System Dynamics Modeling of Development Induced by Transportation Investment

DONALD R. DREW

A modeling paradigm for analyzing transportation-development interactions is described. The new approach is based on isolating underlying causes of development deficiencies in a systematic way, identifying policies and infrastructure investments to deal with the causes, and then assessing the impacts of alternatives against specified goals. The system dynamics methodology uses three alternative forms of the model: verbal (narrative description), visual (causal diagram), and mathematical (set of equations derived from the causal diagram). The methodology is illustrated using three examples: (a) modeling urban systems, (b) modeling regional and national economics, and (c) evaluating user and nonuser benefits.

Reducing the true cost of transport increases the total amount of goods and services available, ultimately increasing the total real income of any society. Tools for estimating the effects of different transportation improvements within these contexts are only now being developed. These tools tend to fall into two classes: (a) models of national and regional economies with a component being the transportation system; and (b) traditional models of various aspects of the development process such as land use models, population models, location models, economic base models and input-output models that are linked either explicitly or implicitly to transportation.

NEED FOR MODELING PARADIGM

Although there are well-established professional activities associated with transportation problems (transportation planning, transportation operations, and transportation economics) and well-established professional activities associated with development problems (development planning, development economics, and development administration), the two classes of activities are usually linked subjectively. Moreover, the actual decision-making processes in each proceeds with nearly total isolation from ongoing planning activities. A new approach is needed for isolating underlying causes of development deficiencies in a systematic way, identifying policies and infrastructure investments to deal with the causes, and then assessing the impacts of alternatives against specified goals.

The whole process starts with a basic restatement of values and goals. Values are those irreducible qualities on which individual and group preferences are based. The groups are defined as the users of transportation, the providers of trans-

portation, and the society. Goals are desirable end-states toward which planning might be expected to lead. A problem exists when a goal is not being achieved. There may be two possible reasons for this failure: (a) the goal is unachievable and (b) the problem results from conflicting goals. There is not much that can be done in the first case except to lower aspirations. In the second case, the problem may be described as an issue— a matter that is in dispute between two or more of the three groups involved (1).

In all, there are three ways in which causality from a policy-controlled variable acts on a goal or uncontrolled variable: (a) the sign of the interaction (positive or negative), (b) the strength of the interaction (strong or weak), and (c) the time lag of the influence. Moreover, because policy variables may act indirectly on several different goals through causal sequences of intermediate variables, cross-impact analysis is best accomplished using a digital computer. The ultimate result is one of creating scenarios—determining future impacts of contemplated policies by setting logical sequences of events in step-by-step relationships (2).

A systems perspective of transportation development analysis requires consideration of software (policies) as well as hardware (technologies), time as well as space, and strategic as well as tactical methods. The principal requirement for viable strategic approaches to solving transportation-development problems is that the approaches be system-wide, causally based, and policy-oriented, and permit the specification of alternative transportation-development concepts in sufficient detail to allow their implications and impacts to be examined.

SYSTEM DYNAMICS APPROACH

Transportation systems—particularly highways, ports, and airports—are essential to the efficient functioning of national economies throughout the world, but experts say that these systems will be increasingly burdened by ever-growing demand, limited supply, and increased congestion. Although transportation systems are particularly vital to national and regional economic productivity, no organized or well-developed body of knowledge exists regarding the effects of transportation infrastructure on development. Indeed, engineers and planners dealing with transportation problems rarely work closely with their counterparts in economic development.

The transportation-development relationship is essentially a two-way interactive process with results of the interaction

Department of Civil Engineering, Virginia Polytechnic Institute and State University, Blacksburg, Va. 24061.

depending on the type of economy involved and on the level of development at which transport improvements are effected. At a given level of development an area requires a certain level of transportation to maximize its potential. Thus, an optimum transportation capacity corresponds to any development level. Existence of unsatisfied demand for transportation may, over time, have serious adverse effects on the economy; conversely, the results of overcapitalization may be unpleasant if too much money is spent on transportation in anticipation of demand that never materializes (3,4).

A model of this process can be complex and can consist of hundreds of variables. Because of the necessary feedbacks, determining the optimal transport system consistent with a specific spatial structure of an area is, to say the least, elusive (5).

Research is needed to develop a methodology for constructing regional transportation-development models. Such a methodology would start with verbal descriptions of perceptions of the process. From these verbal descriptions, key variables and their interactions would be identified and displayed graphically in the form of causal diagrams. Using the causal diagrams, mathematical models would be developed. Verbal description is important in explaining the reasoning leading to a proposed policy and the consequences of that policy. Graphical display provides a gestalt for synthesizing the contributions of experts and specialists. Mathematical models provide an instrumentality that can be subject to manipulation and sensitivity analysis. By examining the sensitivities of hypothesized relationships, priorities for data collection for model calibration can be established (6).

Although experts may understand portions of the transportation-economic development process, to synthesize these portions in a consistent manner without a formal technique is impossible. The transportation-development process is composed of large numbers of variables spanning many disciplines. These variables are causally related and close on themselves to form higher-order feedback loops. Inputs are stochastic, relationships are nonlinear, and delays and noise are present in the information channels. All of these characteristics preclude predicting systems behavior by partitioning the problem along disciplinary lines and then assembling the component solutions (7).

THE MODELING PROCESS

Policy makers, to guide national development effectively, must bring together a variety of mental models, translate them into a common language, and then determine simultaneously all their important implications. Therefore, formal models with assumptions stated explicitly are required. Formal models are best expressed in mathematical equations for three reasons: (a) mathematics is precise and interdisciplinary, (b) equations can be manipulated in response to changing inputs, and (c) the mathematical notation permits processing by computer.

For system dynamics methodology, three alternative forms of the model of a system are used: verbal, visual, and mathematical (8). The verbal description is a mental model of the system expressed in words. Visual descriptions are diagrammatic and show cause-and-effect relationships between many variables in a simple, concise manner. The visual model, or causal diagram, is then translated into a mathematical model

of system equations. All forms are equivalent, with any one form merely serving as an aid to understanding for someone who does not comprehend the other forms. However, the verbal description does not lend itself to formal analysis and the visual causal diagram can only be analyzed qualitatively. Mathematical models are by far the most precise and are the only representations of the system that permit quantitative analysis and the evaluation of alternative solutions to a problem.

Modeling procedure is sequential and iterative and starts with the verbal description of the major elements necessary to represent relevant aspects of the system. Next is the postulation of the model's structure and conceptualization of causal relationships between model parameters in the form of a causal diagram. From the causal diagram, system equations may be written. In order to complete the mathematical model, the model's parameters must be estimated. This step includes placing numerical values on constants and the quantification of causal assumptions. The accuracy of the model can be evaluated through simulation. At each step, the model is exposed to criticism, revision, reexposure, etc., in an iterative process that continues as long as it proves useful (9).

The proposed methodology uses all of the relevant parameter classes in system dynamics—level variables, rate variables, auxiliary variables, supplementary variables, and constants. However, the methodology is different because the geometric shapes—rectangles, valves, circles, etc.—used in system dynamic diagrams are unnecessary. For example, a level variable is always at the head and a rate variable is always at the tail of a solid arrow. Signs on the solid arrow indicate if the rate is added to or subtracted from the level of the state variable. Whereas solid arrows denote physical flows, dashed arrows in the causal diagram define information flows from level variables to rates, or action, variables. Any intermediate variable on the path from a level variable, or from an exogenous input, to a rate variable is called an auxiliary variable. Signs on dashed arrows have the following interpretation: a plus sign ($+$) means that an increase in the parameter at the tail of the arrow will cause an increase in the variable at the head of the arrow; a minus sign ($-$) means that an increase in the parameter at the tail of the arrow will cause a decrease in the parameter at the head of the arrow. Exogenous inputs are easily identified on a causal diagram because they have no arrows leading to them, but have one or more dashed arrows emanating from them. Supplementary variables, in contrast, do not form part of the system itself but merely indicate its performance and, therefore, are always identified by being at the head of a dashed arrow and having no arrows emanating from them. In summarizing the causal diagramming convention: (a) arrows describe the direction of causality between pairs of variables, (b) lines (solid or dashed) denote (physical or information) flows, and (c) signs indicate the nature (direct or inverse) of the relationship between dependent-independent variable pairs.

The methodology uses the DYNAMO computer language associated with system dynamics. In difference equation terminology, any level variable L_i is expressed as a function of rate variables R_j and the previous value of the level.

$$L_i(t + dt) = L_i(t) + (dt) \sum_{j=1}^{n} R_j(t)$$

$$i = 1, \ldots, m \qquad (1)$$

with R_j values assumed constant over the time interval from t to $t + dt$. The rate variables are in the form

$$R_j(t) = F[L_i(t), E_k(t), A_{ij}(t), A_{kj}(t)] \tag{2}$$

where E_k are the set of exogenous inputs that affect variables R_j directly, and A_{ij} and A_{kj} are the impacts of auxiliary variables in the causal streams from the ith variable and kth exogenous input, respectively. Because exogenous inputs are known time functions or constants, if initial values of the level variables are known, all other variables can be computed from them for that time. Then, new values of the level variables for the next point in time can be found from Equation 1. DYNAMO uses a postscript notation for subscripts in which *.K* stands for the present time t, *.J* stands for past time $t - dt$, and *.L* stands for future time $t + dt$. As in all computer programming, upper-case letters are used. *DT* (*dt*) is called the solution interval, the time between successive computations in the simulation. Because rate variables are assumed to be constant over *DT*, the double postscript is used, *.JK* for rates on the right side of an equation and *.KL* for rates on the left side.

MODELING URBAN SYSTEMS

Impacts of transportation on national development are usually focused on urban areas. Transportation is the bloodstream of the urban community because spatial interdependence is the rationale of the urban area. A given transportation system both influences the location of activities within the city and is itself influenced by the location of these activities, because each location pattern constitutes a set of trip demands that is responded to by investment and operating decisions within the transportation system. Unfortunately, despite this strategic importance, the system may diverge from efficient resource use on a number of grounds—economies of scale, mixed public and private sector decision making, and lack of coordinated decision making for the affected metropolitan area and across different transportation modes. Before modeling the impact of transportation on regional or urban development, a model needs to be developed for the region or the urban area, whichever applies.

Urban systems can be arbitrarily divided into two categories: (a) those that are related to the urban socioeconomic structure such as social, industrial, and residential systems; and (b) those that serve the urban community (the urban technological systems) such as water supply, energy, transportation, and the environment. Basic knowledge of how the urban systems are formed and interact with each other provides a basis for a better learning process and, thus, a better decision-making process. Because of interrelationships between urban systems, a sound solution to an urban problem can hardly be attained without knowing the possible effects on other systems. Lack of understanding of this causality in forecasting usually leads to treatment of symptoms rather than causes.

In a system as complex as a city, intuition has proven most unreliable in forecasting the probable consequences of well-meaning policies, simply because the human mind is incapable of dealing with a system containing so many variables. No wonder that urban policies, laws, and decisions have produced results different from those intended, ranging from partial success to tragic failure. Predicting with confidence the long-term consequences of costly programs has been impossible. One of the main causes leading to the failure of many urban development programs is the inability to experiment with the designed policies. Usually, a policy is implemented on the basis of some informally estimated consequences and a few decades later the policy turns out wrong. Therefore, in a decision-making process, facts must be included, but facts about future events cannot be obtained.

With present technology, one means of studying future events is through computer simulation, which is not only economical, but also is a powerful conceptual device that can increase the role of reason at the expense of rhetoric in determining effective policies. Unlike intuition and common sense of informal mental models, computer simulation is comprehensive, unambiguous, flexible, and subject to logical manipulation and testing. Flexibility of a system dynamics model is its least appreciated virtue. If there is disagreement about some aspect of causal structure or the strength of effects between variables of a problem, in a short time the model can be rerun and observations made of its behavior under each set of assumptions. Often, the argument is trifling because the phenomenon of interest may be unchanged by the factor in disagreement.

To illustrate the system dynamics approach to modeling transportation-development interactions, three examples will be presented. The first, METRO, is a model of a metropolitan area consisting of a central city and its suburbs. The model comprises seven sectors (city population, industry, housing, employment, land, suburban carrying capacities, and transportation) that will be described in the traditional system dynamics format: verbally, by causal diagrams, and by DYNAMO equations.

First, the population sector of the central city is displayed in causal diagram form and in equation form (Figure 1). The level variable *CP*, for city population, is controlled by two types of rates: natural increase (births and deaths) and migration in and out. Each of these four rates depends on the population and constant fractional rates of increase. However, in-migration is also assumed to be influenced by an attractiveness multiplier.

Next, Figure 2 shows the industry sector. Although many ways of measuring economic activity are available, industry is chosen as the level variable for this sector. Industries create more industries through industry construction. Amounts of additional economic activity are proportional to the present rate of economic activity. So, at every point in time, industry construction equals the number of industrial structures multiplied by industry construction normal with the word "normal" denoting the conditions under which construction occurs. Conditions within the urban area such as labor availability and land availability that encourage or discourage construction (above or below the normal fraction, respectively) are handled by an industry construction multiplier.

The housing sector, which is shown graphically and mathematically in Figure 3, is handled in a manner similar to the industry sector, except that the basic structural unit is the dwelling instead of the industry.

The employment sector relates the demographic (population) and economic (industry) sectors. Population determines the size of the labor force, that is, the demand for jobs. Industry creates jobs—the supply side of the interaction (see Figure 4).
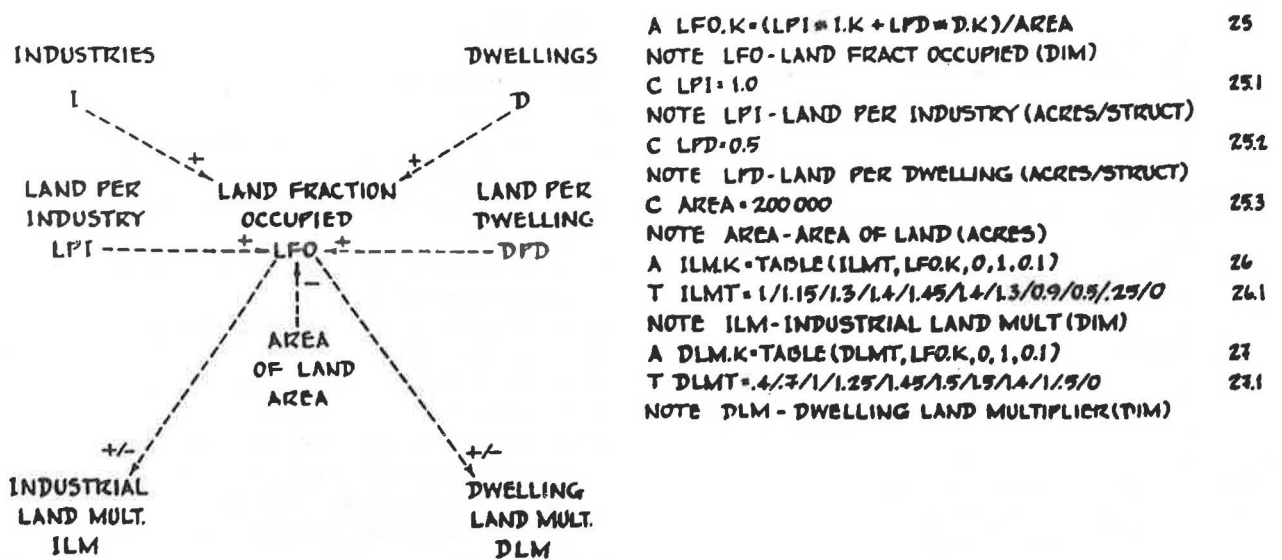
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L  CP.K = CP.J + (DT)(B.JK + IM.JK - D.JK - OM.JK)    1
N  CP = CPN                                           1.1
NOTE  CP - CITY POPULATION (PERSONS)
C  CPN = 290000                                       1.2
NOTE  CPN - CITY POP INITIALLY (PERSONS)
R  B.KL = CP.K * F                                    2
NOTE  B - BIRTHS (PERSONS/YR)
C  F = 0.03                                           2.1
NOTE  F - FERTILITY (FRACT/YR)
R  D.KL = CP.K * M                                    3
NOTE  D - DEATHS (PERSONS/YR)
C  M = 0.015                                          3.1
NOTE  M - MORTALITY (FRACT/YR)
R  OM.KL = CP.K * OMN                                 4
NOTE  OM - OUT MIGRATION (PERSONS/YR)
C  OMN = 0.07                                         4.1
NOTE  OMN - OUT MIGRATION NORMAL (FRACT/YR)
R  IM.KL = CP.K * IMN * AM.K                          5
NOTE  IM - IN MIGRATION (PERSONS/YR)
C  IMN = 0.1                                          5.1
NOTE  IMN - IN MIGRATION NORMAL (FRACT/YR)
A  AM.K = AJM.K * AHM.K                               6
NOTE  AM - ATTRACTIVENESS MULTIPLIER (DIM)
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FIGURE 1 Population sector: *left*, causal diagram; *right*, mathematical form (METRO model).


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L  I.K = I.J + (DT)(IC.JK - ID.JK)                    7
N  I = IN                                             7.1
NOTE  I - INDUSTRIES (STRUCTURES)
C  IN = 4000                                          7.2
NOTE  IN - INDUSTRIES INITIALLY (STRUCTURES)
R  IC.KL = I.K * ICN * ICM.K                          8
NOTE  IC - INDUSTRY CONSTRUCTION (STRUCT/YR)
C  ICN = 0.10                                         8.1
NOTE  ICN - INDUS CONSTR NORMAL (FRACT/YR)
A  ICM.K = ILM.K * ILFM.K                             9
NOTE  ICM - INDUS CONSTR MULTIPLIER (DIM)
R  ID.KL = I.K / ULI                                  10
NOTE  ID - INDUSTRY DEMOLITION (STRUCT/YR)
C  ULI = 40                                           10.1
NOTE  ULI - USEFUL LIFE INDUSTRY (YR)
A  AJM.K = TABLE(AJMT, LFJR.K, 0, 2, 0.2)             11
T  AJMT = 2/1.95/1.8/1.6/1.35/1/.5/.3/.2/.15/.1       11.1
NOTE  AJM - ATTRACTIVENESS JOBS MULT (DIM)
```

FIGURE 2 Industry sector: *left*, causal diagram; *right*, mathematical form.

Figure 5 shows the land sector and the ways that industry and housing compete for land. Availability of land influences the expansion of industry and housing through the industry land multiplier (ILM) and dwelling land multiplier (DLM), respectively.

These five sectors will be considered as a system with interactions within and between the sectors. Job availability modulates migration into and out of the area through an attractiveness multiplier. Availability of housing also influences housing construction because builders and developers cannot make a profit by building and marketing houses for which there is no demand. Population and industry structures are coupled through the ratio of labor force to jobs, population and housing through the ratio of households to housing, and industry structures and housing through values of the land fraction occupied.

A city is not self-sufficient. The hypothetical city must reach out into the hinterland for water, food, clean air, energy, and raw materials. Physical systems that help an urban population eat, drink, breathe, sleep, work, and move about are engineering systems. These systems are lifelines; without them, modern cities could not exist. Transportation is a life support system that can be superimposed on previously modeled socioeconomic systems.

USEFUL LIFE OF DWELLING ULD · HOUSEHOLD TO HOUSING RATIO HHR · CITY POPULATION CP

DWELLING DEMOLITION DD · HOUSEHOLD SIZE HS · ATTRACTIVENESS HOUSING MULT. AHM

DWELLINGS · DWELL. AVAIL. MULTIPLIER DAM

DWELLING CONSTRUCTION DC · DWELL. CONSTR. MULTIPLIER DCM

DWELL CONSTR NORMAL DCN · DWELL LAND MULTIPLIER DLM

```
L   D.K=D.J +(DT)(DC.JK-DD.JK)                          12
N   D=DN                                                12.1
NOTE  D-DWELLINGS (STRUCTURES)
C   DN=56000                                            12.2
NOTE  DN-DWELLINGS INITIALLY (STRUCTURES)
R   DC.KL=D.K * DCN * DCM.K                             13
NOTE  DC-DWELLING CONSTRUCTION (STRUCT/YR)
C   DCN=0.07                                            13.1
NOTE  DCN-DWELL CONSTR NORMAL (FRACT/YR)
A   DCM.K=DLM.K*DAM.K                                   14
NOTE  DCM-DWELL CONSTR MULT (DIM)
R   DD.KL=D.K/ULD                                       15
NOTE  DD -DWELLING DEMOLITION (STRUCT/YR)
C   ULD=66.67                                           15.1
NOTE  ULD-USEFUL LIFE DWELLING (YR)
A   DAM.K=TABLE(DAMT,HHR.K,0,2,0.2)                     16
T   DAMT=.2/.25/.35/.5/.7/1/1.35/1.6/1.8/1.95/2        16.1
NOTE  DAM-DWELLING AVAILABILITY MULT (DIM)
A   HHR.K=CP.K/(D.K * HS)                               17
NOTE  HHR -HOUSEHOLD TO HOUSING RATIO (DIM)
C   HS=4                                                17.1
NOTE  HS-HOUSEHOLD SIZE (PERSONS/STRUCT)
A   AHM.K=TABLE(AHMT,HHR.K,0,2,0.2)                     18
T   AHMT=1.4/1.4/1.35/1.3/1.15/1/.8/.65/.5/.45/.4      18.1
NOTE  AHM -ATTRACTIVENESS HOUSING MULT(DIM)
```

FIGURE 3 Housing sector: *left*, causal diagram; *right*, mathematical form.

LABOR PARTIC. FRACTION LPF · SUBURBAN POPULATION SP

LABOR FORCE LF · POPULATION P

LABOR FORCE JOB RATIO LFJR · JOBS J · CITY POPULATION CP

INDUS. LABOR FORCE MULT. ILFM · JOBS PER INDUSTRY JPI · INDUSTRIES I

```
A   ILFM.K=TABLE(ILFMT,LFJR.K,0,2,0.2)                 19
T   ILFMT=.2/.25/.35/.5/.7/1/1.35/1.6/1.8/1.95/2      19.1
NOTE  ILFM-INDUS LABOR FORCE MULT(DIM)
A   LFJR.K =LF.K/J.K                                    20
NOTE  LFJR-LABOR FORCE JOB RATIO (DIM)
A   LF.K =P.K*LPF                                       21
NOTE  LF-LABOR FORCE (PERSONS)
C   LPF=0.50                                            21.1
NOTE  LPF-LABOR PARTICIPATION FRACT(DIM)
A   P.K=CP.K+SP.K                                       22
NOTE  P-POPULATION (PERSONS)
A   J.K=I.K*JPI                                         23
NOTE  J-JOBS(PERSONS)
C   JPI=38                                              23.1
NOTE  JPI-JOBS PER INDUS (PERSONS/INDUS)
S   UR.K=(LF.K-J.K)/LF.K                                24
NOTE  UR-UNEMPLOYMENT RATE (DIM)
```

FIGURE 4 Employment sector: *left*, causal diagram; *right*, mathematical form.

If the availability of employment and housing is the principal determinant of in-migration to the hypothetical urban area, accessibility of suburban residences to central city work places (achieved through suburban expressways) accounts for the movement of people from the central city to the suburbs. The causal diagram and mathematical model for the suburban sector are shown in Figure 6 and for the transportation sector in Figure 7.

The causal diagram for the entire METRO model is shown in Figure 8. Streams of causality can be followed from variable

to variable through the sectors. The suburban population SP depends on the lane-miles of commuter expressways CE. Figure 8 also gives the control statements for the model outputs, which are presented in Figures 9–12.

Figures 9 and 10 show the standard or base run outputs of the model. Figures 11 and 12 are outputs of alternative scenarios based on parameter changes made to represent various development strategies. In these four figures, the abscissas are time corresponding to 100 years in the lifetime of the hypothetical metropolis. In Figure 10, the ordinate E expressed

FIGURE 5 Land sector: *left*, causal diagram; *right*, mathematical form.

```
A  LFO.K=(LPI*I.K+LPD*D.K)/AREA                    25
NOTE  LFO-LAND FRACT OCCUPIED (DIM)
C  LPI=1.0                                          25.1
NOTE  LPI-LAND PER INDUSTRY (ACRES/STRUCT)
C  LPD=0.5                                          25.2
NOTE  LPD-LAND PER DWELLING (ACRES/STRUCT)
C  AREA=200000                                      25.3
NOTE  AREA-AREA OF LAND (ACRES)
A  ILM.K=TABLE(ILMT,LFO.K,0,1,0.1)                  26
T  ILMT=1/1.15/1.3/1.4/1.45/1.4/1.3/0.9/0.5/.25/0  26.1
NOTE  ILM-INDUSTRIAL LAND MULT (DIM)
A  DLM.K=TABLE(DLMT,LFO.K,0,1,0.1)                  27
T  DLMT=.4/.7/1/1.25/1.45/1.5/1.3/1.4/1/.5/0       27.1
NOTE  DLM - DWELLING LAND MULTIPLIER (DIM)
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FIGURE 6 Suburban sector: *left*, causal diagram; *right*, mathematical form.

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L  SP.K=SP.J+(DT X CSM.JK)                          28
N  SP=SPN                                           28.1
NOTE  SP-SUBURBAN POPULATION (PERSONS)
C  SPN=14000                                        28.2
NOTE  SPN-SUBURBAN POP INITIALLY (PERSONS)
R  CSM.KL=OM.JK*FOMS.K                              29
NOTE  CSM-CITY SUBURB MOVEMENT (PERSONS/YR)
A  FOMS.K=TABLE(FOMST,(SCC.K-SP.K)/SCC.K,0,1,.2)   30
T  FOMST=0/.6/.9/.9/.6/0                            30.1
NOTE  FOMS-FRACT OUT MIG TO SUBURBS (DIM)
A  SCC.K=CCEC.K                                     31
NOTE  SCC-SUBURBAN CARRYING CAP (PERSONS)
A  CCEC.K=(CE.K*DDL*LC*DPP*VOC)/(MCD*LPF)           32
NOTE  CCEC-CARRYING CAP EXP COMMUTING (PERSONS)
C  LC=2000                                          32.1
NOTE  LC-LANE CAPACITY (VEH/HR-LANE)
C  VOC=1.35                                         32.2
NOTE  VOC-VEHICLE OCCUPANCY (PERSONS/VEH)
C  MCD=30                                           32.3
NOTE  MCD-MAX COMMUTING DISTANCE (MI)
C  DDL=0.5                                          32.4
NOTE  DDL-DIRECTIONAL DISTRIBUTION OF LANES (DIM)
C  DPP=3                                            32.5
NOTE  DPP-DURATION PEAK PERIOD (HR)
```

in lane-miles stands for commuter expressways, and ranges from 0 to 1,000. In the other figures, there are two ordinate scales: one for city population (C) and suburban population (S) and the other for the unemployment rate (U). The scales for C and S run from 0 to 2,000 T (2 million) persons and the scale for U from -0.05 to $+0.25$. Unemployment rate is defined in Equation 24 in Figure 4.

By examining the computer outputs, the various strategies for reducing unemployment can be compared and the effects on population distribution between city and suburbs can be observed. Table 1 presents the effects of the strategies at 30 years and Table 2 at 100 years. The pattern of behavior is similar in the five cases. The first 30 years are marked by rapid growth whereas the next 30 years are marked by a transition phase followed by an equilibrium phase. This pattern of growth is typical of the dynamics of the American metropolitan area over the past century.

The four policies tested and reported in Figures 11 and 12 can be described as follows:

1. Industrial Development Policy—aims at reducing the shortage of jobs as unemployment increases by attracting new

Left portion (causal diagram) - Figure 7

Right portion (mathematical form) - Figure 7:
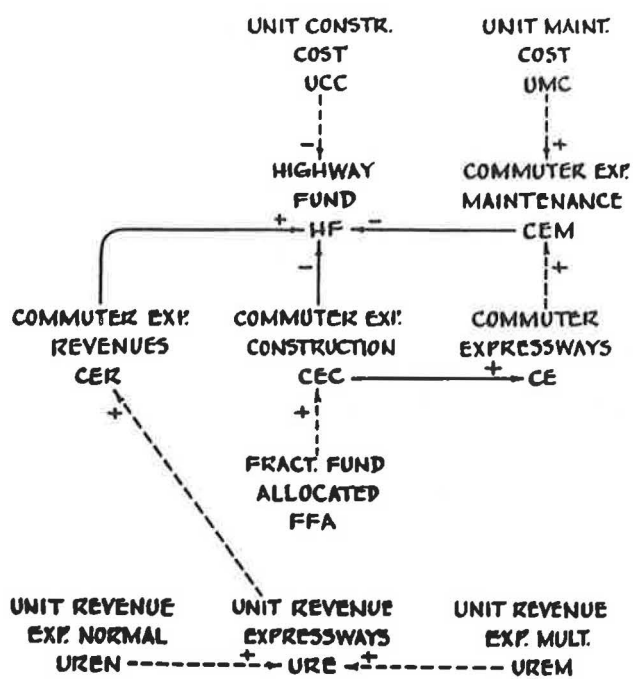
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L   CE.K=CE.J +(DT)(CEC.JK)                              33
N   CE=CEN                                               33.1
NOTE  CE-COMMUTER EXPRESSWAYS (LANE MI)
C   CEN=100                                              33.2
NOTE  CEN-COM EXPRESSWAYS INITIALLY (LANE MI)
R   CEC.KL=(HF.K/UCC)*FFA                                34
NOTE  CEC-COM EXP CONSTRUCTION (LANE MI/YR)
C   UCC=2000000                                          34.1
NOTE  UCC-UNIT CONSTRUCTION COST ($/LANE MI)
C   FFA=1.0                                              34.2
NOTE  FFA-FRACT FUND ALLOCATED (FRACT/YR)
L   HF.K=HF.J +(DT)(CER.JK-CEM.JK-CEC.JK=UCC/FFA)        35
C   HF=0                                                 35.1
NOTE  HF-HIGHWAY FUND ($)
R   CEM.KL=CE.K*UMC                                      36
NOTE  CEM-COM EXP MAINTENANCE ($/YR)
C   UMC=200000                                           36.1
NOTE  UMC-UNIT MAINTENANCE COST ($/YR-LANE MI)
R   CER.KL=CE.K*URE.K                                    37
NOTE  CER-COM EXP REVENUES ($/YR)
A   URE.K=UREN*UREM.K                                    38
NOTE  URE-UNIT REV EXPRESSWAYS ($/YR-LANE MI)
C   UREN=400000                                          38.1
NOTE  UREN-UNIT REV EXP NORMAL ($/YR-LANE MI)
A   UREM.K=TABLE(UREMT,CE.K,0,1000,100)                  39
T   UREMT=0/1/1.2/1.3/1.2/1/.8/.6/.5/.4/.3/.2            39.1
NOTE  UREM-UNIT REV EXP MULTIPLIER (DIM)
```

FIGURE 7   Transportation sector: *left*, causal diagram; *right*, mathematical form.

Control statements - Figure 8:
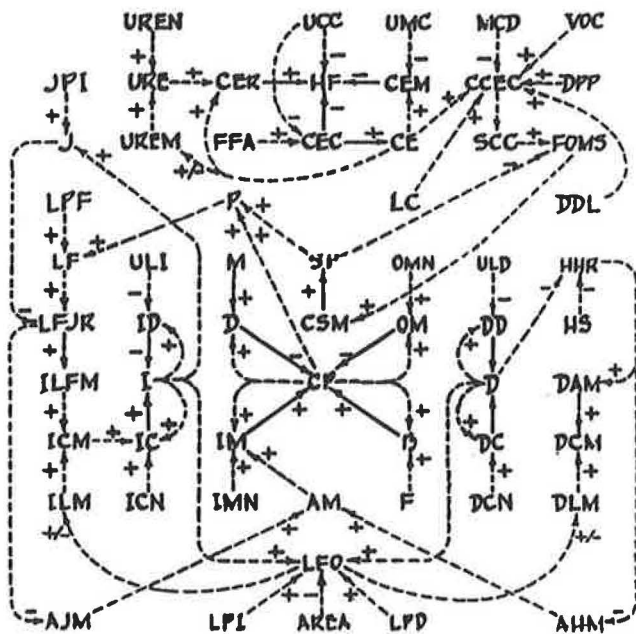
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PLOT  CP=C,SP=S(0,2000000)/UR=U(-.05,.20)      FIG. 9
NOTE  C-CITY POPULATION
NOTE  S-SUBURBAN POPULATION
NOTE  U-UNEMPLOYMENT RATE
PLOT  CE=E(0,1000)                             FIG. 10
NOTE  E-COMMUTER EXPRESSWAYS
C   DT=0.5
NOTE  DT-SOLUTION INTERVAL (YR)
C   LENGTH=50
NOTE  LENGTH-LENGTH OF SIMULATION (YR)
C   PLTPER=1
NOTE  PLTPER-PLOT PERIOD
C   ICN=0.15
NOTE  INCREASE IN ICN FROM 0.10 TO 0.15
RUN  INDUSTRIAL DEVELOPMENT SCENARIO          FIG. 11
C   DCN=0.10
NOTE  INCREASE IN DCN FROM 0.07 TO 0.10
RUN  HOUSING DEVELOPMENT SCENARIO             FIG. 11
C   ICN=0.15
C   ULD=33.3
NOTE  CHANGES IN ICN AND ULD
RUN  MIXED DEVELOPMENT SCENARIO               FIG. 12
C   FFA=0.5
NOTE  CHANGE IN FFA FROM 1.0 TO 0.5
RUN  GENERAL FUND SCENARIO                    FIG. 12
QUIT
```

FIGURE 8   METRO model: *left*, causal diagram; *right*, control statements.
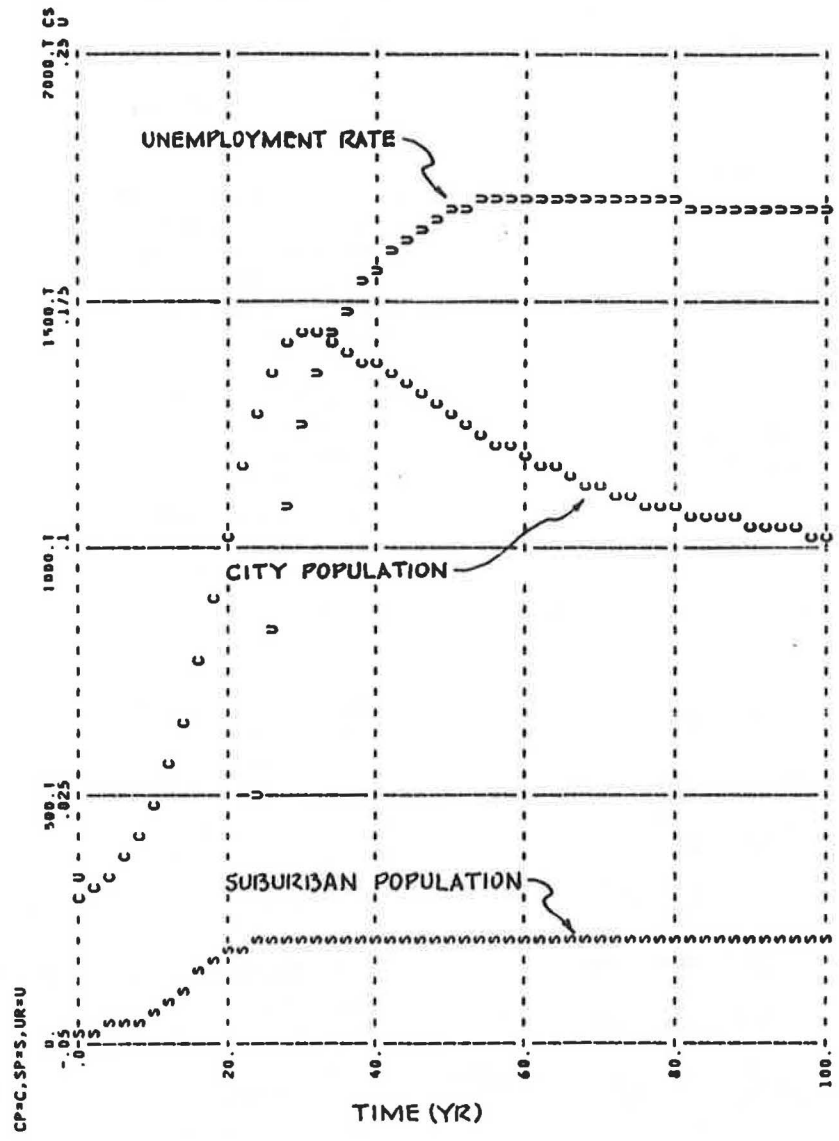
FIGURE 9 Base Scenario 1.
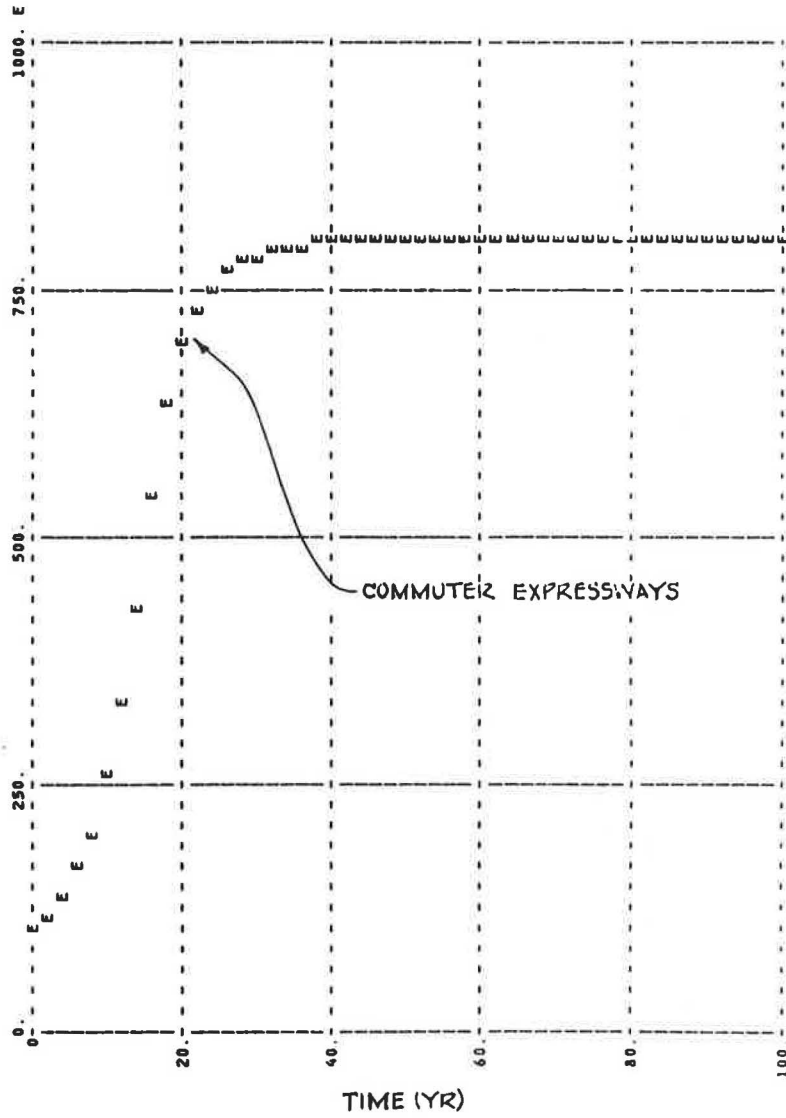
FIGURE 10 Base Scenario 2.

FIGURE 11 Industrial and housing development scenarios.
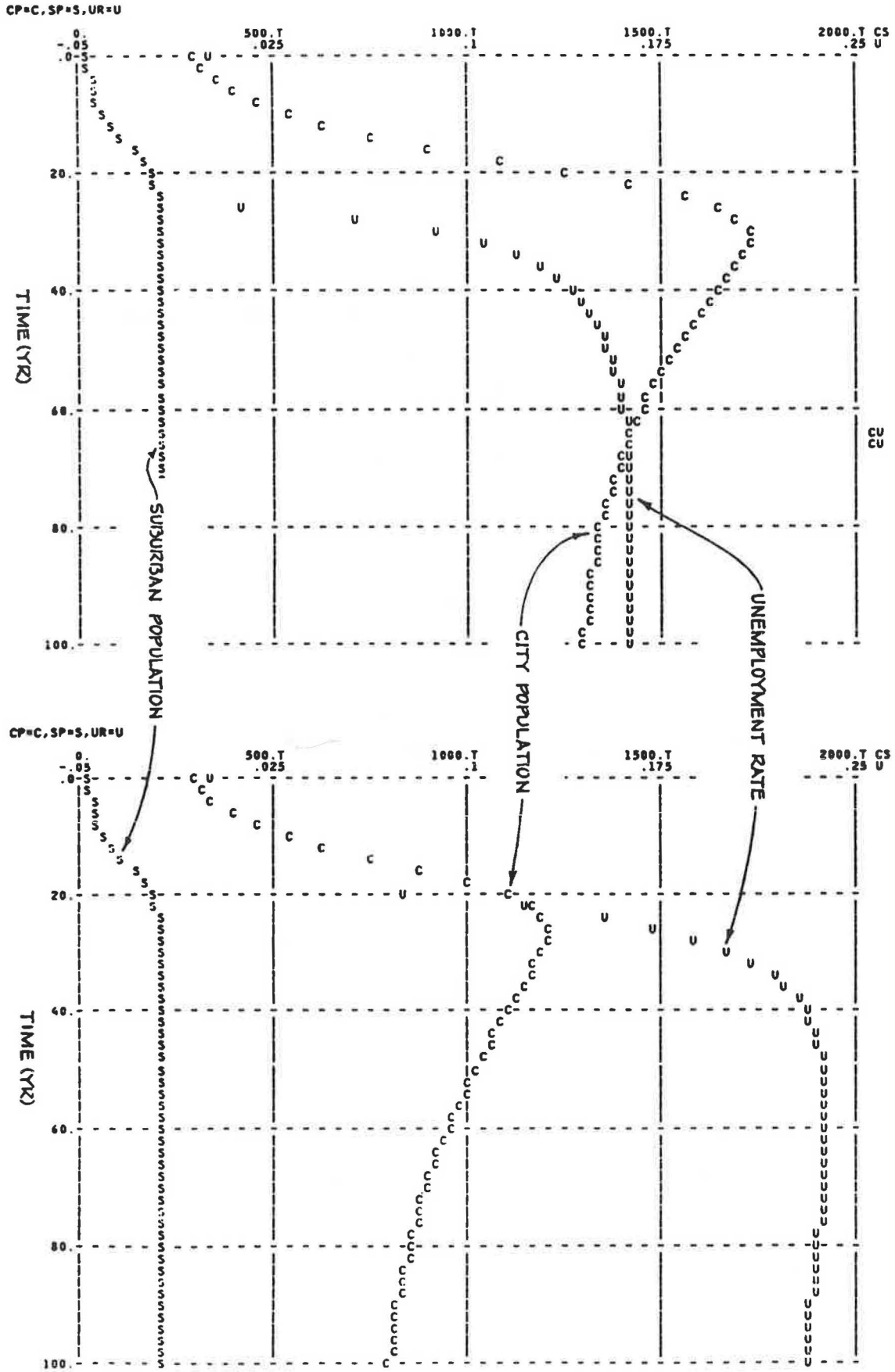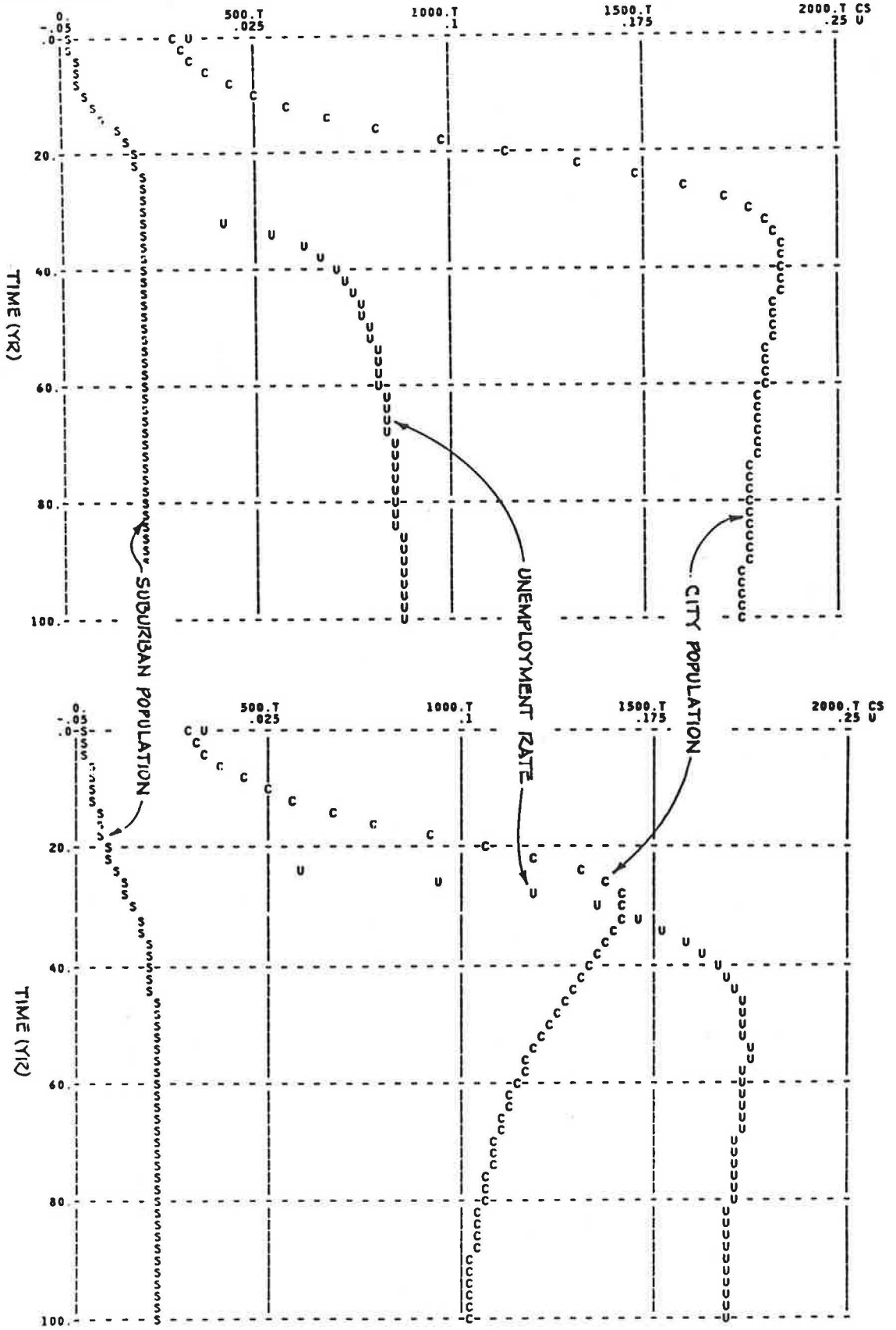
FIGURE 12 Mixed development and general fund scenarios.

TABLE 1 COMPARISON OF SCENARIOS AT TIME T = 30 YEARS

Parameters	Base Run	Policy 1	Policy 2	Policy 3	Policy 4
ICN	.10	.15	.10	.15	.10
DCN	.07	.07	.10	.07	.07
ULD	66.7	66.7	66.7	33.3	66.7
FFA	1.0	1.0	1.0	1.0	0.5
CP	1430T	1719T	1190T	1766T	1424T
SP	212T	212T	212T	212T	147T
UR	0.14	0.09	0.20	-.02	0.15

TABLE 2 COMPARISON OF SCENARIOS AT TIME T = 100 YEARS

Parameters	Base Run	Policy 1	Policy 2	Policy 3	Policy 4
ICN	.10	.15	.10	.15	.10
DCN	.07	.07	.10	.07	.07
ULD	66.7	66.7	66.7	33.3	66.7
FFA	1.0	1.0	1.0	1.0	0.5
CP	1026T	1295T	798T	1754T	1013T
SP	216T	216T	216T	216T	216T
UR	0.20	0.16	0.23	0.08	0.20

industries, accomplished in the model by increasing industrial capacity initial value (ICN).

2. Housing Development Policy—represents a strategy (i.e., low-income housing programs of the 1960s) encouraging the construction of more housing, accomplished in the model by increasing dwelling construction initial value (DCN) (Figure 3, Equation 13.1).

3. Mixed Development Policy—represents a combination of increasing ICN as in the industrial development scenario while reducing useful lifetime of dwellings (ULD) to remove slum housing.

4. General Fund Policy—corresponds to using the highway fund for nonhighway purposes, a proposal that surfaces from time to time. Indeed, it has become commonplace to divert highway earning to transit subsidies. This policy is implemented through the parameter FFA in the model (Figure 7, Equation 34.2).

On the basis of the unemployment rate as a measure of effectiveness, development alternatives can be ranked from best to worst in this hypothetical case as follows: Policy 3, Policy 1, base policy, Policy 4, and Policy 2 (see Tables 1 and 2).

MODELING REGIONAL AND NATIONAL ECONOMIES

National development models should, ideally, be structured to accommodate three development orientations: (a) resource development, (b) regional development, and (c) sectoral development. Resource components include natural resources, land resources, water resources, and human resources (manpower). Regional development is organized on the basis of rural and urban. Sectors represented in the model are agriculture, manufacturing, business, infrastructure, and government. Obviously, the three orientations overlap and are also tied together by two quantities most responsible for material growth: (a) population, including the effects of all economic

and environmental factors that influence human birth, death, and migration rates; and (b) capital, including the means of producing industrial, service, and agricultural outputs.

Many of the sectors of a national or regional model can be thought of as elements in a national account that is concerned with measuring aggregate product originating within some geographical area to provide a picture of economic performance.

End results of economic activity are the production of goods and services and the distribution of those goods and services to members of society. The most comprehensive measure of national output is the gross national product (GNP), which is the value of all goods and services produced annually in the nation. Estimating GNP, however, is not merely adding up the value of all output because that would result in double counting. The value of any product is created by a large number of different industries with each firm buying materials or supplies from other firms, processing or transporting them, and thus adding to their value.

Four major components of GNP, each representing a final use of GNP, are consumption, investment, government purchases, and net exports. Investment refers to that portion of the final output that takes the form of additions to or replacements of capital. Government purchases of goods and services are a second component of GNP. In addition, government makes other expenditures in the form of transfer payments, which do not represent the purchase of output and consequently are excluded from GNP. Consumption refers to the portion of national output that is devoted to meeting consumer wants. Net exports (exports minus imports of goods and services) are a final use of GNP and must be included in the total. Three of the four major components (consumption, investment, and government purchases) can be grouped under the heading of gross domestic product (GDP). The GNP, then, is the sum of the GDP plus net exports.

For purposes of national income analysis, GNP statistics are subdivided into mutually exclusive, collectively exhaustive categories. The most commonly used scheme for subdivision

is based on the International Standard Industrial Classification (ISIC). The nine major ISIC categories are as follows:

Code	Classification and Description
1	Agriculture, hunting, forestry, and fishing
2	Mining and quarrying
3	Manufacturing
4	Electricity, gas, and water
5	Construction
6	Wholesale and retail trade, restaurants, and hotels
7	Transport, storage, and communication
8	Financing, insurance, real estate, and business services
9	Community, social, and personal services

Each of the nine ISIC economic output divisions is associated with a particular capital stock. In a typical model, the agriculture sector provides most of the output in the first ISIC division. Manufacturing capital stock provides the output in ISIC Divisions 2 and 3. Business capital in the model is associated with the activities listed under ISIC Divisions 6 and 8. The infrastructure sector, including transportation in the model, corresponds to ISIC Divisions 4 and 7, and the government services sector to ISIC Division 9.

Transportation-development interactions in a regional and national context are shown in causal diagram form in Figure 13. The causal processes tend to close on themselves forming feedback loops. Polarity of a feedback loop can be determined by counting the number of negative causal relationships—if odd, the loop is negative; if even, the loop is positive. Loop 1 is the economic growth loop and, being positive, would generate exponential growth if unchecked. Loop 2 provides this check and is the constraint on economic growth that is supplied by the environment. Loop 3 (GNP–FB–TII–TI–FIOT–FIOI–GNP) is the development loop induced by transportation investment and is positive.

Economic development and developments induced by transportation investments have been combined into a single second-order (having two state variables, IC and TI) loop (Figure 13, and simplified in Figure 14). This idealization of the transportation-development interaction is the transportation-development model. Analytical treatment of this model to obtain a solution is shown in Figure 15 with the following steps: (a) steady state analysis, (b) formation of the two first-order differential equations representing the two sectors, (c) formation of the second-order differential equation from the two first-order equations, (d) determination of the general solution to the second-order differential equations, and (e) evaluation of the constants in the general solution to obtain the final solutions of the two state variables IC and TI (Figure 15). Because GNP can be found from IC,

$$GNP_t = IC_t(1 - FIOI)/COR \qquad (3)$$

and because GNP and TI are both functions of time t, it follows that GNP and TI are functions of each other. In Figure 16, normalized versions of GNP and TI are plotted for various initial values of GNP_0 and TI_0 and for $t = 10$ years. Four cases are shown. Because the ratio GNP_0/GNP_e is the same for the four cases, the effect of transportation infrastructure on economic growth can be seen.

EVALUATION OF USER AND NONUSER BENEFITS

Until recently, the long chain of impacts of infrastructure improvements on socioeconomic systems could not be estimated except by contemplation, discussion, argument, and guesswork.
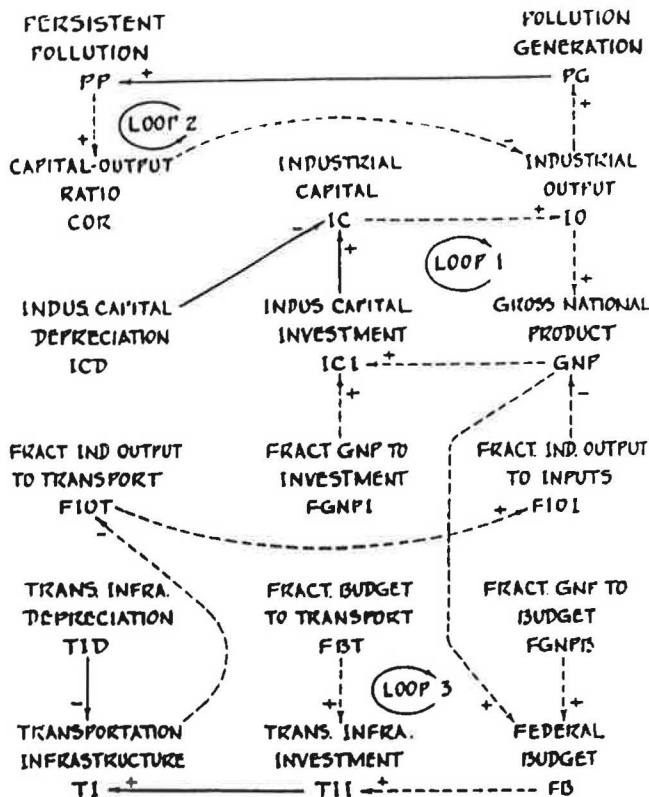
FIGURE 13 Transportation development interactions.
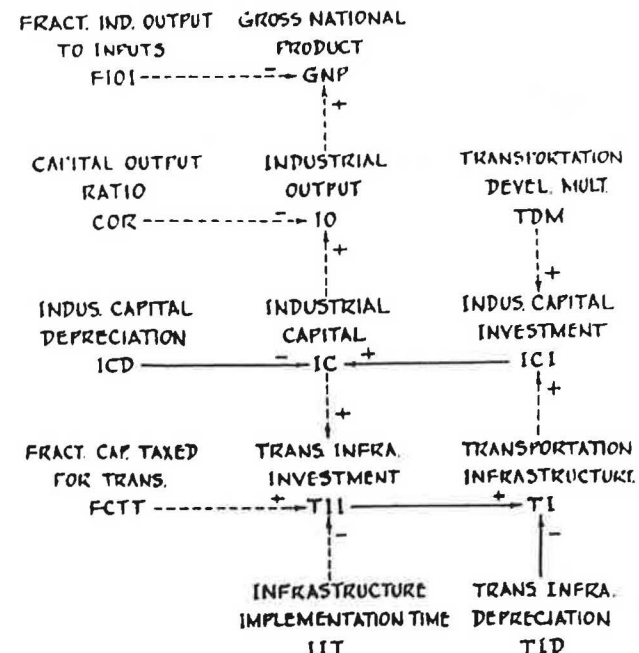
FIGURE 14 Transportation development model.

AT STEADY STATE EQUILIBRIUM, INVESTMENT IS
EQUAL TO DEPRECIATION IN BOTH SECTORS:

INDUSTRIAL SECTOR	TRANSPORTATION SECTOR
$ICI_e = ICD_e$	$TII_e = TID_e$
$TI_e \cdot TDM = ICD$	$IC_e \cdot FCTT/IIT = TID$
$TI_e = ICD/TDM$	$IC_e = (TID \cdot IIT)/FCTT$

THE DIFFERENTIAL EQUATIONS IN THE TWO SECTORS
CAN BE EXPRESSED AS FOLLOWS:

INDUSTRIAL SECTOR	TRANSPORTATION SECTOR
$\dfrac{dIC_t}{dt} = ICI_t - ICD_t$	$\dfrac{dTI_t}{dt} = TII_t - TID_t$
$= (TI_t - TI_e)(TDM)$	$= (IC_t - IC_e)(FCTT/IIT)$

THE SECOND ORDER SYSTEM CAN BE REPRESENTED
BY A SECOND ORDER DIFFERENTIAL EQUATION

$$\frac{d^2 IC_t}{dt^2} = (IC_t - IC_e)(\frac{TDM \cdot FCTT}{IIT})$$

WITH GENERAL SOLUTION

$$(IC_t - IC_e) = C_1 e^{\omega t} + C_2 e^{-\omega t} \qquad (3)$$

WHERE

$$\omega = \sqrt{\frac{TDM \cdot FCTT}{IIT}}$$

$$C_1 = ((IC_o - IC_e) + (TI_o - TI_e)(TDM/\omega))/2$$
$$C_2 = ((IC_o - IC_e) - (TI_o - TI_e)(TDM/\omega))/2$$

THE SOLUTION TO THE OTHER STATE VARIABLE IS

$$(TI_t - TI_e) = (\omega/TDM)(C_1 e^{\omega t} - C_2 e^{-\omega t}) \qquad (4)$$

FIGURE 15 Analytical solution of transportation development
model.
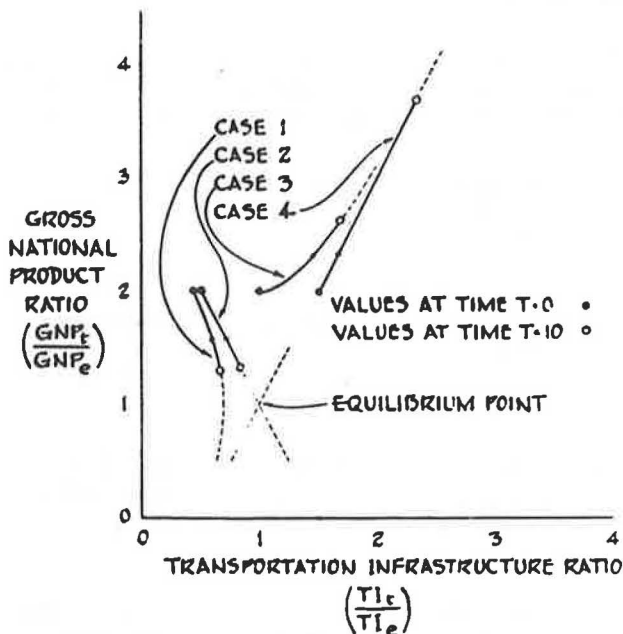
FIGURE 16 Transportation-induced development.

One way out of this present dilemma about transportation-
development problems is to sketch an approach that combines
the strengths of the human mind and the strengths of today's
computers. For example, in Figure 17, Link 32 is a congested
expressway, Link 21 is part of the Interstate system, and Node

A CLASSIC PROBLEM FACING STATE HIGHWAY DEPART-
MENTS IS WHETHER TO ADD LANES TO AN EXISTING CON-
GESTED HIGHWAY SERVING TWO CITIES OR BUILD A NEW,
MORE DIRECT HIGHWAY FACILITY BETWEEN THE TWO
LOCATIONS. THE DECISION TURNS ON THE EVALUATION OF
USER & NON-USER BENEFITS FOR THE TWO ALTERNATIVES.
CONSIDER THE HYPOTHETICAL APPLICATION OF THIS GENERIC
SITUATION DEPICTED BELOW.
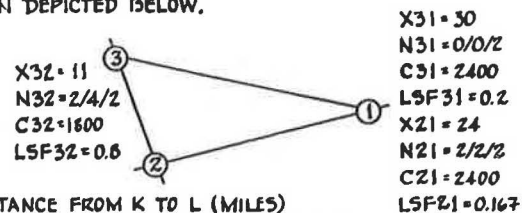
XKL = DISTANCE FROM K TO L (MILES)
NKL = NO. OF LANES FROM K TO L (EA. WAY)
CKL = LANE CAPACITY FROM K TO L (VPH)
LSFKL = LEVEL OF SERVICE FACTOR OVER KL $(0 \leq LSF \leq 1)$

URBAN AREA 3 HAS A POPULATION P & AN UNEMPLOY-
MENT RATE UR. IT IS LINKED TO THE REGIONAL HUB, NODE
1, BY AN EXPRESSWAY FROM 3 TO 2 & A SECTION OF INTER-
STATE HIGHWAY FROM 2 TO 1. THREE ALTERNATIVES ARE
BEING CONSIDERED:
  (1) DO NOTHING
  (2) EXPANSION OF LINK 32 BY INCREASING N32
  (3) CONSTRUCTION OF AN EXPRESSWAY FROM 3 TO 1

USING THE BENEFIT-COST RATIO CRITERION TO EVAL-
UATE HIGHWAY USER BENEFITS & USING THE MODEL THAT
YOU WILL HAVE DEVELOPED TO RELATE HIGHWAY VARIABLES
TO URBAN AREA 3 SOCIO-ECONOMIC VARIABLES TO EVALUATE
NON-USER BENEFITS, RANK THE 3 ALTERNATIVES.

FIGURE 17 Example: application of system dynamics to
evaluate the effect of transportation on development.

3 is an urban area with high unemployment. The solution
being contemplated is to improve accessibility from Node 3
to the regional hub, Node 1. Three alternatives have been
identified. The decision will be based on the evaluation of
user and nonuser benefits for the two improvement alterna-
tives. However, existing methodologies do not permit objec-
tive evaluation because they cannot measure socioeconomic
impacts (such as a reduction in the unemployment rate in this
example) that are the key to finding nonuser benefits. One
approach is to use system dynamics (shown in Figures 18–
20). Steps in finding user benefits for all traffic, including
induced and diverted traffic as well as through-traffic, include
the following:

1. Plot the demand function and the supply functions for
the three alternatives (see Figure 18).
2. Find the changes in annual user costs by finding the areas
under the curves shown in Figure 18.
3. Calculate the benefit-cost ratios for Alternatives 2 and
3 using the well-known benefit-cost expression

$$BC = \frac{R - E}{cr}(1 - e^{-rt}) \qquad (4)$$

where R is obtained from Step 2.

Steps in finding nonuser benefits (in this case the unem-
ployment rate for the urban area designated Node 3) includes
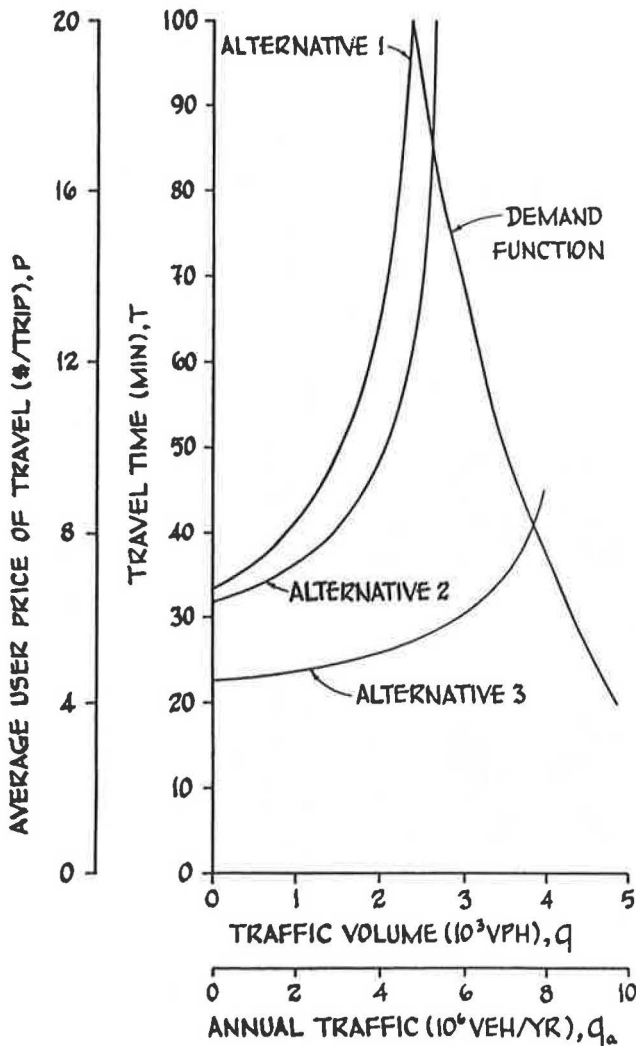the following:

FIGURE 18 Highway user cost-benefit relationships.

1. Extend the chain of causality from the decision variable NUMBER OF LANES (NKL) to the measure of effectiveness UNEMPLOYMENT RATE (UR) (see Figure 19).

2. Develop the mathematical model expressed in the DYNAMO language corresponding to the causal diagram in Step 1 (see Figure 20).

For the initial conditions given in this hypothetical example, a population in Urban Area 3 of 240,000, and basic industrial capital of $10 billion (see Figure 20 for PN = 240000 and BICN = 1.0.E 10), the results for a 25-year horizon or planning year are presented in Table 3. Although the cost-benefit ratio for Alternative 2 is greater than that for Alternative 3, the unemployment rate has been reduced more for Alternative 3. Thus, both user and nonuser benefits have been quantified as a first step to trading them off in reaching the final decision.

In system dynamics, it must be understood that development systems contain causally related variables; every variable depends on every other variable. The causal diagram in Figure 19 shows that the system dynamics model for this example problem contains four sectors: a population sector, an economic sector, an employment sector, and a transportation sector. Arrows and signs on the arrows describe causal hypotheses regarding pairs of variables. In the population sector, the state or level variable POPULATION (P) is affected by three rate variables: NET POPULATION GROWTH (NGP), IN MIGRATION (IM), and OUT MIGRATION (OM). The first two variables increase the state variable, whereas the third decreases it, explaining the signs on the arrows. Arrows are solid to denote accumulation or integration, as opposed to information or feedback, flows, which use dashed arrows. The relationship for POPULATION can be expressed in the following integral equation:

$$P_t = P_{t-1} + \int_{t-1}^{t} (NPG_t + IM_t - OM_t)dt \tag{5}$$

As a difference equation in DYNAMO language (as in Figure 30),

$$P.K = P.J + (DT)(NPG.JK + IM.JK - OM.JK) \tag{6}$$

A body of dynamic behavior and principles of structure is emerging that allows organizing and understanding the development process of a region or a whole nation. The basic building block is the feedback loop formed when two or more variables close on themselves. For example, a feedback loop is formed by POPULATION and NET POPULATION GROWTH because the latter also depends on the former. System dynamics is a methodology especially conceived to deal with feedback.

The entire transportation-induced development process is dominated by feedback because it features the synthesis of demand and supply functions. For the demand function, the transportation improvement required to accommodate a certain socioeconomic load is sought. For the supply function, the level of service obtained for a certain transportation improvement must be known. Because higher levels of service attract socioeconomic activity, the feedback loop is closed.

Within and between the development subsystems—population, economic, employment, and transportation in the example—the feedback continues. For example, in the economic sector in Figure 19 an increase in BASIC INDUSTRY CAPITAL increases BASIC INDUSTRY OUTPUT, which increases BASIC INDUSTRY PRODUCT, which increases BASIC INDUSTRY CAPITAL INVESTMENT, which adds to BASIC INDUSTRY CAPITAL, which increases BASIC INDUSTRY JOBS (in the employment sector), which adds to TOTAL NUMBER OF JOBS, which decreases UNEMPLOYMENT RATE. An improved level of service, as measured by decreased TRAVEL TIME, reduces the FRACTION OF INDUSTRIAL OUTPUT TO INPUTS, which increases BASIC INDUSTRY PRODUCT, which eventually reduces UNEMPLOYMENT RATE. But an improved level of service leads to increases in LAND ZONED FOR RESIDENTIAL in the suburbs, which increases urban area POPULATION, which increases LABOR FORCE and, therefore, UNEMPLOYMENT RATE. Although simple, the example shows why transportation-induced development is not a panacea. There are two causal streams from the decision variable TRAVEL TIME to the measure of effectiveness, UNEMPLOYMENT RATE, that tend to cancel each other.

FIGURE 19   Model of highway user and nonuser benefits.

```
                        POPULATION SECTOR
                        ****************
L P.K=P.J+(DT)(NPG.JK+IM.JK-OM.JK)
N P=PN
NOTE P-POPULATION(PERSON)
C PN=240000
NOTE PN-POPULATION AT TIME 0 (PERSONS)
R NPG.KL=P.K*NGF
NOTE NPG-NET POPULATION GROWTH (PERSONS/YR)
C NGF=.02
NOTE NGF-NET GROWTH FACTOR (1/YR)
R OM.KL=P.K*OMN
NOTE OM-OUT-MIGRATION (PERSONS/YR)
C OMN=0.08
NOTE OMN-OUT-MIGRATION NORMAL(1/YR)
R IM.KL=P.K*IMN*RLAM.K
NOTE IM-IN-MIGRATION (PERSONS/YR)
C IMN=0.10
NOTE IMN-IN-MIGRATION NORMAL (1/YR)
A RLAM.K=1-RLFO.K
NOTE RLAM-RESIDENTIAL LAND AVAILABILITY MULT (DIM)
A RLFO.K=P.K*LPD/(PPD*LZR.K)
NOTE RLFO-RESIDENTIAL LAND FRACTION OCCUPIED (DIM)
C LPD=0.5
NOTE LPD-LAND PER DWELLING (ACRES/UNIT)
C PPD=3
NOTE PPD-PERSONS PER DWELLING (PERSONS/UNIT)
A LZR.K=LZRN*(TN31/T31E)
NOTE LZR-LAND ZONED RESIDENTIAL (ACRES)
C LZRN=100000
NOTE LZRN-LAND ZONED RESIDENTIAL NORMAL (ACRES)
C TN31=100
NOTE TN31-TRAVEL TIME NORMAL(MIN)
NOTE
NOTE                     ECONOMIC SECTOR
NOTE                     ****************
L BIC.K=BIC.J+(DT)(BICI.JK-BICD.JK)
N BIC=BICN
NOTE BIC=BASIC INDUSTRY CAPITAL($)
C BICN=1.0E10
NOTE BICN-BASIC INDUS CAPITAL AT TIME 0 ($)
R BICI.KL=BIP.K*FIBI
NOTE BICI-BASIC INDUS CAPITAL INVESTMENT ($?YR)
C FIPI=0.2
NOTE FIPI-FRACT INDUS PRODUCT INVESTED (DIM)
A BIP.K=BIO.K*(1-FIOI.K)
NOTE BIP-BASIC INDUS PRODUCT ($/YR)
A FIOI.K=FIOIN*EXP(-(1.0-T31E/TN31))
C FIOIN=.7
NOTE FIOIN-FRACT INDUS OUTPUT TO INPUTS NORM (DIM)
C T31E=
NOTE T31E-TRAVEL TIME AT EQUILIBRIUM (MIN)
A BIO.K=BIC.K/COR.K
NOTE BIO-BASIC INDUSTRY OUTPUT ($/YR)
A COR.K=CORN*BIC.K/BICN


NOTE COR-CAPITAL OUTPUT RATIO(YR)
C CORN=1.8
NOTE CORN-CAPITAL OUTPUT RATIO NORMAL (YR)
R BICD.KL=BIC.K/ALC
NOTE BICD-BASIC INDUS CAPITAL DEPRECIATION ($/YR)
C ALC=30
NOTE ALC-AVERAGE LIFETIME CAPITAL (YR)
NOTE
NOTE                     EMPLOYMENT SECTOR
NOTE                     ******************
A BIJ.K=BIC.K/CLR.K
NOTE BIJ-BASIC INDUS JOBS (PERSONS)
A CLR.K=CLRN*SQRT(BICN/BIC.K)
NOTE CLR-CAPITAL LABOR RATIO ($/PERSON)
C CLRN=250000
NOTE CLRN-CAPITAL LABOR RATIO NORMAL ($/PERSON)
A BIW.K=BIP.K*FIPW
NOTE BIW-BASIC INDUS WAGES
C FIPW=0.6
NOTE FIPW-FRACT INDUS PROD TO WAGES (DIM)
```

FIGURE 20   (*continued on next page*)

```
A AWBI.K=BIW.K/BIJ.K
NOTE AWBI-AVER WAGE BASIC INDUS ($/PERSON)
A JBSI.K=BIJ.K*JM
NOTE JBSI-JOBS BUSIN SERVING IND (PERSONS)
C JM=0.7
NOTE JM-JOB MULTIPLIER (DIM)
A JHSI.K=P.K*JCPP
NOTE JHSI-JOBS HOUSEHOLD SERV IND (PERSON)
C JCPP=0.05
NOTE JCPP-JOBS CREATED PER PERSON (DIM)
A JOBS.K=BIJ.K+JBSI.K+JHSI.K
NOTE JOBS-TOTAL NO OF JOBS (PERSONS)
A UR.K=(LF.K-JOBS.K)/LF.K
NOTE UR-UNEMPLOYMENT RATE (DIM)
A LF.K=P.K*LPF
NOTE LF-LABOR FORCE (PERSONS)
C LPF=0.4
NOTE LPF-LABOR PARTICIPATION FRACTION (PERSONS/PERSON)
NOTE
NOTE                            TRANSPORTATION SECTOR
NOTE                            *********************
A TERM1.K=(ALT1+ALT2)*(((FFT32*(1-((1-LSF32)
X     *Q32.K)/(N32*C32)))/(1-Q32.K/(N32*C32)))
X     +(FFT21*(1-((1-LSF21)*Q21.K)/(N21*C21)))
X     /(1-Q21.K/(N21*C21)))
A TERM2.K=T2
A TERM3.K=(ALT3*FFT31*(1-((1-LSF31)*Q31.K)/(N31*C31)))/(1-Q31.K/
X     (N31*C31))
A TERM4.K=T1
A TERM5.K=T3
A T31.K=TERM1.K+TERM2.K+TERM3.K+TERM4.K+TERM5.K
NOTE T31-TRAVEL TIME FROM AREA 3 TO AREA 1 (MIN)
C ALT1=1
C ALT2=0
C ALT3=0
NOTE ALTX-ALTERNATIVE X
N FFT32=60*X32/60
N FFT21=60*X21/80


N FFT31=60*X31/80
NOTE FFTKL-FREE FLOW TRAVEL TIME ON LINE KL (MIN)
C LSF32=0.8
C LSF21=0.167
C LSF31=0.2
NOTE LSFKL-LEVEL OF SERVICE FACTOR ON LINK KL (DIM)
C N32=2
C N21=2
C N31=1E-50
NOTE NKL-NO. OF LANES PER DIRECTION ON LINK KL
C C32=1800
C C21=2400
C C31=2400
NOTE CKL-LANE CAPACITY ON LINK KL (VEH/HR)
A Q32.K=(FDTPH/ACO)*V31.K+Q32T
A Q21.K=(FDTPH/ACO)*V31.K+Q21T
A Q31.K=(FDTPH/ACO)*V31.K+Q31T
NOTE QKL-VOLUME ON LINK KL(VEH/HR)
C Q32T=600
C Q21T=1920
C Q31T=0
NOTE QKLT-THRU TRAFFIC ON LINK KL (VEH/HR)
C FDTPH=0.10
NOTE FDTPH-FRACT DAILY TRAFFIC IN PEAR HOUR (DIM)
C ACO=2
NOTE ACO-AVER. CAR OCCUPANCY (PERSONS/HR)
A V31.K=P.K*TGF


NOTE V31-DEMAND FROM AREA 3 TO AREA 1 (PERSONS/HR)
C T1=0
C T2=0
C T3=0
C TGF=0.2
NOTE TGF-TRIP GENERATION FACTOR
NOTE TK-COLLECTION,DISTRIBUTION,TRANSFER TIME AT NODE K (MIN)
C X32=11
C X21=24
C X31=30
NOTE XKL-DIST BETWEEN NODES K AND L (MILES)
```

FIGURE 20   (*continued*) Estimation of population,
transportation needs, and socioeconomic impact.

TABLE 3 TRANSPORTATION DEVELOPMENT EVALUATION METHODOLOGY RESULTS

USER BENEFIT ANALYSIS					NONUSER BENEFIT ANALYSIS ($t=25$)				
ALTER.	R	E	C	BC	P_t	LF_t	BIC_t	$JOBS_t$	UR_t
2	15 150 000	9 200 000	25 000 000	2.38	265 000	107 000	1.19×10^{10}	101 000	6%
3	73 455 000	18 000 000	250 000 000	2.22	383 000	154 000	1.59×10^{10}	155 000	0%

$$R_2 = \frac{(P_1 - P_2)(q_{a1} + q_{a2})}{2} = \frac{(20-17)(4\,800\,000 + 5\,300\,000)}{2} = 15\,150\,000$$

$$R_3 = \frac{(P_1 - P_3)(q_{a1} + q_{a3})}{2} = \frac{(20-8.2)(4\,800\,000 + 7\,650\,000)}{2} = 73\,455\,000$$

(SEE FIG 16)

$$BC_2 = \frac{R_2 - E_2}{C_2 \, r}(1 - e^{-rL}) = \frac{15\,150\,000 - 9\,200\,000}{25\,000\,000 \times .10}(1-0) = 2.38$$

$$BC_3 = \frac{R_3 - E_3}{C_3 \, r}(1 - e^{-rL}) = \frac{73\,455\,000 - 18\,000\,000}{250\,000\,000 \times .10}(1-0) = 2.22$$

$$UR_t = \frac{LF_t - JOBS_t}{LF_t} \times 100 \quad \text{WHERE} \quad LF_t = P_t \cdot LPF$$

$$JOBS_t = BIJ_t + JBSI_t + JHSI_t$$

$$BIJ_t = BIC_t / CLR \; ; \; JBSI_t = BIJ_t \cdot JM \; ; \; JHSI_t = P_t \cdot JCPP$$

(SEE FIG 30)

IT CAN ALSO BE SHOWN THAT

$$P_t = \frac{P_e}{1 + (\frac{P_e}{P_0} - 1)e^{-(IMN + NGF - OMN)t}} \quad \text{AND}$$

$$BIC_t = BIC_e - (BIC_e - BICN)e^{-t/ALC} \quad \text{WHERE}$$

$$P_e = (\frac{PPD}{LPD})(1 - \frac{OMN - NGF}{IMN})(LZRN \frac{TN3I}{T3IE})$$

$$BIC_e = ALC \cdot FIPI \cdot (\frac{BICN}{CORN})(1 - FIDIN \cdot e^{-(1 - \frac{T3IE}{TN3I})t}$$

In the mathematical model, parameter values have been chosen that support transport improvement to reduce unemployment (see Figure 20). Obviously, the modeling of transportation-induced development in the real world is serious business. The advantage of the system dynamics approach is the absence of the restrictions inherent in the many methodologies. Thus, the dichotomy that exists in a strategy of transport movement becomes explicit and must not be obscured by modeling limitations.

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