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MODELING THE URBAN DEVELOPMENT PROCESS AND THE RELATED TRANSPORTATION IMPACTS

by

Tenny N. Lam, Richard Corsi and Katherine Wages
University of California, Davis
Davis, CA 95616

ABSTRACT

A conceptually realistic but highly idealized approach was taken to create a simulation model of the structural interactions between the many elements of urban land use and transportation decisions. The objective is to use the model to discover elements and links that are amenable to land use intensification policies. While land use decisions are based on system perspective, transportation decisions are individualized. While land use decisions are permanent, transportation decisions are susceptible to be influenced. Through planning and other governmental policies, it is hoped that "infilling" can be achieved and the transportation conditions ensued will be energy efficient and environmentally compatible.

INTRODUCTION

Many planning agencies have adopted policies that would direct future growth to the existing built-up areas. The objective is to renovate and intensify development in city centers. With "infilling", higher transit usage is expected. Consequently, energy conservation, air quality improvement and reduced transport and service costs will result. However, it has become increasingly evident that land use intensification policies are difficult to implement. There are also doubts on the financial capability of transit districts to serve increased demand and support higher level of service. A recent study has been undertaken to examine the political and economic feasibility and the energy and air quality impacts of compact urban development. A model has been developed for this study as the policy analysis tool. The objective of the model is to discover causual links in the urban land use transportation system that are inhibitive or supportive to infill policies. The goal of the study is to develop more effective land use policies and better understanding of their limitations.

The deterministic simulation model is based on binary choice decisions describable by the logit equation (1):

$$P(A) = (1 + \exp(\underline{a}\underline{X}))^{-1}$$

where P(A) is the probability of choosing action A and 1-P(A) is the probability of choosing the alternative. The vector $\underline{a}$ is a set of coefficients and the vector $\underline{X}$ is the set of factors affecting the decision. There are two major elements in the model: land use and transportation. In the land use element, the decisions are whether to locate in the low density suburb or the high density core. In the transportation element, the decisions are whether to use transit or automobile for travel.

Geographically, the model is made spatially simple. The urban area is assumed in the form of two concentric circles. The center represents a core area and the outer ring represents the suburb. The circular urban form follows the example of a number of British models, for example, CRYSTAL(2) and GUTS(3). The radius of the core is fixed. As the level of development increases, the density of the core will increase. However, the suburban ring is assumed to have a uniform constant density. As the level of development increases in the suburb, the radius of the suburban ring will expand outward to form a larger urban area. Two levels of land use intensity are modeled, the traditional low density uses in the suburb and the proposed high density uses in the core. The demand for land use at the two levels of intensity will result from individual considerations of cost, amenities, and accessibility. The supply of land will depend on considerations of demand, construction cost, land cost, zoning, and land availability. Supply and demand interact through decisions based on the logit function with land price serving as the equililbrating mechanism.

Following the tradition of the Lowry model (4), land use is divided into basic employment, residential and secondary employment. The basic employment sector is further divided into a manufacturing and an office component. The manufacturing component will be located only in the suburb, while the office component may be located in the suburb or the core. The residential locational decisions are influenced by accessibility to employment (primary and secondary). It consists of old homes and new homes. A new comer into the area and someone changing residential location may select from an inventory of old homes or from the current supply of new homes. The locational considerations of the secondary, or service, employment sector are usually influenced by the accessibility from homes and jobs. Since there will be no competition for land use within each geographical zone among the different types of land users and their inter-dependent locational considerations, iterative simulation is used to achieve the equilibrium land use patterns. Figures 1 through 3 outline the schematic organization of the land use element in the simulation model.

The transportation element contains two sectors, highway and transit. Modal split will result from

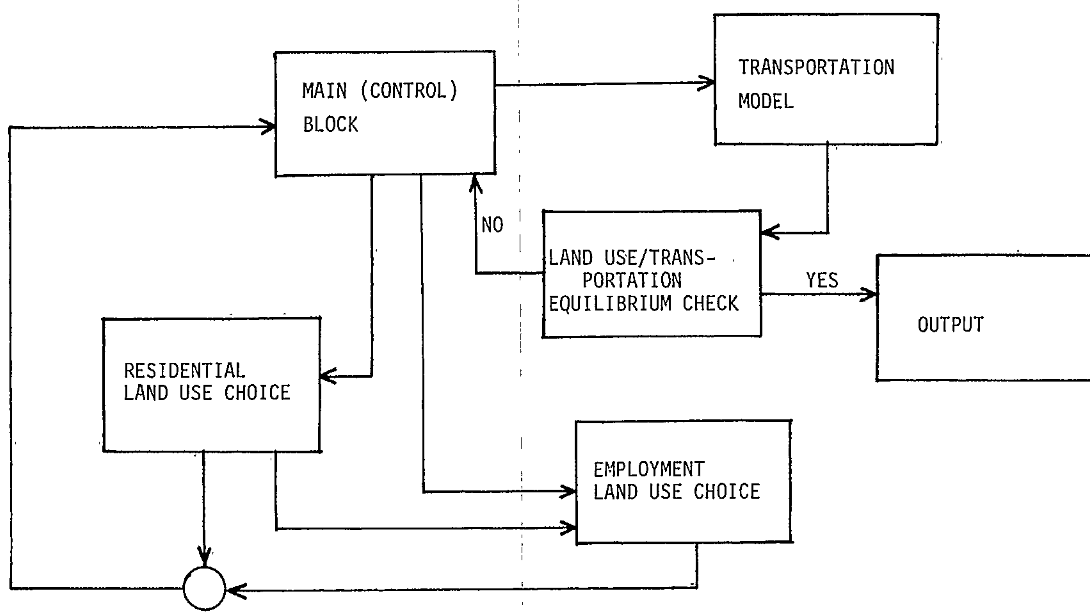

Figure 1. Model Organization

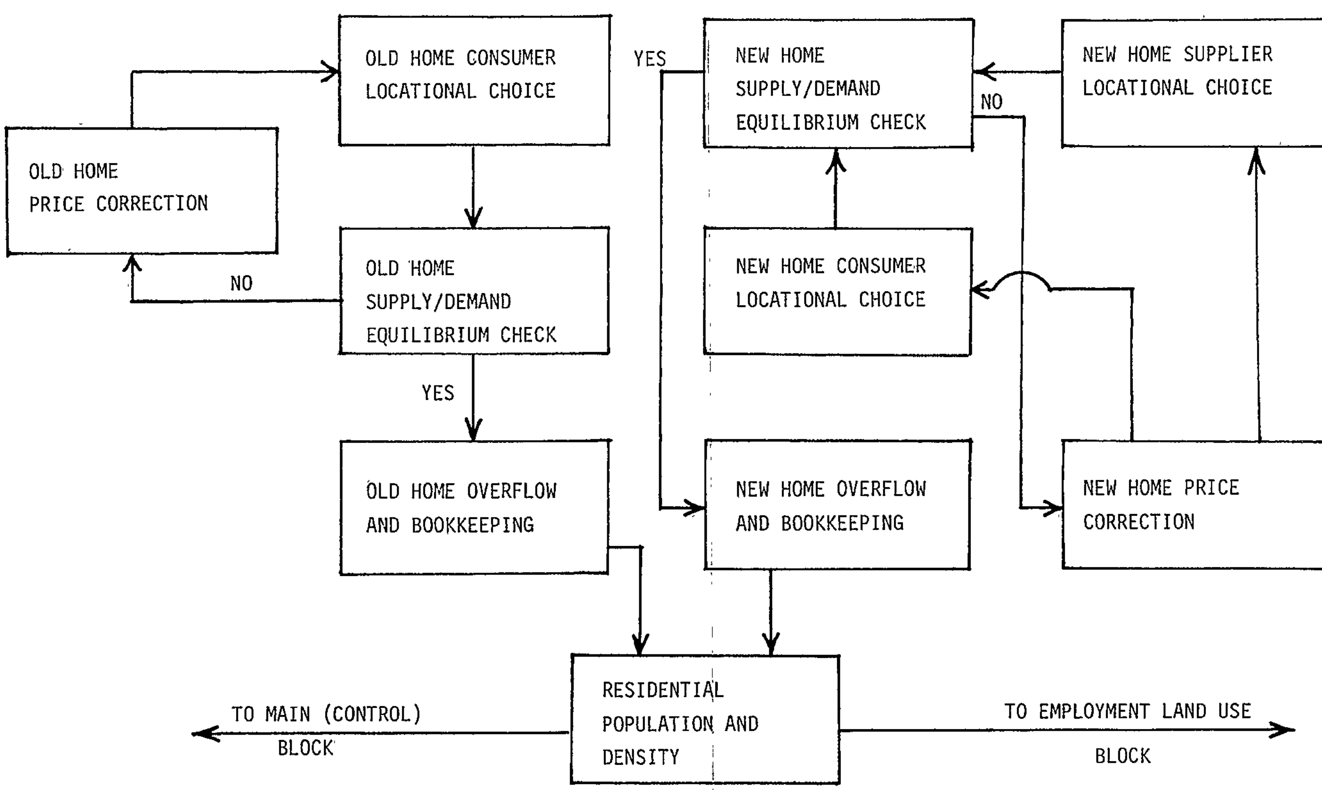

Figure 2. Residential Land Use Elements

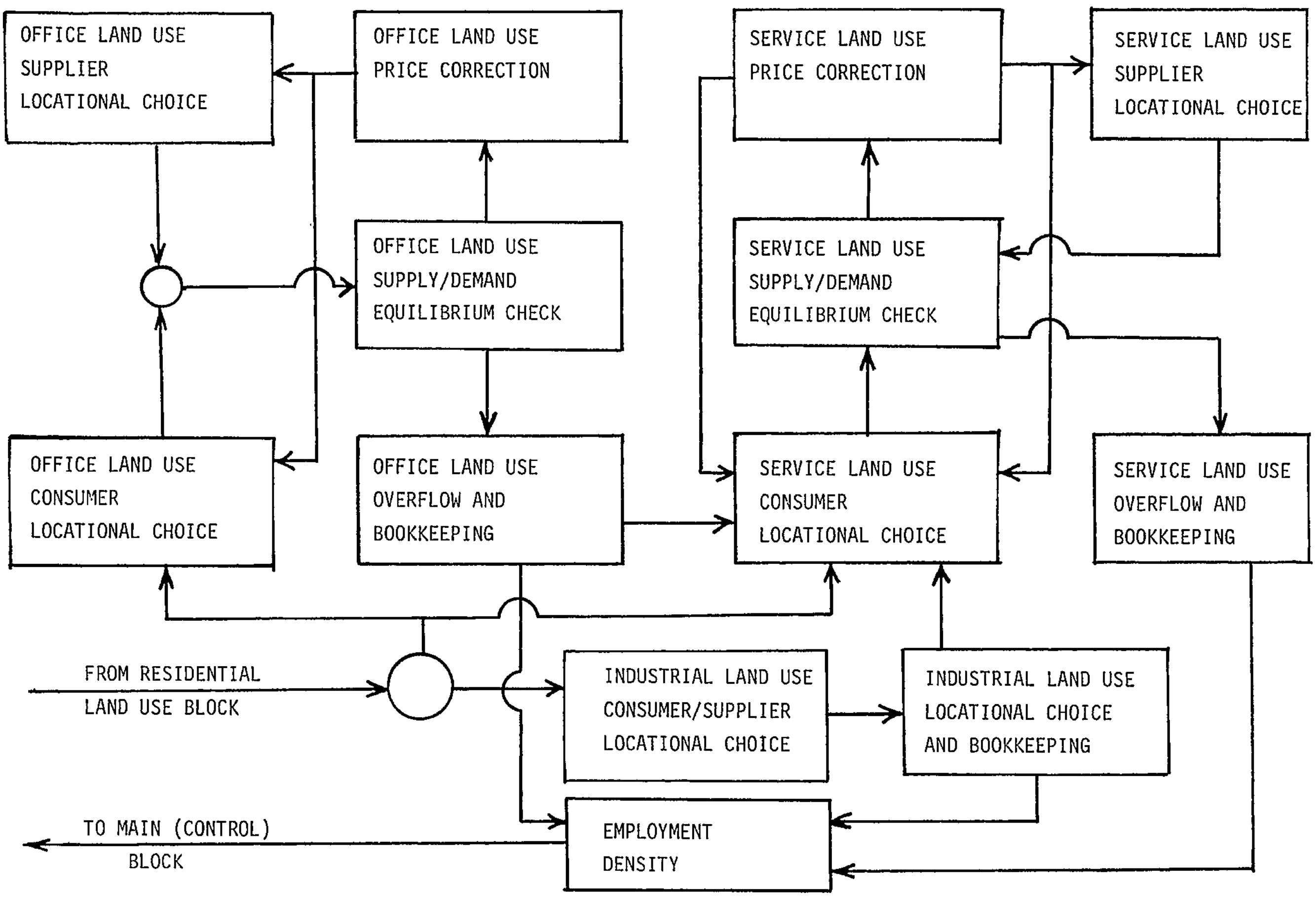

Figure 3. Non-Residential Land Use Elements

the relative service levels and costs of the two modes. The major factor affecting the travel time is congestion. Transit levels of service and costs are determined exclusively by financial considerations of subsidies and revenues. Gross measures, such as number of employees, number of persons, and the geographical dimensions, are used to approximate the total level and distribution of trips. Levels of congestion are estimated from the automobile vehicle miles. From the congestion levels, average speeds for trips of various types (core to core, core to suburb, suburb to core, and suburb to suburb) are estimated. Tranist operations are represented by bus hours and bus miles. Transit operations, in turn, are related to the level of service through route density and frequencies. Through exogeneous policy action in the form of subsidies, transit fares are determined for various levels of transit demand. Transit demand is, of course, dependent on fares and level of service. From the transportation element of the model, transportation impacts are evaluated in terms of automobile vehicle miles, transit ridership and modal split, average system travel speed, transportation costs and transit subsidies. Figure 4 is a schematic diagram of the organization of the transportation model.

The model operation is in an incremental mode. In an established urban area, land use policies take effect incrementally and affect urban development continually. A policy to develop a compact urban core is effective only in directing future growth; and, such growth can only take place gradually. Each simulation of the model deals with the growth that takes place between two time points, for example, over the period of one year. The amount of growth between the two time points is an input into the model. Land use policies are exogenously generated in the form of zoning effects through the availability of land for development, land prices and development costs. Highway transportation may be modified by policies that would affect capacities through improvements, and therefore, congestion. Transit demand can likewise be modified by lower fares and higher levels of service provided through more subsidies. Highway and transit policies, in combination, would determine the modal split even in the absence of land use changes. However, they may be significant as a tool for achieving the desired land use pattern.

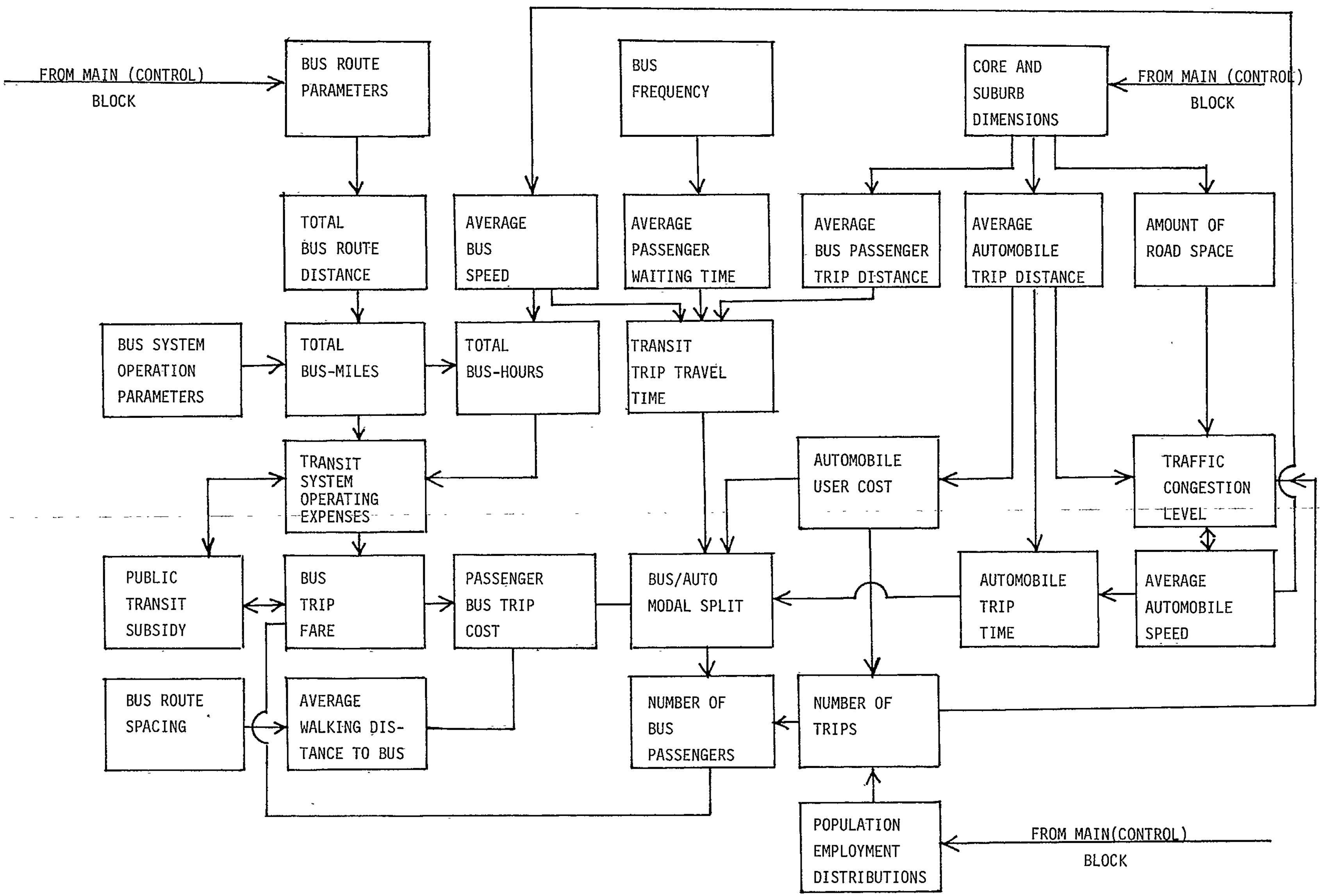

Figure 4. Transportation Model Elements

The interaction between the land use element and the transportation element of the model is through accessibility. Access to employment will primarily determine residential locations. Residential development, in turn, influences employment locations. The travel pattern resulting from the land use pattern determines the level of congestion and the success of public transit operations, which in turn, affect accessibility. The complex feedbacks and interactions can only be managed by simulation, even though much simplified. Such an integration of land use and transportation decisions have not been attempted before. Obviously, the model is more accurate in terms of the structural causual relationships that are only qualitative in nature. It is hoped that the model will also permit estimation, at an aggregated level, of the effects of incremental land use changes, resulting from the infill policy.

MODEL FRAMEWORK

The geographical region of an urban area is idealized into two zones: an urban core and a suburban ring. Figure 5 shows the idealization. The shapes are idealized to be circular. However, depending on the area to be simulated, the areas may be full or part circles. The indices I and J are used to denote the geographical areas:

I, J = 1, core
I, J = 2, suburb.

In the transportation elements, I denotes the origin zone and J denotes the destination. Four types of land use are considered and they are identified by the index, L:

L = 1, new homes
L = 2, old homes
L = 3, industrial
L = 4, office
L = 5, secondary service.

There are two groups of decision makers in the land use sector: supplier and consumer. The supplier is the one who develops the real estate for the various uses. The consumer is the one who chooses the location. In most predictive type of land use models, the results of the supply-demand interactions are modeled. The supplier-consumer decisions are integrated. However, in order to better understand the factors contributing to the locational decisions, we model the decisions separately. The notation, K, is used to designate the decision makers:

K = 1, consumer
K = 2, supplier.

Growth is what usually causes and allows changes in urban development. Growth may come from two different sources:

KK = 1, industrial growth
KK = 2, population growth

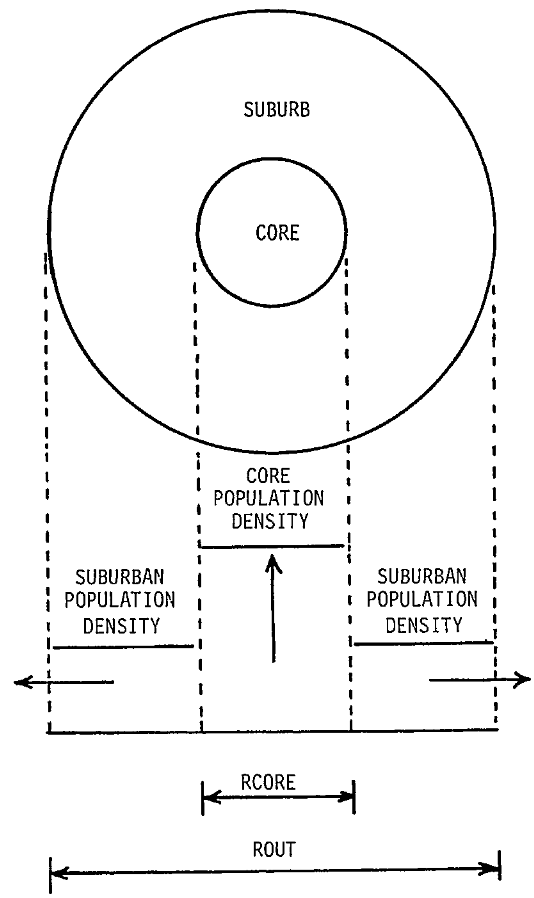

Figure 5. Idealization of the urban area. The arrows indicate directions of growth in the core and in the suburb.

These growths may either be generated internally, as in a closed system, or externally, as in an open system. Although growth may be negative (exodus and decay), we do not entertain this case in the model. This is because the policy problems are very different from those associated with "infilling".

In the transportation sector, there are three types of routes: rings, radials, and rectangular grids. The ring nearest to the center of radius of the geographical areas is at the boundary of the core, i.e., RCORE. Between the suburban boundaries, RCORE and ROUT, the ring routes are spaced equally. The radials extend from the center to ROUT and are spaced equally with respect to the angle. The rectagular grids only exist in the core and they are superimposed over the radials. The grid spacings are also uniform. This type of route idealization was first introduced by Smeed (5) and has since been used extensively in transportation modeling in Great Britian.

Two modes of transportation are available: auto and transit. Here, transit is primarily buses. Land use intensification is contemplated mainly in places with suburban sprawl. In places where there is rail transit, land use intensity is what justifies the existence of rail. There are three sets of decision makers in the transportation sector: the consumer who chooses the modes to use, the transit operator who needs revenues from the riders and subsidies from the public at large, and the highway department who improves the facilities to reduce congestion.

In summary, the model contains ten types of land use decisions and only one type of transportation decisions. The amount of transit sudsidy and the level of service to be provided to the automobile users are considered to be exogeneous policy variables. Inputs into the model representling land use policies are various zoning variables and subsidies that may change the costs to the land consumers or the prices set by the land developers.

The model operation simulates the changes between two time points as the result of an input amount of growth. The simulation begins with a set of urban land use and transportation conditions (state variables). Generally, these are the existing conditions. The incremental increase in land use demand leads to the location of land use activities. Contemporary with growth, however, is certain amount of natural movements of previously located activities. Attempts are made within the model not so much in "simulating" individual actions but more in seeking the equilibria resulting from the growth perturbation. The motiviation to have a simple model is also partly grounded on the necessity to minimize data collection. Once the simulation process gets underway, the iterations take the process from one time point onto the next based on the output conditions of the previous iteration. In addition to the initial conditions and the amount of growth, the model operation also requires the input of values to a number of factors that are related to exogenous policies and formed the decision making bases. The most difficult data to obtained are the elasticity coefficients in the binary choice equations that represent human behavior. To accurately determine these coefficients is a special field of social sciences involving surveys and large amount of data collection and analysis. For the purpose of the present study, we are limited to our own intuitions and trials-and-errors in order to get some approximation of these coefficients. As the coefficients become available in the literature, they will be used instead.

LAND USE ELEMENTS

The land use model combines the elements characterizing three types of land use models. In the Lowry model (4), land use is divided into three types: basic employment activities, nonbasic employment activities, and residential. The basic employment locations are determined exogenous of the model. The interactions are between residential locations and job locations. However, nonbasic, or population-dependent, job locations are related to residential densities and distribution. Since jobs come from both basic and nonbasic sectors, the locational decisions interact. The residential locations are dependent only on accessibility (transportation conditions) and are restricted by policy (planning) dictated maximum and minimum densities. In the present work, land use is identified in five types and the changes between time points (simulated during an iteration) are all interactive with not only the land use distributions and accessibility conditions, but also supply-demand economics.

In the EMPIRIC type of models (6), growth increments of various activities are distributed among subareas of the city by sets of "located variables" and "locator variables." "Located variables" are state space variables related to the overall locational distributions and "locator variables" are factors affecting locational preferences. It is a share model that assumes there will always be a supply of locations adequate for the demand, up to some predetermined limits. In modeling "infilling", one key policy for bringing about "infilling" is by manipulating the supply through economic factors or supply of land through zoning. This is the motiviation for our separating land use into supply and demand decisions.

In the work of Nakamura, et al (7), locational surplus is used as the basis for residential location. Locational surplus is the difference between expected utility and the price. This is different from utility maximization. A probablistic approach is also used in that work. We extend the locational surplus concepts to all land use types and use the logit choice model as the basis for determining core/suburban shares of the incremental land use changes.

The inputs to the land use model are: the accessibility or transportation conditions for travel, zoning and other policy variables and the core area for "infilling", RCORE; amount of land in each zone available through zoning and planning for the various types of development, ZONE(I,L); and the average floor space and/or land area for each unit of development for the various land use types, AAV(L,I).

Consumer Choice Equations

In terms of the logit binary choice equation for the share or probability P(L,K=1,I), the decision or preference factors in the vector $\underline{X}$ are discussed here for the various decisions.

(1) Residential Location Preference, L=1,2, I=1:

(a) travel time to work factor = TTW(1) - TTW(2)
TTW(I) = travel time to work from zone I

(b) cost of travel to work factor
= TCOST(1) - TCOST(2)
TCOST(I) = travel cost to work from zone I

(c) availability of secondary service factor

$$= 1 - \frac{(AAJOB(1)/A(1)}{(SSJOB(2)/A(2)}$$

SSJOB(I) = secondary service jobs in I
A(i) = area of zone I

(d) population density factor = 1 - D(2)/D(1)
D(I) = residential population density in zone I

(e) open space factor = 1 - OLAND(1)/OLAND(2)
OLAND(I) = (land area developed in I)/A(I)

(f) housing price factor = PH(L,1) - PH(L,2)
PH(L,I) = average price of home type L in zone I

(2) Industrial Location Preference, L=3, I=1:

(a) industrial land price factor = PL(3,1) - PL(3,2)
PL(L,I) = average price of industrial land in zone I

(b) worker location factor = 1 - POP(1)/POP(2)
POP(I) = total number of persons in zone I

(3) Office Location Preference, L=4, I-1:

(a) average price factor = POFF(1) - UR*POFF(2)
POFF(I) = average price of office space in zone I
UR = subsidy factor to induce core renewal

(b) worker location factor

(4) Secondary Service Location Preference L=5, I=1:

(a) price of service space factor = PSS(1) - PSS(2)
PSS(I) = average price of secondary service space

(b) worker location factor, or interpreted here, population factor

(c) industrial job locations factor = $1 - \frac{TIRJ(1)/A(1)}{TIRJ(2)/A(2)}$

TIRJ(I) = total industrial related jobs in zone I

(d) competition factor = $1 - \frac{SSJOB(2)/A(2)}{SSJOB(1)/A(1)}$

SSJOB(I) = total number of service jobs in I

Supplier Choice Equations

The factors entered into the supplier locational choice logit equations are described here.

(1) Old Home Turnover, L=2, constants

TOVR(I) = old home turnover rate in I (input)

(2) New Home Supply Locational Preference, L=1, I=1

(a) building cost factor = UP(1,1)*PL(1,1) - UP(1,2)*PL(1,2)
PL(L,I) - average price of home in zone I
UP(I) = added cost for vertical development in I

(b) price-profit and land availability factor

$$= \frac{ZONE(1,2)*PH(1,2)}{AA(1,2)} - \frac{ZONE(1,1)*PH(1,1)}{AAV(1,1)}$$

(3) Industrial Supply Locational Preference, L=3, I=1

Same as the consumer equation

(4) Office Supply Locational Preference, L=4, I=1

(a) building cost factor, same form as L=1
(b) price-profit and land availability factor, same form as L=1

(5) Service Space Supply Locational Preference, L=5, I=1

Similar to L=1 and 4

Cost Adjustment Functions

The cost adjustment equation is identical for all land use types, except for industrial land use, where consumer and supplier are considered to be identical

Price(k) = Price(k-1)+ALF*(demand(k-1)/supply(k-1)-1)

where k denotes the value for the k-th convergence iteration and (k-1) the values at the end of the previous convergence iteration.

TRANSPORTATION ELEMENTS

Compared to the land use elements, the transportation elements are much more complex because of the large number of internal feedbacks as can be seen in Figure 4. A larger number of different variables and parameters are also involved. Traditional transportation planning models (8) are far too detailed and required too much data and computing for this kind of policy analysis. Furthermore, they have been criticized for failing to incorporate the effects of supply-demand interactions (9). Simplification and idealization has been commonly employed to overcome the difficulties (10-12). The approach taken for the present work is to keep the mechanisms of interactions accurate, although the geographical arrangements have been simplified to two zones (core and suburb) and the shape of the urban area has been idealized to the circular form.

Many of the analytical approaches previously used in the British work (2,3,5) are employed here to simplified the computer simulation. By assuming that the origins and destinations are uniformly distributed within the core and suburban zones, routes are either uniformly spaced as in the discrete case of transit or circularly symmetric as in the continuum approximation of highways and streets, and only second order changes take place within a simulation iteration, a number of analytical results are derived. These derivations are, although analytically time consuming to obtain, useful in making the computer simulation program manageable and trackable. The derivations, which are beyond the scope of the paper, will not be presented here.

Inputs

There are three actors within the transportation element: the user, the transit provider and the highway provider. Only the user decisions and the resulting system conditions are simulated. The decisions of the providers, which are part of the external policy elements, will be human decisions of the policy analyst or planner who uses the simulation. From the land use elements, the transportation model obtains the population and employment for the core and the suburb. Output to the land use models are commuting times and costs for housing locational decisions. Also defined by the land use model is the extent of the urban region ROUT, which increases with suburban development. The core dimension is fixed and vertical expansion is used for growth.

The transit operator's policy is represented by the service level, fare, and subsidy. If all three types of policy are simultaneously employed, it may not be feasible to obtain convergence. In other words, the policy is simply not feasible. The approach of most transit operators is to first define the service parameters and the fare, project the ridership and then evaluate the feasibility of the subsidy. However, we input the service level parameters and subsidy and vary the fare within the model. If the fare becomes too high and ridership becomes too low, the transit policy simply fails. Consequently, "infilling" also fails. This way we can attribute the land use policy failure to transit system's failure or infeasibility.

The highway policy, which is often part of the urban planning policy, is reflected through the fraction of usable space devoted to automobile movements for the core and suburb. This parameter combines the effects of various types of improvements and capital expenditures, leading to congestion reduction and speed increase.

Transit Operation

Three route operations are defined for the analysis:

MM = 1 core grid routes
MM = 2 radial routes
MM = 3 ring routes.

The service level is defined by the following parameters:

S(MM) - route spacing
F(MM) - route frequency
OT(MM)- hours of operation/day.

These operation level parameters lead to operating costs, TOE, from which fare is determined.

$$FARE = (TOE - SUB)/ \sum_{LL} TT(LL,M=2),$$

where TT(LL,M) is the number of users by transit (M=2) of trip type LL and SUB is the level of subsidy. The trip types are the outbound directions of travel:

LL = 1 core to core
LL = 2 core to suburb
LL = 3 suburb to core
LL = 4 suburb to suburb.

It is assumed that there is no combination of the auto and bus modes on a particular trip. Bus users will walk to and from the nearest bus routes. The total operating expenditures, TOE, consists of costs associated with the vehicle-miles and vehicle hours:

$$TOE = a_1 \sum_{MM} VM(MM) + a_2 \sum_{MM} VH(MM),$$

where VM(MM) and VH(MM) are vehicle-miles and vehicle-hours on route type MM. The vehicle-miles and vehicle-hours are given by

$$VM(MM) = TD(MM)F(MM)OT(MM)$$

$$VH(MM) = VM(MM)V(MM,2).$$

The route-miles, TD(MM), are defined by the route spacing and the urban dimensions:

$$TD(1) = (4\pi)RCORE/S(1)$$

$$TD(2) = (4\pi)ROUT/S(2)$$

The average speed on the route type MM, V(MM,2) is obtained from the automobile (highway) speeds in the core and suburb for the appropriate portion of each type of route-miles in each zone. TD(1) is entirely in the core; TD(3) is entirely in the suburb; and TD(2) consists of

$$TD(2,core) = (4\pi)RCORE/S(2)$$
$$TD(2,Suburb) = (4\pi)(ROUT - RCORE)/S(2).$$

The bus speeds are

$$V(I=1,M=2) = d_1\ V(I=1,M=1)$$
$$V(I=2,M=2) = d_2\ V(I=2,M=1)$$

Mode 1, M=1, is the automobile mode and the d's are coefficients.

Transit Performance

The performance of the service offered by a transit system is viewed by a user from a number of factors: fare, waiting time, walking distance, and travel time. The travel time is computed from the average trip distance, X(LL), and the average bus speed for the various trip orientations LL.

$$X(1) = 1.15\ RCORE$$
$$X(2) = X(3) = X(2,core) + X(2,suburb)$$
$$X(3) = (\pi/2)RCORE + X(2,suburb)$$

For the case simulated, only one bus ring route at RCORE is considered. For the radial routes involved in core-suburb trips, the components are:

$$X(2,core) = 1.85\ RCORE$$

$$X(2,suburb) = \frac{2ROUT^2 - ROUT*RCORE - RCORE^2}{3(ROUT + RCORE)}$$

The waiting time, assuming uniform arrival rate is, one-half the headway between buses. The headway is the reciprocal of the frequency. The walking distances are, for the single ring route arrangement:

$$XX(1) = S(1)/6$$
$$XX(2) = XX(3) = XX(4) = S(2)ROUT/6$$

It is assumed that the boarding will only take place along radial routes for trip types 2,3 and 4.

Average Highway Trip Distances

The highways are assumed to be very dense such that they can be assumed to be in a continuum, distributed uniformly everywhere according to the layout patterns. The layouts are the same as the transit routes: rectangular grids in the core and ring-radial in the suburb. However, there is no ring-radial travel by automobile within the core. The trip distances traveled within the core for the various trip types are:

$$X(1) = 1.15\ RCORE$$

$$X(2) = X(3) = 1.44\ RCORE$$

$$X(4) = 0.$$

The average trip distance traveled in the suburb are:

$$X(1) = 0$$

$$X(2) = X(3) = \frac{2ROUT^2 - ROUT*RCORE - RCORE^2}{3(ROUT + RCORE)}$$

$$X(4) = \frac{4(ROUT + RCORE)(ROUT^2 + 3ROUT*RCORE + RCORE^2)}{15(ROUT + RCORE)^2}$$

Highway Performance

The performance of a highway system is in its capability to carry traffic-flow at reasonable speed. For a given level of highway design, speed is related to the level of congestion, or density of cars over the available space for movements. The number of cars moving over the road system is the fraction of the traffic volume moving on the road system enroute between origins and destinations. If T(I,J) is the number of auto trips/hour between zones I and J and the average trip time is t(I,J) hours, then the number of autmobiles on the road is t(I,J)T(I,J). Since t(I,J) = X(I,J)/V(I,J), where X(I,J) is the average distance of a trip and V(I,J) is the average speed on the trip, the density is

$$\delta = \sum_{I,J} \frac{X(I,J)T(I,J)}{V(I,J)fA} ,$$

wher fA is the road space effectively carrying traffic. A linear relationship between automobile speed and density, or congesion, is used, namely

$$V = g_1 - g_2\, \delta.$$

The speed and level of congestion are segregated for the core and the suburb. From the speed, the automobile travel time is derived for various trip types. The cost of travel by automobile incorporates a fixed cost and a cost proportional to trip distance:

$$C = c_1 + c_2\, X.$$

Trip Volumes

The number of trips of the type LL is given by the direct demand model (13),

$$T(I,J)=\alpha_2 t(I,J)^{-\beta_4}\, C(I,J)^{-\beta_5}\, POP(I)^{-\beta_6}\, POP(J)^{-\beta_7}\, E(I)^{-\beta_8}\, E(J)^{-\beta_9}$$

The coefficients are α and β's. Travel time and cost are denoted by t(I,J) and C(I,J), respectively. The other determinants are the populations and employments in the origin and destination zones, POP(I) and E(I).

The modal split of the trip volume between transit and automobile is determined by a logit equation with the following factors:

travel time factor = t(auto)/t(transit)
cost factor = c(auto) - C(transit).

SUMMARY

In this paper, a simulation model for analyzing the structural interactions within a land use and transportation complex is described. Simulation is necessary because there are a large number of interactive and feedback elements in the urban system that affect the conditions of travel. The application of the model is primarily educational. Policy and planning are political processes. The development of policies and implementation tools are in the political arena. The system responds through collective human decisions adapting to changes in the system conditions and parameters. The usefulness of the model to policy analysis and urban planning is to discover inherent inconsistencies, infeasibilities, and impracticalities. It is basically a means for checking out policy concepts and catching fallacies before the political process has gone too far. Another use of the model is for identifying elements within the system that are more susceptible to policy manipulation.

Since the model has a specific purpose in mind, namely for exploring urban infill land use policies, we are allowed to place emphasis on model aspects that serve the purpose. Without worrying about many of the problems facing a general purpose simulator, we use simplification and idealization to ascentuate those aspects of importance. The data requirement is reduced to a minimum. Only generally available statistics are needed. They can be obtained easily from published sources, government public information offices, or trade organizations such as chamber of commerce. Some data may be obtained from the wisdom of professionals knowledgeable of the area. For the Sacramento, CA urban area, we did not find it difficult to obtain the input data we need. However, coefficients describing human decision making behavior are not generally well known. Care must be used in interpreting the model conclusions. By supplementing model results with experience in the real world, this limitation should not be an obstacle.

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