

Current and Future Land Use Models

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The urgency of the environmental debate has renewed the interest in the application of integrated models of urban land use and transportation. In the United States new legislation inspired by growing environmental awareness such as the Intermodal Surface Transportation Efficiency Act of 1991 requires that transportation planning must consider the interaction between transportation and land use in a consistent fashion – as it can be done only by land-use transportation models.

However, this new interest in land use models also presents new challenges to the land use modelling community. A new generation of activity-based travel models and new neighborhood-scale transportation planning policies require more detailed information on household demographics and employment characteristics and the location of activities. Moreover, the models need to be able to predict not only economic but also environmental impacts of land-use transportation policies. Today there exist several operational urban land-use transportation models which have the potential to respond to these challenges. At the same time there exist exciting opportunities to incorporate new theoretical developments and methodologies into the field.

The paper reviews the current state of the art of operational land-use transportation models using criteria such as comprehensiveness, overall structure, theoretical foundations, modeling techniques, dynamics, data requirements, calibration and validation, operationality and applicability and evaluates their suitability with respect to the new requirements and speculates about the most promising avenues to further improvement and diffusion of this kind of model.

Introduction

The idea that computer models of urban land use and transportation might contribute to more rational urban planning was born in the 1950s and culminated in the 1960s. The 'new tools for planning' (Harris 1965) were thought to be a major technological breakthrough that would revolutionize the practice of urban policy making. However, the diffusion of urban models faltered soon after the pioneering phase, for a variety of reasons (see Batty 1994; Harris 1994). The most fundamental probably was that these models were linked to the rational planning paradigm dominant in most Western countries at that time. They were perhaps the most ambitious expression of the desire to 'understand' as thoroughly as possible the intricate mechanisms of urban development, and by virtue of this understanding to forecast and control the future of cities (Lee 1973). Since then the attitude towards planning has departed from the ideal of synoptic rationalism and turned to a more modest, incrementalist interpretation of planning; that has at least co-determined the failure of many ambitious large-scale modeling project.

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However, today the urgency of the environmental debate has renewed the interest in integrated models of urban land use and transport. There is growing consensus that the negative environmental impacts of transportation cannot be reduced by transportation policies alone but that they have to be complemented by measures to reduce the need for mobility by promoting higher-density, mixed-use urban forms more suitable for public transport. In the United States new legislation inspired by growing environmental awareness such as the Intermodal Surface Transportation Efficiency Act of 1991 requires that transportation planning must consider the interaction between transportation and land use in a consistent fashion – as it can be done only by land-use transportation models.

However, this new interest in land use models also presents new challenges to the land use modelling community. A new generation of travel models such as activity-based travel demand models require more detailed information on household demographics and employment characteristics, and new neighborhood-scale transportation planning policies to promote the use of public transport, walking and cycling require more detailed information on the precise location of activities. In addition, the models need to be able to predict not only economic but also environmental impacts of land-use transportation policies, and this requires small area forecasts of emissions from stationary and mobile sources as well as of immissions in terms of affected population.

Today there exist several operational urban land-use transportation models which have the potential to respond to these challenges. There is a small but tightly knit network of urban modelers dispersed across four continents. There are a dozen or so operational urban/regional models of varying degrees of comprehensiveness and sophistication that have been and are being applied to real-life metropolitan regions for purposes of research and/or policy analysis. Rapid advances in information and computing technology have removed technical barriers besetting earlier generations of land-use transportation models. At the same time there exist exciting opportunities to incorporate new theoretical developments and methodologies into the field.

This paper reviews the current state of the art of operational land-use transportation models using criteria such as comprehensiveness, overall structure, theoretical foundations, modeling techniques, dynamics, data requirements, calibration and validation, operationality and applicability and evaluates their suitability with respect to the new requirements and speculates about the most promising avenues to further improvement and diffusion of this kind of model.

The Map of Urban Modeling

Before proceeding, it is necessary to define the type of model considered in this paper. The first distinction is that the term model is used here to indicate mathematical models implemented on a computer and designed to analyze and forecast the development of urban or regional land use systems. The second distinction is that the models must be comprehensive, i.e. they must integrate the most essential processes of spatial development; this implies that they must include at least urban land use, where land use denotes a range of land uses such as residential, industrial and commercial. This excludes partial models addressing only one subsystem such as housing or retail. It is essential that the links from transport to land use is considered in the models; transportation itself may be modelled either endogenously or by an exogenous transportation model. The models must be *operational* in the sense that they have been implemented, calibrated and used for policy analysis for at least one metropolitan region.

The number of real-world applications of models falling under the above definition has increased steadily over the last decade. There are more than twenty university laboratories, public agencies or private firms on four continents where research and development in urban and regional modeling is actively being conducted, and there are a dozen or so operational urban/regional models of varying comprehensiveness and sophistication that have been or are being applied to real-life metropolitan regions for research and/or policy analysis.

In this section the geographical distribution of contemporary urban modeling research all over the world is presented. Figure 1 shows the map of active urban/regional modeling centers in the late 1980s and early 1990s and the names of their principal researchers.



1	San Francisco	Landis, Prastacos
2	Urbana	Boyce, Kim, Rho
3	Chicago	Anas, Boyce
4	Buffalo	Anas, Batty
5	Cambridge, MA	Kain, Apgar
6	New York	Oppenheim
7	Philadelphia	Putman
8	Caracas	de la Barra
9	Santiago de Chile	Martinez
10	London	Mackett
11	Cambridge	Echenique, Williams
12	Stockholm	Lundqvist, Anderstig, Mattson
13	Dortmund	Wegener
14	Paris	Pumain
15	Turin	Bertuglia, Rabino
16	Seoul	Rho
17	Tokyo/Yokohama	Nakamura, Miyamoto
18	Nagoya/Gifu	Hayashi, Miyagi, Morisugi
19	Kyoto	Amano, Toda, Abe
20	Melbourne	Brotchie, Roy, Young

Figure 1. The map of active urban modeling centers.

The twenty centers in Figure 1 are numbered from west to east and are associated with the following individuals and modeling projects (more detailed information is contained in Wegener 1994):

1 *San Francisco*. The Bay Area is the home of the Projective Optimization Land Use Informations System (POLIS) of the San Francisco Region, developed for the Association for Bay Area Governments (Prastacos 1986) and of CUFM, the California Urban Futures Model (Landis 1992; 1993; 1994), a successor to the classic BASS (Goldner 1971), developed at the Institute of Urban and Regional Development of the University of California at Berkeley.

2 *Urbana*. At the Department of Civil Engineering of the University of Illinois at Urbana-Champaign nonlinear programming equilibrium models of transportation and location were developed by Boyce (Boyce et al. 1983; 1985; Boyce 1986) and Kim (1989) and Rho (Rho and Kim 1989).

3 *Chicago*. Chicago has been modeled by Anas at Northwestern University in the Chicago Area Transportation and Land-Use Analysis System CATLAS (Anas 1982; 1984) and for the Chicago Area Transportation Study (Anas 1983b; Anas and Duann 1985) and by Boyce at the Urban Transportation Center of the University of Illinois at Chicago (Boyce 1990; Boyce et al. 1992).

4 *Buffalo*. At the State University of New York at Buffalo Anas developed NYSIM, the New York Area Simulation Model (Anas 1992) and CPHMM, the Chicago Prototype Housing Market Model (Anas and Arnott 1991) and a new model, METROSIM, unifying the techniques and concepts of CATLAS, NYSIM and CPHMM. Also in Buffalo, at the National Center for Geographic Information and Analysis, Batty has developed interactive urban models in his research on geographical information systems (Batty 1992).

5 *Cambridge, MA*. HUDS, the Harvard Urban Development Simulation (Kain and Apgar 1985) was the first large-scale urban simulation model employing microsimulation techniques.

6 *New York*. Oppenheim of the City University of New York has produced several equilibrium activity-allocation models (Oppenheim 1986; 1988; 1989).

7 *Philadelphia*. Putman's adaptation of the Lowry modeling framework ITLUP (Integrated Transportation and Land Use Package) has been used for more actual agency policy applications than any other spatial model (Putman 1983; 1991).

8 *Caracas*. TRANUS (Transporte y Uso del Suelo) (de la Barra et al. 1984; de la Barra 1989) has been applied for Latin American cities and for modeling energy use of cities with Rickaby of the Open University of Milton Keynes, United Kingdom (Rickaby 1991).

9 *Santiago de Chile*. Martinez (1991; 1992a; 1992b) developed the '5-Stage Land-Use Transport Model' calibrated for Santiago de Chile.

10 *London*. Mackett at University College, London applied the Leeds Integrated Land-Use/Transport model (LILT) to several British and foreign cities (Mackett 1983; 1990c; 1991a; 1991b) and developed a microsimulation model for Leeds (Mackett 1990a; 1990b).

11 *Cambridge*. MEPLAN, the latest in a sequence of models built on multiregional input-output techniques is being applied to numerous urban regions in the world (Echenique et al. 1990; Hunt and Simmonds 1993; Echenique 1994; Williams 1994; Hunt 1994).

12 *Stockholm*. Stockholm has been the study area of TRANSLOC (Transport and Location) developed at the Royal Institute of Technology (Lundqvist 1978; 1979; 1989) and more recent models (Anderstig and Mattson 1991) as well as of other models reviewed in this paper (Anas et al. 1987; Boyce and Lundqvist 1987; Lundqvist et al. 1992).

13 *Dortmund*. At the Institute of Spatial Planning of the University of Dortmund (IRPUD), Wegener developed a model of the Dortmund region (Wegener 1985; 1986a; Wegener et al. 1991).

14 *Paris*. The Institut National d'Études Démographiques applies dynamic models in the tradition of Allen (Allen and Sanglier 1981) to French cities (Pumain et al. 1984).

15 *Turin*. The Polytechnic of Turin was the origin of a number of models of Piedmont and Rome (Lombardo and Rabino 1984) and of a large dynamic urban model still under development (Bertuglia et al. 1990).

16 *Seoul*. After his work with Kim in Urbana-Champaign, Rho has established an urban modeling group at Hanyang University in Seoul.

17 *Tokyo/Yokohama*. The group of Nakamura at the University of Tokyo implemented the Computer-Aided Land-Use Transport Analysis System (CALUTAS) for the Tokyo metropolitan area (Nakamura et al. 1983) and later spread to Yokohama, where Miyamoto developed the RURBAN model (Miyamoto et al. 1986, Miyamoto and Kitazume 1989).

18 *Nagoya/Gifu*. Hayashi at Nagoya University developed a land-use transportation model of Nagoya (Hayashi and Doi 1989; 1992) and a microsimulation model of residential mobility (Hayashi and Tomita 1989). Equilibrium models of transport and regional development have been developed by Miyagi (1989) and Morisugi et al. (1992) at Gifu University.

19 *Kyoto*. Kyoto University has been the origin of an urban model of Kyoto (Amano et al. 1987; 1988) and of a model for the Kanto Region, by Ando (1991).

20 *Melbourne*. The Commonwealth Scientific and Industrial Research Organization (CSIRO) generated the TOPAZ (Technique for Optimal Placement of Activities in Zones) model (Brotchie et al. 1980) and the modeling work of Roy (1992). At Monash University Young and colleagues developed the urban gaming simulation LAND (Gu et al. 1992; Young and Gu 1993).

Several of the above modelers were members of ISGLUTI, the International Study Group of Land Use Transport Interaction, which between 1980 and 1991 under the direction of Webster, Bly and Paulley of the United Kingdom Transport and Road Research Laboratory conducted the largest and most thorough comparative evaluation of large-scale urban models (Webster et al. 1988; Webster and Paulley 1990; Webster and Dasgupta 1991; Paulley and Webster 1991). Today, the role of ISGLUTI has been taken over by the Special Interest Group "Land Use and Transport" of the World Conference on Transport Research, and by smaller, more informal associations in Europe and Japan. Urban modeling has a firm place at conferences of the Regional Science Association, the Association of Collegiate Schools of Planning (ACSP), the Association of European Schools of Planning (AESOP), or more recently at the International Conferences on Computers in Urban Planning and Management. There has been a continuous reflection of purpose, direction and theoretical basis of land-use transportation modeling as witnessed by volumes edited by Hutchinson et al. (1985) and Hutchinson and Batty (1986) and by reviews by Harris (1985), Wegener (1986b; 1987), Kain (1987), Boyce (1988), Berechman and Small (1988), Aoyama (1989), and Batty (1994), Harris (1994) and Wegener (1994).

Model Comparison

This section attempts to assess the current state of the art in urban modeling. To do this, first a framework for the classification and evaluation of urban models is established. Then thirteen contemporary operational urban models are evaluated, using as criteria comprehensiveness, overall structure, theoretical foundations, modeling techniques, dynamics, data requirements, calibration and validation, operability and applicability. As the previous section, the section is an updated summary of more detailed information presented in Wegener (1994).

A Model of Urban Models

For the evaluation of operational urban models, an idealized urban model will first be sketched out as a benchmark by which the existing models can be classified and evaluated. Eight types of major urban subsystem are distinguished. They are ordered by the speed by which they change, from slow to fast processes (see Figure 2):

- Very slow change: networks, land use. Urban transportation, communications and utility networks are the most permanent elements of the physical structure of cities. Large infrastructure projects require a decade or more, and once in place, they are rarely abandoned. The land use distribution is equally stable; it changes only incrementally.
- Slow changes: workplaces, housing. Buildings have a life-span of up to one hundred years and take several years from planning to completion. Workplaces (non-residential buildings) such as factories, warehouses, shopping centers or offices, theaters or universities exist much longer than the firms or institutions that occupy them, just as housing exists longer than the households that live in it.
- Fast change: employment, population. Firms are established or closed down, expanded or relocated; this creates new jobs or makes workers redundant and so affects employment. Households are created, grow or decline and eventually are dissolved, and in each stage in their life-cycle adjust their housing consumption and location to their changing needs; this determines the distribution of population.
- Immediate change: goods transport, travel. The location of human activities in space gives rise to a demand for spatial interaction in the form of goods transport or travel. These interactions are the most volatile phenomena of spatial urban development; they adjust in minutes or hours to changes in congestion or fluctuations in demand.

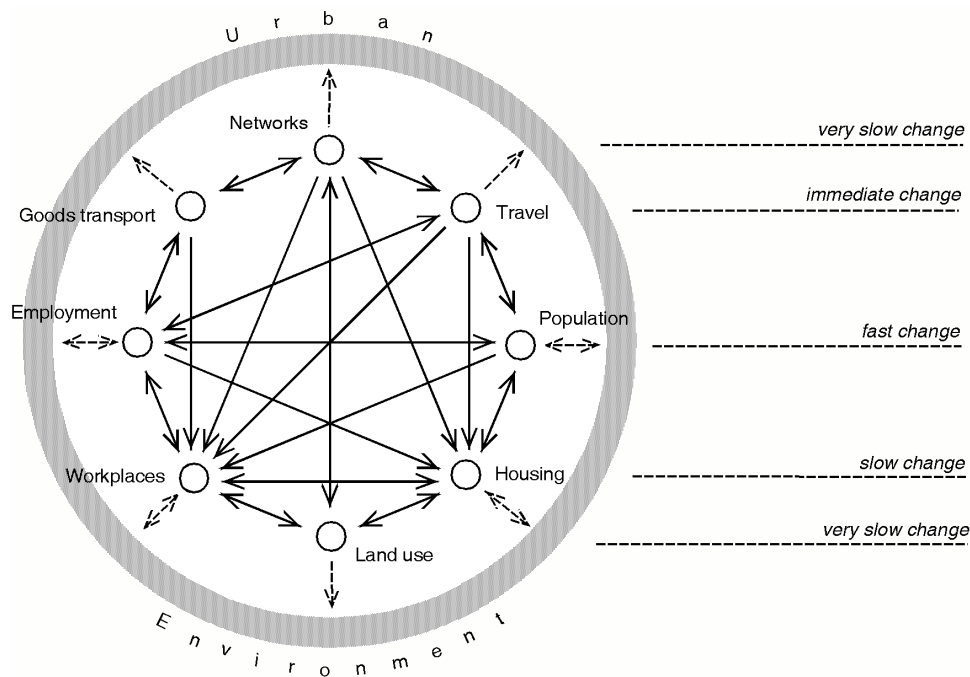


Figure 2. A model of urban models.

There is a ninth subsystem, the urban environment. Its temporal behavior is more complex. The direct impacts of human activities, such as transportation noise and air pollution are immediate; other effects such as water or soil contamination build up incrementally over time, and still others such as long-term climate effects are so slow that they are hardly observable. Figure 2 illustrates the main interactions of the eight subsystems and their multiple links with the urban environment. It can be seen, for instance, that the location of workplaces, i.e. non-residential buildings such as factories, warehouses, office buildings and shops depends on the location of other firms and of clients and workers, on access to goods transportation and travel by customers and employees, and on the availability of land, utilities and housing. All eight subsystems affect the environment by energy and space consumption, air pollution and noise emission, whereas locational choices of housing investors and households, firms and workers are co-determined by environmental quality, or lack of it. All nine subsystems are partly market-driven and partly subject to policy regulation.

Thirteen Urban Models

For the comparison, thirteen models were selected from the work at the twenty modeling centers described above. The selection does not imply a judgment on the quality of the models, but was based simply on the availability of information. These are the thirteen models:

- *POLIS*: the Projective Optimization Land Use Information System developed by Prastacos for the Association of Bay Area Governments (Prastacos 1986).
- *CUFM*: the California Urban Futures Model developed at the University of California at Berkeley (Landis 1992; 1993; 1994).
- *BOYCE*: the combined models of location and travel choice developed by Boyce (Boyce et al. 1983; 1985; Boyce 1986; Boyce et al. 1992).
- *KIM*: the nonlinear version of the urban equilibrium model developed by Kim (1989) and Rho and Kim (1989).
- *METROSIM*: the new microeconomic land-use transportation model by Anas.
- *ITLUP*: the Integrated Transportation and Land Use Package developed by Putman (1983; 1991).
- *HUDES*: the Harvard Urban Development Simulation developed by Kain and Apgar (1985).
- *TRANUS*: the transportation and land-use model developed by de la Barra (de la Barra et al. 1984; de la Barra 1989).
- *5-LUT*: the '5-Stage Land-Use Transport Model' developed by Martinez for Santiago de Chile (1991; 1992a; 1992b).
- *MEPLAN*: the integrated modeling package developed by Marcial Echenique & Partners (Echenique et al. 1990; Hunt and Simmonds 1993, Echenique 1994; Williams 1994; Hunt 1994).
- *LILT*: the Leeds Integrated Land-Use/Transport model developed by Mackett (1983; 1990c; 1991a; 1991b).
- *IRPUD*: the model of the Dortmund region developed by Wegener (1985; 1986a; Wegener et al. 1991).
- *RURBAN*: the Random-Utility URBAN model developed by Miyamoto (Miyamoto et al. 1986; Miyamoto and Kitazume 1989).

These thirteen models will be classified according to the following criteria: comprehensiveness, overall structure, theoretical foundations, modeling techniques, dynamics, data requirements, calibration and validation, operationality and applicability. Table 1 summarizes the comparison for the most important of these criteria.

Table 1. Summary of comparison of thirteen land use models.

Model	Subsystems modeled	Model theory	Policies modeled
<i>POLIS composite</i>	employment population housing land use travel	random utility locational surplus	land-use regulations transportation improvements
<i>CUFM composite</i>	population land use	location rule	land-use regulations environmental policies public facilities transportation improvements
<i>BOYCE unified</i>	employment population networks travel	random utility general equilibrium	transportation improvements
<i>KIM unified</i>	employment population networks goods transport travel	random utility bid-rent general equilibrium input-output	transportation improvements
<i>METROSIM unified</i>	all subsystems except goods transport	random utility bid-rent general equilibrium	transportation improvements travel-cost changes
<i>ITLUP composite</i>	employment population land use networks travel	random utility network equilibrium	land-use regulations transportation improvements
<i>HUDD composite</i>	employment population housing	bid-rent	housing programs
<i>TRANUS composite</i>	all subsystems	random utility bid-rent network equilibrium land-use equilibrium	land-use regulations transportation improvements transportation-cost changes
<i>5-LUT unified</i>	population networks housing	random utility bid-rent general equilibrium	transportation improvements
<i>LILT composite</i>	all subsystems except goods transport	random utility network equilibrium land-use equilibrium	land-use regulations transportation improvements travel-cost changes
<i>MEPLAN composite</i>	all subsystems	random utility network equilibrium land-use equilibrium	land-use regulations transportation improvements transportation-cost changes
<i>IRPUD composite</i>	all subsystems except goods transport	random utility network equilibrium land-use equilibrium	land-use regulations housing programs transportation improvements travel-cost changes
<i>RURBAN unified</i>	employment population housing land use	random utility bid-rent general equilibrium	land-use regulations transportation improvements

Comprehensiveness

All thirteen models are comprehensive in the sense that they address at least two of the eight subsystems identified in Figure 2 (the urban environment will be discussed later). Only TRANUS and MEPLAN encompass all eight subsystems. METROSIM, LILT and IRPUD address all subsystems except goods transport, KIM models goods movements but not physical stock and land use, HUDS has a housing supply submodel but does not model non-residential buildings. Half of the models make no distinction between activities (population and employment) and physical stock (housing and workplaces). Four models (POLIS, CUFM, HUDS and RURBAN) do not model transportation and hence rely on input from exogenous transportation models. Only HUDS, LILT and IRPUD model demographic change and household formation.

Model Structure

With respect to overall model structure, two groups can be distinguished. One group of models searches for a unifying principle for modeling and linking all subsystems; the others see the city as a hierarchical system of interconnected but structurally autonomous subsystems; The resulting model structure is either tightly integrated, "all of one kind", or consists of loosely coupled submodels, each of which has its own independent internal structure. The former type of model is called "unified", the latter "composite" (Wegener et al. 1986). Five of the thirteen models (BOYCE, KIM, METROSIM, 5-LUT and RURBAN) belong to the unified category, the remaining eight are composite. The distinction between unified and composite model designs has important implications for the modeling techniques applied and for the dynamic behavior of the models (see below).

Theory

In the last twenty years great advances in theories to explain spatial choice behavior and in techniques for calibrating spatial choice models have been made. Today there is a broad consensus about what constitutes a state-of-the-art land use model: Except for one (CUFM), all models rely on random utility or discrete choice theory to explain and forecast the behavior of actors such as investors, households, firms or travelers. Random utility models predict choices between alternatives as a function of attributes of the alternatives, subject to stochastic dispersion constraints that take account of unobserved attributes of the alternatives, differences in taste between the decision makers, or uncertainty or lack of information (Domencich and McFadden 1975). Anas (1983a) showed that the multinomial logit model resulting from random utility maximization is, at equal levels of aggregation, formally equivalent to the entropy-maximizing model proposed by Wilson (1967; 1970); he thus laid the foundation for the convergence and general acceptability of formerly separate strands of theory.

Underneath that uniformity, however, there are significant differences between the theoretical foundations of the models. Seven models (KIM, METROSIM, HUDS, TRANUS, 5-LUT, MEPLAN, RURBAN) represent the land (or floorspace or housing) market with endogenous prices and market clearing in each period; one (IRPUD) has endogenous land and housing prices with delayed price adjustment. These models are indebted to microeconomic theory, in particular to Alonso's (1964) theory of urban land markets or bid-rent theory. The six models without market equilibrium rely on random utility maximization; however, two of the microeconomic models (5-LUT and RURBAN) are hybrids between bid-rent and random utility theory. All models with transportation submodels use random utility or entropy theory for modeling destination and mode choice.

Only KIM and METROSIM determine a general equilibrium of transportation and location with endogenous prices. The other models are equilibrium models of transportation only (ITLUP, IRPUD), of transportation and activity location linked by delays (TRANUS, MEPLAN), or of transportation and location combined, but without endogenous prices (BOYCE, LILT). POLIS, CUFM, ITLUP and IRPUD apply concepts of locational surplus (POLIS), random utility (ITLUP, IRPUD) or profitability (CUFM) to locate activities. ITLUP may be brought to general equilibrium, but this is not normally done; METROSIM may produce a long-run equilibrium or converge to a steady state in annual increments.

Several other theoretical elements are built into some models. TRANUS and MEPLAN use export base theory to link population and non-basic employment to exogenous forecasts of export industries. HUDS, LILT and IRPUD apply standard probabilistic concepts of cohort survival analysis in their demographic and household formation submodels. IRPUD also utilizes ideas from time geography, such as time and money budgets, to determine action spaces of travelers in its transportation submodel.

Modeling Techniques

In all thirteen models, the urban region is represented as a set of discrete subareas or zones. Time is subdivided into discrete periods of between one and five years. This classifies them as recursive simulations.

In six models (BOYCE, KIM, TRANUS, LILT, MEPLAN, RURBAN), transportation and location are simultaneously determined in spatial-interaction location models, in which activities are located as destinations of trips; in the remaining models transportation influences location via accessibility indicators. In the nine models with network representation state-of-the-art modeling techniques are applied with network equilibrium the dominant trip assignment method despite its well-known weakness of collapsing to all-or-nothing assignment in the absence of congestion. Only ITLUP, TRANUS and MEPLAN have multiple-path assignment allowing for true route-choice dispersion.

For representing flows of goods, multiregional input-output methods are the standard method. KIM, TRANUS and MEPLAN use input-output coefficients or demand functions for determining intersectoral flows and random utility or entropy models for their spatial distribution. TRANUS and MEPLAN have generalized this to incorporate industries and households as consuming and producing "factors" resulting in goods movements or travel.

With the exception of CUFM and HUDS, all models are aggregate at a meso level, i.e. all results are given for medium-sized zones and for aggregates of households and industries. CUFM and HUDS are disaggregate, i.e. apply microsimulation techniques. HUDS works on a sample of individual households in list form, whereas CUFM uses detailed land information in map form generated by a geographical information system. IRPUD starts with aggregate data but uses microsimulation techniques in its housing market submodel.

Dynamics

Recursive simulation models are called quasi-dynamic because, although they model the development of a city over time, within one simulation period they are in fact cross-sectional. This is however only true for strictly unified models. Composite models consist of several interlinked submodels that are processed sequentially or iteratively once or several times during a simulation period. This makes composite models well suited for taking account of time lags or delays due to the complex superposition of slow and fast processes of urban development (cf. Wegener et al. 1986). However, this feature is insufficiently used by most models, because the typical simulation period of five years has the effect of an implicit time lag – a too long time lag in most cases.

Data Requirements

The data collection for a model of a large metropolis has remained a major effort. However, in many cases the introduction of computers in local government has generated a pool of routinely collected and updated data that can be used as the information base for a model, in particular in the fields of population, housing, land use and transportation. Another factor reducing the data-dependency of urban models is the significant progress made in urban theory in the last decades. The models of today are more parsimonious, i.e. can do with less data than previous models. Examples illustrating this are the techniques to generate regional input-output matrices from national input-output matrices and regional totals through biproportional scaling methods; or techniques to create artificial microdata as samples from multivariate aggregate data.

Calibration and Validation

All thirteen models of the sample have been (or could have been) calibrated using observed data, using readily available computer programs and following well-established methods and standards. In particular, maximum-likelihood estimation of the ubiquitous logit model has become routine. Yet, while calibration has become easier, the limits to calibrating a model with data of the past have become visible. Calibration of cross-sectional models, as it is practised today, provides the illusion of precision but does little to establish the credibility of models designed to look into the far future. There has been almost no progress in the methodology required to calibrate dynamic or quasi-dynamic models.

In the face of this dilemma, the insistence of some modelers on "estimating" every model equation appears almost an obsession. It would probably be more effective to concentrate instead on model validation, i.e. the comparison of model results with observed data over a longer period. In the future, the only real test of a model's performance should be its ability to forecast the essential dynamics of the modeled system over a past period at least as long as the forecasting period. There are only two models in the sample following this philosophy, MEPLAN and IRPUD. These models are partly calibrated not by statistical estimation, but by manual fine-tuning in a long, interactive process.

Operationality

All the models in the sample are operational in the sense that they have been applied to real cities. However, only few models are on their way to become standard software for a wider market. Among these, TRANUS stands out as a particularly advanced and well documented software with an attractive user interface in Spanish or English. The time seems not far when any planning office will be able to buy a complex and versatile urban model with full documentation, default values and test data sets for less than a thousand dollars.

Applicability

If one considers the enormous range of planning problems facing a typical metropolitan area in industrialized countries today, the spectrum of problems actually addressed with the thirteen urban models in the sample is very narrow. The majority of applications answer traditional questions such as how land use regulations or housing programs would affect land use development and transportation, or how transportation improvements or changes in travel costs would shift the distribution of activities in an urban area. These are and will continue to be important questions – questions that can only be answered with the models discussed here. However, other issues are likely to become prominent in the future, and it will be essential that the models are able to contribute to their rational discussion.

Future Land Use Models

The new interest in land-use models essentially originates in the imperative to make transportation more sustainable and to halt or even reverse the trend to ever longer travel distances and goods movements. It has now become commonplace that sustainable mobility cannot be achieved by transportation policy alone but that transportation planning has to be complemented land use policies to promote higher-density, mixed-use types of land use more suitable for public transport, walking and cycling. This makes the integration of land use and transportation planning a necessity.

Models that are to support this integrated land-use transportation planning process need to be more sophisticated than earlier models. State-of-the-art transportation models need to be able to model multimodal trip types such as park-and-ride, kiss-and-ride or bike-and-ride, semi-collective forms of travel such as car-pooling or more complex forms of journey such as multi-destination trip chains. Requirements such as these have led to the development of behavioral, activity-based, micro-analytic travel models and the ascendancy of stated-preference over revealed preference approaches. Land use models that are to interact with these new types of travel model need to have the requisite variety, i.e. a corresponding level of behavioral, spatial and temporal resolution. Activity-based travel models require more detailed information on household demographics and employment characteristics. Similarly, neighborhood-scale transportation policies to promote the use of public transport, walking and cycling require more detailed information on the precise location of activities. In addition, the land use models need to be able to predict not only economic but also environmental impacts of land-use transportation policies. This requires small area forecasts of emissions from stationary and mobile sources as well as of immissions in terms of affected population. The consequences of these requirements for future land use models will be discussed below.

Disaggregation

One conjecture is that future land use models will tend to become more disaggregate. The reasons for this are not only the need for higher behavioral, spatial and temporal resolution stated above, but also methodological reasons. Disaggregate models are easier to implement and calibrate (using stated preference techniques), more parsimonious in their data needs (because they can work with sample data or even synthetic micro data), more flexible with respect to testing new hypotheses or policies and easier to communicate to non-experts and decision makers. One further reason why land use models will tend to become more disaggregate is that geographic information systems (GIS) offer efficient ways to represent and manipulate spatially disaggregate data. There is an implicit affinity between microanalytic methods of spatial research and the spatial representation of point data in vector or raster GIS. Even where no micro data are available, GIS can be used to generate a probabilistic disaggregate spatial data base.

Disaggregate models are based on a decomposition of aggregate change into atomic subprocesses. A microanalytic theory of urban development therefore identifies these subprocesses and their structure. On a disaggregate level of explanation, urban development results from thousands or millions of human decisions, many small and some large, occurring over time as a broad stream of concurrent, unrelated or interrelated, individual or collective choices (Wegener 1986b). However, some processes are not decision-based but simply the result of time such as ageing and death. Figure 3 decomposes urban change into domains and atomistic process modules. Three types of modules are distinguished:

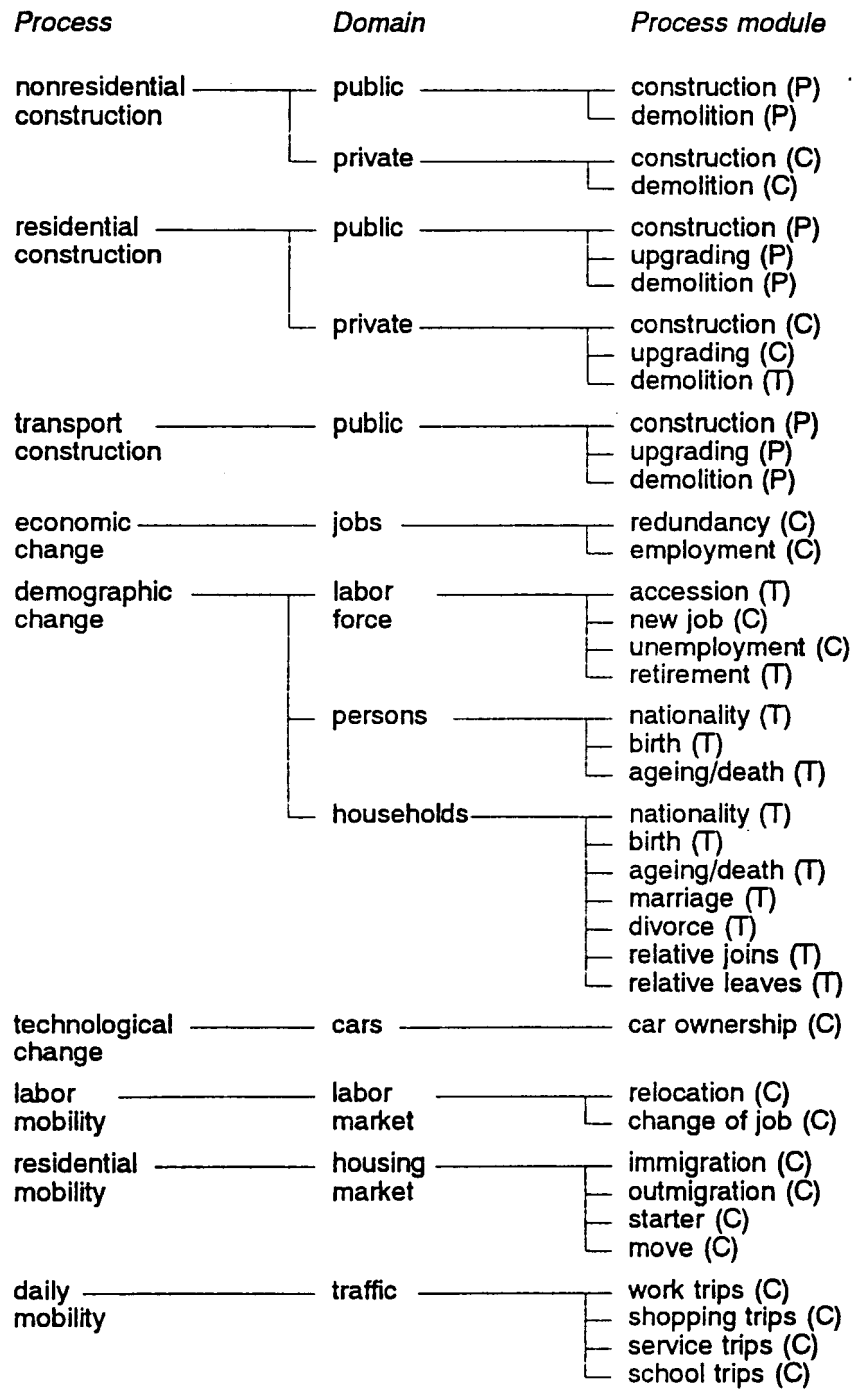


Figure 3. Process modules of urban change: choices (C), transitions (T), policies (P).

- Choices (C). A choice module represents a choice process. A typical choice module represents for instance the behaviour of a household looking for a dwelling in the housing market (Wegener 1985). Its propensity to move depends on its satisfaction with its present dwelling. It first chooses a neighbourhood in which to look for a dwelling, and this is not independent of its present residence and work place. The household then looks for a dwelling in that neighbourhood guided by the attractiveness and price of vacant dwellings there. Finally the household decides whether to accept an inspected dwelling or not. It accepts the dwelling if it can significantly improve its housing condition. If it declines, it enters another search phase.
- Transitions (T). A transition module represents a transition from one state to another. A typical transition for instance is the evolution of a household during a certain time interval during which it is promoted to another household category with respect to nationality, age, income or size conditional on the relevant probabilities for events such as naturalisation, birth of child, ageing/death, marriage, divorce, relative joins or leaves household (Wegener 1985). Note that also choice-based events such as marriage or divorce may be treated as transitions if the causal chain behind them is of no interest for the purpose of the model.
- Policies (P). Choice modules in which the decision maker is a public authority represent decisions by which the public authority intervenes in the process of urban development. Only policies resulting in physical change are indicated.

Most of the models in the sample are still aggregate, though to varying degree. HUDS is an pioneering early example of a consistently disaggregate model using a list-based data organisation. IRPUD in its present form is aggregate but changes into a disaggregate microsimulation in its housing market part. CUFM is highly disaggregate but emulates behaviour by decision rules, i.e. without modeling choice behavior. There are several experimental microsimulation models of urban land use and transport under development (Hayashi and Tomita 1989; Mackett 1990a; 1990b; Spiekermann and Wegener 1995).

Integration

A second prediction is that the formerly separate modeling traditions in transportation, land use and environmental forecasting are likely to converge. This is nothing new for land use modeling which from its beginning has been based on the paradigm of the proverbial 'land-use transportation feed back cycle', which states that land use and transportation interact in pattern of circular causation (Figure 4): The spatial distribution of activities creates the need for travel; trip patterns create accessibility; accessibility influences the locational choice of developers, households and firms; and this in turn determines the spatial distribution of activities.

The two-way interaction between land use and transportation may be less commonplace for transportation modelers who are trained to take the land use forecasts provided by planning departments as something beyond doubt. Now transportation planners, obliged to think about the land use impacts of their proposals, call for 'land use models' as add-ons to their trip generation, trip distribution, modal split and trip assignment models. Nothing could be more shortsighted. The land-use transportation feedback cycle needs to work its way through several iterations to equilibrium or dynamic disequilibrium. Land use modelers have responded to this need by incorporating transportation submodels into their models. These transportation submodels initially were rather crude but over time became no less sophisticated than their transportation-only counterparts. The conclusion is that if transportation planners want land use forecasts, they have to integrate land use models into their models, or vice versa.

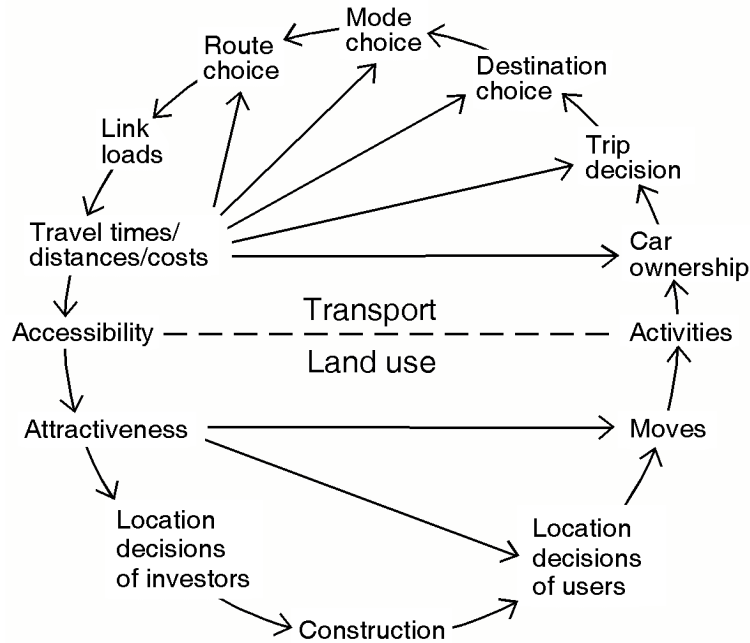


Figure 4. The 'land-use transportation feedback cycle'.

A similar argument applies to environmental modeling. Here, too, exists a cycle of circular causation. Land use and transportation both generate environmental effects which in return affect land use in the form of development constraints or locational factors and, to a lesser degree, also affect transportation. It is therefore not sufficient to append a set of routines calculating environmental indicators to a land use transportation model; the issue is to model the feedback from environment to land use and transportation. This need has now been recognized by the land use modeling community; what used to be called land-use transportation (LT) models is increasingly being termed land-use transportation environment (LTE) models.

Modeling the Urban Environment

Ecological modeling has been an established field of scientific work long before the present debate about environmental sustainability. Important pioneering insights into the nature of complex dynamic systems originated in ecology (Lotka 1920; Volterra 1931; see Nijkamp and Reggiani 1992). Urban modelers, have for a long time ignored ecological aspects in their models and have only recently been prompted to redirect their attention from economic to environmental impacts of land use and transportation policies. The main reason for this is the threat of long-term climate change due to production of greenhouse gases by the burning of fossil fuels for heating and transport. A major additional thrust to include environmental impacts into urban models will come from the United States Intermodal Surface Transportation Efficiency Act (ISTEA) which shifts the criteria for new transportation investment from travel time savings to environmental benefits such as air quality or reduction of single-occupancy vehicle trips. To demonstrate these benefits requires different models.

In this section, a first overview of some pioneering efforts towards such models will be presented. It is difficult to get an overview of the state of the art in this rapidly developing field. Therefore a quick, ad-hoc mini survey among some of the authors of the models reviewed in the first part of this paper was conducted, including two cases where models developed elsewhere are being

adapted to produce environmental indicators. Most of the work is unpublished. The survey is not a comprehensive inventory of urban/regional LTE models in the world today. It can be assumed that particularly in the United States under the impression of the ISTEA legislation numerous new modeling activities are being launched by local governments of all sizes. Table 2 summarizes the main results of the survey.

There are clear priorities. Of the 24 models or model applications included in the survey, thirteen calculate (or are considering to calculate) land consumption, as might be expected from land use models. Seventeen models calculate (or plan to calculate) energy consumption of transport. CO₂ emission of transportation is modeled by fourteen models, other air pollution by transport by twelve models. All other indicators are listed much less frequently. Energy consumption, CO₂ emission and air pollution of land use are considered by seven models each. Surprisingly, only five models calculate traffic noise. Only between one and five models deal with water supply, vegetation, wildlife, micro climate, waste water, soil contamination, solid waste and industrial noise. Immissions are almost absent in present LTE models. Only seven models consider air dispersion, one noise propagation and two surface and ground water flows.

Another question asked in the survey (not shown in the table) was whether the environmental indicators are calculated only as output for later exogenous evaluation, or whether they are fed back into the land use or transportation parts of the models. The purpose of the question was to find out whether there exist two-way relationships between land use and environment and transportation and environment, respectively, just as there is a two-way interdependency between land use and transport. The survey indicates that there is no such symmetry. In only nine of the 24 models environmental indicators enter the attractiveness functions of land use location decisions. In two models transportation decisions are affected by environmental indicators, mainly energy cost.

In summary, most present land use transportation models are still far from deserving the name land-use transportation environment models. Many environmental topics high on the list of controversial issues in contemporary cities have not been taken up by the models even though there exist suitable methods and data. In the majority of cases the environmental indicators calculated are not fed back into the models and so have no impact on the behavior of model actors. This is particularly surprising in the case of land use as it is well known that environmental quality has become a more and more important component of locational attractiveness not only for households but also for services and even for manufacturing. The little feedback from the environment to travel behavior, on the other hand, is realistic and reflects one of the main problems of planning for sustainability: that the negative impacts of the automotive society are felt by everybody but are not linked to individual behavior: it does not pay to behave environmentally. It is one of the key tasks of planning for sustainability to link the environmental indicators, through incentives and penalties, to the daily travel decisions of each individual. It is to be hoped that future urban LTE models will be able to model that kind of feedback.

Another problem encountered in the survey relates to dynamics. Most operational urban land-use transportation models have relatively long simulation periods of five or more years. Environmental processes, however, have different time scales. Some processes such as air dispersion and noise propagation are very rapid and can be dealt with in cross-sectional submodels. However, the impacts of development on water supply, vegetation, wildlife and water quality have long response times between several years and one or more generations. The problems arising from this for the temporal organization of the models may be fundamental. The longer time perspective necessary for environmental analysis is likely to make equilibrium approaches less appropriate and may favor dynamic approaches allowing for a variety of different speeds of adjustment in different parts of the modeled system.

Table 2. Environmental impacts modeled by urban LTE model.

Models (Authors)	Resources							Emissions							Immissions				
	Energy consumption by land use	Energy consumption by transport	Water supply	Land consumption	Vegetation	Wildlife	Micro climate	CO ₂ emission by land use	CO ₂ emission by transport	Air pollution by land use	Air pollution by transport	Water quality	Soil contamination	Solid waste	Industrial noise	Traffic noise	Air dispersion	Noise propagation	Surface/ground water flows
BOYCE (Boyce+)	○	○
ARCTAN-AIR (Kim+)	●	●	●	●	●	.	.
ITLUP (Putman)	.	.	.	●	a	.	a
PSS (Anjomani)	.	.	●	●	●	○	●
LET (Anjomani)	.	●	●	●	●	○	●
TRANUS (de la Barra+)	●	●	.	●	.	.	.	○	○	○	○	.	.	○	○
TRANUS/CUFM ^b	●	●	.	.	○	○	.	○	○	○	○	○	○
MUS (Martinez)	●	●	●	●	●	●	●	.	.
LILT (Mackett)	.	●	.	●
SATURN (Mackett+)	●	.	●	●	.	.
MASTER (Mackett)	.	.	.	●
MEPLAN London (ME&P)	.	●	.	●	●	.	●
MEPLAN Helsinki (ME&P)	.	●	.	●
MEPLAN Santiago (ME&P)	.	●	●	●	●	.	.	.	●	.	●
MEPLAN Vicenza (ME&P+)	●	●	.	●	●	.	.
START/DSCMOD ^c	.	●	●
CODMA (Lundqvist+)	●	.	●	.	.	.	●	.	●	.	.
SALOC (Lundqvist)	●	●	.	●
IRPUD I (Wegener)	.	●	.	●	●
IRPUD II (Wegener+)	○	○	.	○	○	○	○	○	○	○	○	.	.	.	○	.	○	○	.
RURBAN (Miyamoto)	○	○	.	○	.	○	○	○
MAPLE (Hayashi+)	.	●	●	●	○	.	○	.	.
SUSTAIN (Roy+)	.	○	.	●	○	○
LAND (Young, Gu)	●	.	.	.	●

· not modelled ○ under development or planned ● applied or operational

+ et al. a links to standard EPA emission models (MOBIL5)

b by de la Barra (TRANUS) and Landis (CUFM), adapted by Johnston at UC Davis

c by MVA, adapted by Simmonds, Cambridge, UK

Finally it must be noted that most existing land use models lack the spatial resolution necessary to represent environmental phenomena. In particular emission-immission algorithms such as air dispersion, noise propagation and surface and ground water flows, but also micro climate analysis, require a much higher spatial resolution than abstract zones in which the internal distribution of activities and land uses is not known: Air distribution models typically work with raster data of emission sources and topographic features such as elevation and surface characteristics such as green space, built-up area, high-rise buildings and the like. Noise propagation models require spatially disaggregate data on emission sources, topography and sound barriers such as dams, walls or buildings as well as the three-dimensional location of population. Surface and ground water flow models require spatially disaggregate data on river systems and geological information on ground water conditions. Micro climate analysis depends on small-scale mapping of green spaces and built-up areas and their features. In all four cases the information needed is configurational. This implies that not only the attributes of the components of the modeled system such as quantity or cost are of interest but also their physical location.

This suggests a fundamentally new organization of data of urban models. Geographic information systems, in particular raster-based GIS, promise to provide such organization and so will have great importance for future integrated urban models. The tendency from zonal to spatially disaggregate raster-based data structures suggested by environmental modeling is in line with the enormously increased memory and computing capacity of modern computers but conforms also well with the trend towards disaggregate activity-based models in urban transport planning referred to above.

Conclusions

This paper has been an attempt to review the current state of the art of operational land-use transportation models in the light of the new challenges presented by the environmental debate. It has been shown that there have been immense achievements in land use and transportation modeling during the last two decades. There exist a dozen or so operational land use and transportation models which have been and are being used for real-life applications in cities all over the world. There are at least twenty active urban modeling centers on five continents in which new approaches are being generated and tested. There is a worldwide network of urban modelers who meet regularly to exchange ideas and experiences.

However, the review has also exposed deficiencies and blind spots of current models and modeling practice. Many current land use transportation models are still too aggregate in substance, space and time to match the sophistication of contemporary activity-based travel demand models and to respond to the requirements in spatial resolution of neighborhood-scale spatial policies to promote public transport, cycling and walking as well as of state-of-the-art environmental modeling. Many models have remained captive in the tradition of economic equilibrium, which bears little resemblance with a world characterized by disequilibrium dynamics. Too much effort is still being spend on cross-sectional statistical estimation of parameters about which only one thing is certain, that they change; while too little attention is being given to methods for validating models against time-series data. Only few models to date deserve to be called land-use transportation environment (LTE) models, although efforts to incorporate environmental indicators into the models are increasing. However, only very few models have yet implemented feedback from the environment to land use and transportation.

These deficiencies suggest the agenda for modeling research in the next decade. Future land use and transportation models will need to be more disaggregate, more integrated and more responsive to environmental issues.

This may imply a new quantum leap in terms of disaggregation of variables – possibly down to the individual – and spatial and temporal resolution. Fortunately, likely further increases in memory and speed of computers and the growing availability of spatially disaggregate data will make this feasible, even though the number and magnitude of conceptual problems still to be solved may be immense. The association, or even integration, of land use transportation models with geographic information systems will become standard practice, although, given the lack of flexibility of current GIS to be linked with other software, this may be a sizeable research program in its own right.

A second field of research will have to be devoted to integrating the formerly separate traditions of transportation, land use and environmental models. Transportation models will have to be embedded into land use models (or vice versa) and environmental models into land use transportation models. The current practice of feeding land-use and transportation indicators off-line into exogenous environmental models will only be an interim solution as it negates feedback from environment to land use and transport. This also disqualifies feeding transport indicators into separate 'land use models'. The future urban/regional model will be an integrated land-use transportation environment (LTE) model.

A third major task is to select environmental submodels suitable for integration into land use and transportation models and adapt them to the new framework. Environmental submodels without doubt will further increase the data requirements of land use transportation models, so careful consideration of what is essential is needed. For many standard indicators public-domain software routines ready to be interfaced with land use transportation models might be provided by public agencies in order to avoid duplication of effort and to guarantee consistency and comparability of the indicators derived.

Other research needs apply to the way models are used and embedded into the decision making process. One important field of research will have to address problems of evaluation of policy impacts and issues of equity. Predominantly economic evaluation techniques such as CBA need to be complemented by multicriteria methods capable of measuring non-monetary aspects of mobility and neighborhood and environmental quality and their distribution across privileged and disadvantaged socioeconomic and spatial groups. The feasibility of such disaggregate evaluation will be greatly enhanced by the availability of disaggregate land use and population data required by activity-based transportation models.

Finally, more efforts will be necessary to make land use transportation environment models a routine tool by a widening range of institutions and individuals, including non-experts. This must be supported by the development of attractive and efficient user interfaces for interactive manipulation of inputs and inspection of results. The Windows-based user shell of TRANUS, Young's gaming simulation LAND (Gu et al. 1992) and Batty's model visualization system (Batty 1992) are leading the way in this direction.

The greatest challenge, however, seems to keep urban modeling open for new problems. Urban models have in the past been applied mainly to a very narrow set of planning problems, and have repeatedly failed to adapt to changing problem perceptions. The next decade will confront cities and regions in the developed world with complex new problems. Increasing social and spatial inequity, an aging infrastructure and the need to significantly reduce energy consumption and CO₂ emission will require innovative solutions if social conflict is to be avoided. Only if the models prove that they are able to give meaningful answers to the urgent questions facing cities and regions can they establish for themselves a firm position in the planning process of the future.

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