Development of a Simulation Model to Study the Impacts of Rapid Urban Growth on the Transportation Sector—The Case of Charlotte, North Carolina

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ABSTRACT

To successfully plan for the development of a region, it is necessary to understand the possible causal relationships, feedbacks, and interactions between the different sectors of the region, including the transportation sector. In this paper a conceptual framework is presented along with a mathematical model for studying the problems of urbanized regions using system dynamics and simulation techniques developed by J.W. Forrester. The conceptual view of the approach is presented by causal submodels of the eight main sectors of the economy: population, housing, business, heavy manufacturing, light manufacturing, government, agriculture, and transportation. The mathematical model, which is represented by 96 differential difference equations, was used to evaluate the impacts of three urban policies on the transportation sector: (a) heavy manufacturing, (b) light manufacturing, and (c) downtown development. Policy c provided the least negative impacts on the transportation sector; that is, with a level of service of 0.6 for freeways and 0.4 for primary arterials, and even more significant, only 0.3 of the urban land fraction occupied by 1990. The strength of the proposed modeling technique presented here is not so much in the absolute values of the output of the three investment strategies, but, rather, in the use of the model as a planning tool to understand and study the direction in which the economy is likely to go and especially the impacts of a given urbanization policy on the transportation sector.

Urban growth or decline involves a complex interaction and feedback phenomenon among the various socioeconomic sectors and main growth shapers in a region, such as transportation, utilities, open space and major activity centers. As such it should be analyzed with its main socioeconomic and growth shapers explicitly incorporated in the planning model. Past planning models based on the analysis of a single sector or component of an urban system have not been able to deal with some of the significant long-term induced problems, such as traffic jams, in-and-out migration, and urban sprawl. This may be because (a) the nature of the problem has not been fully understood, and (b) the current methodologies cannot explicitly incorporate and trace the key variables that create and sustain the problem of the urban system over time.

PURPOSE AND OBJECTIVES

Essentially transportation in terms of economic development is a derived demand and is dependent on the development plans of the other sectors of the economy. The correct task of transportation planning, therefore, consists of the accomplishments of all necessary movements of people and goods at a minimum overall cost to the economy (1). The overall purpose of the paper, then, is to analyze and evaluate the causal forces and feedback phenomena that underlie growth or changes in an urbanized region and the effect of such growth on the transportation sector. The specific objectives of the paper are to

1. Collect data in order to define urban variables and their relationships.
2. Develop both the causal model and calibrate the mathematical model that explains urban growth or change.
3. Apply the developed model as a tool to determine the strategic or long-term transportation needs for different urban investment plans; that is, manufacturing, and business.

Concept of the Model Development

The model development is based on the fact of the interdependence of the main sectors of the economy. A simple block diagram can portray the interrelatedness or interdependence of the urban economy. Figure 1 shows that any financial allocation in any of the key sectors affects the other sectors and feeds back eventually on itself. Figure 1 also shows that if nothing else, urban land availability will eventually constrain urban growth or that continued growth in one sector will be at the expense of the other sectors in terms of land occupancy.

Several variables must of necessity be required to explain these complex interaction and feedback phenomena of the different sectors. Figure 2 shows a conceptual framework of the socioeconomic sector as an example for the causal and mathematical models. Consider a policy that favors downtown business expansion. Such a policy can be represented by the following variables and their associated impacts. Business Construction increases Business Structure (as indicated by the plus sign at the end of the

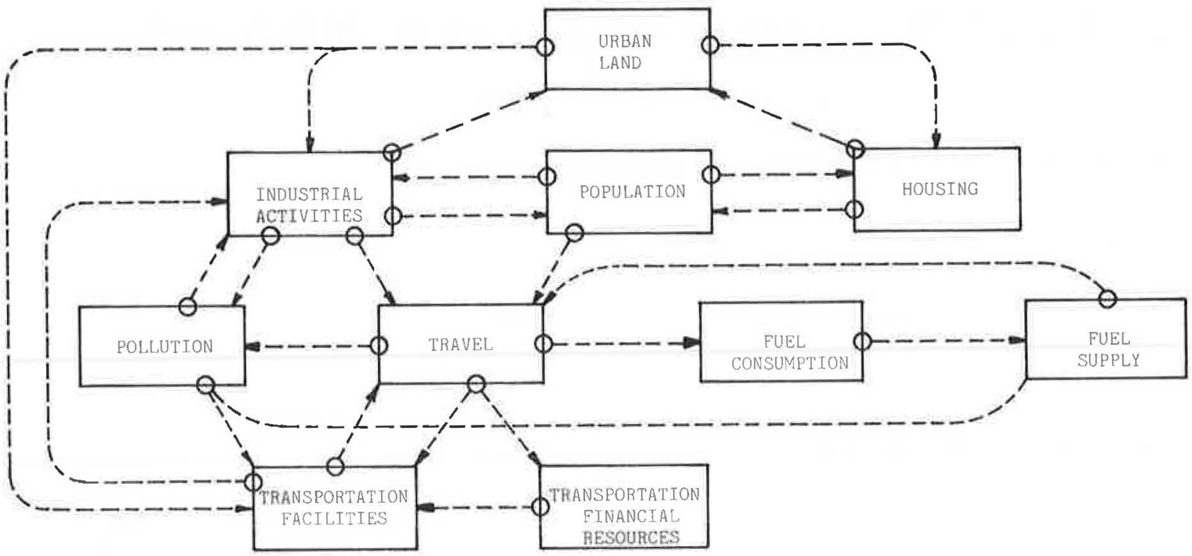

FIGURE 1 Transportation within the urban system *(2)*.

arrow in Figure 2), Business Structure, in turn, increases the number of Employment Opportunities, which positively affects Population; an increase in Population stimulates Land Development, and an increase in Land Development in turn increases Land Availability, which feeds back to Business Construction, thus encouraging further growth. However, a reduction in free land or Land Availability suppresses or negatively affects further business expansion. From this loop, the effect on the transportation sector can be felt through the Population and Employment Opportunities variables; that is, population and jobs are the key variables in most transportation trip generation models.

The causal model depicted in Figure 2, even though it is a powerful tool in understanding the complex interrelationships involved, is of little use in addressing the quantitative needs and resulting impacts in an urban region for any given policy. These relationships must be converted to mathematical forms if meaningful planning is to be done. Both the causal models and the mathematical relationships are developed after Forrester's (2) System Dynamics Methodology. Differential difference equations are developed for each variable in the model; as an example of a formulation, the mathematical equation for highway construction is presented.

$$RCR_{t+1} = \text{Min } [DFR_t (RCB_t/CCPM) URLAM_t]/RCT$$

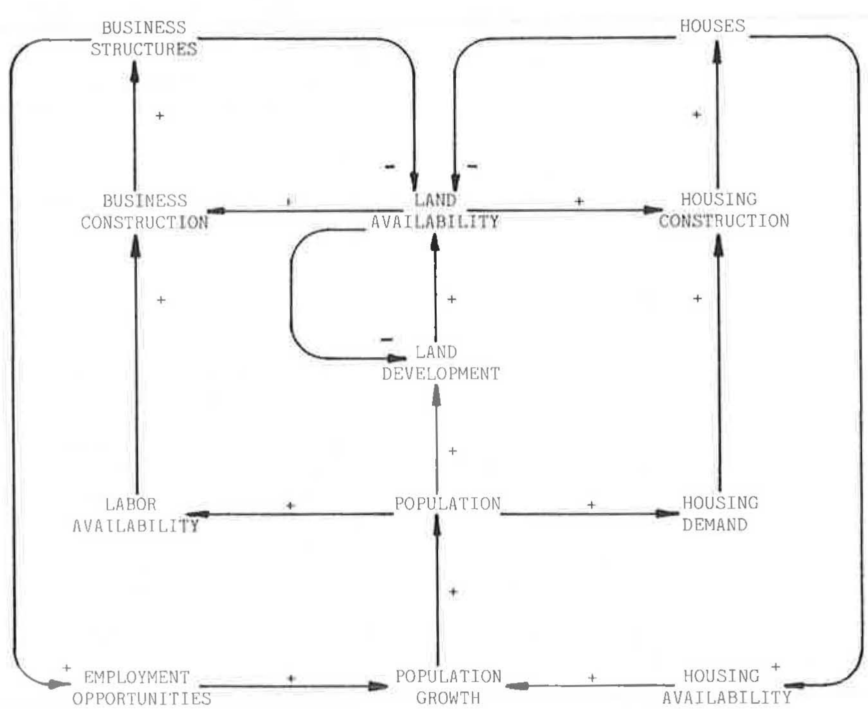

FIGURE 2 Socioeconomic sector.

where

RCR_{t+1} = road construction rate (mile/year) at time t+1;
Min = minimum of the function;
DFR_t = demand for road at time t;
RCB_t = road construction budget at time t;
CCPM = construction cost per representative mile of road in the network;
$URLAM_t$ = urban road land availability multiplier, which represents the availability of urban land for road construction; and
RCT = road construction delay time; that is, the time required for road construction from planning to operation.

Procedure

Each sector of the urban economy presented in Figure 1 was examined and modeled independently to determine the intrasectoral variables, causality, and feedbacks. The key points (variables) of linkages were then identified and the individual sectoral submodels were linked at these key points (variables) to form a single mathematical model for the urban region. Solution of the single mathematical model then provided directions in which the economy is going and the demand for usable highway miles in the simulation period for a given urban development strategy, manufacturing, business, and so forth. The developed model was calibrated with real-world data; in this study, the data base of Charlotte, North Carolina, was used.

CASE STUDY OF CHARLOTTE, NORTH CAROLINA

The city of Charlotte is approximately midway between Atlanta, Georgia, and Washington, D.C., at the intersection of I-77 and I-85. It is the hub of a 12-county region known as metrolina. Its favorable climate; that is, mild winters and summers, and its sparsely populated counties, together with fairly good transportation and proximity to the Atlantic Ocean and the mountains has moved Charlotte into one of the high growth southern Sun Belt cities. The accelerated economic growth has begun to show its impacts on the city road network. Level of service on the main arterials are E to F in the peak. Moreover, the current growth is likely to continue in the foreseeable future. The authors believe that the city presents a good example for an integrated system approach to determine strategic transportation needs under various manufacturing and business investment policies. The basic socioeconomic data for the city is given in Table 1.

Model Calibration

With a model this large [i.e., eight sectors: (a) population; (b) housing; (c) business; (d) heavy manufacturing; (e) light manufacturing; (f) government; (g) agriculture; and (h) transportation] whose formulation is based on observed data, assumptions, and concepts drawn from demography, economics, agriculture, transportation, and technology, it is particularly important to test its predictive ability over a period of time.

Calibration was attempted as follows: a set of variables (over a 10-year period) whose characteristics more or less determine the regional behavior was compared with the model (or simulation) output for the same period. Table 2 gives the comparison between the model values and the observed values (data) for population, housing, heavy manufacturing, business, and highway miles. A difference of less than 10 percent between the predicted model and the observed data was acceptable as an adequate calibration.

TABLE 1 Basic Socioeconomic Data of Charlotte

Basic Data	1970	1980
Population	354,656	404,270
Housing units	114,974	156,134
Business	1,645	2,270
Heavy Manufacturing	652	827
Light manufacturing	1,335	1,987
Agriculture establishment	46	111
Transportation network (miles)	912	1,012
Government establishment	1,000	1,600
Land area (square miles)		138

Note: Data collected from various reports on the socieconomic data base for Charlotte, North Carolina.

TABLE 2 Predicted and Observed Values

	Time (year)	
Variables	1970	1980
Population		
Model	354,656	400,710
Observed	354,656	404,270
Percent difference	0.00[a]	0.88
Heavy manufacturing		
Model	652	886
Observed	652	827
Percent difference	0.00[a]	6.66
Transportation		
Model	912	1,033
Observed	912	1,012
Percent difference	0.00[a]	2.03

[a] Beginning of simulation.

Development Policies

Most cities' growth can be ascribed to a combination of planned growth through zoning, ad hoc decision making, or piecemeal acquisition and conversion of land to different use. Irrespective of the developmental process, today's city transportation engineer is expected to provide, or at least recommend, a plan that would provide viable mobility in the city. As such, the engineer may react to growth or, as suggested in this paper in the case of Charlotte, assume a certain direction of growth for a given planning period and thus identify the probable transportation needs for a given investment direction. The model will be used to simulate the following policies for the city:

1. Emphasis on heavy manufacturing,
2. Emphasis on light manufacturing, and
3. Emphasis on downtown business development.

The impact of each one of these policies on the highway network will be analyzed in terms of lane-miles of road needs and peak-hour level of service provided for (a) freeways, (b) primary arterials, (c) minor arterials, and (d) local roads, under the assumption that the rate of highway construction continues as it is currently being planned and as it is at present.

Policies in the system dynamics methodology are incorporated in the model through the rate variables. Recall from Figure 2 (the causal model of the socioeconomic sector) that Business Structure has a positive impact on both Population and Employment Opportunities and that the population and jobs variables

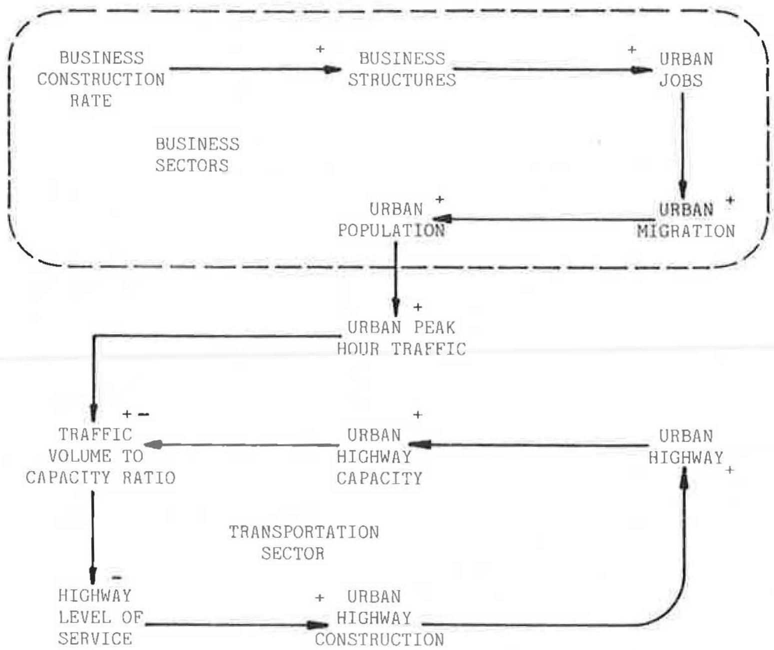

FIGURE 3 Linkage between the business sector and the transportation sector.

are generally the key variables in transportation trip production modeling. A simplified causal model showing the linkage between the socioeconimic sector and the transportation sector is shown in Figure 3.

Figure 3 also shows how the impacts of Policy 3, emphasis on downtown business development, determines Urban Peak Traffic and Traffic Volume-to-Capacity Ratio for the urban highway network. The rate variable Business Construction Rate is used to incorporate various policy decisions on downtown development.

Analyses and Impacts of Different Urban Policies

Table 3 gives a summary of the information on the main socioeconomic indicators for the city at different points in time. A close examination of Table 3 reveals the following impacts:

1. Population: Within 10 years Policies 1 and 2 show an increase in population from 404,270 to 510,520 and from 404,270 to 605,040, respectively, whereas Policy 3 shows a change of 16.5 percent in 10 years.
2. Roads: The demand for new roads; that is, lane miles is most crucial for Policy 2, a change from 1,033 to 2,010.
3. Level of service: Policy 3 will reduce the highway system to a level of service C in 20 years.
4. Land fraction occupied: Policy 2 is the most demanding on land development rate: 60 percent occupied within 10 years.

Figure 4 shows a typical time series plot for total highway needs for the city.

CONCLUSIONS AND RECOMMENDATIONS

In dealing with a complex system, the structure of the solution process sometimes appears more important than the solutions themselves because the lack of definition of the right problem is much more crucial than finding a sound answer to the wrong problem. System Dynamics, through the use of feedbacks and simulation allows constant evaluation of the approach to the problem because a trace of the behavior of a given policy is provided instead of a projection to a given point in time.

TABLE 3 State of the Economy Under Different Urban Policies

	Policies		
Indicators	No. 1	No. 2	No. 3
Time (years)	1990 or in 20 years[a]	1990 or in 20 years[a]	1990 or in 20 years[a]
Population	510,520	605,040	470,860
Roads			
Freeway (miles)	118	130	128
Primary arterials	426.7	460	430
Level of service			
Freeways	C	C	C
Volume-to-capacity ratio	0.6	0.7	0.6
Primary arterials	C	B	B
Volume-to-capacity ratio	0.7	0.5	0.4
Land fraction occupied	0.4	0.6	0.3

[a]Beginning of simulation, 1970.