MODELS OF TRANSPORTATION AND LAND USE CHANGE: A GUIDE TO THE TERRITORY

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ABSTRACT

Modern urban regions are highly complex entities. Despite the difficulty of modeling every relevant aspect of an urban region, researchers have produced a rich variety models dealing with inter-related processes of urban change. The most popular types of models have been those dealing with the relationship between transportation network growth and changes in land use and the location of economic activity, embodied in the concept of accessibility. This paper reviews some of the more common frameworks for modeling transportation and land use change, illustrating each with some examples of operational models that have been applied to real-world settings.

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INTRODUCTION

Models are the basic tool of analysis for planners working in the fields of transportation and land use forecasting. Current practice in these fields generally accepts the notion of some type of reciprocal relationship between transportation and land use. For more than four decades now, urban researchers have sought to formalize this relationship using mathematical, statistical and logical methods, and to produce models capable of predicting changes to transportation and land use systems as the result of policy measures.

This paper reviews some of the important theoretical frameworks adopted by researchers to represent the complex relationship between transportation and land use. Each framework has guided the development of a number of different operational models, that is, models that have been applied using data from real-world metropolitan regions. Several of these models are described in some detail to illustrate how each modeling framework is used to represent the processes of urban change[1]. Before turning to the models however, some background is provided on the transportation-land use relationship and the chronological development of transportation and land use modeling.

The first two modeling frameworks to be discussed are those based on aggregate models of spatial interaction and random utility theory. These two modeling frameworks provide the vast majority of current operational models that are used in planning practice. We might refer to these first two frameworks as “top-down” modeling frameworks, since they specify the interaction between transportation networks and location as a set of aggregate relationships based on the behavior of a representative individual, usually the mean calculated from a representative sample of the population. The third class of models to be introduced falls under the general category of microsimulation models. These models cover a number of different approaches to representing the dynamics of land use change and travel behavior, but generally share the common focus of attempting to disaggregate the population and to simulate changes from the "bottom up", redefining the nature of actors in the model. Models of activity-based travel are discussed here, along with multiagent models and cell-based models, a special type of multiagent model that offers an alternative mechanism for representing the dynamics of land use change. Some examples of prototype urban models that are being developed entirely within a microsimulation framework are described.

The later sections of the paper review some of the common criticisms directed toward land use and transportation models and note how these criticisms have (or have not) been addressed in the most recent generation of models. Some outstanding issues are discussed and suggestions offered as to important future research directions. A concluding section follows with some general remarks on the state of transportation and land use modeling and its relationship to planning as a discipline.

THE TRANSPORTATION-LAND USE RELATIONSHIP

Transportation networks and the spatial patterns of land use they serve are assumed to mutually influence each other over time. Changes to transportation networks, such as the construction of a new link or expansion of an existing one, eventually influence the location of investment in land, which in turn influences the demand for travel to and from a particular location. This relationship is sometimes referred to as the transportation-land use "link" or "cycle", emphasizing a feedback relationship (Kelly 1994). The mediating factor in determining changes in the location of activities and the demand for travel is *accessibility*, which measures the situation of a location relative to other activities or opportunities (work, shopping, etc.) distributed in space. Changes in relative accessibility are measured indirectly when researchers attempt to identify the influence of new infrastructure, such as a highway link or transit station, on local land markets. In these cases, accessibility is usually approximated by some measure of access to the transportation network, such as travel time or distance (Ryan 1999). Generally, the degree of land market impact is related to the impact of the new transportation link on regional accessibility, and so is roughly proportional to the increase in speeds (and reduction in travel time) permitted by the new link (Cervero 1984).

In order to operationalize the transportation-land use relationship within models of transportation and land use, measures of accessibility are incorporated in determining the location of activities. It is typically assumed that households wish to locate in areas with higher accessibilities to opportunities such as employment or shopping, while firms are assumed to locate in areas with higher accessibility to labor markets, perhaps stratified by occupational type. In models where land and floor space markets are considered explicitly, these accessibility factors can be important determinants of price. Since most models of transportation and land use contain a land use component that is integrated with, or at least loosely coupled with, a travel demand model containing a network assignment component, congested network travel times can be fed into the calculation of accessibility, thus providing a measure of the impact of congestion on regional accessibility and activity location.

In order to simulate these changes within models of metropolitan regions, the region is typically broken down into a set of small geographic zones, similar (or in many cases identical) to the set of zones used for regional travel forecasting. Accessibility is typically calculated from each zone to all other zones in the region via the regional transportation network. Changes to the travel network that alter zone-to-zone travel times thus impact the relative accessibility of a location.

CHRONOLOGY OF MODEL DEVELOPMENT

The history of simulation models of transportation and land use is dated back to the late 1950s (Batty 1979). While models of regional travel demand had been established as far back as the early 1950s and some early experiments with transportation and land use models were carried out in the following years, it wasn't until the early 1960s that the first operational land use simulation model was built. The 'Model of Metropolis' developed by Lowry (1964) is widely considered to be the first operational simulation model of urban land use. Lowry's model was the first of a generation of models based on theories of spatial interaction, including the gravity model that was popular in quantitative geography at the time. Models based on a spatial interaction framework continued to be developed through the early to mid-1980s, when they became largely replaced by models grounded in random utility theory and econometric methods of discrete choice.

Figure 1 (insert here) describes this process and gives an approximate timeline for the adoption of various modeling frameworks within transportation and land use research. Several of the models that follow a random utility framework continue to be used today, although some, like the UrbanSim simulation system (Waddell 2002; Waddell et al. 2003) are being redeveloped within a microsimulation design. The broad class of transportation and land use models that could fall under the title of 'microsimulation' began to be developed in the early 1990s, in parallel with major improvements in computational power that allowed for their operation. These included prototype models of activity-based travel, cell-based models land use change and the introduction of multi-agent models for urban simulation. More recently, some researchers have begun to devote effort to developing comprehensive urban microsimulation models that fully reflect the dynamics of changes in the population and the urban environment within which they make choices.

SPATIAL INTERACTION MODELS

The earliest class of land use and transportation simulation models are a set of highly aggregate models based on principles of spatial interaction that were popular in the regional science and quantitative geography fields in the 1950s and 1960s. There were many different formulations of this type of model, though most revolved around variations of the gravity model, an adaptation from Newtonian physics. The derivation of the gravity model from principles of entropy maximization (Wilson 1967, 1970) was a major accomplishment and formed the basis for many of the allocation mechanisms within spatial interaction models. A general form of the gravity model can be expressed as:

$$T_{ij} = A_i B_j O_i D_j \exp(-\beta c_{ij})$$

where T_{ij} represents trips (or other measures of interaction) between two zones, O_i represents origins at zone i, D_j represents destinations to zone j, and A_i and B_j are balancing factors to ensure that total origins equal total destinations. The exponential term in the model is used to capture the effect of decreasing interaction as a function of travel cost, including travel time.

As mentioned previously, the first operational land use simulation model was the model developed by Lowry (1964) for the Pittsburgh region. This model has great importance, since many of the other land use and transportation models that follow a spatial interaction framework have similar structures. A detailed review of this model and its variations are provided in Horowitz (2004).

The Lowry Model and Derivatives

The land use model developed by Lowry was a spatial interaction model designed to simulate patterns of residential and service location in the Pittsburgh, Pennsylvania region. The impetus for building the model was to be able to simulate the effects of urban renewal and slum clearance programs on the distribution of activities within the region. The model borrowed from economic base theory, which divides a region's employment into basic and non-basic services. Basic industries are assumed to export much of their product outside the region, generating additional income which can then support additional non-basic services. Non-basic industries then serve households (e.g. retail activities) and other industries within the region.

Lowry's model assumed that the location of basic industries were fixed. This required an initial allocation of basic employment to zones within the region. Households were then allocated to zones *from* the initial basic employment locations, using a function similar to the deterrence function used in the trip distribution step of most trip-based travel forecasting models (Horowitz 2004):

$$f(t_{ij}) = \exp(-\beta t_{ij})$$

where $f(t_{ij})$ is a deterrence function value representing the likelihood of workers working in zone i and living in zone j, and t_{ij} is a measure of the disutility of travel between zones. This functional form implicitly assumes that workers choose to locate near their workplace and that only one household member is employed outside the home. Lowry chose to define this measure of disutility as the airline distance between zones. He did this partially because of the difficulty of generating matrices of trips between zones using the travel models that existed at the time, but also because he noted a high degree of correlation between observed airline and network distances in his study region (Lowry 1964). Using the deterrence function described above, $f(t_{ij})$, the number of workers working in zone i and living in zone j (defined here as T_{ij}) could be calculated by using a modified expression that included a value of attractiveness for each residential zone (w_j):

$$T_{ij} = \frac{e_i w_j f(t_{ij})}{\sum_j w_j f(t_{ij})}$$

where e_i is the employment in zone i. The residential attractiveness measure as used in this formulation simply relates to the amount of land available for residential development in a particular zone. Deleting the variable for zonal employment in the above expression yields an expression for the probability of residing in a zone given a fixed workplace location that is very similar to the probability expression in the multinomial logit model. This relationship is important, since it is used extensively in transportation and land use models that derive from random utility theory, as will be discussed in the next section.

The process of worker/household allocation is followed by a similar process in which the locations of non-basic industries serving households and other (basic) industries are allocated assuming fixed locations for these quantities. Once these activities have been allocated, it is possible to couple the land use model with a conventional, trip-based travel forecasting model to produce a set of network flows. These new flows and travel times can be used to modify the deterrence function and produce a new allocation of households and non-basic employment.

Several models extended the basic Lowry framework in new directions. Table 1 (insert about here) lists some of these models along with their distinguishing features. For example, the

Time Oriented Metropolitan Model (TOMM) described by Crecine (1964) disaggregated the population into socio-economic groups in order to improve the model's representation. It also differed from the Lowry model in that only some of the non-basic activities in a region would be reallocated between model iterations, reflecting a certain degree of inertia in location. Garin (1966) recast the original Lowry model by proposing a matrix representation for the model's components and substituting a production-constrained, gravity-type interaction model as the basis for allocation. Garin's version also allocated all activities at each iteration, an improvement over Lowry's formulation since it improved the coupling between allocation and generation (Timmermans 2003). Another land use model designed by Goldner (1971) allocated activities according to an intervening opportunity model, a special case of the gravity model (Wilson 1971). The design of the model also sought to improve realism by using different dispersion parameters for each of the nine counties of the San Francisco Bay area, where is was calibrated and tested.

ITLUP/METROPILUS

Building on the Lowry-Garin framework, Putman (1974, 1983) developed the Integrated Transportation and Land Use Package (ITLUP), widely considered to be the first fully operational transportation-land use modeling software package. ITLUP has been applied in over a dozen locations within the U.S., and has been calibrated over 40 times (Hunt et al. 2005). Designed in the mold of the Lowry model, ITLUP initially contained a land use model that was similar to Goldner's PLUM model. ITLUP offered a network representation that allowed for the incorporation of congested travel times in the distribution of activities. At the core of ITLUP were two allocation submodels: a household allocation submodel called DRAM, and an employment allocation submodel, EMPAL. Trip generation and distribution functions for the travel forecasting model are developed within DRAM, simultaneously with household location, while mode choice and trip assignment are handled with separate submodels. Travel times from runs of the travel model are fed forward to calculate new activity distributions.

More recently, the ITLUP model framework has been updated to incorporate modifications to some of its submodels and new data and visualization tools (Putman 2001). The new package, called METROPILUS, is housed within a geographic information system (GIS) environment that permits improved visualization of output. Other important features of METROPILUS include multivariate, multiparametric attractiveness functions that include lag terms to better capture location dynamics. The addition of zonal constraints can limit allocation of activities to zones where land is not available. Land supply in the model is managed by a land supply function that translates the location demands from employers and households from DRAM and EMPAL into land uses and intensities.

LILT and IRPUD

Two other spatial interaction-based models merit attention, since they have been extensively applied and tested. The first is the Leeds Integrated Land Use (LILT) model, developed by Mackett (1983, 1991). LILT combines a Lowry-type land use model with a conventional, four-step travel model. Forecasts of change in population are allocated to zones according to accessibility functions derived from work trips and zonal attractiveness functions. Other salient features of LILT include the ability to handle demolition, changing occupancy rates and vacancies, and a car ownership submodel, which estimates vehicle ownership as a function of network travel times and costs (Timmermans 2003).

The IRPUD model (Wegener 1982) was developed by Wegener and colleagues at the University of Dortmund in Germany. IRPUD is quite complex and contains seven interlinked submodels of aging, firm relocation, residential and non-residential construction, rehabilitation and demolition, change of job, change of residence and car ownership/travel demand. IRPUD is somewhat unusual in that it contains a microsimulation model of land use, in which land uses are allowed to change through aging. Another desirable feature of IRPUD's design is that it allows different submodels to take place at different spatial scales (intra-regional location takes places at a meso-scopic scale, while land development takes places at a micro/tract level). These features are emulated in some of the newer, emerging urban microsimulation models. As a practical matter, the IRPUD model can be classified along with other spatial interaction models, since it uses gravity models to allocate the distribution of land use.

The first generation of land use and integrated transportation and land use models based on spatial interaction formulations produced a multitude of models that were tested and applied in numerous settings. Some models, such as the METROPILUS planning support system package, continue the legacy of these models to the present. However, very few examples of this type of model framework remain. The shortcomings of these models were numerous: most were static equilibrium models incapable of capturing the dynamics of urban systems, none of models actually represented land markets with explicit prices, zones were highly aggregate and lacked spatial detail, and the models were inadequately supported by theory. Inadequate theory may have also been a reason that many of the models forecasted so poorly. There were many high-profile failures in terms of using the models for policy analysis purposes (Batty 1979). Some of these were seized upon by Lee (1973) in a critique which highlighted some of mistakes of the first generation of models. Lee characterized them as being too complicated, overly aggregate, data hungry, wrongheaded, extraordinarily complicated, too mechanical and expensive. Many of these criticisms informed the next generation of models, which took their cue from developments in econometric modeling based on random utility theory.

RANDOM UTILITY/DISCRETE CHOICE MODELS

As noted previously, one of the major shortcomings of the aggregate spatial interaction models was the absence or use of inappropriate theory to describe the behavior captured in the model. Developments in the use of random utility theory to describe choices among discrete alternatives, such as the choice of travel mode, provided the impetus for a new generation of models based on the study of disaggregate behavior. When it was shown that discrete choice models could be applied to problems such as residential location (Lerman 1976; McFadden 1978), researchers began to look for ways to model the interrelated choices individuals made in terms of location and travel behavior.

Land use and transportation models that follow random utility frameworks can be thought of as comprising two types of models: regional economic models and land market models. In these two types of simulation models the economic model and the land market model each form the core of a simulation system that includes the prediction of transportation flows. Both types tend to have improved representation of land markets that include endogenously-determined (determined within the model) prices and market clearing mechanisms. A summary of these models and their characteristics are provided in Table 2 (insert about here).

Regional Economic Models

Two of the most important and widely-used transportation and land use models grounded in random utility theory, MEPLAN and TRANUS, are largely built around a core of a regional economic model. MEPLAN (Echenique et al. 1990; Echenique 2004) is a model that began as a more simple model of urban stock and activity (Echenique et al. 1969) and expanded into a more comprehensive urban simulation model. Similar to other types of models, MEPLAN has a zone-based structure. In contrast to spatial interaction models though, the activities in zones are determined by a spatial input-output model which predicts trade flows by sector between zones of a region, driving the demand for space. Production and consumption are linked in the spatial input-output model, replacing the trip generation and distribution steps in trip-based travel forecasting models. The trade flows are converted to demand for commercial and passenger traffic through the application of scaling constants. The generated traffic is then fed into models of mode and route choice. Congestion and travel times from the transportation model are then fed back into the land use and economic model, yielding time-lagged measures of accessibility, which affect location choice. The structure of MEPLAN, including its spatial economic model, make it appropriate for modeling not only at an *intraurban* scale but also at an *interurban* scale. It has been used in a variety of major applications, including modeling the regional impacts of the Channel Tunnel between England and France (Rohr and Williams 1994).

The TRANUS model (de la Barra 1989) is similar to MEPLAN in that it incorporates a spatial input-output model as the basis of its generation and allocation of activities. The regional economy is disaggregated into sectors, with the demand for each zone and sector generated and then allocated to production zones and sectors via a multinomial logit model. A land supply model is also available to simulate the behavior of developers, who choose where to build (new land vs. existing sites), what type of space to build, and at what density. This choice process is governed by explicit prices or rents for new or replacement stock, demolition and building costs. Another unique feature of TRANUS is its relatively advanced trip-based travel forecasting model. Similar to MEPLAN, flows of traffic between zones are generated from input-output matrices. Personal travel is estimated by time of day by mode as a function of cost. Trips are assigned to the network according to distinct mode-path combinations. Accessibility is calculated as a logsum composite utility measure from the mode choice model and input directly to the land use model to generate a new set of spatial flows.

Land Market Models

Improved land market representation is a distinguishing characteristic of many of the random utility-based transportation and land use models. In fact, several them have at their core markets for residential and commercial real estate, with transportation models linked into the overall model structure. Some of these models, such as those developed by Anas (1982, 1984), seized on theoretical advances in linking the related strands of gravity-based models with those based on the multinomial logit specification (Williams 1977; Anas 1983).

Anas and colleages developed a series models (Anas 1982; Anas 1994; Anas 1998) designed to simulate the effects of transportation improvements on land markets and overall social welfare. The first such model, CATLAS, emphasizes a discrete choice framework to describe both the supply and demand sides of the housing market. The supply side of the model contains vacancy-occupancy, construction and demolition submodels that respond to factors such as construction costs, land prices, taxes and operating costs, and expected future resale values. Developers are assumed to be profit maximizers, and so select the location and type of construction to maximize profit. The demand side of the model takes a nested logit choice model form, assuming that households have a fixed workplace location and choose a residential location and travel mode to maximize their utility. Only two workplace locations are considered in the model (CBD and non-CBD), though commuters have a variety of modes available (auto, bus, heavy rail and commuter rail), depending on their residential location. The model is calibrated with Census data and can predict changes in mode splits, house prices and rents, demolitions, and new construction activity (Anas 1987). The economic evaluation component of the model estimates changes in economic welfare due to changes in modal utility arising from investment in different modes. The changes in utility are captured in an inclusive value (logsum) accessibility measure and are capitalized into housing prices or rents.

The original CATLAS framework was modified in an enhanced model called METROSIM (Anas 1994), designed for the New York City metropolitan region. METROSIM incorporated a dynamic model of metropolitan housing markets (Anas and Arnott 1994), along with a model of commercial floor space markets. The full modeling system combined models of employment, residential and commercial real estate, vacant land, households, work and non-work travel and traffic assignment, which was absent in the CATLAS system. A recent extension of this system is the NYMTC-LUM model (Anas 1998), a simplification of METROSIM designed to facilitate the evaluation of changes in transit policies for the New York City transit system. The model is slightly refined, adding a local labor market submodel and using very small zones to better model transit and auto network flows. The combined model determines housing prices and floor space rents endogenously (within the model), and uses modal utilities from the mode choice model as accessibility inputs to the land use model.

An alternative framework for modeling land markets in transportation and land use models was provided by Martinez (1992, 1996), who built an integrated model called MUSSA for the city of Santiago, Chile. MUSSA adopted a modified version of the “bid-rent” framework for land markets, first articulated by Ellickson (1981). The “bid-choice” framework used by Martinez combines bid-rent and discrete choice approaches to land markets by dealing simultaneously with both sides of an auction in a bi-level framework. The MUSSA system provides an equilibrium model of building stock supply and demand, where buyers maximize their surplus, sellers maximize price, and builders maximize profits. Building stock prices are then endogenously determined in the model.

The MUSSA system also includes a rather sophisticated four-step travel forecasting model that is linked to the land use component. The travel model features a detailed transit network representation and the ability to forecast demand for 11 separate alternatives, including road, transit and mixed modes. The combined transportation and land use models are referred to as 5-LUT (indicating a 5-step forecasting procedure), and are able to provide equilibrated forecasts of land use and travel demand. A notable feature of MUSSA is that the model uses rather small zones as units of analysis. Likewise, there is an effort to disaggregate the treatment of households within the model, with the Santiago application containing 65 different household types. This is an important step in the development of transportation and land use models, and one that is being replicated in the current generation of transportation and land use models based on microsimulation techniques, as will be discussed in the following section.

Another transportation and land use simulation model that adopts this highly disaggregate structure is the UrbanSim model developed by Waddell and colleagues (Waddell 2000, 2002a). Like MUSSA, UrbanSim is primarily a model of land markets, though extensions have been pursued to add an activity-based travel forecasting model (Waddell 2002b), as well as an environmental analysis module (Waddell and Borning 2004). Like MUSSA, UrbanSim initially contained a highly disaggregated household treatment, with 111 distinct household types identified in an early calibration of the model (Waddell 2000). Demographic transition in population and household formation are microsimulated within a separate submodel. Residential mobility of households is characterized by a two-stage process in which households decide whether to search and then whether to move. Location choice of households and firms are represented by a multinomial logit model considering all zones in the region within the choice set.

UrbanSim's structure is also unusual in that it operates in *disequilibrium* from year to year, with no general equilibrium in land markets assumed at the end of a time step, though market clearing does occur at the transportation analysis zone (TAZ) level. This feature sets it apart from all of the preceding models that incorporate land markets, which are typically static within each time step of a simulation. Researchers in the field of urban modeling have previously commented on the importance of modeling different elements of urban systems at the time scales in which they operate (Wegener 1994; Miller 2003). Since urban areas do not really ever reach a general equilibrium in land and travel markets, this disequilibrium structure will likely be adopted in many future attempts to model land markets.

UrbanSim's model of land markets also estimates supply at the parcel level, using parcel databases within a GIS. Demand for housing and floor space are calculated at the TAZ level in the original version of the model, though subsequent versions are attempting to reconcile the spatial scale of the supply-demand relationship. Land markets are simulated using the bid-choice framework, similar to the MUSSA model (Waddell 2000). Land prices are estimated from hedonic regressions containing building unit and neighborhood characteristics, and regional accessibility to work and shopping. The neighborhood characteristics are determined by partitioning the region into 150 by 150 meter grid cells, each containing information about neighborhood composition and nearby land uses.

Further work on UrbanSim is focusing on converting it to a comprehensive microsimulation modeling system (Waddell et al. 2003). Many of the elements of the original model lent themselves to this treatment, including the high level of household type disaggregation and demographic transition submodel. The land market simulation is already highly disaggregated and requires only further refinement of developer behavior. The introduction of an activity-based model of travel behavior to the original simulation system suggests that this is a possible complement to the microsimulation system. Long-term goals of the project include developing the software architecture to support an agent-based simulation version of the modeling system and the exploration of new model structures.

The experience with the generation of transportation and land use models based on random utility frameworks has been valuable and addressed one of the most pointed criticisms of the previous generation of spatial interaction models, that of lack of theory. The use of random utility theory and advancements in discrete choice modeling of individual behavior have allowed for the inclusion of economic evaluation components in several of the models, as well as improved accessibility measures based on utility functions. Also, the introduction of model systems built around a regional economic model allowed for the inclusion of commercial travel in forecasts and the general treatment of travel as a derived demand. Despite these advancements, many of the random utility models retained a number of problems left over from the previous generation of models. For example, most of the models remained highly aggregate, despite the use of disaggregate calibration methods. This became one source of bias in the model forecasts. Also, with the exception of UrbanSim, all of the models were essentially static in nature. Their structure forced them to reach a general equilibrium between each time step in the model; this was especially true of the models focusing on land markets. Furthermore, little advancement was made in the transportation component of the model. Most models continued to use trip-based, four-step forecasting procedures, where all submodels except mode choice were run at an aggregate level. Much of the current research into microsimulation methods is attempting to address this issue, along with other pressing research questions in the design of comprehensive simulation models of transportation and land use.

DISAGGREGATE AND MICROSIMULATION MODELS

Since the late 1980s, advances in computing power and efficiency of data storage have allowed researchers to begin to build models that address many of the shortcomings associated with previous large-scale modeling efforts and represent important change processes in cities with the detail they require. Examples of these include activity-based models of travel behavior, multi-agent models of urban land use and transportation, and cell-based models of urban land use. The common conceptual underpinning of each of these models is that they attempt to represent processes of change from the bottom up, that is, they account for the behavior of individual agents in space and/or time, along with interactions between agents. The use of the term *microsimulation* can be applied to each of these types of models, though it requires some definition. As defined by Miller (2003), microsimulation relates to “a method or approach (rather than a model *per se*) for exercising a disaggregate model over time.” All of the types of models identified above are what would be considered disaggregate models and all have a significant temporal element. Microsimulation methods are particularly effective for modeling systems that are dynamic and complex, which urban systems invariably are.

Activity-Based Travel Models[2]

Research into the foundations of travel behavior dating back to the 1970s has identified many shortcomings in the use of sequential, trip-based travel demand forecasting models (Hagerstrand 1970; Chapin 1974). However, there was little incentive until this time to attempt to recast travel forecasting procedures. Oil crises during the 1970s precipitated research into various energy use reduction strategies, including demand management measures and transportation system management techniques. It was then that the inability of existing forecasting models, which were mostly static and aggregate, to predict behavioral responses to such policy measures became apparent (McNally 2000).

A combination of factors brought about a resurgence in interest in reconceptualizing travel behavior for modeling purposes during the 1990s. The completion of the interstate system and the difficulty of expanding existing urban road networks led many regional planning organizations to emphasize preservation and management of transportation systems through such policies as flexible working hours, travel information provision, traffic flow improvements and diversion of some travel to alternate modes. The potential changes in travel behavior implied by these types policies cannot be forecast using existing methods, since trip-based models separate travel decisions from their broader context of activity participation and temporal constraints. At the same time, improvements in computing power and the use of geographic information systems have allowed for the formalization and testing of models that previously only existed at conceptual or limited empirical levels. Support from the Federal Highway Administration in the form of the Travel Model Improvement Program (TMIP), which attempted to improve the state of practice in transportation modeling and facilitate development of a new generation of travel demand models, has also had a significant impact.

The first demonstration of an operational model of activity-based travel preceded the TMIP, and was conducted by Recker et al. (1986 a,b). The STARCHILD model was developed to investigate dynamic ridesharing, but was designed for research purposes only and required collection of data that is still not commonly available (McNally 2000). Models of activity chains and travel behavior were coupled with a mesoscopic traffic simulation in work by Axhausen (1990). Pendyala et al. (1997) developed an activity-based simulation model capable of predicting activity scheduling changes in response to transportation control measures. They demonstrate the their model with an application to evaluate the impacts of control measures in the Washington, D.C. metropolitan region. Activity-based forecasting models incorporating GIS applications have also been developed by McNally (1998). Bowman and Ben-Akiva (2001) structured a model of activity participation within a nested logit framework to predict travel tours (clusters of chained trips). Their model was calibrated using travel survey data from the Boston region. A model system developed by Arentze and Timmermans (2004) attempts to simulate learning behavior by agents within the context of activity scheduling and travel behavior. Perhaps the most ambitious effort to date in the U.S. has been the research program associated with the TRANSIMS modeling system, which is designed to combine an activity-based forecasting model with a region-wide traffic microsimulation system (Barrett 1995).

Activity-based models are necessarily disaggregate and attempt to simulate travel behavior within the limits of time and space. Due to spatial and temporal interdependencies, this process cannot be modeled within a framework that treats trips as independent and generates trips at an aggregate level. An alternative, agent-based approach is typically adopted in formal travel forecasting applications. This focus on the behavior of individual agents and addition of temporal elements makes activity-based travel models a natural complement to microsimulation models of transportation and land use that focus on the activity of agents at an individual of household level.

Agent-Based Microsimulation Models

The state-of-the art in transportation and land use modeling is defined by current research efforts aimed at building comprehensive microsimulation systems of urban areas, with representation at the level of individual agents (persons, households, firms, etc.) and simulations of the behavior of the entire population of interest. The advantages of adopting such a modeling approach for urban systems are many (Miller 2003):

- Urban systems are dynamic, with a significant time element and components changing at different speeds
- The behavior of these systems are complex, with interacting agents, complex decision-making processes, and significant probabilistic elements
- Closed-form mathematical and statistical representations of urban systems often introduce large amounts of bias and lead to poor forecasts

The seeds of comprehensive microsimulation models had been sown in a number of earlier models, where one or more elements of the system were governed by a microsimluation process. For example, Wegener's IRPUD model contained microsimulations of population and building stock. Mackett's (1990) MASTER model simulated location choices and travel decisions, and MUSSA and UrbanSim disaggregated households at a level sufficient to operate them in a static microsimulation format, where a representative sample is used within a microanalytic framework for short-run applications. However, for long-term forecasts, which most transportation and land use models are designed for, the population must be synthesized or updated to represent the dynamics of individuals and the environments within which they make choices.

An overview of some of the comprehensive microsimulation systems currently under development are presented in Table 3 (insert here). The UrbanSim system was the only simulation model to transition from a static simulation format to a dynamic microsimuation model. As noted previously, the original version of UrbanSim contained a number of microsimulation submodels within its structure, thus eliminating the need for as radical a redesign as would be needed for many of the static, equilibrium models.

The ILUMASS simulation system (Moeckel et al. 2003; Strauch et al. 2003), being developed by a research team at the University of Dortmund, builds on the experience of Wegener and others with the IRPUD model in the 1980s. The design of ILUMASS embeds a microscopic dynamic simulation model of urban traffic flows within a comprehensive model system incorporating changes in land use and building stock.

The microsimulation modules of ILUMASS include models of demographic change, household formation, firm lifecycles, residential and non-residential construction, labor mobility in a regional labor market, and residential mobility in a regional housing market. These modules are linked with models of daily activity participation and travel, as well as goods movement. The activity-travel module uses data collected via a hand-held survey instrument. This innovation in data collection allows for near-real-time information on activity and travel behavior, obviating the need for respondents to recall their activities later on. The GIS component of ILUMASS combines raster-based and vector-based representations, allowing for the advantages spatial disaggregation in land use representation and efficient network algorithms for the transportation network model.

The ILUTE model (Salvani and Miller 2005), being developed by researchers at a number of Canadian universities, represents the most complete microsimulation model to date. The product of a long-term effort to design an ‘ideal’ simulation model of transportation and land use, ILUTE centers around a behavioral core consisting of four interrelated components:

land use, location choice, auto ownership and activity/travel patterns. The model system is highly integrated with feedback mechanisms whereby higher-level (longer-term) decisions, such as residential mobility, affect lower-level (shorter-term) decisions, such as activity participation and travel.   ILUTE is not based on a single modeling technique (e.g. discrete choice), but rather uses a variety of modeling approaches to represent the behavior of agents in the model, such as state transition models, random utility models, computational rule-based models, learning models, and hybrids of previous approaches.

ILUTE's treatment of land markets explicitly assumes a constant disequilibrium framework, indicating that a particular house could be on the market for several months without selling, since no market clearing is assumed. The time steps in the model are brought down to the level of *months*, rather than years, to provide greater temporal detail. The disequilibrium framework and absence of market clearing also means that projects with extended construction periods (e.g. greater than one year) can be accommodated. The housing market submodel within ILUTE assumes a three-step process to describe residential mobility, involving a mobility decision, a search process, and bidding and search termination.

The transportation component of ILUTE is quite sophisticated and includes submodels for automobile transactions and activity scheduling. The activity scheduling submodels characterizes activities as occurring in time and space, with various scheduling dependencies to represent temporal constraints (Roorda et al. 2005). Future plans include adding a network model, which is needed to provide travel times and costs by mode, along with a formal model of activity participation. Like most comprehensive microsimulation models, ILUTE is still in the process of calibrating some of the submodels in the system, and has yet to be used in a full forecasting application, though the travel demand component has been applied in a policy simulation (Roorda and Miller 2006).

Another agent-based simulation model that merits attention is the Ramblas model (Veldhuisen et al. 2000, 2005). While it is not as comprehensive as the other models described here, Ramblas is designed to simulate the effects of land use and transportation planning policies, with an emphasis on the prediction of activity participation and traffic flows. An unusual aspect of Ramblas is that it is designed to simulate the effects of policies on the entire Dutch population (estimation at over 16 million). The model also distinguishes itself by being entirely rule-based, rather than adopting a formal theoretical framework to guide the behavior of agents. These aspects of the model derive from its stated purpose of being a practical planning tool to assess the impact of various transportation and land use scenarios.

Ramblas is run by selecting households, stratified according to size and structure. Individuals are classified according to one of 24 population segments, defined on the basis of age, gender, education and employment status. An activity agenda and transportation mode are drawn at random, with seven activity types available. Destinations are randomly drawn from a choice set, sometimes delimited by a given action space or distance constraint. Origin-destination pairs are generated from the activity and mode allocations and traffic flows are then microsimulated, calculating travel times via a speed-flow method. Output from the microsimulation of traffic is used to forecast changes in land use, dwelling stock and road construction.

Cellular Models

The representation of land use in integrated models of transportation and land use change has been one of the less satisfactory elements of these models (Chang 2006). Until recently, land use had generally been represented by zones that served as convenient areal units for the location of activities, and coincided with zonal designations for transportation models. Models that provide greater simplicity and a clearer representation of the dynamics of land use change using cell-based representations of regions have emerged within the past two decades as an increasingly attractive land use modeling alternative.

Cell-based models, and particularly those based on cellular automata (CA) theory, arise from the application of *complexity theory* to cities (Batty 1997, 2005). Complexity theory conceptualizes systems, such as urban systems, as being too complex to synthesize using closed-form, predetermined mathematical representation. Rather, these systems arise from the collective interaction and self-organization of large numbers of individual agents which generate the observed macro-level states (Benenson 1998). Cell-based models of land use can range from simple state transition models in which cells change states (land uses) according to some observed probability, to the more general form of CA, in which cell states are also a function of states in neighboring cells. CA models can be seen as extension of agent-based microsimulation models, in which individual cells are the agents, rather than persons or households.

CA models generally require four basic elements: a lattice of regular spaces or cells, a set of allowed states, neighborhoods that are defined by the lattice, and a set of transition rules governing the evolution of individual cells in the system. Many CA models also add a fifth, temporal element. CA models are basically deterministic, rule-based models, using “if-then-else” logical statements to build their transition rules, though stochastic elements can be added to transition rules using probabilistic expressions and random number generation. Other types of modifications to CA models intended to introduce complexity include changes to the structure and dimension of the lattice of cells, expansion of allowable cell states, expanded neighborhood definitions to include action at a distance, and changes to temporal elements, such as Markov chains (Torrens and O'Sullivan 2001).

A precursor to many of the contemporary cellular models being used to describe the dynamics of urban systems is the model of self-forming neighborhoods presented by Schelling (1978). As part of a larger exposition of self-organizing principles, Schelling demonstrated how "individually motivated" forms of segregation could arise through the interaction of many agents (households) pursuing their own objectives. Preferences for individuals of a different race, income, or any other form of social stratification were shown to lead to highly segregated outcomes under a variety of initial conditions and preference structures.

The compatibility of CA models with GIS, remote sensing data and associated visualization capabilities make them particularly suitable for land use modeling applications (Torrens and O'Sullivan 2001). It is here that they have received the most attention. One example is the model of urban land use developed by Clarke et al. (1997) to estimate the regional impact of urbanization on the San Francisco Bay Area's climate. This model is an example of a self-modifying CA, in which the CA can adapt to the circumstances it generates. Clarke and Gaydos (1998) applied the same model to the Baltimore-Washington region to generate long-term urban growth predictions. Jantz et al. (2004) also studied growth in the Baltimore-Washington region using CA, with the objective of simulating the effects of different patterns of land use on the Chesapeake Bay watershed. Levinson and Chen (2005) describe the development of a Markov Chain model of land use change for the Minneapolis-St. Paul region. Their model adopts the discrete-time version of a Markov Chain and predicts the evolution of transportation networks and land use patterns over the period from 1958 to 1990. A next step for this model would be to add neighbor effects, which would move it to a CA-Markov Chain framework.

Other applications of CA include simulating land use density conditions, as in the model developed by Yeh and Li (2002). Their model incorporates a density gradient in the simulation of urban development for different urban forms. The transition rules of their model specify a density, obtained from a distance-decay function, to be applied to cells as they are converted to developed cells. Kii and Doi (2005) provide a similar application to demonstrate the effects of compact city form and mixed land use on total trip length, energy consumption and social welfare in Takamatsu, Japan. The model they present, MALUT, is a multi-agent model of transportation and land use, where a CA model of land use is coupled with a microsimulation model of travel. Accessibility can be incorporated into a CA model of land use change, as demonstrated by Ottensmann's (2005) LUCI2 model. LUCI2 was designed to predict employment and land conversion change over a 44-county region of Central Indiana, consisting of eight separate metropolitan statistical areas. The model found access to employment to be an important determinant of residential development and density.

CA models appear to be growing more complex. Their many applications reflect the relative ease and flexibility with which they can be modified to describe processes of change. CA are not without their weaknesses, though. Their simplicity, which is one of their most desirable attributes, is also a significant limitation. In most cases, they are inappropriate for modeling systems with complex interactions. For example, processes like land development represent the interaction between human and physical systems, but CA models cannot capture both. Also, CA models are not designed to be forecasting tools. Since they are calibrated on historical data and lack a strong behavioral interpretation, most forecasts have little meaning.

Rather, CA are better suited to idealized principles of cities and urban design applications than large-scale simulations or strategic planning (Batty 1997).

RESOLVED AND ONGOING MODELING ISSUES

Old Issues

The models currently being developed to describe change in transportation and land use systems look very different than those that existed a few decades ago. One might question then, to what extent these newer models have overcome the deficiencies of earlier generations of models, such as the criticisms lodged against the first generation of spatial interaction-based simulation models.

Reflecting on the earlier experience, some modelers claimed in the early 1990s that advances in computer processing power and data storage would obviate many of the problems identified by Lee (1973) in his critique of the early modeling experience (Harris 1994). While these advances have undoubtedly reduced some of the costs of building, operating and maintaining transportation and land use models, concomitant expansions in the scope of these models, as exemplified by the current generation of urban micrsosimulation models, ensures they will continue to be a resource-intensive effort. These models also remain highly complex, with many interacting submodels. Calibration is still a daunting task, even for models that are available as commercial packages. Data requirements are still large, especially for dynamic models that require synthesis of a population or continual updating of a sample.

It must also be recognized though, that a number of problems identified with earlier models have been, at least partially, resolved. Most microsimulation models are no longer static, and can simulate changes in transportation network performance and land use through time.

Nearly all models now are able to model land markets with explicit prices and the ability to simulate the behavior of various agents in the land development process. The level of aggregation of agents is being reduced, especially in comprehensive microsimulation models. The size of zones in most models is now much smaller, and should continue to decrease as computing power permits, though spatial detail in many models could certainly improve. Perhaps most importantly, the theoretical basis of models has improved, especially in ongoing efforts to reconceptualize the relationship between individual activity patterns and travel choices for travel demand forecasting.

New Directions

The development of advanced models of transportation and land use change brings about opportunities for exploring some important topics related to the models themselves and their representation of real-world urban regions. The following are some issues worthy of more attention.

The Use of Theory

Some researchers question the continuing use of broad theoretical frameworks to guide agent behavior in model systems. Timmermans (2003) points to the use of random utility theory to describe a wide range of spatial choices in many models. Noting that utility is a concept that must be built up over several repetitive choice situations, he questions the applicability this concept to rare decisions such as mobility and residential location. Also, it is questionable whether discrete choice methods and random utility theory are applicable to entities such as firms, which comprise collective choice situations, as opposed to individual agents. Models like Ramblas and ILUTE, which use rule-based or hybrid modeling approaches, suggest that tailoring the right tool to each model component can overcome this issue. Timmermans also noted that most models are consumers of theory rather than producers, indicating that model development ought to coincide with the process of theory development.

Forecast Accuracy

Recent studies that have sought to explore the propagation of uncertainty through transportation and land use models (Pradhan and Kockelman 2002; Krishnamurthy and Kockelman 2003; Clay and Johnston 2006) have identified a continuing trend of large variation in output from these models. Presumably, the addition of better model dynamics and disaggregation of population groups within microsimulation models will reduce some of the bias present in earlier, more aggregate models. However, long-term forecasting models of many types necessarily retain significant amounts of irreducible uncertainty, and the lack of available forecasting results from applications of newer models leaves some room for concern.

Treatment of Supply Side

In most forecasting applications the supply side of transportation, as represented by the extent and capacity of networks, is held fixed or treated as a policy variable. The limited available evidence on the evolution of networks over time (Yamins et al. 2003; Yerra and Levinson 2005; Levinson and Yerra 2006; Zhang and Levinson 2007) suggests that scenarios such as alternative ownership regimes and their impact on transportation-land use systems are a topic worthy of exploration with more comprehensive models.

Agglomeration Effects

Previous reviews of operational models of transportation and land use (Berechman and Small 1988) identified the absence of agglomerative effects as a major weakness of the land use component of these models. Recent work using multi-agent systems (Arentze and Timmermans 2003) suggests that modeling this effect is possible, and it is deserving of further exploration.

Person-Based Accessibility

Since accessibility is still seen as an important component of location choice in transportation and land use models, especially for residential location, it makes sense to pursue measures of accessibility that recognize the importance of treating travel behavior as a process constrained in time and space, as is reflected in activity-based travel models. Examples have been provided in work by Kwan and Weber (2003) and Miller (2005).

CONCLUSION

Models of transportation and land use change have evolved significantly since their early applications more than four decades ago. In the search to design models that capture the recursive relationship between transportation and land use, there has been a general trend toward the disaggregation of the representation of people and space. Newer models represent in greater detail the dynamics of the transportation-land use change process. Experiments with bottom-up approaches to modeling urban systems, especially those that recognize the interactions between agents, provide an alternative means for understanding their complexity. Yet, the ability to forecast these processes for policy applications remains and important goal. Most of the newer generation of microsimulation models are designed with the objective of making them more policy sensitive. Unfortunately, few of them have yet reached a point where they can be fairly evaluated on this criterion, and the older operational models still raise important questions about the utility of such complex tools.

One must be more circumspect though, in evaluating the transportation and land use modeling experience more generally. In reflecting on the experience with the first generation of models nearly three decades ago, Batty (1979) noted that models should be evaluated in terms of their contribution to both science and design (i.e. policy). Many of the earliest models were failures on both accounts, though there has arguably been some success on the science side since then. Models continue to represent an important means of testing theories about the behavior of urban systems.

Another observation by Batty related to the status of planning as a science. He argued that planning was (at the time) an ‘immature’ science, marked by poor theoretical development, continuing controversy about methods and results, and the tendency to follow ‘fashions.’ In many respects this is true of the field today, as in the continuing controversy over the influence of land use patterns on travel behavior. Batty suggested that this status may be inherent to planning, which is considered a ‘policy’ science, and hence subject to the dictates of short-term policy needs, albeit at the expense of long-term theory development. He noted though, that periodic reflection and critical review by those engaged in research can be seen as a sign of maturity. There has been much of this in the field of transportation and land use modeling, as in the related field of travel demand analysis (see, for example Pas (1990)). Continued reflection, along with a commitment to developing models that reflect the relevant theoretical constructs of the behavior or system being studied, are seen then as the most promising paths toward developing transportation and land use modeling toward a more ‘mature’ state and building more practically useful tools.

Figure 1: Chronological development of land use and transportation models

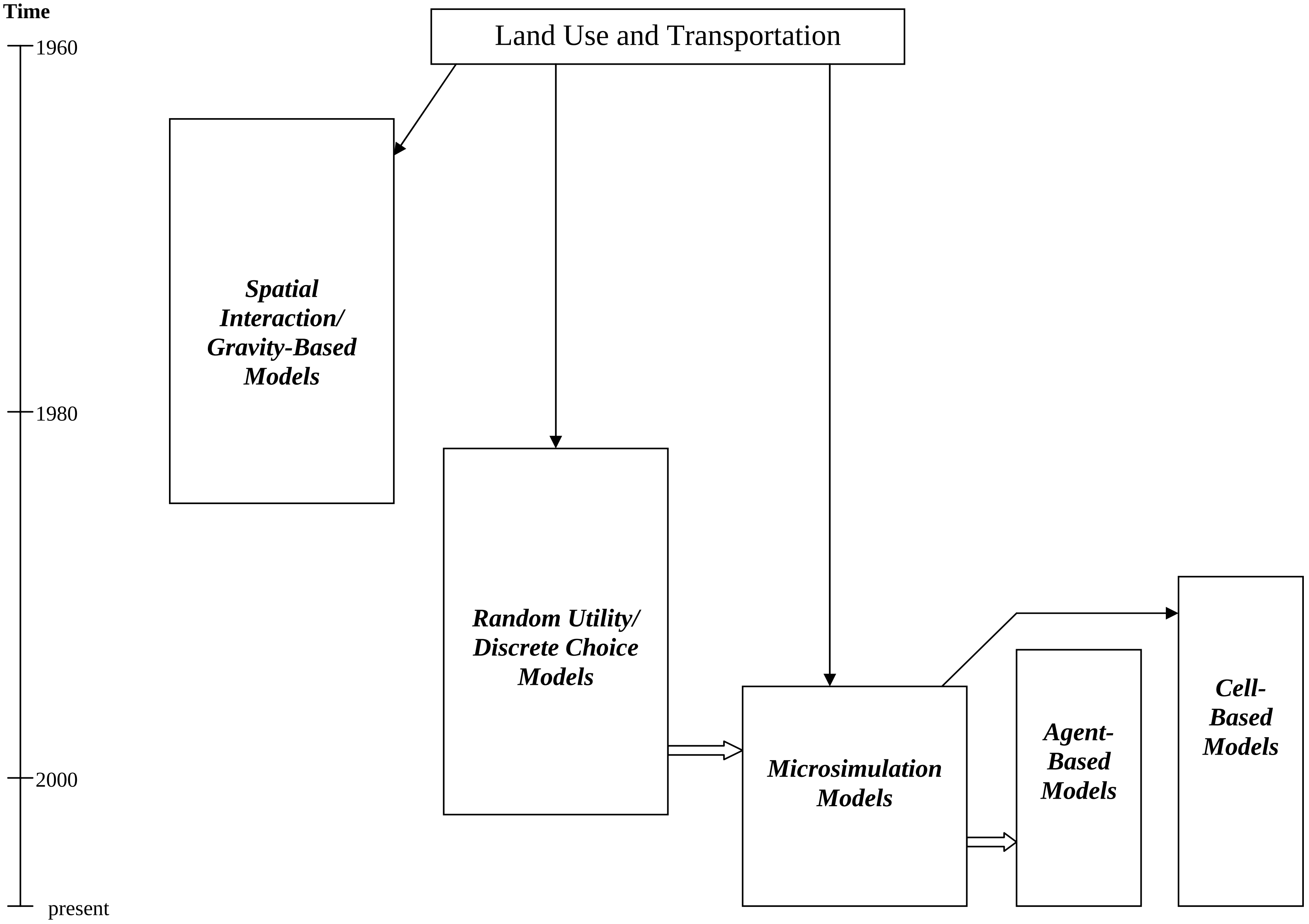

Table 1: Summary of Spatial Interaction / Gravity Models

Model	Reference	Distinguishing Features
Model of Metropolis	Lowry (1964); Garin (1966)	First recognized operational land use model; Garin provided matrix representation
TOMM	Crecine (1964)	Disaggregation of population; incorporation of inertia effects in activity allocation
PLUM	Goldner (1971)	Replaced standard gravity model with intervening opportunity model; use of county-specific dispersion parameters
ITLUP	Putman (1983)	First complete software package for integrated modeling; improved calibration techniques; improved network model with multiple modes; incorporation of congestion effects in activity allocation
LILT	Mackett (1983)	Use of accessibility function; car ownership submodel; land use model capable of handling demolition, changing occupancy and vacancy rates
IRPUD	Wegener (1982)	Contains seven separate submodels; microsimulation of land use; use of differing spatial scales for submodels; separates discretionary and non-discretionary travel

Table 2: Summary of Random Utility / Discrete Choice Models

Model	Reference	Distinguishing Features
CATLAS	Anas (1982)	Improved representation of economic agents and decision making; explicit treatment of housing markets; economic analysis capabilities
MEPLAN	Echenique et al. (1969); Echenique et al. (1990)	Incorporation of spatial input-output model with economic evaluation component; able to forecast commercial trip generation; travel treated as a derived demand
TRANUS	de la Barra (1989)	Development supply model simulates choices of developers; sophisticated travel model with combined mode-route choice
MUSSA	Martinez (1992)	Incorporation of bid-rent framework for land, floor space markets; detailed representation of transit network in travel model; high level of household type disaggregation
METROSIM	Anas (1994)	Model extended to commercial real estate markets; addition of dynamic CHPMM housing market model
NYMTC-LUM	Anas (1998)	Endogenous determination of housing prices, floor space rents, and wages; high level of spatial disaggregation suitable for transit and land use policy evaluation
UrbanSim	Waddell (2000); Waddell (2002)	Dynamic, disequilibrium model framework; parcel-level land use representation; high level of household type disaggregation

Table 3: Summary of Microsimulation Models of Transportation and Land Use

Model	Reference	Distinguishing Features
ILUTE	Salvani and Miller (2005)	Comprehensive urban system microsimulation model; structured to accurately capture temporal elements urban change; activity-travel model includes household member interactions; disequilibrium modeling framework
ILUMASS	Moeckel et al. (2003); Strauch et al. (2003)	Descendent of IRPUD model; incorporates microscopic dynamic simulation model of traffic flows and goods movement model; designed with environmental evaluation submodel;
Ramblas	Veldhuisen et al. (2000)	Entirely rule-based model framework; designed to simulate very large populations
UrbanSim	Waddell (2003)	Random utility model incorporating microsimulations of demographic processes, activity-travel choice and location

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[1] Reviews that cover a larger number of models, including some that have seen less commercial application, are provided in recent papers by Timmermans (2003) and Wegener (1994 and 2004). Chang (2006) also provides a review of models based on mathematical programming formulations, which are not discussed here.

[2] The literature on activity-based approaches to travel analysis is quite extensive and dates to the 1970s. Thus, a comprehensive review of this literature is not possible here. Instead, the focus will be on covering a few of the models that have been tested using real-world data at least once. The interested reader is directed to papers by Axhausen and Garling (1992), Ettema and Timmermans (1997), McNally (2000), Vovsha et al. (2005), and the collection of papers in the August 1996 issue of the journal *Transportation*, which describes the early results of research work funded through TMIP.

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