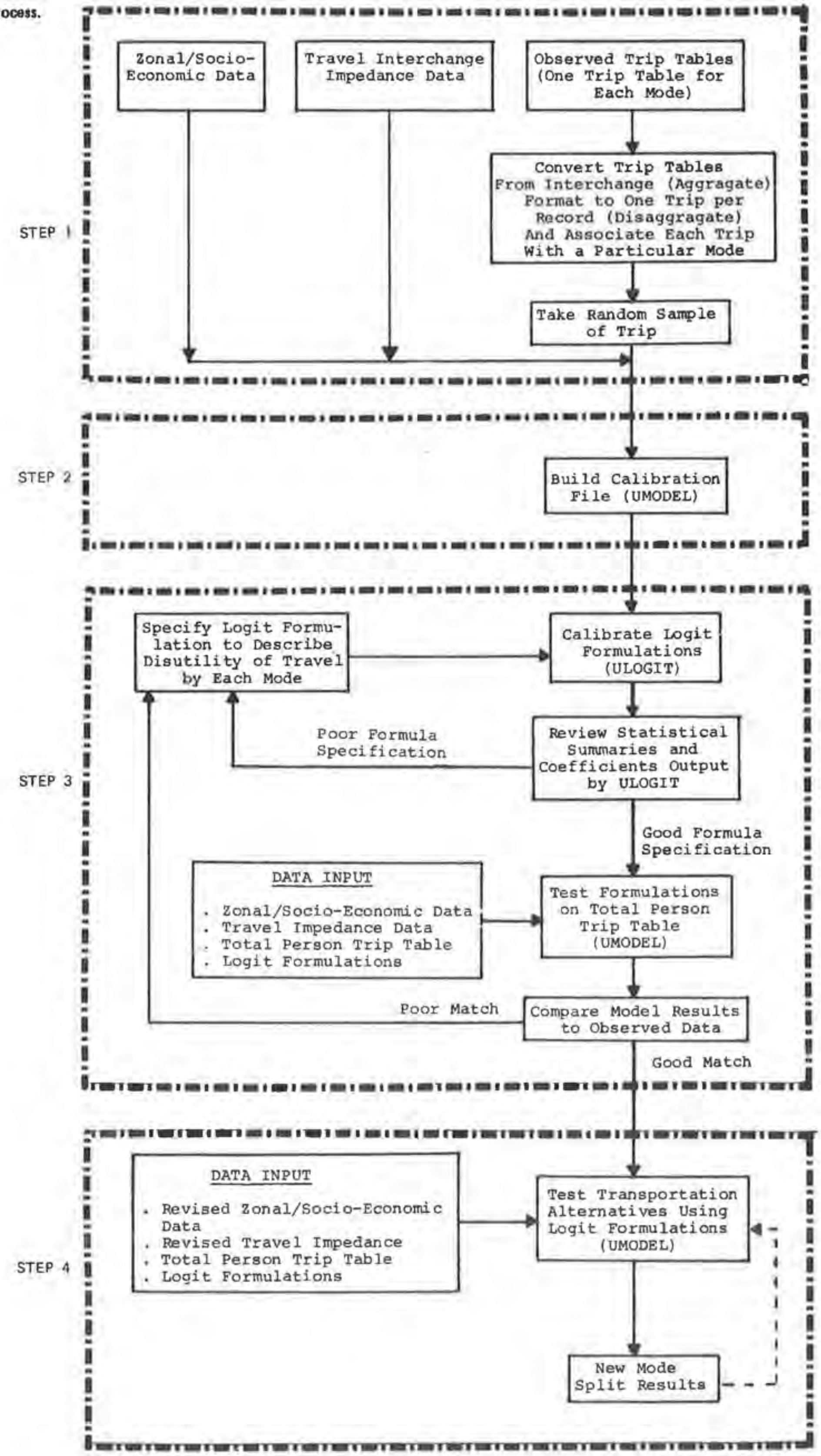


Figure 1. Flowchart of logit modeling process.

ciated with one and only one mode, and the mode is identified by a 0 or 1 in the appropriate column.

In step three, the ULOGIT module is used to develop coefficients for the disutility equations. The input to the ULOGIT program is the calibration file (developed in step 2) and a set of explanatory variables for each disutility equation. The variables should be related to the tripmaker's decision to use this particular mode. The output of the ULOGIT calibration program is a value for each coefficient that best fits the model formulation to the observed trip data, along with a set of statistics that are used to evaluate each model.

Once an acceptable model is calibrated to a sufficient degree of accuracy, it can be employed to test various transit options or TSM strategies (step 4). The application of a calibrated model to a new design year, revised economic situations, or other options is completed by using UMODEL to perform the modal-split process. Once trips are assigned to their respective modes, the adequacy of the transportation system can be evaluated as well as the energy and air quality impacts.

MODEL APPLICATION

The area that comprises Genesee County, Michigan (1980 population, 324 703), was used as the case study. This area was selected because it represented a typical medium-sized urban area in its land use, socioeconomic, transportation system, and travel characteristics. The major metropolitan area in Genesee County is the City of Flint, which has a strong industrial base and a 1980 population of 166 739. The primary mode of travel is the automobile; less than 1 percent use public transportation.

Table 1. Observed trip distribution for work and nonwork trips.

Trip Purpose	Mode	Observed Trips	Percentage of Total
Work	Automobile, drive alone	175 690	86.4
	Automobile, one passenger	18 934	9.3
	Automobile, two passengers	4 395	2.2
	Automobile, three or more passengers	2 607	1.3
	Transit	1 721	0.8
	Total	203 347	
Nonwork	Automobile, drive alone	438 087	38.2
	Automobile, one passenger	367 304	32.1
	Automobile, two passengers	152 085	13.3
	Automobile, three or more passengers	183 002	16.0
	Transit	4 747	0.4
	Total	1 145 225	

Several work and nonwork models were developed and calibrated in this study. For the sake of brevity, only one work-trip model and one non-work-trip model will be discussed in detail in this paper. The distribution of trips among the five modes, developed from previous studies in the area, is shown in Table 1 for each trip purpose.

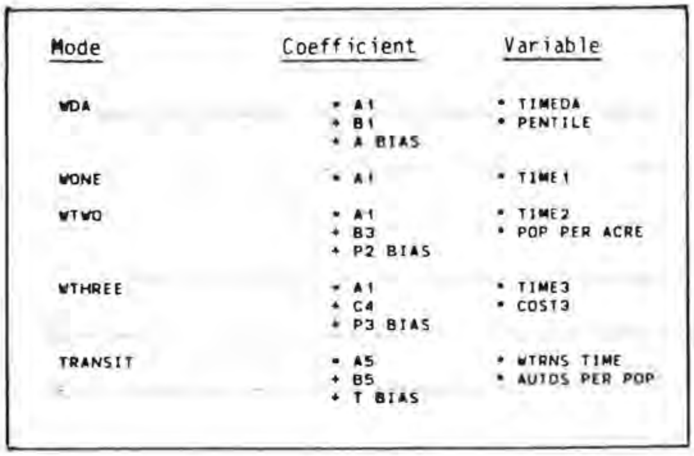
The models were calibrated by using a sample of the total trips. The selection of the sample size was designed to accomplish two objectives: (a) reduce the high computation costs associated with using a large number of trips, and (b) obtain a large enough number of trips to accurately calibrate the model, particularly for modes that experience very low ridership. The work-trip models were calibrated by using a 5 percent sample of the work trips (10 165 trip records), and the non-work-trip models were calibrated by using a 1.3 percent sample of nonwork trips (15 268 trip records).

Work-Trip Model

The formulation for this model is shown in Figure 2. Travel time and other variables (income pentile, population size, driving cost, etc.) were used to describe the disutility of using each mode. A small time penalty was used in the higher automobile-occupancy modes to reflect the time spent picking up each additional passenger. The modes, travel times, and other variables used in Figure 2 and throughout the rest of the paper are described below:

1. AUTOS PER POP--A density variable that indicates the number of automobiles owned divided by the population in the production zone of the trip;
2. BIAS--A constant developed by the ULOGIT program;
3. COST3--The out-of-pocket travel costs per vehicle occupant for the three-or-more-passenger automobile mode; this variable includes a distance cost (per vehicle mile) plus parking costs, where the costs are assumed divided equally among the vehicle occupants;
4. PENTILE--A five-level classification of income groups based on median zonal income for the production zone;
5. POP PER DU--The average household size in a zone associated with the production zone of the trip;
6. TIMEDA--The travel time for the automobile mode for the drive-alone trips, which includes in-vehicle time plus parking and "unparking" time;
7. TIME1--The travel time for the one-passenger automobile mode for work trips, which consists of

Figure 2. Formula specification for work model.



Mode	Coefficient	Variable
WDA	= A1 + B1 + A BIAS	* TIMEDA * PENTILE
WONE	= A1	* TIME1
WTWO	= A1 + B3 + P2 BIAS	* TIME2 * POP PER ACRE
WTHREE	= A1 + C4 + P3 BIAS	* TIME3 * COST3
TRANSIT	= A5 + B5 + T BIAS	* WTRNS TIME * AUTOS PER POP

the TIMEDA travel time plus a minute time penalty for picking up the passenger;

8. TIME2--The travel time for the two-passenger automobile mode for work trips, which consists of the TIMEDA travel time plus a minute time penalty for picking up the two passengers;

9. TIME3--The travel time for the three-or-more-passenger automobile mode for work trips, which consists of the TIMEDA travel time plus a minute time penalty for picking up the passengers;

10. TRANSIT--A dependent variable that describes mode of travel; transit mode (bus service) for work purposes;

11. WDA--A dependent variable that describes mode of travel; drive-alone automobile mode for work purposes;

12. WONE--A dependent variable that describes mode of travel; one-passenger (in addition to the driver) automobile mode for work purposes;

13. WTWO--A dependent variable that describes mode of travel; two-passenger automobile mode for work purposes;

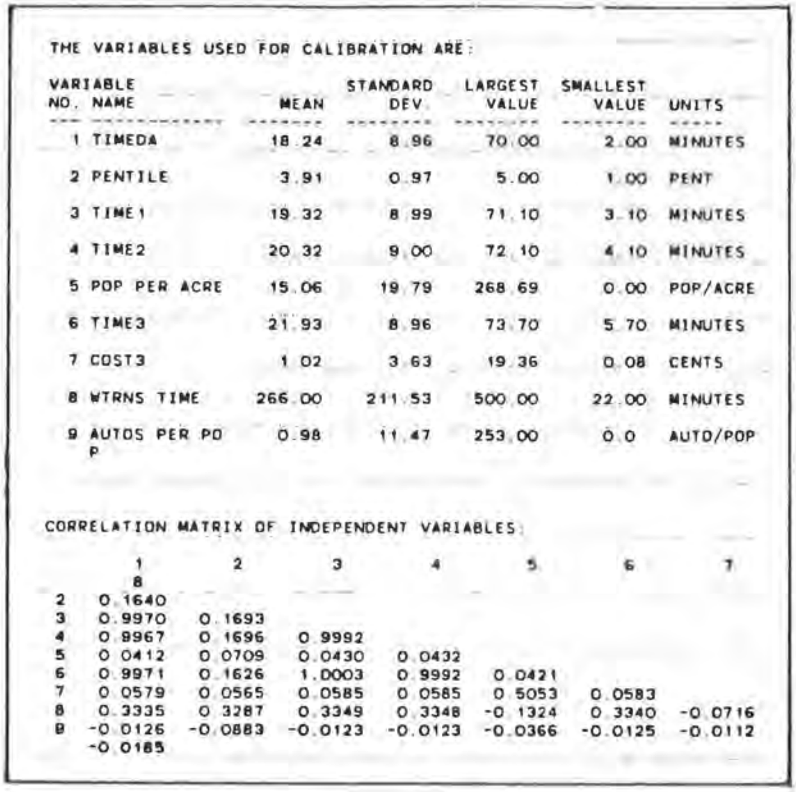
14. WTHREE--A dependent variable that describes mode of travel; the trip is by the three-or-more-passenger automobile mode for work purposes; and

15. WTRNS TIME--The weighted time (minutes) by the transit mode, which consists of the in-vehicle time plus a constant times the walk time plus a constant times the wait time; it recognizes that 1 min of wait and walk time has a higher disutility than 1 min of in-vehicle travel time.

The values of the variables and the correlation matrix of the independent variables are shown in Figure 3. The independent variables were obtained from the calibration file developed in an earlier step. Figure 4 shows the final values of the coefficients that result from the ULOGIT calibration process.

Several statistical tests are also provided by

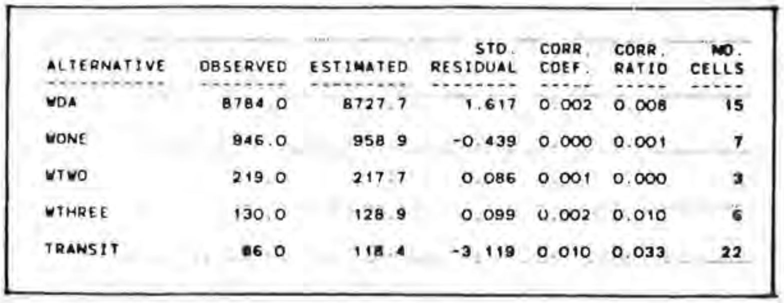
Figure 3. Statistical summary of independent variables used in work model.



```
THE VARIABLES USED FOR CALIBRATION ARE:

VARIABLE                         STANDARD   LARGEST   SMALLEST
NO. NAME                  MEAN       DEV.     VALUE      VALUE  UNITS
--- ------------       -------  --------  --------  ---------  -----
  1 TIMEDA               18.24      8.96     70.00       2.00  MINUTES

  2 PENTILE               3.91      0.97      5.00       1.00  PENT

  3 TIME1                19.32      8.99     71.10       3.10  MINUTES

  4 TIME2                20.32      9.00     72.10       4.10  MINUTES

  5 POP PER ACRE         15.06     19.79    268.69       0.00  POP/ACRE

  6 TIME3                21.93      8.96     73.70       5.70  MINUTES

  7 COST3                 1.02      3.63     19.36       0.08  CENTS

  8 WTRNS TIME          266.00    211.53    500.00      22.00  MINUTES

  9 AUTOS PER PO          0.98     11.47    253.00        0.0  AUTO/POP
    P


CORRELATION MATRIX OF INDEPENDENT VARIABLES:

          1          2          3          4          5          6          7
          8
 2   0.1640
 3   0.9970     0.1693
 4   0.9967     0.1696     0.9992
 5   0.0412     0.0709     0.0430     0.0432
 6   0.9971     0.1626     1.0003     0.9992     0.0421
 7   0.0579     0.0565     0.0585     0.0585     0.5053     0.0583
 8   0.3335     0.3287     0.3349     0.3348    -0.1324     0.3340    -0.0716
 9  -0.0126    -0.0883    -0.0123    -0.0123    -0.0366    -0.0125    -0.0112
    -0.0185
```

Figure 4. Final coefficient values and other statistics for work model.

Mode	Variable or Bias Coefficient	Coefficient Value	T-Ratio	Pseudo R-Square
WDA	TIMEDA	0.2620	11.95	0.680
	PENTILE	-0.1010	- 3.43	
	BIAS	-1.5290	-12.55	
WONE	TIME1	0.2620	11.95	
WTWO	TIME2	0.2620	11.95	
	POP PER ACRE	0.0110	2.27	
	BIAS	1.0760	11.08	
WTHREE	TIME3	0.2620	11.95	
	COST3	-0.0740	- 5.02	
	BIAS	1.4480	12.47	
WTRAN	WTRNS TIME	0.0810	11.58	
	AUTOS PER POP	-0.0070	- 1.80	
	BIAS	0.8310	2.53	



ALTERNATIVE	OBSERVED	ESTIMATED	STD. RESIDUAL	CORR. COEF.	CORR. RATIO	NO. CELLS
WDA	8784.0	8727.7	1.617	0.002	0.008	15
WONE	946.0	958.9	-0.439	0.000	0.001	7
WTWO	219.0	217.7	0.086	0.001	0.000	3
WTHREE	130.0	128.9	0.099	0.002	0.010	6
TRANSIT	86.0	118.4	-3.119	0.010	0.033	22

Figure 5. Comparison of observed versus estimated trips for work model.

the ULOGIT program for the purpose of evaluating the calibrated model (Figures 4 and 5). These tests should be used carefully to avoid accepting a poor model as well as to avoid rejecting a good model.

Statistical Tests

The test used to assess the reasonableness of the model is to review the sign of the coefficients to determine whether the variables represent a utility or a disutility. If a variable, by intuitive judgment, is considered to be a disutility (or impedance to travel) and is actually represented as a utility, the validity of the model becomes questionable. The final values as provided by the ULOGIT report (shown in Figure 4) are given as disutilities. Therefore, if the final value of the coefficient is a positive value, the corresponding variable is a disutility and is interpreted as an impedance to travel. With this understanding, the variables used in the model formulations are as follows:

1. The travel-time variables (TIMEDA, TIME1, TIME2, TIME3, and WTRNS TIME) represent a disutility, which indicates that longer travel times will result in less tripmaking by the respective mode;
2. The PENTILE variable represents a utility for the WDA mode, which indicates that tripmakers in the higher-income category are more likely to use the automobile drive-alone mode;
3. The population-density variable (POP PER ACRE) represents a disutility factor for the WTWO mode, which indicates that areas with higher population density would generate a smaller number of two-passenger automobile trips;
4. The travel cost factor (COST3) represents a utility factor for the WTHREE mode, which indicates that increased out-of-pocket costs of driving would result in more three-or-more-passenger automobile trips; and
5. The AUTOS PER POP variable represents a utility for transit trips, which indicates that increased automobile availability would result in increased transit trips.

For all cases except AUTOS PER POP, the variables and coefficients adequately explain the expected travel characteristics. The automobile per population factor, however, results in some inaccuracy for the transit-trip estimates. Due to the problems with the AUTOS PER POP variable, it will be necessary to eliminate or replace this variable in further fine tuning of the model.

The t-ratio is used to measure the significance of the variable in the disutility equation (Figure 4). Considering a 95 percent confidence level (t-ratio = 1.96), all variables are considered significant in defining trip characteristics except for the automobiles per population variable used in explaining transit trips.

A comparison of the observed versus estimated trips is provided in Figure 5. This comparison displays an excellent match for trips by all modes except transit trips. The discrepancy that occurs in transit trips can be partly attributed to the small sample size (86 transit-trip records) used in calibrating the model. It should be noted that an effort to increase the number of transit-trip records in the sample may provide better results. But there would also be a proportional increase in trip records by all other modes in the sample, thus increasing the computer costs of the analysis. Other statistics that can be used to evaluate the model's acceptability include the pseudo R-square value (Figure 4) and the standardized residual (Figure 5).

Comparison of Work-Model Results with Observed Trip Tables

The report provided by ULOGIT that compares the observed and estimated trips (Figure 5) is a relatively weak statistical test and does not necessarily provide conclusive evidence regarding the model's adequacy. The ULOGIT reports are based on only a 5 percent sample of work trips. As a further test, the results of the work-trip models were compared with the total person trip table for work trips.

To accomplish this summary, the logit model with the utility or disutility coefficients (Figure 4) was used in allocating the total work-trip table among the five competing modes, following the modal-split procedure presented earlier. The results of modal split are given in the table below:

Mode	Observed Trips	Estimated Trips
Drive alone	175 690	174 870
One passenger	18 934	19 205
Two passengers	4 395	4 355
Three or more passengers	2 607	2 578
Transit	1 721	2 280
Total	203 347	203 288

In an attempt to test the goodness of fit of the models to the observed trip data on a trip interchange basis, the trip length frequency (TLF) curves for the observed trips were compared with the TLF curves for the estimated trips by each mode. This check would ensure that the trip data from the two sources were from the same population or distribution. This test, although not entirely conclusive, is a good indication of the acceptability of the models.

The comparison of TLF curves was obtained by using the UTPS program UFMTR. A visual comparison of the observed and estimated TLF curves showed a high degree of similarity in the curve shape and size, particularly for the drive-alone automobile mode.

A more accurate comparison between the observed

Table 2. Comparison of observed versus estimated TLF means and variances for work trips.

TLF	Drive Alone	One Passenger	Two Passengers	Three or More Passengers	Transit
Mean					
Observed	18.320[a]	17.930	17.924[a]	18.498[a]	40.152[a]
Estimated	18.279[a]	18.125	18.147[a]	18.320[a]	40.369[a]
Variance					
Observed	79.195[a]	93.990[a]	95.486[a]	91.193[a]	199.055
Estimated	81.271[a]	80.090[a]	82.500[a]	80.400[a]	263.571

[a] No significant difference at 95 percent level of confidence.

Table 3. Comparison of observed versus estimated TLF means and variances for nonwork trips.

TLF	Drive Alone	One Passenger	Two Passengers	Three or More Passengers	Transit
Mean					
Observed	12.317	13.236	12.580	12.364	47.261
Estimated	12.650	12.646	12.645	12.635	53.481
Variance					
Observed	52.784[a]	62.703[a]	57.418[a]	54.239[a]	250.003
Estimated	57.222[a]	56.889[a]	56.870[a]	55.831[a]	423.401

[a] No significant difference at 95 percent level of confidence.

and estimated TLF curves can be accomplished by comparing the means (t-test) and variance (F-test). The results of the t-tests, or test of means, is given in Table 2. This table shows that, except for one-passenger automobile trips, there were no significant differences in the mean trip lengths between the observed data and the estimated trips. The F-test is a comparison of variances of the TLF distribution. The F-tests also indicate an acceptable fit between the TLF curves from the model and the observed TLF curves in four out of five cases, with the exception of transit trips.

Non-Work-Trip Model

A five-mode non-work-trip model was used, similar to the work-trip model discussed above. The travel time variable was the primary variable used to describe the utility or disutility of using a particular mode for nonwork trips. Other variables used in the formulation include income, family size, and automobile availability. For the sake of brevity, only the final results of the nonwork model are presented in this paper.

Statistical Tests

For most of the variables used in the model, the sign of the coefficient adequately represents the expected utility or disutility. As in the case of the work-trip model, the AUTOS PER POP factor results in a slight inaccuracy in the transit-trip estimates. With a 95 percent confidence level, all variables were considered significant in defining the trip characteristics except for AUTOS PER POP. In the process of fine-tuning the model, the AUTOS PER POP variable should be replaced or eliminated.

A comparison of observed versus estimated trips indicated an acceptable match for all modes. Other statistics, such as the pseudo R-square value and the standardized residual, also indicated an acceptable model.

Comparison of Non-Work Model Results with Observed Trip Tables

To further evaluate the predictive capability of the model, a comparison was made of the estimated results with the total observed nonwork trip tables, as given in the table below:

Mode	Observed Trips	Estimated Trips, Model Results
Drive alone	438 087	427 874
One passenger	367 304	366 755
Two passengers	152 085	151 878
Three or more passengers	183 002	193 534
Transit	4 767	9 597
Total	1 145 245	1 149 638

As this table shows, the estimated trips by the model are reasonably close to the observed data for all modes except transit.

A visual comparison of the TLF curves for the observed versus estimated trips shows a similarity in the curve form for all automobile-occupancy levels. A statistical comparison for the TLF means indicates that there is a statistical difference in the mean travel time for all modes (at a 95 percent level of confidence), although the numerical difference does not appear significant (see Table 3). The test for variance indicates no significant difference between the observed and estimated results for automobile modes (Table 3).

SENSITIVITY ANALYSIS

One of the most important attributes in a travel-demand model is its sensitivity to changes in transportation system characteristics. A model should be developed so that it can accurately reflect the possible impacts that result from changes in the transportation system associated with the new alternative. The model must be able to test new transportation strategies (or variations thereof) that are of concern to transportation planners. In medium-sized urban areas, these transportation system strategies may include ridership incentive programs, park-and-ride facilities, new transit systems, and other TSM concepts.

The ULOGIT program produces a table of elasticities that can be used to evaluate the sensitivity of the model to changes in each variable. The elasticities are defined as the percentage in alternative choice probability (i.e., demand) expected from a 1 percent change in the associated independent variable (5). The elasticities provided by ULOGIT are only defined at the mean value of the independent variables used in the model formula specification. The elasticities are likely to be different at different values of independent variables.

To illustrate the sensitivity of these models, the modal-split results of three transportation system alternatives are presented by using the work model. The three alternatives were developed for the study area as a part of ongoing planning activities in the area (4,7).

The principal attributes of these alternatives are as follows:

1. Alternative A: Decrease total transit travel time by increasing the frequency of bus service. The average wait time was reduced by 50 percent to represent an increase in service.
2. Alternative B: Addition of three transit routes to the base transit system and an increase of operating headways to 30 min (from the existing 20-min headways).

Table 4. Modal-split results for changes in transit operating strategies by using adjusted work model.

Mode	Observed Trips	Alternative		
		A	B	C
Drive alone	175 690	173 306	176 302	172 165
One passenger	18 934	19 026	19 376	18 908
Two passengers	4 395	4 316	4 397	4 295
Three or more passengers	2 607	2 553	2 607	2 535
Transit	1 721	5 786	1 179	9 387
Total	203 347	204 987	203 861	207 290

3. Alternative C: Addition of three transit routes as in alternative B with a reduction of headways to 10 min.

The results of this analysis are presented in Table 4. The reduction of waiting time by 50 percent (alternative A) resulted in increasing transit ridership by a factor of 3 over the base condition. Transit use increased from 0.9 percent of the total work trips to 2.8 percent of the total work trips. Travel by the automobile-occupancy modes each decreased by a small amount.

Alternative B (adding three transit routes while increasing bus headways to 30 min) resulted in a sizable reduction in transit ridership. As a result of the reduction in transit ridership, a slight increase in each automobile-occupancy mode was recorded.

Alternative C (adding three routes and decreasing bus headways to 10 min) resulted in a significant increase in the use of transit over the base conditions. This increase is approximately 5 times the base condition ridership of 1721 daily transit work trips. As a result, ridership for each automobile-occupancy mode decreased by approximately 2 percent.

These results indicate that the model is highly sensitive to changes in travel time. Changes in transit ridership also have some form of impact on travel demand for all four remaining modes. Changes in the travel system for the automobile modes can be tested in a similar manner to determine the sensitivity of the model to changes in these variables.

CONCLUSIONS

The purpose of this study was to investigate the feasibility of using the logit approach for modal- and multimodal-split purposes in medium-sized urban areas with the use of commonly available data. A number of conclusions can be drawn from this study regarding the logit approach, the feasibility of using aggregate data for demand-estimation purposes, and the transferability of the model to other urbanized areas of similar sizes. The conclusions are outlined below:

1. The logit model is a valid approach to travel-demand modeling for multimodal analysis. The use of a utility or disutility function to describe mode selection based on impedance to travel is consistent with the behavioral aspects of the tripmaker decision process and the effect of variables on the travel decision.
2. The logit approach lends itself to the simultaneous modeling of several modes that represent various levels of automobile occupancy and transit. The ULOGIT program can calibrate up to 10 modes at a time. It is extremely difficult, if not virtually impossible, to accomplish this task by using the traditional branching or submodal-split approach.
3. The study shows that the lack of disaggregate household data is not a significant problem for logit models. Although it is desirable that such disaggregate data be used when available, in the absence of such data the use of aggregate data can produce valid and acceptable results.
4. Many of the statistical tests and model-evaluation measures produced by the ULOGIT computer program are inconclusive. The statistical tests should be used primarily for the purpose of eliminating unacceptable model formulations. The selection of the best model requires a clear understanding of all the statistical tests and should not be based on the highest statistics alone. In addition, model results should be compared with the total person trip table to properly evaluate the models' capability to estimate demand.
5. When developing the utility or disutility formulations, the explanatory variables should be carefully selected to reflect the actual modal-choice decision criterion used by the tripmaker. In addition, the explanatory variables must be quantifiable, predictable, and available for use in the design year. The use of variables that do not have the above properties should be discouraged. Furthermore, the model should be designed such that it is sensitive to the transportation alternatives that are to be tested.

This paper indicates that the potential for applying this approach in other urban areas is quite high, although further calibration and validation is warranted before a more widespread application of this concept is practiced. Specifically, the following recommendations are made:

1. Studies should be directed toward identifying various time or cost penalties related to high-occupancy vehicles (i.e., time or cost penalties associated with picking up and dropping off passengers).
2. Further studies should be directed toward selecting proper sample sizes for calibrating the model. In particular, there is a need to develop measures for designing sampling rates that would take into account the trade-offs between the predictive quality of the model and the associated computer costs for larger sample sizes.
3. The logit concept should be used in other medium-sized urban areas to further test the logit modeling process. Because the type of data used in the Flint case study is commonly available for similar medium-sized urban areas, the transferability of the model to other urban areas does not appear to pose any major problem.
4. When employing the logit modeling process to a new area, the specific logit models developed for other cities must be recalibrated. In recalibrating an existing model to a new area, it is advisable to use previously calculated values as initial estimates of the coefficients. This may reduce the calibration effort as well as the computer costs.

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