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**A Technical Review of Urban Land
Use—Transportation Models as Tools for
Evaluating Vehicle Travel
Reduction Strategies**

Frank Southworth

MANAGED BY
MARTIN MARIETTA ENERGY SYSTEMS, INC.
FOR THE UNITED STATES
DEPARTMENT OF ENERGY

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A Technical Review of Urban Land Use—Transportation
Models as Tools for Evaluating Vehicle Travel
Reduction Strategies

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EXECUTIVE SUMMARY

The continued growth of highway traffic in the United States has led to unwanted urban traffic congestion as well as to noticeable urban air quality problems. These problems include emissions covered by the 1990 Clean Air Act Amendments (CAAA) and 1991 Intermodal Surface Transportation Efficiency Act (ISTEA), as well as carbon dioxide and related "greenhouse gas" emissions. Urban travel also creates a major demand for imported oil. Therefore, for economic as well as environmental reasons, transportation planning agencies at both the state and metropolitan area level are focussing a good deal of attention on urban travel reduction policies. Much discussed policy instruments include those that encourage fewer trip starts, shorter trip distances, shifts to higher-occupancy vehicles or to nonvehicular modes, and shifts in the timing of trips from the more to the less congested periods of the day or week. Some analysts have concluded that in order to bring about sustainable reductions in urban traffic volumes, significant changes will be necessary in the way our households and businesses engage in daily travel. Such changes are likely to involve changes in the ways we organize and use traffic-generating and-attracting land within our urban areas. The purpose of this review is to evaluate the ability of current analytic methods and models to support both the evaluation and possibly the design of such vehicle travel reduction strategies, including those strategies involving the reorganization and use of urban land.

The review is organized into three sections. Section 1 describes the nature of the problem we are trying to model, Section 2 reviews the state of the art in operational urban land use-transportation simulation models, and Section 3 provides a critical assessment of such models as useful urban transportation planning tools. A number of areas are identified where further model development or testing is required. The following is a synopsis of each section of the review.

Section 1 of the review describes the considerable technical difficulties associated with identifying the causes and directions of urban traffic growth. It is concluded that to be effective, transportation planning needs to bring together an understanding of (1) how the transportation sector operates, (2) how traffic-generating and attracting land is developed, (3) how other technologies affect the demands for travel, (4) how modern companies make their siting and site relocation decisions, and (5) how the modern industrial lifestyles of today's households affect, and are in turn affected by, each of the above. Besides the complex conceptual issues involved, challenging practical issues result from the need to handle large amounts of spatially explicit data, and the need to consider a wide range of possible, and sometimes competing transportation control measures (TCM). Significant, sustainable, and socially acceptable travel reduction strategies will require careful multiyear land use planning. Given the typical time lag between the opening of a major transportation infrastructure or service and the

subsequent land use response, interest is focussed in this review on models capable of simulating policy impacts anywhere from 15 to 50 years into the future.

Section 2 reviews the current status of operational land use-transportation planning models, and in particular the development of "integrated" urban analysis models. A listing of the most commonly referenced models is provided. The key theoretical and operational developments of the past 30 years are discussed, using the mathematical details from selected modeling systems to illustrate the range of approaches now available for simulating urban travel patterns and their multiyear impacts. Taken as a set, current models have managed to combine the entropy maximization and locational accessibility premises that are the basis of spatial interaction theory with economically rational notions of utility maximization and consumer choice. From the urban economics literature they have taken the idea of equilibration between transportation demand and supply and linked it to a residential market clearing process. Methodologically, they make use of nonlinear mathematical programming methods, interregional input-output methods, and the latest developments in econometrics and microsimulation to model jointly the demands for travel, residences, employment, services, and urban land. The more comprehensive models also simulate demographic changes in the urban population as well changes in physical stocks other than transportation infrastructure, including models of the aging and renewal process associated with the urban housing market.

The key trait these models have in common is their ability to feed back the expected results of adding new transportation infrastructure or services, computed within a transportation submodel, to a travel cost sensitive land use submodel. They simulate urban dynamics by iterating the simulated urban system through a series of discrete time intervals. Here the level of sophistication varies considerably across models: from a simple one-shot, 30-year forecasting process, to recursive formulations which move the urban system forward in time through a series of successively updated, 1- to 5-year intervals. They model these events using an extensive database, usually resulting in the allocation of traffic volumes and speeds over detailed link-node representations of multimodal urban transportation networks. They have been used in a number of different countries to simulate a range of travel reduction strategies, including fuel and road pricing policies, the spatial reallocation of traffic-generating land uses, and the introduction of new highways and transit services.

However, despite advancing in a number of theoretical and practical directions since Lowry's 1964 "Model of Metropolis," these models are only now finding their way into U.S. practice. Past reticence to employ them has stemmed in part from their analytic complexity, in part from their significant data requirements and similarly significant demands on computational resources. While today's desktop computers can now provide much of the computing power required, the other issues remain unresolved. Spurred on by the demands placed on metropolitan planners by the CAAA and supporting ISTEA legislation, these models are now receiving renewed scrutiny. At the same time, recent

empirical and theoretical developments suggest that current models may need to be either adapted or replaced if realistic simulations of traveler responses to travel-reduction strategies are to be forthcoming. Here a difficulty facing model assessment is the limited information available from model validation exercises, a process exacerbated by the extended time frames required to capture the true effects on travel of the more significant land use changes.

Section 3 considers a number of frequently voiced criticisms of currently operational models and recasts these perceived weaknesses as candidate areas for further research. Many of these criticisms are linked to continued use of the traditional four-step urban transportation planning model, and in particular, the persistence of a single-destination, single trip-purpose-based approach to travel generation. There is a widely recognized need to develop more effective ways to capture nontraditional travel reduction options, such as telecommuting and teleshopping, alternatively fueled but perhaps limited-range vehicles, and nontraditional work weeks. Improved "travel activity analysis" models under development include the modeling of multideestination, multipurpose trip chains; the simulation of private vehicle use by different household members and types of households; and the simulation of daily travel schedules which recognize the growing number of noncommute, non-peak period trips which are taking place. Similarly, our treatment of the urban goods movement process lacks any underlying behavioral rationale and needs to be tied to a more comprehensive understanding of company logistics planning. Some recent developments in both personal and goods movement modeling are referenced as useful starting points for subsequent analysis.

Needed improvements to the land use modeling process are also discussed. In particular, and despite the frequently referenced polycentric nature of urban growth over the course of this century, there has been a failure to come to terms with the causal mechanisms underlying intraurban, notably suburban, center growth. The urban economics literature, while extensive, has so far contributed little in the way of operationally implementable theories of urban development. Among other barriers to understanding, outmoded notions of what constitutes "basic" and "nonbasic" employment activity make it difficult to identify the underlying causes of commercial and industrial business location decisions. A reassessment of this traditional distinction, already evident in a number of recent modeling efforts, needs to be pursued in a more comprehensive manner.

A second area of land use planning warranting further study is a more normative, or design-based, approach to urban activity center planning. This includes approaches centered on transit-oriented development and pedestrian- and cycle-oriented land use arrangements.

Third, a gradual move towards more behaviorally realistic, truly dynamical modeling approaches is discussed, based on differential or difference equation forms and supported by longitudinal data such as multiwave panel analysis of empirically validated travel behaviors. If such dynamical analysis can be combined with a better understanding of why and how urban centers form, and how designs of mixed use activity centers influence household and business travel patterns, we would have the basis for more realistic, and perhaps eventually prescriptive, travel activity pattern simulations.

Finally, these urban simulation models need to be placed within today's highly interactive software environments. We need to produce not only policy-relevant, but also policy-usable analysis tools. Urban planning ought to be a highly interactive, consensus-building process. Black box models should be neither acceptable nor necessary. Models should be placed within spatially explicit decision support aids taking advantage of the latest geographic information systems and relational database technology to open up the planning process to well-informed local and regional planners. Ultimately, urban planning comes down to compromise and common sense. Yet we would be taking considerable risk, as we have often been forced to do in the past, if we were to assume away the complexity associated with multiyear planning by selecting travel policies based largely on professional intuition. Simulation models are necessary if we are to understand the consequences of trying to control future traffic growth, and a degree of complexity in model design cannot be avoided.

1. INTRODUCTION

1.1 URBAN TRAVEL GROWTH: WHY THE CONCERN?

Highway transportation today accounts for some 22% of the nation's annual energy consumption: 97% of it in the form of petroleum-based fuels (Davis, 1994). The century has been one of steadily growing demand for vehicular travel. Between 1970 and 1990 total vehicle miles of highway travel within the United States grew at an average annual rate of 3.2% (Davis, 1994, Table 3.2). While some reduction in this rate of growth may result from a saturation in vehicle ownership and license holding, many experts expect urban travel to continue to increase as a result of (1) significant population gains within our largest cities (Downs, 1992), (2) a generally growing interest in discretionary forms of nonwork travel (see Hu and Young, 1994), and (3) our continued failure to develop alternatives to low-occupancy vehicle use (Johnson, 1993).

One evident impact of this traffic growth has been urban pollution. Mobile source emissions from the highway transportation sector alone are estimated to account for some 70% of our society's carbon monoxide generation, 39% of its nitrogen dioxide, 30% of emissions of VOCs¹, and 28% of its small particulate matter (PM-10) generation, along with significant contributions also to nitrogen oxide and sulphur dioxide emissions (Curran et al., 1992). Nor are these the only emissions of interest. Increased atmospheric accumulations of carbon dioxide and related tracegases—notably ozone, nitrous oxide, methane, and chloroflourocarbons—are today considered by many scientists to be contributing to a “greenhouse effect,” in which the level of heat retained within the planet's atmosphere is causing global warming of the earth's surface. As such concerns have passed from the scientific community into wider public notice, interest in the amount of carbon dioxide (CO₂) resulting from motor vehicle use has begun to surface with some regularity. It has been estimated that the consumption of energy within the transportation sector contributes some 32% of the nation's emissions of carbon dioxide (Hillsman and Southworth, 1990).

In addition to these now often-discussed “direct,” or vehicle miles of travel-based, estimates of fuel consumption and emissions production, DeLuchi, Johnson, and Sperling (1987) identified five additional, indirect sources of greenhouse gases which result from the consumption of highway and other transportation fuels. These are (1) end-use combustion of fuels, including trucking of liquid transportation fuels to retail outlets; (2) combustion of fuel in pipeline compressors and pumps, and in barges and trains during wholesale transmission of fuels to the distributor; (3) CO₂ formed by the chemical reactions of fuel synthesis; (4) CO₂ formed by the use of process energy in fuel

¹Volatile organic compounds, which along with nitrogen oxides are precursors of ozone (O₃).

production plants; and (5) combustion of fuel in the initial extraction, preparation, and transportation of raw fuel feedstock. To these sources we also need to add the emissions generated in those processes used to build and maintain our transportation infrastructure and its operating components, including our roads, bridges, and vehicle and vehicle parts manufacturing plants, and in the manufacture of the vehicles themselves.

Air quality and fuel consumption are not the only public policy issues, of course. Activities associated with the transportation sector now cover a significant percentage of the land in use within our cities. With infilling of development between the major highway arteries that were the original facilitators, if not progenitors of that growth, the need for additional centers of activity besides the CBD emerged. The result has been multicentered urban development in most large cities and a consequent increase in suburb-to-suburb trips. Many of these suburban centers are now suffering from their own versions of traffic congestion and the losses of personal and employee time that entails (see Orksi, 1985; JHK and Associates, 1989; Garreau, 1991; Southworth and Jones, 1995). And what the ubiquitous automobile has done for personal mobility the truck has done for the intraurban movement of goods, leading to a growing number of instances of mixed truck-automobile interaction, which raising additional issues of travel safety as well as traffic congestion. A question now being asked is where our overcongested cities will go from here. How can we most cost-effectively deal with traffic growth and traffic congestion in a socially as well as environmentally sound manner?

1.2 PURPOSE OF THIS REVIEW

Spurred on by this interest, this review focusses on the extent to which current theories and supporting methodologies are sufficiently developed to be used (a) to help urban planners assess the impacts of transportation plans and policies which support the evolution of more energy-efficient and less polluted cities, and (b) to aid in the design of specific travel-reduction strategies.

Given the complexity of the subject, methods are here synonymous with models: conceptual, mathematical, and for practical purposes, computer-based. For almost four decades now, we have been using computer-based urban transportation planning models to improve our assessment of current travel activity patterns and to predict future transportation infrastructure needs in support of steadily growing automobile and truck traffic. For the purposes of longer-range forecasting, in the 15- to 50-year range, such transportation planning models need to be tied to a broader-based land use plan for the same region. Often, such land use plans are themselves the result, at least in part, of a modeling exercise. As our cities have grown, the relative advantage of locations within them has changed because of the growing demand for goods and services, the buildup in traffic congestion, and the further development of the transportation system in response to both of these forces. That is, the ease or cost of travel between locations in turn

contributes to the economic vitality of specific business enterprises, as well as to the desirability of specific residential locations. With the passage of time, changes in transportation costs may in turn cause a change in land use. Linking transportation and land use planning exercises is therefore a natural step in both the physical and the subsequent economic planning process. The current status of “integrated” urban land use-transportation models is the central topic of this review.

Of particular interest is the ability of such integrated models to provide useful inputs to the selection of travel-reduction strategies that will result in a net reduction in aggregate fuel use and emissions. Such reductions are usually thought of as resulting from one or more of the following five outcomes:

1. a reduction in the number of trip starts;
2. a reduction in the length of individual trips, through changes in destination;
3. a shift to either nonvehicular or higher-occupancy modes of travel; and/or
4. a reduction in the amount of travel during the congested, or “peak,” commuting periods
5. a reduction in trip length and/or traffic congestion, through changes in route.

In this review the strategies we are most interested in are those that can maintain such travel reductions over a period of years, and thus improve urban lifestyles collectively as well as individually. For this reason also, the sort of planning horizons we are interested in, and those also best suited to the types of models reviewed below, cover the 15- to 50-year time frame, although many of the processes modeled may express themselves (and be simulated to do so) with much shorter cycles. The emphasis of the review, the reader should note, is on applicability of current methods, and not on the applicability of specific travel-reduction strategies per se.

1.3 OVERVIEW OF THE TECHNICAL CHALLENGE

1.3.1 Conceptual Issues

It is important first of all to note the complexity of the relationships we are seeking to simulate. The role transportation plays in the multiyear development of urban systems remains far from clear. This is due in part to the often long lag times between the introduction of a new highway, rail line, or travel terminal and the subsequent effects on surrounding businesses and residents. To date, our ability to track such changes in a comprehensive manner has been a cost we have generally not been willing to accept. What is clear is that many different factors work simultaneously to shape our cities. While the root causes of travel growth are found in the development of urban land—what it is used for and how intensively it is used—we are currently much less certain about the subsequent effects of transportation system changes on land use, and hence, in turn,

on longer-run travel patterns (Giuliano, 1989; TRB, 1991; Kitamura, 1994). Public policies intended to produce sustainable forms of energy-efficient and environmentally acceptable travel must encompass a better understanding of the broader topic of urban land use, and in particular, of the way transportation and other forms of urban land use feed back on one another.

Demonstrating the difficulties we face in unravelling causes and effects, Zimmerman, West and Kozlowski (1974) separated traffic which occurs on a new or newly expanded highway into the following classes quoted by Kitamura, 1994):

- existing traffic,
- natural-growth traffic—due to traffic arising from demographic or socioeconomic changes,
- diverted traffic—traffic from other streets and highways,
- transferred traffic—traffic from other travel modes,
- shifted traffic—traffic going to new destinations,
- induced traffic—“new” trips encouraged by the presence of the new highway, and
- development traffic—traffic generated by land-use changes.

In recent years the opening or widening of a major stretch of urban highway has frequently resulted in rapid traffic growth. The road seems to fill up in a surprisingly short period of time, then settles down to a new and generally higher level of daily use. In areas where the demand for additional road space has been building for some time, much of this new or induced trip making by businesses or households may be an expression of the latent demand for greater access to opportunities which already existed within the system. Recent evidence suggests that within U.S. cities over one million in population, such latent demand may represent as much as 13% of any new travel induced by a highway capacity expansion (Rathi et al., 1991).

In addition to the above effects, temporal changes in trip making may also influence the picture. Greater ease of travel may induce some freight as well as personal travel to shift to the now less congested highway, possibly into the peak period of use. Many cities in recent years have experienced a temporal spreading of such peak congestion periods, in what is a collective expression of trip departure timing adjustments in the face of congestion delays. Certainly, experts are often at odds on the likely effects of adding new highway capacity in a given situation (see Deakin, 1991).

As with highways, the full impacts of introducing new transit infrastructure also remain far from clear. Over the past three decades a number of studies of the effects of introducing new or improved rail service, and to a lesser extent new bus or trolley lines, have been carried out. Armstrong (1994) summarizes the results of the best-known U.S. studies (see also Dehghani and Harvey, 1994; Hunt, McMillan, and Abraham, 1994). The

findings appear to support the notion that property values suffer in the immediate vicinity of intraurban rail stations, and possibly (though less conclusively) along rights-of-way but that rents may increase on average within the communities supporting heavy rail or commuter rail transit stations. However, results are far from consistent across studies, except that any tendencies toward more compact urban growth or higher urban densities appear to be offset by larger forces towards urban decentralization (Deakin, 1991; Giuliano, 1989). Giuliano (1986a), Mackett (1994), and Pisarski (1994) each briefly review a number of past highway and transit investment programs and their attributed impacts on subsequent urban development and land prices. While the transportation-land use feedback effects do often occur, current evidence and understanding does little to clarify the situation for the next study to be carried out. What is clear is the need to use models which recognize the above complexities if we are to unravel the conundrum posed by transportation infrastructure-initiated urban development.

In trying to model not only the more immediate mode and route shifts but also the longer-term relationships between transportation and other forms of urban land use (notably destination shifted, induced, and development traffic) we are dealing with both a large number and a wide variety of activity types, decision makers, and underlying motives for action. While urban residents have chosen in growing numbers to move outward from the city centers in search of more space at lower rents, most commercial and industrial land users still seek the economies of scale associated with spatial proximity to similar and complementary employment activities. With the onset of the information society, a third important trend is the emergence of locationally indifferent, or "footloose," service and information-based companies which are no longer tied to the location of key resource inputs or local markets for their products. We therefore have at least three very different types of locational activity operating within our urban areas. Making the situation more complex, the locational decisions within each of these residential and employment activity sectors ultimately impact each other. Where workers live determines the available labor pool, and where residents work affects their choice of residence. Choice of residence in turn affects the size of the consumer market for service and retail products.

Further complicating the situation, the very urban stage on which we are trying to apply our models has been shifting quite rapidly of late. As a society we are undergoing some significant changes not only in the way we travel but also in the way we communicate and indeed live with each other. New urban lifestyles are emerging as new forms of urban household take shape (see Putman, 1994, for a discussion related to recent land use modeling experience). Similarly, the role to be played in future cities by the ongoing telecommunications revolution is far from clear (US DOT, 1993; Greene, Hillsman, and Wolfe 1994). To be useful planning tools our models must be capable of incorporating different assumptions about the effects of today's emerging travel and communications technologies on the ways we interact with one another, both within and between future cities.

As a minimum then, effective transportation planning must bring together an understanding of (1) how the transportation sector operates, (2) how traffic-generating and-attracting land is developed, (3) how other technologies affect the demands for travel, (4) how modern companies make their siting and site relocation decisions, and (5) how the modern industrial lifestyles of today's households affect, and are in turn affected by, each of the above.

Figure 1 shows the sort of complexity we are trying to come to terms with, if we take up the challenge of trying to simulate, in any reasonable detail, the multiyear impacts of urban transportation plans. Transportation demand and supply considerations are shown at the center of a readily and rapidly expandable series of interconnected causes and effects. Demands for new and better transportation services are shown as resulting from changes in the utilization of urban land. The travel cost changes which result from providing new transportation services cause activity pattern shifts which in turn affect the local economy (i.e., the revenue generated by the purchase of goods and services at specific sites). These changes in turn affect local employment, which in turn affects local demographics. Changes in employment and population affect demand for services (of all kinds) which can either create new businesses or cause businesses to close down with loss of their competitive advantage. These sociodemographic changes also affect local housing prices and eventually the need for new housing starts. With new business ventures and new residential neighborhoods come new demands for travel—and the cycle begins again.

Shown at various locations within Figure 1 is the potential for federal, state, metropolitan and local governments to influence urban activity patterns—notably through transportation service pricing and capacity control, through urban land utilization and labor supporting policies, and through environmental legislation. Within the United States this includes the use of private/public sector partnerships in the development of local services. Also shown in Figure 1 are a number of “other factors” involved in both the transportation and land use decision-making processes of each of the actors involved. These include the regionwide and nationwide adoption of cost, time, and labor saving technologies, including the advances in automotive engine design and alternative fuels technology which have been the key sources of travel-related fuel and emissions reductions to date.

Adding the need to understand the energy related environmental impacts of particular transportation system developments further complicates the matter. Shape, size, density of development, and the spatial dispersion of activities have all been found to influence transportation energy requirements. However, even highly abstract studies

Fig. 1. Complexity of functional linkages in urban system dynamics.

of energy-efficient land use patterns quickly throw up complexities which cloud interpretation of results (see Owens, 1989), while past empirically based modeling efforts leave considerable room for uncertainty of cause and effect (see Southworth and Jones, 1995). The actual outcome for fuel use, and in particular for emissions, of specific spatial arrangements of activities is, again, far from clear. What such studies demonstrate is the underlying complexity of the issues involved in the development of energy efficient and environmentally clean cities. As Pisarski puts it (TRB, 1991), "The attempt to express, much less understand, the nature of the relationships inherent in transportation, urban form and the environment is a great challenge. Analysis can be overwhelmed by the inextricable linkages between them, each shaping, and shaped by, the others."

1.3.2 Practical Issues

The above is a summary of the many conceptual issues involved in urban land use-transportation interactions over time. On a more pragmatic note, simulating the real behavior of a complex urban system also requires the manipulation of substantial detail, what Harris (1983) has called the "central dilemma" with regard to our design and construction of policy useful urban planning models. This detail is required because metropolitan transportation plans are by their nature spatially explicit. They are involved at the fully urban scale with planning for hundreds of thousands of travelers and hundreds of firms. Depending on the model used, developing such plans requires the availability of substantial amounts of spatially referenced data, including socioeconomic-demographic data, network structure data, travel cost data, and possibly housing, commercial, and industrial stock data as well as data on land rents and other factor prices. Indeed, past models have to a significant degree been used to apply theory to fill gaps in existing travel survey and land use inventory data.

As a corollary to this situation, the possible policy actions are also very numerous, and quite varied. Consequently, the attempt to configure policy sets out of combinations of these actions can quickly lead to a combinatorial explosion. The necessary detail required to accommodate such policy analyses within suitably comprehensive model-based tools can, if not cleverly controlled, become quite staggering.

Table 1 lists many commonly cited transportation control measures (TCMs) as they correlate with the five general types of travel-reduction strategies listed in Section 1.2 (see, for example, Boyce et al., 1981; Ferguson, 1990; Euritt et al., 1994). A concern clearly evident within recent literature is that many of these TCMs are only stopgap measures or short-term solutions to the larger questions of how our cities ought to evolve (see Giuliano, 1992; Bae, 1993). The search for cleaner and more fuel-efficient futures may require more radical assessments of our current position. Among the TCMs listed in Table 1 the most promising for *sustainable* reductions in travel appear to be associated with the following:

Table 1. Commonly Referenced Transportation Control Measures

Type of Strategy:	Example TCMs:	Benefits Sought:
1. Vehicular Trip Elimination	Telecommuting, teleshopping, teleconferencing, reduced work week, employer or developer based ridesharing programs,	Fewer commutes, fewer shopping and business trips
2. Trip Length Reduction	Zoning for higher density and/or mixed use developments, satellite workcenters, land use zoning ordinances	Walk trips, multi-purpose trip chaining, shorter commutes, shifts in commuter destinations
3. Mode Switching	Transit subsidies, higher parking prices, road tolls, ramp metering HOV lanes, park-n-ride lots, fringe parking, paratransit, bicycle lanes, pedestrian malls	Moves from LOV's to HOV's, multi-modal trips or nonb-vehcular trips
4. Schedule Shifts	Flexi-time, mixed use centers	Reduced peak period travel
5. Route Changes	Street or area closures to through traffic, ramp metering, tolls, advanced traffic advisory systems (ATIS), advanced traffic management systems (ATMS), commercial vehicle parking, idling controls, automobile-only lanes	Use of less congested routes, reduced double parking and idling, reduced auto-truck interaction

- (1) more efficient urban land use arrangements;
- (2) different forms of travel pricing policies (road tolls, parking charges, high-occupancy-vehicle fare subsidies, fuel and/or emissions taxes);
- (3) how best to use the latest developments in low-cost information processing and telecommunications technology as both a substitute for and a complement to the movement of people and goods.

Within this review, considerations 2 and 3 are subsumed under the notion of a more comprehensive view of “integrated land use-transportation modeling” which encompasses responses to pricing policies and to real-time information systems as part a broader, multiyear analysis of urban lifestyles and business practices. Writing more generally about systems modeling for public policy, Simon (1990, p. 7) sums up the significant technical challenge we face as follows: “We must separate what is essential from what is dispensable in order to capture in our models a simplified picture of reality which, nevertheless, will allow us to make the inferences that are important to our goals.”

A review of urban land use-transportation modeling can therefore be viewed as an assessment of how well we have managed to build such a picture. This is the perspective within which the rest of the review is framed. To get a proper picture we will certainly need to model it. How fine-grained a picture we need to create in order to produce policy-sensitive and sensible models remains a difficult question, but is arguably the most important technical question we need to answer.

Finally, it is important to remember that urban planning is typically a multijurisdictional affair, involving local metropolitan, as well as—where transport is concerned—regional and federal decision-making. Effective modeling must take place within such institutional arrangements and is subject, like the rest of the planning process, to the reigning institutional priorities. This suggests the development of flexible and highly interactive decision support tools which intimately involve planners at all levels in the policy analysis process.

1.4 ORGANIZATION OF THE REVIEW AND MAJOR CONCLUSIONS

The rest of this review is organized as follows. Section 2 describes the current state of the art in operational, integrated urban land use-transportation modeling. This includes a review of the major theoretical and methodological underpinnings of both the transportation and land use components of such modeling systems, as well as a brief summary of current best practice. Section 3 summarizes the strengths and weaknesses of existing approaches as reflected in recent commentaries within the literature. While real

progress has been made over the past three decades, and many advances have passed from one modeling system to another, a number of important weaknesses remain. Just how significant current weaknesses are for policy analysis is currently difficult to assess, given relatively limited application of the majority of these modeling systems in actual planning practice. Reasons for the limited application of these models to date are discussed. As detailed forecasting tools, none of the current models are entirely acceptable, even in the hands of experienced users. However, the nonintuitive results which such model-based exercises regularly throw up suggest that they represent a necessary component of future planning practice. To better replicate traveler responses, however, more behaviorally explicit models appear to be necessary if we are to achieve greater realism.

We also need to recognize that such models, in their software manifestations, are most useful as aids to scenario generation and plan robustness testing, rather than as detailed forecasting tools. By taking advantage of today's low-cost and high-speed computers, we have the opportunity to move into a new generation of urban transportation planning methods which place planners within a highly interactive, multimedia-based approach to the development of strategically focused and incrementally adaptable urban transportation plans. Here, the strategic role of models is to look for the errors that may be associated with planner intuition, especially the errors which can result from single or limited objective and perhaps myopic policymaking.

2. INTEGRATED URBAN LAND USE—TRANSPORTATION MODELS

2.1 OVERVIEW

This section of the report is devoted to a review of operational integrated urban land use-transportation—models, that is, models which have been empirically applied in either a research or actual planning context within the past decade. The term “integrated” implies a feedback mechanism of the type shown in Fig. 2, between the transportation system and the rest of the urban land use system. Here the “land use” system supplies the transportation system with estimates of the location and volume of travel generators. “Land use” is a general term here, covering both the types and intensities of activities taking place at specific urban sites as well as the physical area of land and any built structures used in support of such activities. This involves modeling the demand for employment, residential, shopping, and other activities at different sites, and then translating and possibly constraining these demands on the basis of appropriate physical or artificial (i.e., planner-imposed) land utilization rates. The more ambitious models also include the simulation of housing stocks and floor space requirements for industrial buildings. Within some models this also means simulation of pricing effects on, in particular, residential choice. A further extension in a limited number of modeling systems is a linked simulation of demographic change, allowing the urban area’s population to evolve along with the evolution of the physical city within which it lives and works. Wegener (1994) refers to these types of model as “integrated urban models,” although the interaction between transportation and other land uses remains their key trait.

The spatial distributions of residents and workers are assumed to create the major demands for travel which drive development of the transportation system. The “transportation” system in Fig. 2 represents both the physical infrastructure and services provided by the different travel modes, either separately or in combination, as well as these demands, now translated into mode-specific vehicular and nonvehicular trips, for either passenger or freight movement. This interplay between travel demand and supply resolves itself within the typical transportation model into a series of single-purpose and single-destination trips which together form the on-the-road traffic volumes of interest to an environmental analysis of fuel use and mobile source emissions.

The origin-to-destination travel costs resulting from this interplay between transportation demand and supply can be fed back into the residential and employment activity location models, where they are used to allocate the area’s residents and workers to specific urban zones within the land use model. This allows transportation system

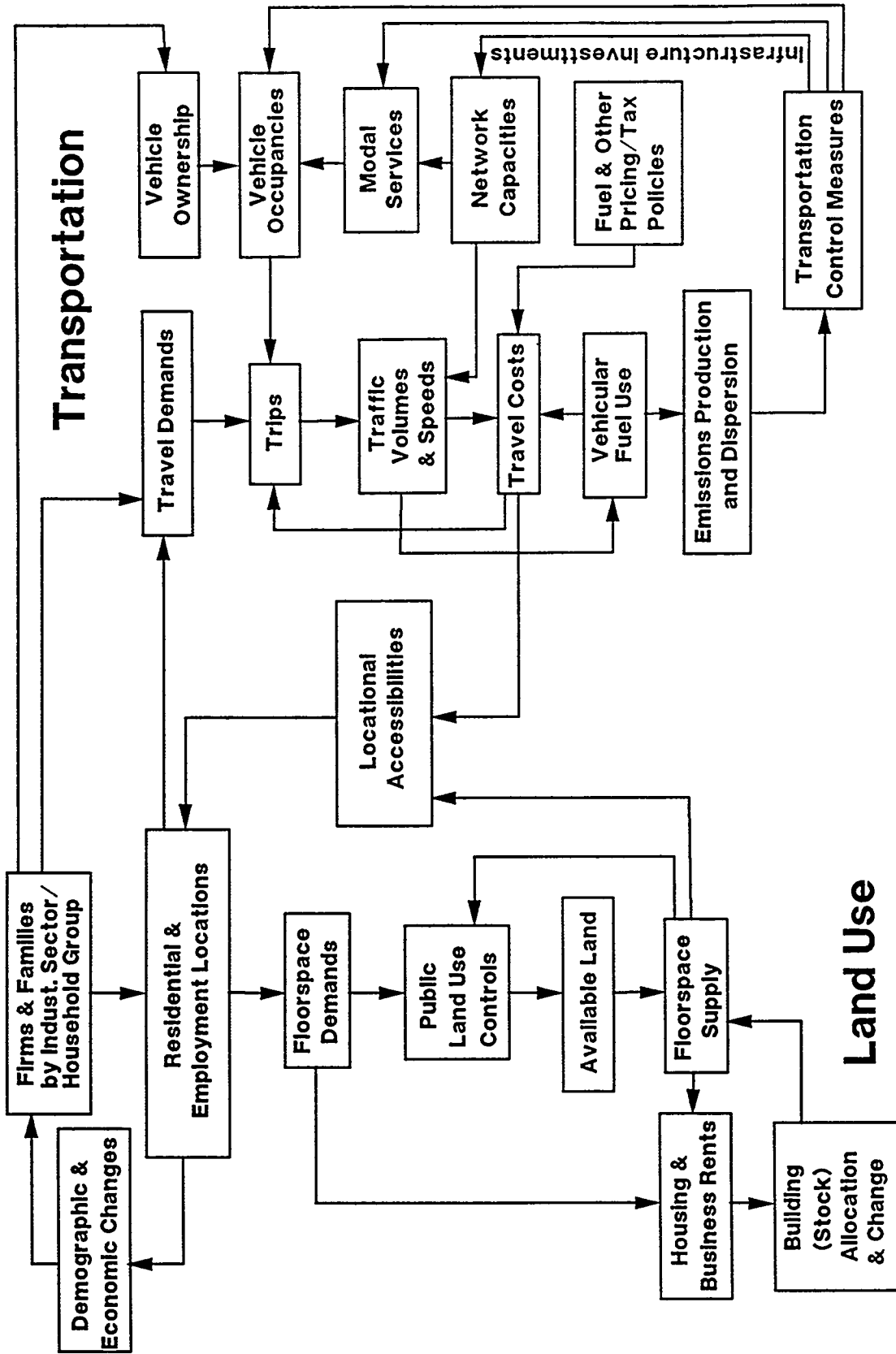


Fig. 2. Integrated modeling: general schematic flow chart.

changes to affect land utilization, which in turn feeds back its effects in the form of new levels (and locations) of traffic generation. The notion of locational accessibility here plays a central role in all currently operational models. As an integral component of such accessibility, travel cost changes become part of the mechanism used to reallocate labor, residents, retail and service activities, and when modeled, freight flows between spatially separated land uses.

In terms of an urban dynamic, most models employ static-recursive approaches to multiyear forecasting or (more realistically) scenario generation. That is, cross-sectional representations of the urban system are moved forward through a series of discrete time intervals. However, both the operational details and level of sophistication imposed on this dynamic vary considerably across existing models. This is the topic for Sect.2.5 below. A common planning horizon for such a single-time-period forecast is 5 years, although intervals from 1 year to as many as 30 years have been used. Forecasting further into the future, an obviously risky business, is accomplished in the more advanced modeling systems by iterating the land use and transportation subsystems through a series of discrete time intervals. In an effort to keep transportation and other urban land uses in some kind of synchronization, both lagged and marginally incremental methods are used to update and to control for selected variables as part of this process.

Figure 2 also shows the location of three types of public policy instruments commonly used to simulate the effects of significant travel reduction strategies: (1) land use controls, (2) fuel pricing policies, and (3) those transportation control measures which impact directly the capacity and level of service of the specific transportation modes.

2.2 SURVEY OF EMPIRICALLY APPLIED MODELS

2.2.1 Survey of the Literature

Table 2 lists the better-known and documented operational models, along with some of their applications to specific urbanized area studies. The table draws heavily on the models reported by the International Study Group on Land Use-Transportation Interaction (ISGLUTI) (Webster, Bly and Paulley, 1988),¹ on the survey of available models by Cambridge Systematics and The Hague Consulting Group (1991), and on the

¹Coordinated through the British Transport and Road Research Laboratory, the ISGLUTI effort carried out comparisons of nine different land use-transportation models using data from cities in seven different developed countries (Annerstokt in the Netherlands; Tokyo and Osaka in Japan; Dortmund in Germany; Leeds in the England; Bilbao in Spain; Uppsala in Sweden; and Melbourne in Australia). Subsequent work has extended these model comparisons to (a) the application of more than one model to the same city (see Wegener, Mackett and Simmonds, 1991) and (b) the application of the same model to more than one city (Mackett, 1991b). This sort of coordination is now being continued through the SIG1 working group within the World Conference on Transportation Research.

Table 2. Some integrated and empirically applied land use—transportation models

Model	Useful References	Example Urban Studies
AMERSFOORT	Floor and de Jong(1981) ^a	Amersfoort, Utrecht, Netherlands; Leeds, UK
BOYCE, ET AL	Boyce, Tatineni & Zhang (1992), Boyce, Lupa, Tatineni & He (1993)	Chicago
CALUTAS	Nakamura et al (1983) ^a	Tokyo, Nagoya, Okayama, Japan
CATLAS/NYSIM /METROSIM	Anas (1983b), Anas & Duann (1986), Anas (1992, 1994)	Chicago, New York
DORTMUND	Wegener (1982a,b; 1986, 1995a) ^a	Dortmund, Germany
KIM	Kim (1989)	Chicago
ITLUP	Putman (1983, 1991) ^a	San Francisco, Los Angeles Houston, Dallas, Portland, Others
LILT	Mackett (1983, 1990a, 1991a,b) ^a	Leeds, England; Dortmund, Germany; Tokyo, Japan
MASTER	Mackett (1990b, 1990c)	Leeds, England
MEPLAN	Echenique et al (1985) ^a , Hunt & Simmonds (1993), Hunt (1993, 1994)	Bilbao, Spain; Sao Paulo, Brazil Santiago, Chile; Naples, Italy; Others.
OSAKA	Amano et al (1985) ^a	Osaka, Japan
POLIS	Prastacos (1986a,b), Caindec & Prastacos (1995)	San Francisco Bay Area.
PSCOG	Watterson (1993)	Puget Sound, Washington.
TRANSLOC	Boyce & Lundqvist (1987), ^a Lundqvist (1989)	Stockholm, Sweden
TOPAZ	Brotchie et al (1980) ^a ; Dickey and Leiner (1983), Sharpe (1978, 1980, 1982)	Melbourne, Darwin, Australia; Prince William Co. Virginia; Others
HAMILTON	Anderson, et al (1994); Kanaroglous, et al (1995)	Hamilton, Canada
TRANUS	de la Barra (1989)	Caracas, La Victoria, Venezuela

^a indicates participation in the International Study Group on Land Use—Transportation Interaction (ISGLUTI) study; see Webster, Blye, and Paulley (1988).

reviews by Berechman and Gordon (1986), Berechman and Small (1988), Mackett (1985), Putman (1983, 1991), and Wegener (1994, 1995b). These sources were supplemented by a further literature search and through contacts with a number of the field's leading model developers.

Among the most recent round of empirically supported U.S. studies of note are those for the Chicago area (Anas and Duann, 1986; Boyce et al., 1992, 1993; Kim, 1989); for the San Francisco Bay Area (Prastacos, 1986a,b; Caindec and Prastacos, 1995); the Puget Sound Region of Washington State (Watterson, 1993); and Portland, Oregon's Land Use, Transportation, and Air Quality (LUTRAQ) study (Cambridge Systematics — Hague Consulting Group, 1991). The most widespread application of a particular modeling approach in the United States comes out of the extensive model development and calibration efforts of Putman and colleagues (see Putman 1983, 1991), whose joint implementations of the Disaggregate Residential Allocation Model (DRAM) and the Employment Allocation Model (EMPAL) are currently used in some fourteen of the largest U.S. metropolitan planning agencies (Putman, 1994). During the 1970s and 1980s Putman also developed the Integrated Transportation Land Use Package (ITLUP), linking DRAM and EMPAL with selected components of the traditional four-step transportation planning model, containing submodels to estimate trip distribution, modal choice, and traffic assignment. References to past empirical applications of ITLUP include studies in Kansas City, Washington, D.C., and Houston. The LUTRAQ study also recommended use of an ITLUP-like approach (Cambridge Systematics et al., 1992b). Recently DRAM and EMPAL have been linked to the TRANSPLAN suite of transportation planning models in a 772-zone application to the southern California region, centered on Los Angeles (Putman, 1994).

Building on the CATLAS model of combined residential location, housing and mode choice, the modeling of non-work travel choices and commercial real estate markets in the New York region (the NYSIM model), and the modeling of metropolitan housing market dynamics in a number of US cities (the CHPMM model), Anas and colleagues have developed a highly integrated economic model of transportation and land use called METROSIM. METROSIM (Anas, 1994) consists of 7 sub-models, providing analysis of a region's basic industry, non-basic industry, residential and commercial real estate, vacant land, households, commuting and non-commuting travel and traffic assignment, within a single, jointly solved-for structure that is strongly oriented towards theoretically sound and empirically workable economic relationships.

In the United Kingdom notable efforts to develop land use-transportation models are found in both the theoretical and the empirical work begun by Wilson and colleagues at the University of Leeds (see Wilson et al., 1977, 1981), and carried on by Mackett at the University College, London. Mackett has devoted considerable effort to building and calibrating both the Leeds Integrated Land Use-Transportation modeling package (LILT) (Mackett 1983, 1991a,b) and the MASTER microsimulation-based modeling system (Mackett, 1990b). Echenique and colleagues at the University of Cambridge, and subsequently within the commercial sector, have been especially energetic in developing

and applying the MEPLAN modeling system. Their work includes planning applications for the city of Bilbao, Spain, and for the Third World cities of Sao Paulo, Brazil (Echenique, 1985); Caracas, Venezuela (Feo et al., 1975); and central Chile (de la Barra et al., 1975). Hunt and Simmonds (1993) reference 22 different empirical applications of MEPLAN, including a recent study for Naples, Italy (Hunt, 1994). A similar but now separate modeling system, TRANUS, has also been applied to the island of Curacao and the city of La Victoria in Venezuela (de la Barra, 1989), as well as to more idealized simulations of energy and urban form relationships (de la Barra and Rickaby, 1982; Rickaby, 1987, 1991). Johnston (1995) indicates that TRANUS is currently being experimented with in Sacramento, at the University of California at Davis, where it is being examined in conjunction with the California Urban Futures Model, or CUFM (see Landis, 1994).

Pioneering work in the field has also resulted from a long-term involvement in the area by the Commonwealth Scientific and Industrial Research Organization (CSIRO) in Australia, based largely on use of the TOPAZ modeling system (Brotchie, 1969; Brotchie, Dickey, and Sharpe, 1980; Sharpe, 1978, 1980, 1982 and other references therein). As its name implies (Technique for Optimal Placement of Activities in Zones), the approach taken in the TOPAZ model is a normative one, using a very general location-allocation modeling system adaptable to a number of different scales of spatial analysis. In recent work, the object-oriented SUSTAIN model (Roy and Marquez, 1993) is being developed to facilitate more idealized, less idiosyncratic comparisons of different energy-efficient forms of urban transportation infrastructure development.

Other work of interest in Australia includes development of the LAND gaming-simulation model by Young and colleagues at Monash University in Melbourne (Gu et al., 1992), and the proposed PIMMS (Pricing and Investment Model for Multi-Modal Systems) model, described by Hensher et al. (1993) at the University of Sydney.

In Canada, initial progress in the development and empirical application of an integrated land use-transportation model to the Hamilton Consolidated Metropolitan Area is reported by Anderson et al (1994), Kanargolou et al (1995) and Anderson, Kanargolou, and Miller (1994). Here the early focus has been placed on simulating automobile fuel consumption and emissions.

In Japan, integrated urban modeling includes the CALUTAS model (Computer-Aided Land Use Transport Analysis System) (Nakamura et al., 1983) and the Osaka model (Amano et al., 1985). Wegener (1994) briefly references other recent Japanese developments. Other non-U.S. studies include van Est's (1979) modeling of the Eindhoven urban area; Bertuglia et al.'s (1981) modeling of Turin and Rome in Italy; and a number of modeling applications to the city of Stockholm in Sweden, including application of the Transportation and Location, or TRANSLOC, model listed in Table 2 (see Boyce and Ludqvist, 1987, for example).

For the Middle East, Garnett (1980) reports a planning model and policy application for Tehran, Iran. Martinez (1992a,b) recently calibrated his own version of an integrated land use-transportation model for Santiago, Chile. Finally, Cambridge Systematics and The Hague Consulting Group (1991) also report the existence of two commercially available, ITLUP-like computer packages known as TRACKS and TRANSTEP, with 51 reputedly different applications in Australia and the Far East.

2.2.2 Nature of Model Applications

As a set, the models listed above have been empirical by applied to a wide range of policy questions. While the initial reasons for developing the various modeling approaches may have differed, the ISGLUTI study found sufficient similarity across nine of the models reported in Table 1 to carry out a set of common tests. These tests covered the effects on travel choices and land use arrangements from introducing changes in the following variables:

- population,
- land use restrictions,
- employment location policies,
- the location of retail (shopping) facilities,
- the costs of travel,
- mode-specific travel speeds and network structure,
- the timing of transport investment, and
- general economic climate (economic recession, narrowed income distribution).

Moving into specific policy impact studies, Mackett (1994) concludes that current models can be particularly useful for analyzing either congestion reduction or energy reduction strategies. (Also considered were safety, the environment, social equity, quality of life, public expenditure and privatization policies.) He lists the following commonly available (if not always popular) public policy instruments as being well suited to analysis with models which integrate transportation planning decisions into a broader and longer-range analysis of land use.

- restrictions of peripheral urban development,
- increases in the gasoline tax,
- increases in public transportation subsidies,
- increases in investments in public transportation infrastructures,
- increases in transportation system (supply) management,
- increases in transportation demand management, and
- introduction of road pricing schemes.

In a research context a handful of past studies have also used such models to look specifically at alternative, if rather abstract, energy-efficient urban futures (see Sharpe, 1978, 1980, 1982; de la Barra and Rickaby, 1982; Rickaby, 1991; Roy and Marquez, 1993). In the United States the 1990 Clean Air Act Amendments and supporting legislation within the 1991 Intermodal Surface Transportation Efficiency Act have caused recent practice to focus on using such models to forecast future levels of urban air quality (see Putman, 1994, using the DRAM/ITLUP modeling approach; and Watterson, 1993, using modified versions of the DRAM and EMPAL models within the Puget Sound Council of Governments model).² The spatial as well as temporal extent of such applications also varies, from specific highway or transit corridor analyses to full-scale urban area or complete transit network simulations.

2.3 MODELING THE URBAN TRANSPORTATION SYSTEM

Urban transportation modeling began in earnest in the mid-1950s in the United States (see Weiner, 1992, for historical developments). Since the 1960s most metropolitan areas have used variants of the Urban Transportation Planning System (UTPS) models shown in Fig. 3. This four-step, single-destination, separable-purpose, daily trip-based approach has dominated the transportation modeling literature. This includes its use within the integrated land use-transportation models listed above. It has been used to address a wide range of issues covering the physical, economic, and (in recent years) energy and environmental impacts of major highway or rapid transit investments. The approach is sequential in order to avoid some very difficult multicollinearity problems found to affect more direct estimation techniques. It is also meant to be iterative in order to bring the transportation costs computed within the trip distribution (= destination), modal choice, and traffic assignment (routing) submodels down to a common set of values.

In this system the urbanized area is first divided up into a set of spatially contiguous traffic-generating and attracting zones. For our largest cities this involves definition of dozens, sometimes hundreds, of zones linked to highway and transit networks containing hundreds, sometimes thousands, of link and node records. The computational process can be started with a simple all-or-nothing assignment of traffic to least-cost interzonal travel paths. This can be done before any actual trip volumes are "loaded" onto the network. Land use, when modeled explicitly, comes into the process through its influence on trip generation rates. Alternatively, daily trip frequencies are estimated directly from zonally based population and employment forecasts. These

² A summary of the transportation programs and provisions of the CAAA has been written by the Federal Highway Administration (FHWA, 1992a). Summaries both of the complete ISTEA, and of its air quality programs and provisions are also provided by the Federal Highway Administration (FHWA, 1992b,c).

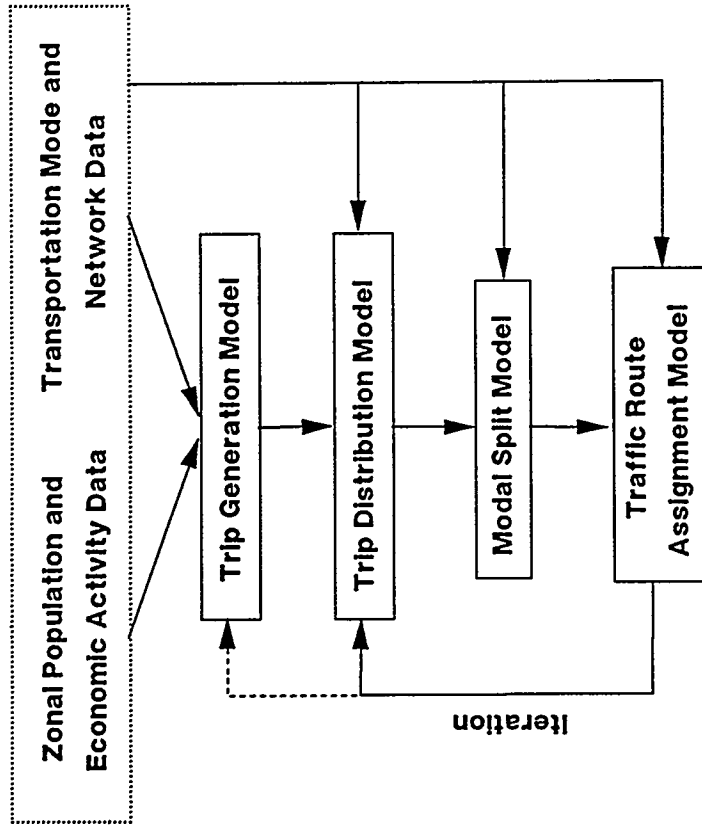


Fig. 3. Traditional four step urban transportation planning model.

forecasts are suitably disaggregated by household type or economic sector based on significantly different observed averaged trip rates. The trip generation (and trip attraction) models are usually regression based, or built on category analytic techniques (see Douglas and Lewis, 1970/71; Institute of Traffic Engineers, 1987).

For a set of zone-specific, average daily trip originations, one or more trip distribution models are then used to allocate purpose-specific trips to destinations within the remaining set of urban analysis zones. Within these spatial interaction models the concept of locational accessibility to opportunities plays a central role in the allocation process. If travel is a derived demand, then accessibility is the "good" it provides. Such locational accessibility indices have the form

$$a_i = \sum_j a_{ij} = \sum_j W_j^\alpha f(c_{ij}) \quad (1)$$

where W_j = the level of demand, or more generally a measure of the attractiveness of a potential destination zone j for trips of a given purpose (e.g., journey to work, shopping); c_{ij} = the cost of travel from the trip's origination zone, i , to destination zone j ; α = an economies-of-scale parameter ($0 \leq \alpha \leq 1$); and $f(\cdot)$ = a travel mode and distance-based cost decay function, such as $\exp(-\beta \cdot c_{ij})$. Here β is a distance-based cost sensitivity parameter, which the modeler must estimate. Within a work trip model, W_j may refer to the number of jobs available in zone j . More generally, it may be a composite, multiplicative, or additive index of locational attractiveness. Similarly, the travel costs c_{ij} may be of a composite or a "generalized" form, typically including both travel time and any fares or other monetary operating costs incurred during a trip.

The use of spatial interaction models in urban planning studies gained a boost with the elaboration of both entropy maximizing (Wilson, 1967, 1970) and utility maximizing (Neidercorn and Bechdolt, 1969; Golob, Gustafson and Beckmann, 1973) theories, which have provided, respectively, a more robust statistical mechanics/information theoretic basis and a rational economic basis for spatial interaction theory. Subsequent theoretical efforts to link these two approaches during the 1970s and 1980s have further strengthened the hold of "logit" forms of interaction model on the discipline (see Anas, 1983a; Brotchie et al., 1979; Williams, 1977; Wilson, et al., 1981). Such a logit model can be stated as

$$T_{ij} = O_i [\exp(v_{ij}) / \sum_j \exp(v_{ij})] \quad (2)$$

where T_{ij} = the number of trips between zones i and j , O_i = the number of trips generated at location i (for a particular trip purpose), and v_{ij} = a multicriteria value function reflecting the attractiveness of location j as a destination for such an i -based trip. By setting each $v_{ij} = [\alpha \ln W_j - \beta c_{ij}]$ we have the following direct connection to Eq. (1):

$$T_{ij} = O_i (a_{ij} / \sum_j a_{ij}) \quad (3)$$

This is a popular form of origin, demand or “production”-constrained spatial interaction model, which Wilson (1971) placed within a family of possible models, including destination (supply, “attraction”)-constrained as well as demand *and* supply (“doubly”)-constrained forms.³ The issues of why and when we travel are handled within this framework by incorporating disaggregations by trip purpose and time of day, respectively. This usually leads to separate matrices of zone-to-zone flows coming out of a work trip model and one or more types of nonwork trip (e.g., shopping, social and recreational, school trip) distribution models.

The modal choice submodel “splits” these interzonal trip volumes across the most likely travel modes (usually auto versus public rail or bus transit, but with walk, cycle or multimodal trips also possible). The logit is again the most popular form in use. At this step “disaggregate”—that is, individual traveler—response-based multinomial logit models have also become popular in the United States, using McFadden’s (1974) maximum likelihood method to include a wide range of explanatory variables as well as multiple travel choices within such model calibration efforts.

A subsequent and now increasingly used theoretical development was the specification of “nested” logit forms, which allow the results from one production-or attraction-constrained logit model to be passed into another in a behaviorally consistent manner (see Williams, 1977; Ben-Akiva and Lerman, 1985). For example, mode m-specific travel (dis)utilities, c_{ijm} (i.e., modal travel costs), can be averaged into a destination choice model such as Eq. (2) above, using log-sum or inclusive value terms of the form

$$c_{ij}^* = -(1/\lambda) \ln \sum_m \exp(\lambda c_{ijm}) \quad (4)$$

where c_{ij}^* is now the modally averaged disutility of travel between i and j . Here λ is a calibrated model parameter representing the sensitivity to modal cost differences in a manner analogous to the way β represents sensitivity to distance-based destination choice in Eq. (2). Taking such a nesting one stage further, we can also compute the expected or averaged travel (dis)utility associated with the set of mode *and* destination combinations available to a traveler located in zone i , v_i^{**} , using an inclusive value index of the form

$$v_i^{**} = \ln \sum_j \exp(\alpha \ln W_j - \beta c_{ij}^*) \quad (5)$$

³ Doubly constrained spatial interaction models have been popular as journey-to-work models where a planning agency has census data or other means of producing what it considers reasonably accurate estimates of zonally based trip productions and attractions.

which, in terms of equation (1) above is a log-accessibility measure, and which in economic terms is often interpreted as a locational or consumer's surplus measure associated with zone i (see Williams, 1977; Fisk and Boyce, 1984).

The resulting mode-specific interzonal traffic volumes are then assigned to one or more routes, or paths, by the traffic assignment submodel shown in Fig. 3. This results in a new set of interzonal travel costs which ought to be submitted back to the trip distribution model. The process of model calibration should then be continued by iterating the travel costs within the various mode, destination, and assignment submodels until they converge to a single set of values.

A number of variants on this iterative procedure are now used (see Boyce, Lupa, and Zhang, 1994). At the traffic assignment stage the auto trips and any truck trip matrices that have been generated are converted into passenger car equivalent traffic volumes before being simultaneously loaded onto the highway network. Logits can also be used to select alternative routes and have been incorporated within a number of different assignment methods (see Sheffi, 1985). However, the most commonly referenced assignment model is the capacity-sensitive approach proposed by Wardrop (1952). Under this approach, which is geared to handling the congested conditions experienced during the commute to and from work, urban traffic volumes are distributed such that all multilink routes used between any origin-to-destination pair of traffic zones have the same travel time, while all available but unused routes have a higher travel time. The result is termed a user optimal equilibrium assignment in which no traveler can change his or her route without incurring extra en route delays (Beckmann, McGuire, and Winsten, 1956). Mathematically, this can be stated as

$$\text{Minimize } \sum_a \int_0^{f_a} C_a(x) dx \quad (6)$$

subject to

$$f_a = \sum_i \sum_j \sum_p \delta_{ij}^a X_{ij}^p \quad \text{for all links } a \in \text{network} \quad (7)$$

$$\sum_p X_{ij}^p = T_{ij} \quad i, j = 1, \dots, N \quad (8)$$

$$f_a \geq 0 \quad \forall \text{ links } a \quad ; \quad X_{ij}^p \geq 0 \quad \forall \text{ paths } p \in \text{network} \quad (9)$$

where T_{ij} is a trip matrix, and we are solving for f_a = the flow of traffic on link a . Here $C_a(f_a)$ = the congestion-sensitive cost of travel along link a , such as a convex function of

the form $c_a(1+\gamma_a f_a)^4$ for c_a = free flow travel time, and γ_a = a function of the link's design capacity.

The X_{ij}^p variables in Eq. (7) represent the number of trips from origin i to destination j using multilink route (path) p , and $\delta_{ij}^{ap} = 1$ if link a belongs to route p , and is zero otherwise. Equation (7) ensures that each link's assigned traffic volume is the sum of the volumes of each path using it, while Eq. (8) ensures that all route volumes from a given origin-to-destination sum to the original number of i -to- j trips input to the algorithm (from the trip distribution modeling step described above).

Figure 4 shows a simple two-route, two-link example for the type of link speed-volume relationships often used in practice. The area created under these two marginal link travel cost curves is the solution to the objective function given by Eq. (6) above. Efficient computational procedures now exist for solving this and similar capacity-constrained traffic assignment problems for quite large and detailed urban area networks. Recent developments by Janson (1991) and Janson and Southworth (1992) have also extended this sort of equilibrium assignment model into computationally tractable dynamic forms, which may soon allow the analysis of such strategies as staggered work trip departure times and their effects on traffic congestion. Such developments also take us squarely into the realm of Intelligent Transportation Systems (ITS) research, an area currently receiving large amounts of funding from the U.S. Department of Transportation (DOT) in support of the 1991 ISTEA legislation.

Rail transit options are usually modeled over their own, separate network. Where bus transit is a significant alternative, passenger car equivalent (pce) conversion factors can be used to simulate the effects of each bus within the resulting traffic stream, and suitable network coding techniques can handle the presence of bus-only lanes or other forms of high-occupancy vehicle (HOV) facility. A similar pce procedure can also be used to portray the effects of larger trucks in the traffic stream.

Variants on this same four-step transportation system modeling process are often used for both long-term (10-to 30-year) planning, and shorter range (1-to 5-year) transportation system management (TSM) planning (see Yu, 1982, for an overview). In some cases specifically designed variants on the overall modeling approach have been developed to better focus on a particular TSM strategy; these include the Network Performance Evaluation Model developed for the U.S. Department of Energy (DOE) to analyze the energy and environmental impacts of various types of HOV lanes, (see Janson, Zozaya-Gorostiza, and Southworth, 1987).

Fuel use and related mobile-source, pollutant-specific emissions estimates are typically computed using these assignment model-generated traffic volumes and speeds. For this purpose baseline emissions estimates for light-duty motor vehicles (automobiles and light trucks) are generated by the Federal Test Procedure. Under the FTP vehicles go

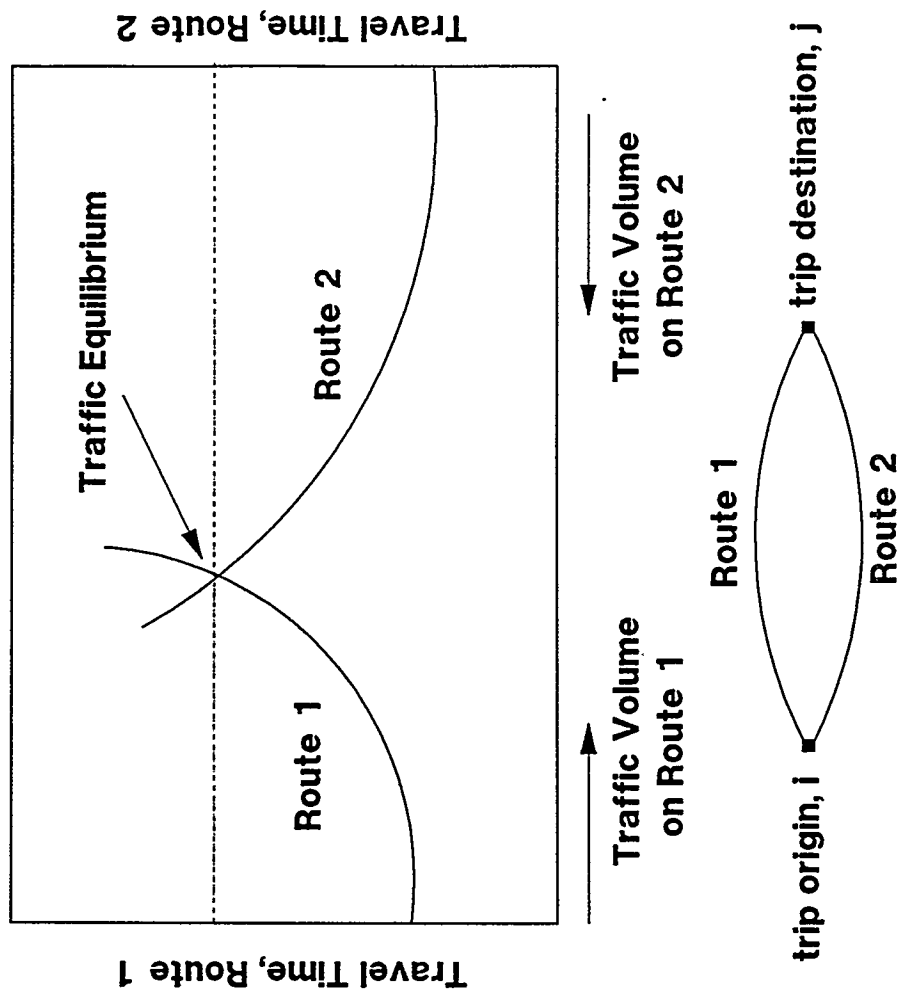


Fig. 4. Simple two route, two link congested traffic assignment.

through a series of stops and starts with an average driving speed of 19.6 mph. Emissions rates for vehicles at other speeds are derived by a statistical regression of fuel consumption against average speed for cycles other than the FTP. Speed correction factors (SCFs) for this purpose have been developed by the U.S. Environmental Protection Agency and by the California Department of Transportation.

However, these emissions outputs, and the traffic volumes themselves, are usually aggregated or averaged over one or more traffic analysis zones for the purposes of computing emissions on a wider regional or "gridded" basis (see Quint and Loudon, 1994; Outwater and Loudon, 1994). Currently, there is a good deal of uncertainty surrounding the accuracy of emissions calculations for carbon monoxide (CO), hydrocarbons (HC), and oxides of nitrogen (NOX) and, in particular, their relationship to actual traffic conditions (see Guensler, 1993; Bae, 1993). Nor were the traffic volumes and speeds from static traffic assignment models meant to handle such details. While detailed traffic simulation programs based on individual vehicle movements are now also in use, it has been only recently, and in a research context, that this sort of detailed traffic flow modeling has been tied directly to emissions estimation (see Matzoros and Van Vliet, 1992a,b), and little testing of its accuracy has been carried out.

For the purposes of estimating areawide CO₂ emissions, which are highly correlated with total fuel used, less concern for such accuracy may be warranted. Unlike the CAAA-controlled pollutants, which are by volume comparatively marginal engine emissions, CO₂ emissions are highly correlated with fuel used and associated, congestion-conditioned vehicle miles traveled (VMT). Nor need we be concerned within such an analysis of greenhouse gas buildup with such location-specific issues as the health effects of CO hotspots.

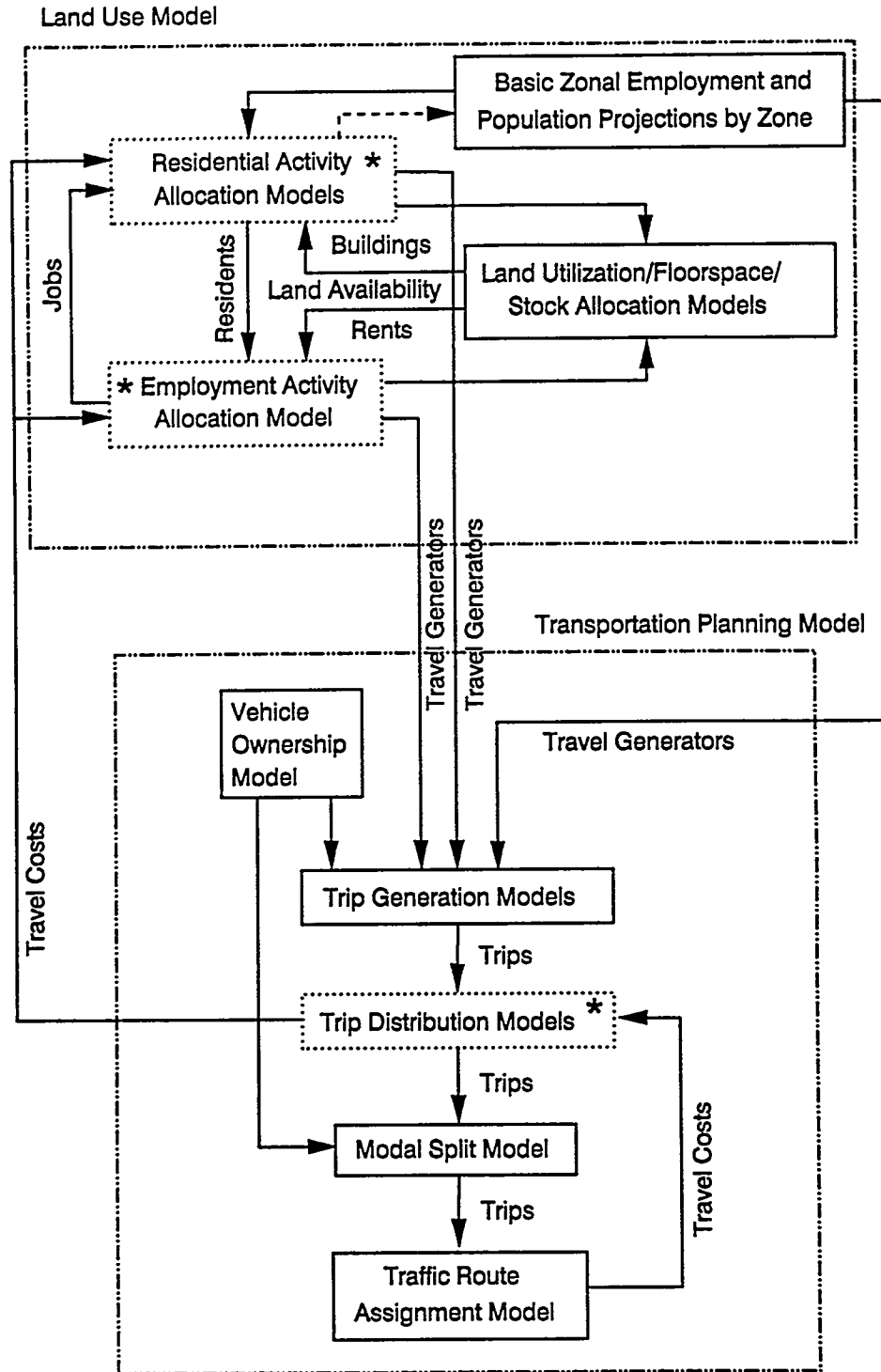
2.4 LINKING TRANSPORTATION AND URBAN LAND USE MODELS

Urban land use modeling also began in the 1950s, again in the United States (see Batty, 1980, who dates such efforts from 1958). Most of today's operational land use-transportation models derive from ideas and model forms introduced into the wider literature during the 1960s and 1970s. There is now an extensive literature dealing with the theoretical and methodological as well as operational aspects of such models. The discussion presented below draws on the historical and technical accounts and efforts at synthesis described in, among others, Anas (1984), Batty and Hutchinson (1983), Berechman and Gordon (1986), Berechman and Small (1988), Bertuglia et al. (1987), Echenique and Williams (1980), Echenique (1985), Kim (1989), MacGill and Wilson (1979), Mackett (1985, 1994), Putman (1983, 1991, 1994), Transportation Research Board (1990), Wegener (1994, 1995b), Wilson (1987), and Wilson et al. (1977, 1981).

Figure 5 shows the basic idea behind linking a land use model to the four-step transportation planning model described above. As noted in this figure, a number of modeling systems use the spatial interaction formulas at the heart of their residential and employment location submodels to replace (obviate the need for) a separate set of trip-based distribution models. The ITLUP model can be used to generate such trip distributions within the DRAM submodel. The MEPLAN and TRANUS models generate all of their inter-zonal flow matrices as a series of “trades” within the land use modeling system. Within a number of operational models, including the MEPLAN and Kim models described later in this review, the urban system is modeled as a series of markets, with emphasis placed on clearing a transportation market and one or more other land use markets, by solving endogenously for a suitable set of spatially varying market prices; which include travel costs and site rents. Within the less inclusive models, such as ITLUP, which avoid endogenous modeling of nontransportation price mechanisms, an equilibrium between the transportation system’s demands and supplies can also be brought about; this also stabilizes the parameters within the residential and employment activity location submodels. Such considerations of equilibrium in urban evolution quickly take us into the area of temporal dynamics. Within the ITLUP, MEPLAN, and Dortmund models described in some detail below, lagged effects play an important role in linking different submodels within the transportation and land use systems both across as well as within a single time period (see Sect. 2.5, below).

While operational transportation planning models have tended to be built around the above four-step approach, once we link these developments to urban land use models a good deal more variety is evident. At least five significantly different theoretical and/or methodological approaches have combined to produce the current state of best practice among such extended and “integrated” modeling systems. Each of these approaches—the Lowry model, normative and mathematical programming developments, spatial input-output analysis, urban economics, and microanalytical simulation—is reviewed briefly below.

In the discussion of each of these approaches a model from Table 2 has been selected for detailed presentation, as a means of demonstrating how such developments translate into current modeling practice. *The reader should note, however, that the assignment of a model below to a particular approach is somewhat arbitrary.* The order of presentation was selected to show how current models have brought developments from a number of the above discussed advances into their frameworks. A significant feature of model advances over the past 30 years has been the gradual incorporation and unification of different theories and methods within individual modeling frameworks. The purpose of the following descriptions is not to fully elaborate on any single modeling system but to use specific models to elaborate on key areas of development. In selecting examples for presentation there is also a strong bias towards U.S.-based modeling efforts. For a complete list of a model’s current functionality the reader should see the references cited in the text.



* in some systems these are substitutable spatial interaction models

Fig. 5. Integrated urban modeling showing typical submodels.

2.4.1 The Lowry Model and Related Developments

2.4.1.1 Background

Most operational urban land use models today, and all of those discussed below, can trace their beginnings to Lowry's (1964) "Model of Metropolis" for the city of Pittsburgh. The original Lowry model incorporates the spatial distribution of population, employment, retailing (the entire service, or "non-basic," sector), and land use within a compact iterative procedure requiring only nine equations and three inequalities. In essence, the approach consists of linking together two spatial interaction models. One of these models allocates workers to a predefined set of land use zones on the basis of exogenously supplied basic employment levels (i.e., employment in manufacturing and primary industries). The dependent families of these workers are then defined using a suitable activity ratio (the ratio of total regional population to total regional employment). These workers and their families demand services, and these demands are met by means of a second spatial interaction model which allocates this service supply, in the form of "nonbasic" employment, across the same spatial zoning system. Iteration is required to then bring the resulting residential and nonbasic employment activity allocation models into line with each other. To generate estimates of either land area occupied or floor space used within each zone a two-stage process is required. First, the residential and employment activity levels are allocated across the set of available zones, then suitable activity-to-floor space rates are assigned, with checks to ensure that the physical limits and any planning restrictions on the space within a zone are not violated.

2.4.1.2 DRAM, EMPAL, and ITLUP

In the United States the most used successors to Lowry's model are the Disaggregate Residential Allocation Model (DRAM) and the Employment Allocation Model (EMPAL) as developed by Putman and colleagues (see Putman, 1983, 1991). Both are now in use in a number of U.S. cities (a recent count was 14; Putman, 1994). On the basis of empirical testing Putman (1983, Ch.7) specified DRAM to have the form

$$N_i^n = \sum_j (\sum_k a_{kn} E_j^k) [W_i^n f^n(c_{ij}) / \sum_i W_i^n f^n(c_{ij})] \quad (10)$$

where N_i^n = the number of type n residents in zone i; $f^n(c_{ij})$ = a cost of travel function for type n residents moving from i to j ($= c_{ij}^{\gamma^n} \cdot \exp[-\beta^n \cdot c_{ij}]$, where γ^n and β^n are parameters to be estimated); E_j^k = the amount of employment in sector k in zone j; a_{kn} = a regionwide coefficient relating the number of type k employees to type n households; and W_i^n = a composite measure of the attractiveness of zone i to employees from residential group n, and given as

$$W_i^n = (L_i^u)^{q^n} \cdot (1+x_i)^{r^n} \cdot (L_i^r)^{s^n} \cdot \prod_n \{ [1 + (N_i^{n'} / \sum_n N_i^{n'})^{b^n}] \} \quad (11)$$

and where L_i^u = the area of vacant, developable land in zone i ; x_i = the proportion of developable land in zone i which has already been developed; L_i^r = the area of residential land in zone i ; and q^n , r^n , s^n and b^n are parameters to be estimated.

A similar level of elaboration has gone into development of a number of service employment location models. Putman (1983) provides the following formula for EMPAL:

$$E_{jt}^R = \lambda [\sum_i P_{it-1} A_{it-1}^R W_{jt-1}^R f(c_{ijt})] + (1-\lambda) E_{jt-1}^R \quad (12)$$

where E_{jt}^R refers to the amount of retail employment in sector R in time period t in zone j ; P_{it-1} is the total population in zone i in prior time period $t-1$, and W_{jt-1}^R is the attractiveness of zone j for sector R activity in period $t-1$. This is also a composite index of the form

$$W_{jt-1}^R = (E_{jt-1}^*)^\alpha L_j^\beta \quad (13)$$

for E_{jt-1}^* = total employment in zone j in prior period $t-1$; L_j = the total land area of zone j ; and α and β are parameters to be estimated. Finally, the "balancing term" A_{it-1}^R in Eq.(12) has the form

$$A_{it-1}^R = [\sum_j W_{jt-1}^R f(c_{ijt})]^{-1} \quad (14)$$

which is interpreted within this and most spatial interaction models as the inverse of a spatial accessibility index of the Hansen type (Hansen, 1959) (recall Eq. 1).

Putman (1994) discusses the recent experience of regional and metropolitan planning agencies with these iteratively linked models, which require an additional subroutine or submodel to translate their activity allocations into suitable zonal land utilization rates. He notes that income group quartile and quintile disaggregations (the latter matching trip generation model groupings) are most common within DRAM; but that ethnicity may be at least as useful a component in residence selection within some of our larger cities. He also discusses possible lagged variable forms of DRAM as a means for improving next period forecasts of zonal populations by income group (Eq. 10 above). Similarly, within EMPAL a number of employment sectors may be defined, for example, based on Standard Industrial Classification (SIC) groupings.

The first operational and truly "Integrated" Transportation Land-Use Package (ITLUP) in the United States appears also to have been developed by Putman (see Putman, 1983, 1991) to provide a feedback mechanism between DRAM, EMPAL, and the mode split and traffic assignment components of the UTPS model described in Sect. 2.3. First EMPAL allocates employment across analysis zones in the forecast time period (period t) using prior period ($t - 1$) accessibility, population, and employment totals. A typical sectoral breakdown might be two industrial (heavy and light), one basic nonindustrial, and one nonbasic (e.g., retail) sector (Webster et al., 1988). These are typically 5-year forecasts. DRAM next forecasts the future allocation of households using prior period ($t - 1$) locational accessibilities but also using the forecast period t distribution of zonal employment.

A third submodel, actually within DRAM and termed LANCON, calculates land consumption in the forecast period by combining base year data with a forecast based on multiple regression. DRAM also contains the system's trip distribution models, by converting the housing allocation probabilities into vehicle trips using region-specific vehicle utilization rates. Three trip matrices are produced: home-to-work, home-to-shop, and work-to-shop trips. The home-to-work trip matrices are then split into private and public vehicular modes using a multinomial logit model, and private trips are allocated to the highway network using one of at least four available types of capacity-constrained traffic assignment (see Putman, 1983, 1991). Travel cost changes are fed back into the residential and employment allocation models, which in turn—and subject to suitable physical capacity or other planning constraints on zonal land use—will then generate new interaction matrices as a result of revised locational accessibility measures.

Over the years Putman and colleagues have explored a number of variations on this static-recursive approach to forecasting (Putman, 1983, 1984, 1991). Miller (1990) also describes a number of different approaches to this recursive modeling process and provides a matrix formulation for ITLUP which mirrors Garin's (1966) matrix formulation of the original Lowry model.

In a recent study for PSCOG, Watterson (1993) also describes the results of linking modified versions of DRAM and EMPAL (see Watterson, 1990) to the widely used UTPS software. This study is notable for its use of widely available modeling packages, as well as an interesting description of their application to a highly visible public planning study, beset with real-world problems and deadlines. The process of generating alternative scenarios used was, however, a much simpler one: first set basic employment levels, then for the year 2020 create a baseline set of travel costs and run DRAM and EMPAL, then create scenario-specific sets of transportation system improvements for 2020, rerun DRAM and EMPAL, and then rerun the UTPS travel models. Scenario-specific results are then compared to the 2020 baseline model run. That is, a series of alternative 30-year scenarios (1990–2020) are generated within a single feedback loop. Attention was given to environmental concerns, including the

simulation of regionwide mobile source emissions estimates. Scenarios developed included application of a wide range of TCM strategies to different forms of polynucleated urban development.

An advantage of the DRAM/EMPAL-based approaches is their basis in generally available data sources. This emphasis also translates into a weakness of the approach: the absence of any mechanism for simulating the land market clearing process underlying multiyear infrastructure change. Clearly, more comprehensive simulation of the land market requires additional data that is generally difficult to collect, notably data on the pricing of land, housing, and other forms of development. An unresolved issue is how effectively we can generate multiyear land use-transportation plans without incorporation of such additional details.

2.4.2 Normative Planning and Related Mathematical Programming Developments

2.4.2.1 Background

A second and equally consistent line of advance has resulted from a normative approach; reflecting a long held interest within the planning profession for best possible solutions. Emphasis on prediction of future outcomes, or indeed the replication of current or past ones, is replaced here by efforts to define, or to "design," more efficient urban futures. This viewpoint brings with it at least three advantages: (1) it can make use of generally simpler mathematical forms that are readily tied to theories of system efficiency, cost minimization, or net gain; and therefore (2) it avoids the need to account for a wide range of empirically observed idiosyncrasies, while (3) using mathematical programming frameworks to state the urban land use-transportation problem as a single, if rather complex, mathematical formulation.

From early beginnings in the use of linear programming models of residential location (see Herbert and Stevens, 1960; Harris, 1965), in which the "bid-rent function" (see Sect. 2.4.4 below) made its operational appearance, an important step forward came with the recognition that spatial interaction models could also be written as convex programming problems which could themselves be embedded within activity-allocation modeling frameworks (see Wilson et al., 1981, for an extensive technical treatment; also Erlander, 1977.)

The resulting urban "location-allocation models" usually take the form of convex mathematical programs subject to a set of linear planning constraints. For example, an interesting rearrangement of Eq. (1), using the logit/entropy maximizing form of travel cost function, gives

$$a_i = \exp\left[\beta\left(\frac{\alpha}{\beta} \ln W_j - c_{ij}\right)\right] \quad (15)$$

A theorem for embedding interaction models within mathematical programs (see Wilson et al., 1981, Sect. 7.2.3) then allows the following mathematical program to be formed, in which the maximization is now based on the selection of suitable values for both the volume of flows $\{S_{ij}\}$ and the size of activity centers $\{W_j\}$:

$$\text{Maximize } Z(S_{ij}, W_j) = \sum_{ij} S_{ij} \left(\frac{\alpha}{\beta} \ln W_j - c_{ij} \right) \quad (16)$$

subject to

$$S_{ij} = O_i [W_j^\alpha \exp(-\beta c_{ij}) / \sum_j W_j^\alpha \exp(-\beta c_{ij})] \quad (17)$$

[which is a restatement of Eq. (2)] , and

$$\sum_j W_j = W = \text{total supply of floorspace} \quad (18)$$

Coelho and Wilson (1976) show how to remove the nonlinearities in the constraint set (17) to form the following mathematical program:

$$\text{Maximize } Z(S_{ij}, W_j) = \sum_{ij} S_{ij} \left(\frac{\alpha}{\beta} \ln W_j - c_{ij} \right) - \left(\sum_{ij} S_{ij} \ln S_{ij} \right) \quad (19)$$

which can be stated more generally as

$$\text{Maximize } Z = \text{Net Locational Benefits} + \text{Spatial Entropy}$$

subject to the constraint (18) on the overall supply of floor space (in their example, shopping floorspace), and to the following origin-zone-specific activity constraints:

$$O_i = \sum_j S_{ij} \quad \forall i \quad (20)$$

The entropy term $(-\sum_{ij} S_{ij} \ln S_{ij})$ here reflects recognition of the systemwide level of spatial dispersion associated with destination choice. That is, not always the nearest (or largest) activity center will be chosen. Again β reflects a travel distance decay effect, while α , with values between 0.0 and 1.0, ameliorates the effects of spatial concentration of activities on this destination choice. Model calibration requires that we find suitable values for the parameters α and β ; a procedure for which a number of numerical analysis techniques (e.g., Newton-Raphson, linear interpolation) are in general use.

These and related discoveries led researchers in a number of countries to use the mathematical programming approach to pursue alternative formulations of interrelated facility location-allocation problems. This includes the prolific work in the United

Kingdom by Wilson and colleagues (MacGill and Wilson, 1979; Wilson et al. 1977, 1981; see also the review by Wilson, 1987), in Italy, by Leonardi (1979) and Bertuglia and Leonardi (1980); in Sweden (see Boyce and Lundqvist, 1987), in Australia (see Brotchie, et al., 1980; Sharpe, 1978, 1980, 1982, using the TOPAZ model), and in Canada (Los, 1979). Similar efforts are well represented in the United States. The mathematical model proposed by Boyce and Southworth (1979), for example, embeds each of Wilson's singly constrained, doubly constrained, and unconstrained spatial interaction models within a single programming framework which recognizes different population subgroups on the basis of the temporal stability in their residence and/or employment location. Boyce and Southworth's "quasi-dynamic" formulation also incorporates traffic route assignment and mode split within a single optimization framework. The incorporation of further components of the residential, employment, and travel choice decisions within a single jointly optimized modeling framework has been extensively studied in recent years by Boyce and colleagues in Illinois, working with Chicago area data (see Boyce 1988; Boyce et al., 1983, 1992, 1993). Two related mathematical programming-based models to have been applied empirically within the United States are Kim's Chicago area model (Kim, 1989), used in a research context and Prastaco's POLIS model (Prastacos, 1986a,b; Caindec and Prastacos, 1995) now used in actual planning practice.

2.4.2.2 The POLIS Model

Within the United States a combined land use-transportation model built around a single mathematical programming formulation has recently been applied within the San Francisco Bay Area. This follows a long tradition of land use-transportation modeling which began in the Bay Area in the early 1960s with a Lowry-derived approach, leading to a system of two interactively operating models known as the Base Employment Model (BEMOD) and the Projective Land Use Model (PLUM) (see Goldner, 1983, for a retrospective summary of these early efforts). During the 1980s the Association of Bay Area Governments (ABAG) again developed a modeling system for the region. This model is known as the Projective Optimization Land Use System, or POLIS. Both the mathematical and algorithmic details of POLIS, as well as a description of the model calibration efforts, are described by Prastacos (1986a,b), and more recently by Caindec and Prastacos (1995).

POLIS incorporates a number of the theoretical developments introduced throughout Sect. 2 of this review. The model can be stated as a single mathematical program which seeks to maximize jointly the locational surplus associated with multimodal travel to work, retail, and local service sector travel, and, significantly and jointly, the agglomeration benefits accruing to basic-sector employers (Prastacos, 1986a):

$$\text{Maximize } Z(T_{ijm}, S_{ij}^k, \Delta E_i^n, \Delta H_i) = \quad (21)$$

$$-(1/\beta) \sum_{ijm} [\ln(1/W_i \sum_m T_{ijm}) - 1] - (1/\lambda) \sum_{ijm} T_{ijm} [\ln(T_{ijm})] \quad (22)$$

$$-\sum_{ijm} T_{ijm} c_{ijm}^w - \sum_{k \in K_{ur}} (1/\beta_k^s) \sum_{ij} S_{ijk} [\ln(S_{ij}^k/W_j^k) - 1] \quad (23)$$

where

$$-\sum_{ijk} S_{ijk} c_{ijk}^k + \sum_{i, n \in K_{bas}} (f_i^n) \Delta E_i^n \quad (24)$$

T_{ijm} = the number of work trips from zone i to zone j by mode m (private or public transport),

S_{ij}^k = the number of trips in the "retail" or local service sector k,

c_{ijm} = the interzonal travel cost by mode m (all service sector travel assumed to be by automobile),

W_i = the attractiveness of zone i for residence;

W_j^k = the attractiveness of zone j as a center for retail or local service activity,

f_i^n = an agglomeration potential function specific to zone i,

α^n = the exponent of this agglomeration function (a model parameter to be estimated),

ΔE_i^n = the number of additional jobs in basic employment sector n ($n \in K_{bas}$) to be located in zone j,

β^w , β_k^s and λ spatial interaction and modal split submodel parameters to be estimated

The term ΔH_i refers to the number of new households locating in zone i . Its inclusion in Eq. (21) is made clear below.

The joint objective function given in Eq. 21 incorporates two spatial entropy terms, two travel cost terms (both for work and service-sector trips, respectively), and a term which adjusts the zonal distribution of basic employment within the region. This is maximized subject to a significant number of linear constraints. These include the usual non-negativity constraints on all flow and stock variables as well as constraints to ensure consistency between the flows (work trips, dollars of retail and service expenditures) generated by the model and the number of workers and households in each zone. They also include a set of linear planning constraints which both ensure consistency between the amount of residential and industrial land available in each zone and the additional amount of new housing and new employment assigned to those zones by the model. Finally, zonal totals for households and jobs are reconciled with county-wide sectoral as well as spatial totals in a manner that reflects the spatial agglomeration economies of basic sector activity at this more macro-spatial level. For example, the allocation of new households to zone i is subject to the following constraint:

$$H_{i,lb} \leq d_i^h \Delta H_i \leq V_i \quad (25)$$

where $H_{i,lb}$ = a lower bound on H_i , the number of houses in zone i ; V_i = the vacant residential land in zone i ; and d_i^h = the average density of residential development allowed in zone i . For policy analyses the value assigned to d_i^h could be used in selected zones to reflect nonmarket (e.g., government-owned) land use or other zoning constraints.

Both residential attraction factors, W_i , and retail and service sector attraction factors, W_j^k used in these entropy-maximizing spatial interaction models are themselves composite indices. W_i has the form

$$W_i = V_i [1 + H_i / (H_i + V_i) q_i] \quad (26)$$

where q_i = the ratio of median household income to median price of housing in zone i (interpreted as a housing affordability index). The W_j^k have the form

$$W_j^k = L_j [1 + Y_j / (Y_j + L_j) (E_j^k / E_j^*)] g_j^k \quad (27)$$

where L_j = total available land in zone j , Y_j = nonresidential developed land in j , E_j^k = the employment total in sector k in zone j , and E_j^* is the summation of employment in j over all k sectors. Finally, the g_j^k are accessibility indices of the now familiar form

$$g_j^k = \sum_i [\Delta H_{i,t-1} \exp(-\beta_k^s c_{ijk})] \quad (28)$$

Within POLIS this index represents the propensity of local service sectors to locate near new population centers, using in this instance the number of new houses built in zone i in the prior period ($t - 1$), $\Delta H_{i,t-1}$, to reflect such opportunities.

The zonal agglomeration factors, f_i^n , are of considerable interest since they extend the approach beyond the basic Lowry framework to provide a linkage between traditionally accessibility-determined nonbasic activity and traditionally exogenously determined (and incrementally projected) basic economic activity. Despite extensive early recognition of the importance of agglomeration economies in the growth of urban systems, as Berechman and Small (1988) note, little has been done to bring such effects into operational models.

Lacking any data below the county level against which to construct such functions, they are estimated by factoring the base year zonal employment totals in sector n , E_i^n , to be consistent with both county-wide and regional employment totals and recent rates of growth. These county and sector-specific employment levels are themselves estimated as functions of prior period employment levels in both basic and nonbasic sectors. For example, for the manufacturing sector, $n = 1$, this equation has the general lagged, linear form

$$E_{co,t}^1 = \theta_0 + \theta_1 E_{co,t-1}^1 + \theta_2 \Delta E_{*,t}^1 + \theta_4 E_{co,t}^4 \quad (29)$$

where θ = a regression coefficients, co refers to county values and $*$ to regionwide values, and $n = 4$ refers to the nonbasic "services" sector. That is, period t manufacturing employment within each county is a function of prior period employment in the sector, the overall growth in the sector regionally within the current period, and the current level of employment in services within the county. A similar regression model was also created to estimate the amount of "transportation, and finance, insurance, and real estate" activity within each county in time period t , and which in this instance also brought in the nonbasic retail as well as services sector. There is an implicit assumption being made here that changes in basic employment are a function of macrospatial effects which cut across county boundaries. To render the agglomeration potentials zone-specific POLIS defines f_i^n as follows:

$$f_i^n = \frac{E_i^n}{E_{co}^n} \frac{(\Delta E_i^n / \Delta E_{co}^n)}{(\Delta E_{co}^* / \Delta E_{*}^n)} \frac{(\Delta E_i^* / \Delta E_{co}^*)}{(\Delta E_{co}^* / \Delta E_{*}^*)} \frac{\Delta E_{co}^*}{\Delta E_{*}^n} \quad (30)$$

where the changes in employment variables, (represented by ΔE), denote changes in the previous time period.

As Prastacos (1986b) points out, however, using equations such as (29) in longer-term forecasting may produce erroneous results, since the coefficients should not remain constant if the model is indeed expected to capture the shifts in locational patterns. He proposes either the use of relaxed versions of these regressions or derivation of confidence intervals for each of the θ parameters; a significant extra modeling burden. We return to this topic of urban agglomeration tendencies in Sect. 3 of the review.

Prastacos (1986b) describes the practical implementation of this model for the Bay Area, including a discussion of data sources and the multistep procedure required for model calibration. The nine county San Francisco Bay Area, which includes some 5.2 million residents, was divided into 107 planning and traffic zones. Two basic economic sectors (manufacturing; transportation and finance, insurance and real estate) were modeled, as were a single "retail" and a single "services" sector, using selected SIC codes. Employment in the primary sectors of agriculture and mining are also allocated to zones by POLIS, using base year conditions and land availability to determine these natural-resource-constrained activities.

Two transportation modes are modeled, termed private and public. Calibration consists of choosing values for the parameters β^w , β^s_k , λ , and α^n . This is accomplished by first calibrating the spatial interaction submodels to obtain the work and retail travel flows, T_{ijm} and S_{ij}^k , by matching the entropy levels in both model-generated work and service trip matrices to "observed" data. In the case of the work trip model this process also requires iteration with a logistic modal split model, so that not only is λ calibrated but it is also used to weight the resulting work trip destination model's bimodal (private and public) i-to-j cost matrix [recall Eq. (4) above]. A single β^s is calibrated to both service and retail sectors. Once suitable mode and spatial interaction model parameters are found, a separate calibration stage uses these best-guess values to search for suitable α^n values which would reflect existing spatial (zonal) agglomeration of activities in the two basic sectors. This calibration process is the reverse of that used in most previous models, which typically have begun with the calibration of the parameters affecting activity location decisions, followed by calibration of the travel behavior parameters.

POLIS represents an ambitious attempt to bring a range of planning constraints as well as a concern for spatial agglomeration economies into a practical land use modeling process within the context of consumer surplus, utility, and entropy maximization theory. The approach also demonstrates the viability of using methodological advances in nonlinear programming coupled with the application of a number of useful numerical analysis routines. Caindec and Prastacos (1995) describe the most recent empirical application of the latest version of POLIS to the Bay Area, including a detailed description of a slightly modified mathematical model and the associated calibration

exercise. This technical report also overviews the use of POLIS as one step in a four-tiered modeling process used by ABAG. A detailed description of this process, as applied in the Projections 92 project, is provided by Brady and McBride (1992). The process consists of using ABAG's Regional Economic-Demographic System (REDS), a dynamic input-output (I-O) model (see Sect. 2.4.3 below) which estimates regional population and employment totals in 38 different industrial sectors to feed data to the County Employment Forecasting System (CEFS) model (Caindec, 1994). CEFS in turn uses multivariate regression and historical data to estimate job growth for 32 industrial sectors within each of the nine Bay Area counties. These growth trends are then used as inputs to POLIS, which forecasts the distributions of future population, housing, and employment among 114 Bay Area analysis zones. Finally, these POLIS-generated forecasts are used within the Subarea Projections Model (SAM) (see Yang, 1993) to allocate employment (by three "basic" and three "local serving" SIC categories), population, number of households, land use, and forecast household income and its distributions across the region's 1,209 census tracts.⁴ SAM then uses a series of incremental formulas based on combinations of base year activity levels and survey-based "development potentials," the latter defined in terms of acreage, housing units, and employment opportunities.

As described by Brady and McBride (1992), this four-tier spatially hierarchical modeling process uses historical data from 1980 and 1990 to generate inputs to a series of forecasts for the years 1995, 2000, 2005, and 2010. The system has a number of uses. It helps the region's planners address issues associated with the allocation of federal and state funds to not only transportation infrastructures but also sewage treatment plants and other capital facilities. The system's projections are also used to inform mandated housing needs studies for each city and county in the region, to inform local government congestion mitigation plans, and to provide inputs to the estimation of stationary and mobile-source air pollutants. The system's documentation provides considerable technical detail and an excellent perspective on the role of integrated land use-transportation planning models within the larger urban/metropolitan planning process. It also educates the reader as to the considerable data requirements and level of effort required to generate such planning forecasts; a process developed over many years in the Bay Area.

Currently missing from the framework is any form of detailed, congestion-sensitive network routing submodel. On a more conceptual note, an unresolved debate within the literature concerns the use of optimization frameworks which seek to jointly solve for both travel activity patterns and urban activity allocations. Much of the issue revolves around whether forcing a jointly optimal solution is a valid target for simulation,

⁴ A probit model was calibrated against 1990 Census data to project household income distributions within each census tract.

given the general instability inherent in, and many additional factors conditioning, urban growth and change. A subissue is the extra computational time and more sophisticated optimization routines it may take to achieve such a jointly optimized solution. The conceptual issue is indeed a complex one and needs to be tied to the specifics of each model's underlying assumptions, computational form, and intended use. There is no doubt that the above mathematical programming developments have helped analysts to shed new light on the meaning of different model structures. They have also provided an effective mechanism for simultaneously introducing a variety of planning constraints into the problem. As to whether, or to which set of planning variables, we need to jointly optimize over may depend on the question being asked. It should certainly depend on the time frame being modeled. Complicating the issue is the tendency to associate a model's objective functions with particular, and in general partial, forms of economic as well as spatial equilibrium; opening up a whole theoretical debate involving the temporal progression in both travel and nontravel prices and their resulting influences on urban form. This issue is developed further in Sect. 2.5 below.

2.4.3 Multisectoral Spatial Modeling Using Input-Output Frameworks

2.4.3.1 Background

A third line of development draws its inspiration from the intersectoral I-O approach to economic analysis introduced by Leontief (1967). In particular, this approach provides a general framework from which to begin to integrate the manufacturing and other basic industrial activities, which are treated as exogenous inputs to the urban development process by Lowry-based models. The basis of this approach is to extend the classical I-O model to include spatial disaggregations. Notable early developments in this area include the work by Leontief and Strout (1963) and, bringing entropy and therefore logit forms of interaction model into the process, by Wilson (1970, Ch. 3).

We begin with the following definitions. Let X^m = the total output of economic sector m in zone i ; X_i^{mn} = the output of m from zone i used in sector n in destination zone j ; Y_i^m = the final demand for the output of sector m in zone i ; and let a_i^{mn} = a set of spatially explicit technical coefficients which translate a unit of output m into a unit of input n . We then have the following identities:

$$X_i^m = \sum_{jn} X_{ij}^{mn} + Y_i^m = \sum_{jn} a_{ij}^{mn} X_j^n + Y_i^m \quad (31)$$

which in matrix representation implies a spatially disaggregated version of the familiar I-O relation:

$$\underline{X} = (\underline{I} - \underline{A})^{-1} \underline{Y} \quad (32)$$

where \mathbf{X} is a vector of endogenous sector outputs, \mathbf{Y} a vector of exogenous demands, \mathbf{A} a matrix of technical coefficients, and \mathbf{I} an $N \times N$ unit, or identity matrix (a matrix composed of 1's in the diagonals and zeros elsewhere). Now (after Wilson et al., 1981, Ch. 10), if we let

$$a_{ij}^{mn} = Z_j^{mn} \exp(-\beta^m c_{ij}^m) / \sum_i \exp(-\beta c_{ij}^m) \quad (33)$$

we have a set of technical coefficients, a_{ij}^{mn} defined as an amalgam of a set of Z_j^{mn} destination (receiving) zone specific coefficients, and an attraction-constrained spatial interaction model. This lets us restate Eq. (28) as

$$X_i^m = \sum_j [Z_j^{mn} \exp(-\beta c_{ij}^m) X_j^m / \sum_i \exp(-\beta c_{ij}^m)] + Y_i^m \quad (34)$$

which is an intersectoral, destination-constrained spatial interaction model in the popular logit form. With similar forms also possible for origin (production) as well as both production and attraction-constrained coefficients, such developments extend Lowry-like intersectoral modeling, in concept at least, into more comprehensive basic and nonbasic frameworks.

Other variations on such intersectoral/interzonal modeling are discussed in MacGill and Wilson (1979) and Wilson et al. (1981), who also show how such models may be embedded within a variety of entropy-maximizing, utility-maximizing and spatial surplus-based mathematical programming formulations.

2.4.3.2 The MEPLAN Model

A number of operational models make use of such developments in intersectoral I-O modeling, including the MEPLAN, TRANUS, and Kim models listed in Table 2. MEPLAN appears to offer the most experience with, and elaborate extensions of, the approach to date. The following description is based on Hunt and Simmonds (1993) and Hunt (1993, 1994).

Land and transport are treated in MEPLAN as two parallel and interacting markets. Behavior in each system is modeled as a response to price or price-like signals (including travel disutility). As with other operational approaches a key relationship is the effect on locational accessibility of travel cost and time changes, which find their way back, in a temporally lagged manner, into a set of activity-location models. This once again occurs in a Lowry-like context, but within a much extended set of sectoral selection options, subject, given suitable data, to explicit market pricing variables. Within MEPLAN, the demands for transport are calculated directly from the interactions predicted by the spatial economic system defined within the land use model. The need for a trip distribution modeling step is obviated by the direct translation of what are

termed trade flows, or “trades” from the land use model into suitable modal volumes. An elaborate interface between the land use and transportation models translates these trade flows (labor, materials, services) into mode specific trip matrices. Trips are assigned to modes by logit models and, subsequently, onto the highway network using a version of Dial’s (1971) probabilistic, multipath assignment routine that takes into account costs and congested travel times. In terms of the simulated dynamic, land use is influenced by the pattern of use in the prior period and by previous period transport accessibilities. Transport is influenced by previous infrastructure and present activity patterns arising from land use.

The land use model here requires further elaboration. Within this model, goods, services, and labor (households) are grouped into various categories, or “factors.” Some factors are consumed in the production of other factors within a modified I-O framework. Total consumption of any factor n , T_{cj}^n , in land use zone j is computed on a zone by zone basis using equations of the form:

$$T_{cj}^n = D_{cj}^n + Q_{cj}^n \quad (35)$$

with

$$D_{cj}^n = \sum_m a_j^{mn} \cdot T_{gj}^m \quad (36)$$

where m and n again refer to different factors of production, a_j^{mn} = a “demand coefficient” equal to the volume of factor n consumed in production of factor m in zone j , D_{cj}^n and Q_{cj}^n refer respectively to the endogenous and exogenous components of the total volume of factor n consumed in zone j , and T_{gj}^m refers to the total volume of factor m produced in zone j . Such a factor may be employment within the retail sector, for example, leading to a set of “trade flows” which are subsequently also converted into vehicular trips.

Flexibility is added to this modeling system by allowing the demand coefficients, a_j^{mn} , to be treated as either fixed, factor price sensitive, or factor price and income sensitive. Price elastic consumption is modeled using the following equation:

$$a_j^{mn} = a_j^{*mn} + b \cdot \exp[-\alpha^{mn}(T_{pj}^n)] \quad (37)$$

where a_j^{*mn} = fixed consumption, T_{pj}^n = the price of consuming a unit of factor n in zone j , α = a price sensitivity parameter, and b = a constant. Alternatively, a Stone-Geary consumption function (Theil, 1980) can be invoked, which represents households as utility maximizers in the consumption of housing space and various goods and services (see Hunt, 1993, for mathematical details of what is an embedded optimization problem).

The transfer of factors between land use zones is introduced by allowing demand arising in a given zone to be satisfied by production brought from other zones using the following logit model:

$$t_{ij}^n = T_{Ci}^n \left[\exp(\lambda^n V_i^n) / \sum_i \exp(\lambda^n V_i^n) \right] \quad (38)$$

where Hunt (1993) defines V_i^n to be:

$$V_i^n = T_{bi}^n + d_{ij}^n + s_i^n + Q_{ei}^n \quad (39)$$

and where t_{ij}^n = the volume of factor n produced in zone i and consumed in zone j ; λ^n = a dispersion parameter associated with the distribution of production of factor n ; and where the four terms on the right hand side of Eq. (39) refer respectively to the cost of producing a unit of n in i (T_{bi}^n), the disutility of travel between zones i and j , (d_{ij}^n), a size term which accounts for the *a priori* likelihood that a unit of factor n is produced in zone i (s_i^n), and a zone-specific disutility associated with producing factor n in zone i (Q_{ei}^n).

The price associated with consuming a unit of factor n , given as T_{pj}^n in Eq. (34) above is endogenously determined within MEPLAN in one of two ways (Hunt, 1993). One way is to compute it as the weighted average of the cost of producing and shipping the factor in each zone i plus the cost of getting it to zone j , as follows:

$$T_{pj}^n = \sum_i (t_{ij}^n / T_{Cj}^n) \cdot (T_{bi}^n + \delta_{ij}^n) + Q_{pj}^n \quad (40)$$

where δ_{ij}^n = the monetary cost of transporting a unit of n from i to j , and Q_{pj}^n = an exogenous component of the price in zone j (to help calibrate the model, or to introduce taxes into the framework). Alternatively, an iterative process can be used to establish it as the market price which results from equilibration between supply and demand for factor n in a zone:

$$T_{pj}^n = T_{pj}^{n'} \left[\sum_i (t_{ij}^n / S_j^n) \right]^{(1/\lambda^n)} \quad (41)$$

where $T_{pj}^{n'}$ = the unit consumption price for factor n in the previous model iteration, and S_j^n = the total availability of factor n in zone j .

Equation (41) is typically used to represent the market process that establishes the price for floor space or land, with the demand for land being elastic with respect to price, thereby allowing total demand to respond to zonal space constraints. The resulting

prices, as established by Eq. (34), then determine the costs of production within zones, i.e.,

$$T_{bj}^m = \sum_n a_j^{mn} T_{pj}^n + Q_{bj}^m \quad (42)$$

where T_{bj}^m = the cost of producing a unit of factor m in zone j , and Q_{bj}^m is another exogenous component of the cost of producing, in this case, a unit of factor m .

Running the MEPLAN model involves solving simultaneously for the above equations, in practice via a sequence of nested iterations. Hunt (1993) describes the above process as a series of "chains" in prices and costs that run opposite to the "chains" in demand (the I-O structure), beginning whenever a market price is determined by a constraint on supply (typically supply of space) and resulting in the prices for factors being exported. In terms of the overall simulated dynamic, land use is influenced by the pattern of such use in the prior period and by previous period transport accessibilities. Transport is influenced by previous infrastructure and present activity patterns arising from land use. Once the system of land prices and trades has settled down to provide a single point in time representation, recursion then moves the system from one equilibrated point to another—a cross-section static-recursive system supplemented by judicious use of lagged effects between some variables.

Within this general framework, a range of different travel modes, household groups, and industrial sectors have been tailored to specific studies (see Hunt and Simmonds, 1993, for examples). This can include walk and mixed modal trips; assignment of combined freight and passenger flows to networks; the modeling of work, education, shopping, and other nonwork trips, and home delivery of goods. A further MEPLAN module uses the results from these models to carry out a detailed cost-benefit analysis, including social and environmental indicators. While data requirements for a fully implemented model are potentially rather daunting, Hunt and Simmonds (1993) claim that the generality of this highly synthetic modeling framework allows it to be tailored to handle relatively modest data inputs—no more than less comprehensive systems which do not contain any land rent, production costs, or other pricing variables. This is a testimony to many years of software and model refinement. They do, however, point out the difficulties often involved in selecting the model's many parameters, typically involving extensive iterations and retrials, not always in a purely automated fashion (see Hunt, 1994, for a discussion of this process).

2.4.4 Contributions from Urban Economics

2.4.4.1 Background

The concept of treating both land and transportation systems as market processes with endogenously determined costs, as exemplified by MEPLAN, grew out of the urban economics literature. Beginning with the work of Wingo (1961) and Alonso (1964), this involves the application of neoclassical economic theory to urban land use patterns, notably residential land use, which is allocated across space on the basis of a land market clearing process. Mills and Mills and Hamilton (1989) and Bertuglia et al. (1987) provide reviews. Under this general approach, individuals are assumed to maximize utility by selecting an optimum residential location, which in turn depends on a trade-off between housing price (which in the early models simply decreased with distance from the CBD) and transport costs (which increased with distance from the CBD). This trade-off is represented in the form of a "bid-rent function," which describes how much each household is willing to pay to live at each location. On the supply side, each location is simply assumed to be rented to the highest bidder. Such bid-rent functions are now incorporated in a number of operational models.

The work of Mills (1967, 1972), using linear programming formulations, further advanced the notion of a spatial market equilibration process in which stability occurs when all households of a given type (typically reflecting income group) are located so as to be equally well off. Subsequently, these same notions have been extended by Anas (1984) and Kim (1989) into more comprehensive, nonlinear, entropy/utility-maximizing and network-based programming forms. This includes empirical work to implement their ideas, both using Chicago area data. This work also has important overlaps with the combined modeling of Boyce and colleagues (see Boyce et al., 1983, 1992, 1993) discussed in Sect. 2.4.2 above, where the ideas of systemwide optimization across a number of choice dimensions (mode, location, etc.) find a basis in the search for a suitable, systemwide equilibration of various travel and land use supplies and demands. An excellent text by Oppenheim (1995) now also offers a comprehensive mathematical treatment of the connection between individual choice behavior based on an economic (utility maximizing) rationale and an urban system's behavior in searching for an equilibration between transportation supplies and travel demands.

2.4.4.2 Kim's Chicago Model

By combining Mills's ideas of a general urban system equilibrium with Wilson's approach to probabilistic spatial interaction, Boyce et al.'s notions of combined transportation-facility location models, and Beckman et al.'s concept of equilibrated demand and supply over networks, Kim's Integrated Urban Systems Model for Chicago (1989) offers a complex if computationally tractable model with strong ties back to urban economic principles. The model offers a general equilibrium solution between the

demand for and supply of transportation and activity locations in the strict economic sense. Like the MEPLAN model discussed above it also determines prices endogenously, if in a different way. It is selected for presentation here because it shows quite clearly its strong linkages to the type of inter-regional input-output modeling described above, while also being formulated (and therefore succinctly presentable) within a single mathematical programming framework. Specifically, Kim's combined model of "land use and density, shipment route and mode choice with network congestion" has the form (Kim, 1989, p. 88):

$$\text{Minimize } Z = \sum_{k,a} \int_0^{f_a^k} C_a^k(x) \delta x + \sum_{i \in I^*, r} d_i^r E_i^r + \quad (43)$$

$$+ \sum_{i \in I^*, r} d_i^r E_i^r + \sum_{i, r, s} [L(a_{r,1,r,s} x_i^{rs}) + R(a_{r,2,r,s} x_i^{rs})] \quad (44)$$

subject to:

$$f_a^k = \sum_r g^r \sum_i \sum_j \sum_p x_{ijp}^{rk} \delta_{aijp}^{rk} \quad \forall a, k \quad (45)$$

$$\sum_i E_i^r \geq E_r \quad \forall r \quad (46)$$

$$\sum_j x_{ji}^r + x_i^r \geq \sum_j x_{ij}^r + \sum_{q,s} a_{rq,s} x_i^{qs} + E_i^r \quad \forall r, i \quad (47)$$

$$x_i^r = \sum_s x_i^{rs} \quad ; \quad x_{ij}^r = \sum_{k,p} x_{ijp}^{rk} \quad \forall i, j, r \quad (48)$$

$$- \sum_{i,j,k} (\sum_p x_{ijp}^{rk}) \ln(\sum_p x_{ijp}^{rk}) \geq S_r \quad \forall r \quad (49)$$

where the following are exogenously supplied model variables:

E^r = total export of commodity r from the urban area as a whole.

a_{qrs} = the amount of input q required per unit output r with the s production technique when production takes place in an area at s -intensity of land use (i.e., s -story building).

Here q ranges from 1 to $r+2$, in which the range 1 to $r-1$ represents input of produced goods, r = labor input, $r+1$ represents land inputs, and $r+2$ represents capital

inputs. The range $r = 1$ to $r - 1$ can specify typical urban production sectors, such as service, retail, and manufacturing. Sector r is the household sector, each of which consumes some of each good produced plus housing. (Goods imported into the urban area and used by households are not in the model).

d_i^r = the unit cost of exporting commodity r from each zone i , if i belongs to the set of export zones $i \in I^e$

g^r = the passenger car equivalent of road space occupancy required for shipping commodity r

δ_{ijp}^{rk} = the incident matrix; = 1, if route p from zone i to j by mode k includes link a for shipping r ; = 0, otherwise

l_i = the available land in zone i

S^r = the level of spatial interaction (entropy) in the system for commodity r

L = the opportunity cost of land at urban periphery. It is assumed that as much land as needed can be rented by expanding the urban area; i.e., by increasing the number of zones.

R = the rental rate of a unit amount of capital. It is assumed that unlimited amounts of capital can be acquired at this rental rate.

and the following variables are solved for within (endogenous to) the model:

E_i^r = total export of commodity r from zone i .

x_i^r = the output of commodity r in zone i

x_i^{rs} = the output of commodity r produced with s -intensity of land input at zone i

x_{ij}^r = the units of r shipped from zone i to zone j . $\sum_i x_{ij}^r$ represents the total amount of commodity r shipped to zone i from all other origins and $\sum_j x_{ij}^r$ represents the total amount of commodity r shipped from i to all other destinations.

x_{ijp}^{rk} = the units of r shipped from i to j by path p on travel mode k .

$C_a^k(x)$ = the generalized cost of travel (shipment) by mode k on link a at flow volume of x

f_a^k = the flow volume of mode k on link $a \in A^k$, the set of links used by mode k

Substitution between land and other inputs is represented by the a_{qrs} coefficients, in which s represents a production technology which equates with various intensities of land use. Within the model, goods and services can therefore be produced in tall buildings by using smaller land-output ratios and higher capital-land ratios, as typically observed in the service sector in many urban areas.

The objective function (43–44) is a joint minimization of the solution to a Wardrop equilibrium assignment of flows to network links [recall Eq.(6)–(9) above]; the total costs of exporting commodities out of the urban system; and the total land plus rental costs summed over all zones, commodities, and production techniques used in the urban system. Equation (45) ensures that the model-assigned link traffic volumes equal the volumes assigned to all origin-to-destination specific paths using that link, and Eq. (46) constrains zonal exports of each commodity r to match given totals. Equation (47) ensures that the total amount of commodity r produced in zone i plus any brought into it from other zones is at least equal to the amount of r sent to other zones, used in other sectors, and exported from the zone. Equation (48) ensures that all commodity r production summed over all s -intensity land uses equals the total production of r and that flows of r from i to j are correctly summed over all modes and network paths used in the traffic assignment model. Equation (49) ensures that a suitable level of entropy (spatial dispersion) in destination and mode choices takes place (these can be solved as nested logits), and Eq. (50) ensures that the amount of land used to produce commodity r in zone i at various intensities of use s does not exceed the amount of land available for the purpose. Finally, Eq. (51) sets nonnegativity constraints on all flows, zonal product totals, and exports.

Solution of the program yields a combined network demand-supply balance supported by an allocation of activity levels to zones which ensures that the marginal cost of producing r at location i plus the equilibrium unit shipment cost from i to j by mode k should equal the marginal cost of producing r at location j . Also at equilibrium, commodity r in zone i will be produced at intensity level s as long as the net benefit associated with doing so is at least equal to the capital (R) plus land (L) costs of producing a unit of r in i at that intensity level.

Kim (1989) has managed to calibrate a version of this model, at a rather aggregate spatial (zonal) level, using various and extensive data sources collected for the Chicago region. To date this model does not appear to have been applied in a policy study to which its output was a required contribution. Nevertheless, the various calibration routines exist, and in this sense the model is an operational one. The approach

demonstrates the possibility of bringing important aspects of urban economic theory into intersectoral, spatial-interaction-based discrete choice models in order to move towards more comprehensive urban modeling frameworks. As described, the model does not contain a procedure for translating its activity allocations into actual land use arrangements within zones. However, it does operate directly upon detailed representations of modal (highway and rail transit) transportation networks. In the above form it appears best suited to a decidedly strategic, multiyear analysis of alternative urban development options.

2.4.5 Uses of Micro-Analytic Simulation

2.4.5.1 Background

Microanalytic simulation, or "microsimulation" for short, refers to the method of generating random numbers from within prespecified probability distributions, which numbers are then assigned to a specific response or response value. For our purposes such a response may be associated with a particular traveler attribute or with a specific travel choice. The idea is to generate a series of traveler attributes and/or travel choices in this manner, to build up a detailed representation of specific trips or multitrip travel activity patterns. Summing over all of these individually simulated travel patterns provides aggregate values for planning studies. With the advent of low-cost, high-powered computers, this procedure has become an increasingly popular analysis tool.

In recent years, the technique has been applied within a range of multistage decision-making models. These include the use of the Recker et al. (1986) STARCHILD model to represent a complex series of individual traveler-within-household decision-making processes and of the Harvard Urban Development Simulation (HUDS) (Kain and Apgar, 1985) and California Urban Futures Model (CUFM) (Landis, 1994), both large-area housing simulation models, the latter with a potential for analyzing transportation improvements. Most recently, Barrett (1994) describes an ongoing set of developments in which Monte Carlo simulation once again plays a key role. This is the TRANSIMS modeling effort funded by the Federal Highway Administration as an experiment in simulating a complete areawide set of individual traveler-based urban activity patterns. Microsimulation is also the technique around which the MASTER land use-transportation model described below is constructed (Mackett, 1990b).

The principal utility of the microsimulation approach is that it lets us incorporate a number of dimensions of both individuals and their choice processes which would otherwise require an excessive amount of disaggregation in model-based accounts. Within the Dortmund model listed in Table 2, for example, Monte Carlo based microsimulation is used to simulate the intraregional migration of households as a search process on the regional housing market (Wegener, 1982b). Here the technique was used to overcome an otherwise impractical disaggregation of this submodel into 30 household

types, 30 housing types, and 30 traffic zones, yielding 24.3 million possible kinds of moves to be analyzed.

A second appealing feature of the method is that it is relatively easy to understand and to implement. To create a piece of software to simulate a particular process using Monte Carlo simulation, all that is required is a suitable random number generating routine, a suitable probability distribution (or the raw data itself, perhaps in histogram form), a routine for allocating values between 0.0 and 1.0 to randomly selected choices on the basis of this distribution (data), and a routine for collecting the results of the sampling exercise. All are readily available today on personal computers. A more significant challenge involves the acquisition of suitable data, the determination of a suitably representative sample size for analysis purposes (for which well established methods exist in most cases), and the ability to place such sampled responses within an appropriate modeling framework. Procedures must also be developed to capture the cumulative effects of common activities such as traffic congestion and spatial agglomeration of commercial or industrial activity. This raises some interesting and challenging questions for model design, issues not yet clearly elaborated within the literature.

A third useful feature of the method is that it allows not only the explicit tracking of simulated individuals' (travelers, households, companies) status over time, but also a detailed tracking of the simulated changes in the use of individual land lots. Where suitable time series data exists, even at a quite aggregate level of resolution, this provides a useful means of checking the reasonableness of the model processes underlying the simulated outcomes. Scrutiny of such microsimulated temporal paths has also been found by the present author to provide useful insight into the implications of using alternative model forms as well as alternative parameter values to replicate a particular multistage process (Dale et al., 1993). Certainly, microsimulation offers a good deal of flexibility in experimenting with different event sequencing, which is not present in traditional land use or transportation planning models. Its application to the nature and timing of landowner and land developer decision-making processes offers an interesting possibility here.

2.4.5.2 The MASTER Model

The MASTER model (Micro-Analytical Simulation of Transport, Employment and Residence), developed in the United Kingdom by Mackett (1990a,b), is an integrated land use-transportation model based on microsimulation, using Monte Carlo methods to simulate the decision processes that a set of individuals and their households go through over time. The following description is based on Mackett (1990b), where additional details are to be found.

Households are considered one at a time, but are grouped together at certain points in the simulation to allow use of aggregate values. The first processes considered are demographic ones, including aging, giving birth, dying, divorce, and marriage. Population change is modeled explicitly within the model. Marriage and divorce lead to the creation of new households. With divorce, what were once joint possessions, including children and automobiles, are divided up. Divorcees become one class of "forced movers." Voluntary movers include newly married couples, singles leaving the parental home, and wholly-moving households influenced by changes in a family's life cycle. Both public and private housing markets are recognized, and dwelling occupancies are tracked from one period to the next. Choice of residence zone is based on a weighted function of generalized travel to work costs for the head of household. Both the supply of jobs and dwellings are exogenous, zone-specific inputs to the model. Zone size appears to be at the discretion of the modeler, recognizing of course the geographic detail contained in the available data. Choice of dwelling type is based on household size and composition. Other household members' job selections are also considered, and changes in economic status for simulated individuals may include redundancy and retirement. The availability of vacant dwellings is tracked for each residence zone in the system. Changes in economic activity are considered after a household moves residence. Young people become economically active as a function of their education level, sex, and parents' social group. They become employed, unemployed, or, eventually, retired. Retirements and job changes create job vacancies. Jobs are associated with specific salary ranges.

The transportation processes modeled are becoming an auto license holder, car ownership, car availability, and choice of mode to work: each variously functions of age, sex, household income, household composition, and mode-specific costs of travel. To change mode of travel to work, either a change in job or home location or a change in vehicle ownership or availability must occur or a significant change in travel costs must be introduced. Logit forms are used to select the mode of travel. If family members work along the same travel corridor, carpooling is also possible. Only the work trip is discussed, shopping and other trip purposes are not included in the process described. Assignment of traffic to specific routes is also not included in the model, therefore, congestion is not modeled explicitly. Mackett suggests that including such a routine would be relatively straightforward. However, it would require an expansion of the results from the 1% sample of households he suggests is sufficient to calibrate the model, up to a 100% sample for the purposes of placing the aggregate travel demands for roadspace to network capacities. It's not clear how this would be accomplished.

Mackett (1990b) compared the application of the MASTER model with the Leeds Integrated Land use Transportation (LILT) model, a more traditional, if extensively modified, Lowry-type of zonally aggregated simulation model. In his analysis, he compared the sensitivity of the two models to large increases in bus fares and automobile operating costs. He computed two sets of model-specific linear elasticities for

automobile ownership; mode choice to work; and work-trip length, time, and costs changes. He also compared linear elasticities associated with employment and population redistribution over the 20-year time frame. His general finding was that the MASTER model produced sensible results, and that differences in elasticities between the two models were readily interpretable.

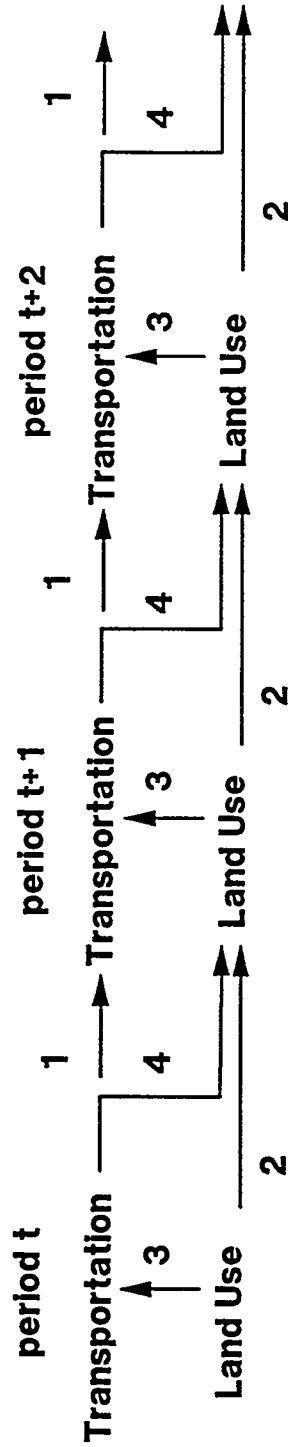
While such findings are reasonably encouraging, Bonsall (1982) points out that microsimulation is not panacea for data-hungry simulation models. He concludes that using the technique in conjunction with suitable travel activity scheduling models (see Sect. 3.3 below) and sample enumeration techniques offers some attractive possibilities. However, he emphasizes the need to establish carefully the accuracy of the mechanisms being simulated and, in particular, the applicability of generic procedures to different traveler groups.

2.5 APPROACHES TO URBAN DYNAMICS

2.5.1 Background

Figure 6 presents a general representation of the sort of discrete multiperiod dynamic employed by currently operational systems in their attempts to simulate the evolution of the urban system. The usual means of forecasting the effects of different transportation system improvements into the future is to "fit" both the transportation and land use models to a base year, denoted as time period t , and then try to project these same relationships forward into time period $t + 1$. The time interval between time t and $t + 1$ in Fig. 6 varies by modeling system, from as little as 1 year to as many as 30. In the simplest case, a single 20-or 30-year time interval may be used to project both transportation and land use forward in time under various investment and growth scenarios (the Puget Sound Council of Government model used such an approach). A better approach is to iterate through successive shorter-term(1-, 2-, or 5-year) forecasts, using the results from the latest forecast as a baseline for each subsequent projection. Some model structures can allow both options. Anas (1994) indicates that the METROSIM model can be used either to obtain a one-shot, long run equilibrium forecast for transportation and land use in a metropolitan area, or to create a sequence of annual changes in both land use and transportation which can be run until convergence to a steady state is achieved.

Difficult to predict changes, such as changes in the location of new basic employment, are usually handled, even within the more advanced models, in an incremental fashion and often treated as exogenous inputs. Residential, service, retail, and, in some cases, selected manufacturing employment activities are then advanced and redistributed on the basis of travel cost-adjusted locational accessibilities. How this occurs in practice varies by modeling system. Both residential and employment activity



Interactions Modeled:

- 1 = Inter-period transportation system changes
- 2 = Inter-period land use changes
- 3 = Intra-period effects of land use changes on travel patterns
- 4 = Inter-period effects of travel and transportation system changes on land use

Fig. 6. Multi-period, recursive simulation of urban system dynamics.

locations may be stabilized within a single time period, or one may be related to another in a subsequent time period using lagged equations (recall the ITLUP model description above). The accessibility-based travel patterns which result from such redistributions are often simulated to reach a stable demand-supply equilibrium during the current time period. Alternatively, the process may become a more open-ended one, in which constant readjustments in both land/floorspace allocations and transportation infrastructure and services are taking place within lagged equation forms (see Wegener, 1994, for a discussion). For example, Hunt and Simmonds (1993) conceptualize the urban dynamic simulated in MEPLAN as follows (pp. 223–224): “In each market there is at any time an adjustment towards equilibrium. However, this adjustment is limited. It is limited by the impossibility of instantaneous changes in either building stock or transportation infrastructure and by the imperfection of the information exchanges in the system. This leads to delays and lags in the adjustment of the system to its own price and congestion signals. The result is that the urban structure continually moves toward but probably never reaches an equilibrium.”

The implication is that transportation system changes, notably major infrastructure investments in new highways or rail transit lines, will need time to affect urban land use patterns. Once introduced, such land use patterns may then also, but within shorter time frames, induce further changes in urban travel demand. Just how this is accomplished in terms of intraperiod versus interperiod increments often depends upon the time interval chosen between model iterations, which in turn usually depends upon the original purpose behind a model's development.

Greater subtlety as well as realism is introduced into the more elaborate modeling approaches by allowing different rates of change in housing and transportation stock adjustments versus residential and employment activity reallocations, or versus short range travel (mobility) adjustments. Wegener's (1986) model for Dortmund provides one of the most conceptually satisfying implementation of such ideas in practice. His approach is presented briefly below.

2.5.2 The Dortmund Model

As we learn, and perhaps in order to learn, more about the true nature of urban system dynamics, it appears that increasingly comprehensive urban simulation models are required. The Dortmund modeling system, along with MEPLAN, METROSIM, and the 'Bay Area system of models containing POLIS, all strongly reflect this trend. Wegener's Dortmund model is selected for review below. It not only offers one of the most advanced implementations of a multistaged urban land use-transportation systems dynamic to date, but also makes innovative use of spatial interaction models as well as microsimulation methods within its framework.

The Dortmund modeling system was developed for the city of that name in Germany by Wegener and colleagues (Wegener, 1982a,b; Wegener, 1986; Wegener et al., 1991). Dortmund, as discussed below, refers to the intermediate level model in a three model hierarchy. Within this hierarchy, a macroanalytic model of economic and demographic change simulates employment by industrial sector and population by age, sex, and nationality within each of 34 labor market regions, as well as interregional migration rates within the State of Nordrhein-Westphalen. Dortmund is a mesoscopic spatial model which uses this regional context to simulate the intraregional location decisions of industry, residential developers and households, and associated public policy impacts in the fields of housing and infrastructure. The model was developed primarily to study the impacts of long-range economic and technological change. The model was also used recently by Wegener (1995a) to examine the effects of urban activity reorganization on the reduction of carbon dioxide emissions.

The Dortmund model is applied to a 30-zone region centered on the city of Dortmund, a region with a population of some 2.4 million residents. At the third level in the complete model hierarchy is a microanalytic model of land use development within any subset of 171 statistical tracts in the Dortmund urban region. Tracts vary greatly in size, but the majority contain between 2000 and 5000 residents (Wegener, 1982a). The purpose of this more spatially detailed model is to allocate construction generated by the mesoscopic or zonal Dortmund model to tracts within a zone.

The following description is focused on the mesoscopic model only and is based largely on the version described in Wegener (1986). A simulation run involves seven interlinked submodels dealing respectively with (1) car ownership and transport; (2) aging of people, households, dwellings, and workplaces; (3) relocation of firms, redundancies, and new jobs; (4) nonresidential construction and demolition; (5) residential construction, rehabilitation, and demolition; (6) labor mobility (change of job); and (7) household mobility (change of residence).

A good deal of thought has been put into the issue of simulating urban dynamics. Wegener (1986; see also Wegener, Gnad, and Vannhahme, 1986) classifies urban and regional changes as falling within either fast-, medium-or slow-response processes. While relatively rapid changes in mobility can be brought about by trip mode or route choice and, possibly a little more slowly, by home, job, or firm relocations, much slower processes are involved in changing the more expensive physical structures of the city (its housing, factories, office and shopping centers, and transportation routes). Also at work are medium-speed changes, involving either socioeconomic or technological developments forced on the area by broader regional or national influences: such as economic cycles, biological changes such as population aging, or the advent of new technologies which are again not area controlled but over time are area affecting.

This conceptual framework is translated into practice in a number of ways. Rather than simultaneously determining locations as trip ends in a unified transport-and-location equilibrium, an explicit separation of the transportation and land use subsystems is maintained. The transportation model iteratively solves for a user-optimal set of flows where car-ownership rates, trip rates, trip destinations, and mode and route choices are in capacity (congestion) constrained equilibrium; accomplished by using an extended version of Evans'(1976) algorithm. At the trip distribution stage this involves calculating sixteen interrelated spatial interaction models for work, shopping, services or social, and education trips for four socioeconomic groups and three travel modes: car, public transport, and walking. First, however, household car ownership and trip generation rates are computed within an iterative process which makes such choices nominally subject to a household budget constraint on travel and car ownership costs. Within this framework, mode choice is nested within destination choice and recognizes car availability as well as generalized travel costs (recall the discussion in Sect. 2.3 above).

The framework distinguishes in a reasonably traditional way between nondiscretionary forms of travel (work and school trips) and discretionary travel, such as shopping and social trips. It does this by using doubly-constrained spatial interaction models for the former and production-constrained forms (logits) for the latter. However, the work trip model is solved only once, for the base year. Subsequent and matrix element specific adjustments to this home-work trip matrix then rely on direct inputs from the submodels dealing with change in residence and change in job respectively. This is done to get around the problem (also noted by Mackett, and by Wilson) of inappropriately using doubly constrained spatial interaction models in a dynamic context. That is, such a model may require that workers who have changed neither home nor workplace over the current time period be assigned to another cell in the work trip matrix in order to satisfy a revised set of zonally aggregated trip generations (workers) and attractions (jobs). This leads to an overestimation of the effects of changes in transport costs on the resulting pattern of urban commuting. By limiting the ability of such interaction models to reallocate work trips, the impacts of transportation costs on the subsequent location of these home and workplace activities becomes less direct, more lagged and more aggregate in its effects than would be the case if spatial interaction models were used less discriminately. The reader is referred to Wegener (1986) for an elaboration of this matrix-adjustment process.

Within Dortmund transportation cost and related accessibility changes are anyway not the only determinants of locational change. They are traded off against other non-transportation variables which appear to be at least as important in the evolution of urban form, a point made frequently in the recent empirical literature (Giuliano, 1989). The simulation takes place in 2-year cycles (up to a 30-year planning horizon), allowing a "perception delay" of 1 year, on average, to take effect. The transport model is processed at both the beginning and end of each 2-year simulation period. Through the implicit lag structure of this recursive system, changes in land use variables only become visible to

the transportation model at the beginning of the next (2-year) time period. Longer delays are accounted for in some submodels. New housing only finds its way onto the market three or more simulation periods (6 years) after a simulated change in the transportation system has occurred. As a practical matter, the spatial distribution of urban activities is allowed to change within the modeling process in two ways. One way is through "aging," which in the model depends only on time and not endogenously modeled choices. The mechanics of this aging process involve the use of a probabilistic Markov process, which is applied once each model iteration within an aging submodel. An additional practical facet of the approach is the recognition that the opening or closing of large industrial plants may not be predictable by any modeling system, hence their treatment as exogenously entered "historical events." All other changes depend on accessibility based spatial choices generated explicitly within the model. For this purpose the model uses nested logits and a variant on the inclusive value method described by Fisk and Boyce (1984) as its basic building blocks.

3. USING INTEGRATED MODELS IN POLICY ANALYSIS: AN ASSESSMENT

3.1 INTRODUCTION

Recognizing an inevitable lag between latest theory and best practice, if we were to evaluate currently operational models on the basis of their collective ability to incorporate latest theories within their frameworks, they would get quite high marks. Taken as a set, the previously reviewed integrated models have advanced in a number of important directions since the 1960s. They have managed to combine the minimum effort and locational accessibility premises inherent in spatial interaction theory with the statistical and information theoretic notions of entropy and the economically rational notions of utility maximization. Methodologically, they make use of nonlinear mathematical programming methods as well as the latest developments in econometric and microsimulation modeling of the demand for travel, residences, and employment. The more comprehensive models also tackle demographic change in the urban population, and some also model physical stocks other than transportation infrastructure, notably the aging and renewal process associated with the urban housing market. Finally, they model these events using an extensive database, resulting in the allocation of traffic volumes and speeds over detailed link-node representations of multi-modal urban transportation networks.

But this, of course, is not the test in which we are most interested. How well such theories stand up in practice is the true test. Here we are currently at something of an impasse. In contrast to the considerable effort made to develop the theoretical aspects of the relationships between transportation and spatial structure, the practical application of models has been relatively neglected. This conclusion is mirrored, with respect to U.S. practice, in the review by Cambridge Systematics and Hague Consulting (1991), which found that only a handful of the top 18 metropolitan areas were using integrated models in their planning processes. In their relatively brief history, the land use-transportation models reviewed in Sect. 2 have been subjected to a good deal of criticism (see Batty, 1980, for an early historical review; see also the Winter, 1994 edition of the *Journal of the American Planning Association* for a retrospective). Past criticisms have tended to revolve around (1) conceptual issues of model realism and hence usefulness; (2) practical issues of data availability and quality, as well as computational requirements and ease of use; and, as something of an offshoot from these two issues, (3) the role such models are to play in the planning process. While recent computational advances have done much to remove concerns over both computer costs and computer run times, the other issues remain. Each is discussed below, highlighting some concerns frequently voiced in the recent literature.

3.2 MODEL VALIDATION ISSUES

As Lee (1994) points out, the role of large scale urban land use-transportation simulation models remains a cause for debate. Should they be considered as tactical or as strategic planning tools? If used as tactical planning tools, their most common application would probably be to evaluate travel policies along specific urban corridors, with an eye to an environmentally influenced benefit-cost ratio being realized within a suitable time period. Even so, such an evaluation period might cover as long as 15 or 20 years depending on the TCM being proposed (i.e., up to the expected lifetime of a typical urban highway pavement, if the addition of new infrastructure is involved).

However, a danger with using models solely to analyze individual travel reduction projects is the potential for disjointed, piecemeal planning. Ideally, and central to the aims of this present review, we need to find a way to embed such project evaluations within more strategically developed, areawide transportation plans. If these plans are to make the sort of contributions to petroleum savings and CO₂ reductions which have come from more efficient engine and fuel technologies, areawide impacts will almost certainly be required. We also need to think in terms of longer planning horizons. Watterson (1993) concludes that even a planning horizon of 30 years may not be long enough to capture the true impacts of a plan which contains significant transportation infrastructure investments. He notes that such plans may go on to influence urban form, and therefore urban travel activity, for many years into the future.

Lee (1994) argues that in searching for such a strategic role we may be trying to get too much detail into our models. As we add more detail and functionality to what are already rather ambitious models, we lose flexibility in their application and increase expensive data requirements. In contrast, Harris (1994) prefers to view such efforts as an aid to comprehensiveness of understanding, rather than comprehensiveness in forecasting. This second argument meshes well with Wilson's (1984) perspective on the use of integrated models as tools for evaluating the robustness and resilience, rather than the details, of alternative urban and regional plans. As Owens (1989, p. 233) puts it; "In the end, perhaps, accurate prediction matters less than flexible normative planning, based on an intelligent assessment of the most likely directions of certain trends."

To carry out such planning, mathematical, computer-based models would seem to be our only realistic alternative if we wish to apply, and properly test the results of applying, a formally developed logic behind our planning decisions. Without reasonably comprehensive models, we cannot hope to simulate the often nonintuitive effects of combining a wide range of policy options within any single plan. Our ability to determine the general magnitude and direction of policy-generated effects seems well worth the effort. This, however, raises the issue of how we gain confidence in our model-based results. Such a question moves us on to issues of model validation.

Validation means carrying out checks to establish how well a model did in forecasting a future situation by comparing the model's results with observed data. As Wegener (1994, p. 25) points out, "remarkably few validation exercises are reported in the modeling literature." Travel data availability constitutes the major constraint on validation exercises to date, especially data covering time intervals long enough to capture some of the important changes in urban infrastructure and land use.

An obvious problem for cross-sectionally calibrated models is that they are using the many parameters established in their base year calibrations to predict changes over time. In doing so, they may be placing an overreliance on the behavioral implications of spatial variability in traveler and land owner responses to differing conditions. Of greater interest is the temporal variability in such responses for a suitable range of geographically as well as socioeconomically varying urban environments. To understand and model such behavioral responses, we need to make more and better use of time series data. Webster et al. (1988) briefly describe the results of using seven of the nine models covered by the international study group on land use-transportation interaction (ISGLUTI) to project both zonal employment and population totals, using data for intervals from 3 to 12 years into the future. This includes versions of MEPLAN used in the studies of Sao Paulo, Brazil, and Bilbao, Spain, which apparently used specially developed follow-up survey data for the purpose (Echenique, 1985). All results reported R^2 values > 0.95 when comparing absolute values, using from 30 to 148 zonal observations, depending on the particular model and its application. The 3-time period, 12-year, incremental forecasts produced by the Dortmund model gave particularly high R^2 values. However, R^2 values took on much wider ranges, from 0.98 to 0.59, when comparing observed versus modeled *rates of change* in these same variables.

Similar R^2 values are reported by Prastacos (1986b), using the POLIS model to predict changes in the number of households as well as employees per zone within two basic and two nonbasic sectors for the period from 1975 to 1980. This involved regressions on 107 observations (i.e., land use zones) within the nine county San Francisco Bay Area. Noticeable improvements in these coefficients occurred when aggregating the results to county totals or when using such county totals to control the subsequent allocation of employment to zones within a county. Some checks were also made on the resulting interzonal private and public trip matrices produced by POLIS, but with synthetic rather than observed 1980 flows for comparison. Recent recalibrations of the trip distribution and modal choice (auto versus transit) submodels using 1990 journey-to-work data from the Census Transportation Planning Package (Caindec and Prastacos, 1995) produced R^2 s for auto trips around 0.80 and for transit around 0.77, with model averaged travel times within 10% of expected results. In general, however, producing similar comparisons of modeled versus observed non-work trip matrices is problematic, with little in the way of consistent historical data for guidance.

Hunt (1994) also describes an extensive series of model validation tests carried out as part of the application of MEPLAN to the city of Naples, Italy. Maps and graphs are used to show the generally good fit between the model generated versus observed number of households as well as the private residential floorspace rents per zone (26 zones). Also examined were (1) expenditures on travel; (2) floorspace and other purchases by each of five household types; (3) average trip distances for four trip purposes (work, shopping, school, other); and (5) selected modeled versus observed average weekday morning peak period traffic cordon counts. He also describes the considerable time and effort required to calibrate, or "fit" the model, including the definition of suitable household classes and the too often experienced problem of having land use data for one year and transportation systems data for another, somewhat earlier or later one.

Whether using data sets from two or more periods to forecast or "backcast", using a cross-sectionally calibrated set of model parameters, ideal requirements for such tests would include use of the same set of traffic analysis zones as well as the same trip purpose definitions from one period to the next. In the past this has often meant considerable data reconciliation efforts. Wegener (1994) suggests that a model's performance should be based on its ability to forecast the essential system dynamics over a past period at least as long as the forecasting period to which it is being applied. He goes on to note that only Dortmund and MEPLAN, among currently operational models, appear to have followed this philosophy. In both cases these models are only partially calibrated by statistical estimation techniques and partially by manual fine-tuning as part of a long, interactive process. Often, as Hunt (1994) points out, it's difficult to distinguish data problems from errors in a model's formulation or in its underlying assumptions.

Clearly, greater emphasis on validating the models is required, including the establishment of procedures to track the major data sources necessary to calibrate them. This constitutes the most significant obstacle to model validation and, by implication, further useful model development. More comprehensive models mean more demanding data requirements.

Given current data limitations, how are we to assess the value of such models in a strategic context? Here the ideas expressed by Cowing and McFadden (1984) and restated by Hensher et al. (1992) are apropos. When an analysis task involves forecasting over a long period of time with substantial deviation from historical experience to be expected, they suggest that assessment of a simulation model is best focused on *realism in process*. This contrasts with more direct assessment of a model's predictive capability, involving the above discussed comparison of model results against a known, and empirically observed, reality; a validation process they term *realism in performance*. At the present time any discussions of current model weaknesses and associated research needs are necessarily focused heavily on such realism in process. However, more realism

in process suggests that we also use more behaviorally based (i.e., more realistic) models. That is, it suggests that we focus more attention on how travelers behave and, for the purposes of policy impact assessments, how such behavior changes over time once policies are implemented which act upon it. This in turn suggests that more attention be given to the collection and use of longitudinal data sets. In particular, multiwave traveler panel surveys, collecting information from the same group of travelers at discrete time intervals, are discussed below as an important data collection option. A concerted effort will be required to design, collect, and maintain such temporally anchored databases. A first step is to determine which are the major variables of interest to such longitudinal analyses and (since cost of data collection remains the major constraint) which data we can effectively relegate to less regular data collection activities. To do so, we need to better understand the causes of current variability in travel demand.

3.3 THEORETICAL ISSUES: TOWARDS MORE REALISTIC MODELS

3.3.1 Household Travel Mobility Modeling

3.3.1.1 Criticisms of The Traditional Transportation Planning Model

The traditional four-step transportation planning model described in Sect. 2.3 of this review (Fig. 3) has been the focus of a good deal of criticism for many years. Within the United States, the need for metropolitan planning organizations to address the vehicle travel reduction requirements of the 1990 Clean Air Act Amendments (CAAA) is now leading to a new round of model development, known as the Transportation Model Improvement Program (see Texas Transportation Institute, 1993). Much of the criticism within the modeling literature argues that we need to place both household and company-based travel decisions within more behaviorally realistic decision-making frameworks. Treatment of travel as a good composed of separately modeled attributes of frequency, mode, destination, and route choices is being challenged. While energy, economic, and environmental impact analyses may require that we translate the demands for travel into numbers of temporally and spatially explicit vehicular trip volumes, the current methods we use for getting there are proving increasingly restrictive. Frequently voiced criticisms of the traditional Urban Transportation Planning (UTPS) process are described on the following pages. Cumulatively, these weaknesses act to obscure the relationship between cause (including policy-induced cause) and effect.

The Relationship Between Trip Frequencies and Travel Costs

An appropriate feedback mechanism between the trip generation model and the rest of the four-step urban transportation modeling procedure continues to elude modelers. The dashed arrow in Fig. 3 shows the desired (hypothesized) linkage. While travel speeds and costs are often interactively solved for within the destination, mode, and

route choice steps, traffic generation remains inelastic with respect to such travel cost changes. To date, no sound and generally reproducible basis has been found for such a linkage. Similarly, empirical efforts at direct incorporation of the effects of cost-determined locational and modal accessibility within existing trip generation models have met with almost universally poor results (see Kitamura, 1994, for a recent discussion).

It may be the case that where trip frequencies are concerned, even among the more discretionary forms of travel, transportation costs or traditional forms of cost-based accessibility are in many cases not the only, or even the most important, determinants of daily or weekly travel activity schedules. However, one difficulty associated with obtaining a relatively simple functional relationship between trip frequency and trip length or cost may be the nature of past survey data. Cross-sectional, single day trip sampling may not contain the information required to fathom a behaviorally sensible and statistically consistent relationship. Implicit in nearly all past efforts to simulate urban travel activity patterns is the treatment of transportation as a separable good to be purchased independently of other household needs. However, once we place our analysis within a longer-term perspective, other nontravel cost factors become important. That is, housing, food, health, education, and other costs may compete with travel costs for the household budget in ways which may affect trip frequencies every bit as much as urban accessibility surfaces do.

An argument for the use of integrated land use-transportation models is that they currently offer the only means of getting the costs of travel back into the trip generation process; albeit via a rather complex series of modeling processes. However, while a residential allocation submodel is used to link housing rents to travel costs within a number of the models reviewed in Sect. 2, these models don't go any deeper into the trade-offs between travel and other goods which take place within budget-constrained households. For strategic planning purposes it may be sufficient to model travel versus housing costs in this manner, as long as a household's share of its income spent on travel and activities remains reasonably constant (see below). However, many short term decisions by household members may reflect a wide range of responses to daily or weekly time as well as monetary travel budgeting. The cumulative variability in such responses may be an important reason why no simple empirical relationships between daily trip frequencies and travel accessibilities or costs appear to repeat themselves across different studies.

Trip Chaining and Destination Choice

Making the relationship between trip frequency and travel cost more difficult to assess, many trip destinations in urban areas occur within multipurpose, multistop daily travel chains such as the home to work to shop to home type of travel circuit (see, for example, the travel data described by Hummon and Burns, 1981; Kitamura and Kermanshah, 1983; O'Kelly and Miller, 1984). By ignoring such trip chaining activity,

the traditional transportation planning model fails to capture the time and cost savings offered by multistop travel activity patterns. This in turn means that integrated models of land use and transportation which use traditional, single destination spatial interaction models also fail to provide support for the analysis of land use policies which might take advantage of such mileage saving options.

The destination choice set problem, a frequently revisited technical problem within the travel demand literature, further exacerbates the problem of destination choice. Spatial interaction models, whether calibrated at the zonal level or fitted to a sample of individual traveler responses, require a prespecified set of alternative destinations to choose from. Removal of a possible destination from the available choice set within a logit model changes the absolute probabilities of selecting each of the remaining options. The behavioral dilemma results from not knowing what the choice set really is or how it differs across individual travelers at different originating locations and by different trip purposes. While a number of approaches to the problem have been tried (Stopher and Meyburg, 1976; Richardson, 1982; Recker et al., 1986), the usual approach is to allow all traffic zones in the system or all zones chosen by survey respondents (where such data is available) to be in the choice set. This approach recognizes that more distant and less attractive locations will receive few or no trips and, hopefully therefore, will affect the results only marginally and well within the bounds of modeling error. Significantly, the way in which multdestination trip chaining opportunities affect such choice sets has not been thoroughly researched to date (but see Recker et al., 1983 for some interesting work on simulating feasible, including multistop, activity programs for specific household members).

Discretionary and Off-Peak Travel Activity Modeling

Both time of day and time within the week need to be recognized and modeled as important travel options. Nonwork, and frequently non-peak, trips are now responsible for 78% of annual trip starts and 73% of total vehicle miles traveled (VMT) in the United States (Hu and Young, 1994). Also, since many daily trip chains combine peak period commutes with more "discretionary" forms of off-peak travel (e.g., shopping, social and recreation, and personal business trips), this needs to be recognized in some fashion if we wish to understand the effects of such transportation control measures as staggered work hours and compressed work weeks, or the potential for mixed use urban activity centers to encourage midday walk, paratransit, or public transit use for personal business and shopping.

3.3.1.2 Implications for Modeling Travel Reduction Strategies

Collectively, the above weaknesses render policy analysis for specific highway impact projects rather suspect. For example, the potential for a particular highway capacity expansion project to lead initially to less congested, less polluting travel may in

reality erode over time as the greater ease of travel over this highway induces some travelers to change their daily or weekly movement patterns, resulting in a revised form of multideestination trip chaining activity and shifts in the temporal distribution of traffic. Among other effects, such temporal adjustments may affect existing vehicle availability within multidriver households. For example, the introduction of an high-occupancy vehicle (HOV) lane as part of a highway capacity expansion may induce ride-sharing, which in turn leads to a rearrangement of vehicle utilization within the household. Vehicles left at home by the ride sharing commuter may then be used by a spouse or other family member. In total, some of the new weekly household travel activity patterns which form may, on balance, involve more VMT, consume more fuel, and put more pollutants into the atmosphere than before.

It's also not obvious how to introduce the effects of emerging telecommunications options, such as telework or teleshopping, into such a rigid trip-oriented approach. Are such options considered trip generation or travel mode options, and more importantly, how does the adoption of frequent telecommuting affect the travel activity patterns of other household members? The recent reports by DOT (1993) and DOE (Greene et al., 1994) discuss this topic in some depth, and recognize our currently limited understanding of what to expect. Indeed, the whole area of in-vehicle as well as in-home real-time information systems and their effects on travel patterns raises questions not well suited to a single destination, separable trip purpose approach.

Single destination trip based models also run into problems in evaluating such low energy, and potentially low emissions options as electric or hybrid fuelled vehicles. Should petroleum prices rise sharply in the future, it would help to know what percentage of household travel could be supported by a single daily vehicle charge, given a particular land use arrangement within which trip chaining is an option.

3.3.1.3 Some Recent Developments in Travel Demand Modeling

If we are to make current models more behavioral, or replace them with new models, the following areas warrant further study and possible unification:

Analysis of Multi-Day Household Travel Activity Schedules

An increasingly popular approach to travel demand modeling is to look for ways to link travel decisions more closely to such lifestyle factors as intrafamily obligations, leading to jointly organized trips. Such considerations place us firmly within what is termed the "travel activity analysis" literature (see Carpenter and Jones, 1983, and Kitamura, 1988, for extensive literature coverage). This empirical and modeling literature suggests that shifts in travel behavior may only be properly understood within the wider context of how people organize their lives over a series of planning horizons

and, notably, over multiday rather than single day periods (see, for example, Hirsh, Prashkea and Ben-Akiva, 1986; Kitamura and Van Der Hoorn 1987; Pas, 1988).

An important aspect of such an approach is the study of how households make use of their various automobiles (and, increasingly in the United States, of their light trucks and minivans) to carry out their activity schedules. Hensher et al. (1992) provide a review of past literature on this topic, as a prelude to describing an econometric modeling approach and supporting empirical study of the various dimensions of household-based automobile demand. In the United States, this recent literature on vehicle utilization includes the nested logit modeling of vehicle class, vintage, and fleet size by Train (1986) and the ordered probit modeling of household vehicle ownership decisions by Golob (1990). It also includes the analysis of gasoline price effects on vehicle use in multivehicle households by Greene and Hu (1984) and the statistical modeling of multiday vehicle utilization levels by Greene (1985). Greene (1985, p. 350–351) pointed out that "in particular, while single-day surveys of a large sample of households have been extensively studied and modeled, there is a lack of information and analysis of how usage of a particular vehicle varies from day to day over a long period of time."

With a limited but growing collection of multiday travel surveys for the past decade, notably in the form of panel surveys (see below), this situation is beginning to change. Much greater use of longitudinal data on travel activity patterns, including vehicle utilization patterns, is needed if we are to understand how policies intended to discourage low occupancy vehicle travel actually affect behavior. Currently, as Bhat and Koppleman (1993) point out, even conceptualizing the activity scheduling framework within which travel and other weekly activity decisions are made constitutes a new and challenging task.

Microsimulation appears to be a natural candidate for making operational such ideas as the simulation of multiday household travel activity patterns, and efforts such as the STARCHILD model (Recker et al., 1986) and TRANSIMS (Morrison and Loose, 1994; Shunk, 1994) fall into this category. Such efforts have a growing, if rather varied theoretical and empirical literature on the modeling of multistop travel chains to begin from, as evidenced by the review of trip chaining research by Thill and Thomas (1987). This literature includes the empirical work on vehicle use by Hummon and Burns (1981); the empirical and theoretical work with logit-based models of destination choice by Kitamura (1984); the suggestions for using nested logits to identify and capture the empirical linkages between primary versus secondary destinations within such trip chains by Wilson et al., (1981); the use of microsimulation linked to logit demand functions to investigate the effects of chaining on locational accessibilities (Southworth, 1985b); the extensive empirical and theoretical work on multistop, multipurpose shopping trips by, among others, Narula, Harwitz and Lentnek (1983) and O'Kelly and Miller (1984); and the use of Markov models to assess the effects of trip chaining on the location specific demands for retail facilities (O'Kelly, 1983). However, these and similar ideas have yet

to find their way into actual use within the integrated urban modeling systems described in Sect. 2 of this review.

Multi-Wave Panel Analysis of Household Travel Behavior

A new development in recent years has been the emergence of travel panel analysis. By surveying the same group of travelers or households at two or more intervals in time, with successive surveys separated by a few months or years, we are now beginning to acquire data on how travelers actually responded to a specific event. Hensher and Raimond (1992) provide a summary of the major transportation panels studies to date. These include panels used to analyze household vehicle ownership and utilization decisions, and the effects of staggered work hours, an HOV lane, and telecommuting on household travel behavior. Greater use of such panels should allow us to get away from the always suspect use of disaggregate travel demand models whose calibrations are based on limited size, single cross-sectional samples of urban residents.

However, travel panel analysis is still in its early stages. The first text devoted exclusively to the topic was compiled only recently (Golob, Kitamura, and Long, 1994). The recent theoretical work of Jiang et al. (1992) and the related methodological and empirical work by Hensher and Raimond (1992) are particularly interesting. By treating the speed at which potential travelers change their travel behavior as a process of adaptation, Hensher and Raimond embed a stochastic process within their differential equations model. In this way they can affect the timing (including instantaneous adoption) at which such changes occur from one state to another (in their case a change in route from a free to a new toll road). Here the considerable literature on hazard response and survival models becomes very useful and is likely to be visited more often in future travel-related research.

These last authors also describe the problems involved in translating data from a series of discrete time panels into a continuous time stochastic model of the real world process. Currently, we are at a relatively early stage in the design and use of such models and also in our design of the panel data sets which can best support them. In one of the best-documented research efforts to date, Hensher et al. (1992) collected four waves of panel data, spanning a 70-month period, from households in metropolitan Sydney, Australia. They use this data to develop an automobile market share and energy demand forecasting system based on a combined discrete-continuous econometric model of household automobile choice. Nested logits are used to model the discrete choices of household fleet size (i.e., ownership of 0, 1, 2, or 3+ cars), vehicle type/vintage, and vehicle body mixes. These are linked to a series of continuous vehicle utilization models. Lagged operators and other devices are used to render these models dynamic in the sense of capturing what the authors refer to as "experience effects" and "expectation effects" within the multidimensional choice process. The approach shows what can be done today to improve the behavioral basis of vehicular travel demand modeling given a suitable

longitudinal database. The authors used their modeling system to generate a range of automobile demand and fuel use scenarios at 5- to 7-year intervals for up to a 20-year period (1985–2005). Policy variables analyzed were vehicle and fuel prices, advances in vehicle fuel saving technology, and socioeconomic changes which affect household demands.

Use of Household Budgets to Bound Travel Activity Estimates

A number of researchers have hypothesized that the amount of travel we undertake is highly constrained on the individual level. Proponents of this approach argue that the total amount of travel people engage in is strongly constrained by either time or money budgets. Such budgets, the latter strongly related to available income, are claimed to either remain quite stable over time for any given city and population subgroup, or to change in clearly recognizable directions as a function of a few independent variables. Such constraints allow the amount of travel that a person or household engages in to be determined by appealing to a simple utility maximizing model, subject to budget constraints. For example, the longer-term decisions faced by the household as to how much total travel to engage in (that is, number of trip generations \times trip distances) is modeled in utility terms (U) by Golob, Beckmann, and Zahavi (1981), as:

$$\text{Maximize } U = a \cdot \ln(\sum_m x_m) + b_1 \cdot \ln(Y - M^*) + b_2 \cdot \ln(T - T^*) \quad (52)$$

where x refers to the amount of travel, measured as travel distance; m refers here to one of $m = 1, 2, \dots, M$ travel mode options; Y is household income; T is the time available to the household members for the completion of their activities, such as an “averaged” travel day; M^* and T^* are equal to the optimal fixed travel time and money budgets of the household, given by $M^* = \sum_m c_m \cdot x_m$ and $T^* = \sum_m x_m / v_m$; c and v refer respectively to mode specific average costs and velocities (speeds); and a , b_1 and b_2 are the model parameters associated, respectively, with modal share weights, income, and time budget constraints.

The idea here is that by maximizing over the expenditures on time and money themselves, the longer term relationship between the travel and nontravel budgets (leisure time, consumption of other goods) of the household can be explored. If stable relationships between such budgets can be shown over a number of years, then we would have a very useful approach for placing reasonably tight bounds on the total amount of travel consumed. Zahavi and colleagues used such an approach to develop the Unified Mechanism of Travel (UMOT) to investigate empirically such hypothesized relationships (Zahavi, Beckmann and Golob, 1981; Zahavi, 1982). While conceptualized at the level of the individual household, the supporting empirical modeling is carried out on an aggregate, urban areawide scale.

However, the empirical evidence to date has been less than conclusive, and no operational models based on household travel budgets have been generally adopted (although as noted in Sect. 2.5, the Dortmund model does incorporate a travel budget constraining procedure within its transportation modeling process). Household stratification along at least car ownership and income lines would appear to be required if reliable forecasts of future budgets are to be made. Also, to be strictly applicable, nonmotorized modes of travel (walking, cycling) need to be included in the analysis. It may also be argued that people actually seek to maximize their accessibility to opportunities, rather than seeking to maximize their (budget constrained) distance traveled. Since maximizing accessibility to a set of spatially diverse opportunities need not involve minimizing distance or cost of travel, the latter is really a special case of the former. Various other pros and cons of a travel budget based approach are reviewed by Gunn (1981), Wigan and Morris (1981) and others in the same volume of *Transportation Research*.

In the most general terms, the notion of dealing with travel distance (VMT) as the result of a budgetary process appears to have considerable behavioral merit. Further empirical study is needed to determine if a travel budget-based approach can be developed directly into an effective forecasting mechanism. Rather, it may offer a check on the economic realism implied by otherwise unconstrained modeling approaches. To be most useful such investigations should, however, be time-series as well as cross-sectional in nature.

3.3.2 Urban Goods Movement Modeling

A second area of deficiency in current practice is the underdeveloped treatment of urban freight modeling. Attention to the behavioral aspects of urban goods movement (i.e. to the logic behind shipper and carrier operations) has seen little application at the fully urban scale (UMTA, 1982). If the behavioral waters of personal travel demand analysis are murky, then those associated with freight generating business practices appear downright obscure. Limited effort to date has gone into determining the relationships between company logistics and management practices and their effects on either the daily scheduling and use of multivehicle fleets or on the longer term decisions of where to (re)locate factories and offices with respect to customers and existing freight terminals (including some quite large break-bulk terminals).

Urban trucking research has, as we might expect, dominated what literature there is in urban goods movements. The most comprehensive attempt to come to terms with this area to date was carried out by Transport Canada (1979), which produced a multivolume report on various aspects of urban freight movement. This work includes calibration (to Vancouver data) of an urban truck transport model which links traditional forms of trip generation, distribution, and shortest path-based traffic assignment models to a truck load consolidation model which "consigns" freight to trucks of different sizes.

Such consignments are based on effective vehicle weight capacity, the maximum daily hours of operation (industry regulated), and the expected dwell times at pick up and delivery sites. To allocate this consigned traffic between inner and outer city traffic zones, an optimization based model was used to determine whether to route this traffic directly or via a freight consolidation terminal. At the strategic, urban areawide level, Southworth, Lee, and Zavattero (1986) also examined the efficiencies involved in the use of alternative primary truck route designations and the clustering of freight terminals within the Chicago metropolitan area. Their approach and its empirical application embeds circuit based measures of locational accessibility within spatial interaction models. They also propose a method for using the resulting flows within a mixed person-freight traffic assignment model which in turn could be used to compute fuel use and emissions. Recently, Oppenheim (1993) has proposed an interesting and improved urban-areawide formulation of a combined personal and freight equilibrium traffic assignment model. Among other useful studies, the recent work on freight logistics by Daganzo (1991) and Hall (1993) consider the design of local area freight networks. However, such efforts again reflect a series of largely independent studies, focused on very specific aspects of urban freight travel. A suitably rewarding conceptual framework for urban goods movement analysis remains to be defined.

As with personal travel, much intraurban trucking is also known to involve highly circuitous, multistop daily routing activity (Southworth, 1982a). Circuit-based transportation costs have been used within logit models of destination choice similar in form to those used in passenger travel modeling (Southworth, 1982b, using data from the Chicago region). An interesting possibility, discussed by Wigan and Morris (1981), is the application of a travel budget approach to freight movements. This notion has appeal, since it is the activities at pick-up or delivery sites that often dominate the urban trucker's daily time budget, and since we might expect very similar allocations of travel time to such goods movement services across cities of similar size, given the highly competitive nature of the industry.

Our major hope for projecting aggregate levels of freight-creating industrial activity lies in the belief that businesses follow recognizable profit-maximizing or cost-minimizing development paths. As with the above developments in household travel, freight movement models based on the individual firm have moved into, among other directions, logistic demand based (Sheffi, Eskandari, and Koutsopoulos, 1988) as well as constraint based, multi-criteria mathematical programming forms (McGinnis, 1989). These models again place transport costs (including freight rates) as one among a number of important decision variables in activity pattern (notably, truck route, and schedule) generation. McGinnis (1989), for example, found that carrier reliability, transit time, and shipment loss and damage experience could be more important to shippers than freight rates when selecting a particular carrier.

Finally, in addition to the above issues, we now also need to address the impacts of just-in-time inventory/delivery systems, electronic message transfers, and the increasing interfirm as well as intrafirm coordination of logistics apparently taking place within today's information society. A major shift away from expensive warehousing costs to just-in-time parts and product deliveries clearly has the potential to increase vehicle miles traveled within a number of industries.

3.3.3 Modeling Transportation's Continued Role in Urban Development

3.3.3.1 Transportation Infrastructure Investment Impacts

Looking at longer-term responses in the form of site (re)locations, nontransportation factors again loom larger than traditional industrial location theory suggests. Both intraurban personal and freight travel patterns are affected by the location of such companies; the former through the necessary daily journeys to and from work and, less directly but with increasing significance, through the effects such demands place on the rest of a household's typical weekly activity patterns. As reviewed by Giuliano (1989), much of the recently available empirical evidence supports the view that transportation is at best only one of many determinants in both a household's or a company's location decisions, sometimes acting as a constraint on subsequent economic and related land development without alone being a sufficiently motivating reason to cause a change in current location. Giuliano argues that most large U.S. cities now have such dense transportation networks that the perhaps once more obvious relationship between new highway infrastructure and land development is much less straight-forward, at least within the boundaries of urbanized areas.

In an assessment of the influence of road investment on economic development, Forkenbrock et al. (1990) reviewed a number of studies that reached the following conclusions (also listed by Parker, 1991):

- Transportation investment may be a necessary but not a sufficient factor for economic development.
- The impact of highway investments today, with a mature highway system, may not be the same as in earlier periods.
- Relationships between highways and local development one mainly by association — there is little confidence that highways led to growth, rather than vice versa.
- The economic development process is too complex and the role of transportation is not likely to be sufficiently dominant to allow causal relationships to be established.

- Education, unionization, physical amenities, business climate, energy, and tax rates define a region's developmental prospects to a much greater extent than do highways.

In an often quoted national study of beltway (circumferential highway) impacts, Payne-Maxxie Consultants (1980) found no consistent relationship between the presence of such beltways and land use. Rather, land use impacts were dependent on (1) overall local economic conditions, (2) access to medium income or high income residential areas, (3) availability of developable land, and (4) favorable local zoning ordinances.

However, the empirical evidence suggests care in reaching to too general a set of conclusions. For Texas cities with over 4000 population, Buffington, et al. (1992) found significant correlations between 67 bypass, loop and radial highway improvements and the growth in employment and wage rates for the period from 1954 to 1988. They also cite a number of other studies reporting positive relationships between highway investment and employment growth. Their results may reflect the small size of many of the areas defined as urban, plus a starting point in 1954, when our urban and transportation systems were far less developed. However, even though much of the nation's basic urban highway infrastructure may now be in place, if we are going to use our models to project a similar distance into the future, then we should at least recognize the possibility of similarly large (if in practice very different types of) changes in transportation's future relation to economic development. How we make use of our built structures is changing, if gradually, with each important new laborsaving technology to come along.

Of the above nontransportation factors of significance, the presence of suitably trained labor pools has become an important concern for companies looking to locate, or relocate a factory or office. A recent survey of 504 manufacturers in North Carolina (Hartgen et al., 1991) provides an informative empirical study. Transportation related accessibility measures (state-to-state highway access, access to input materials, and local access by road) were generally ranked below labor factors (notably worker attitudes, availability, and trainability), while other important factors included quality of life (public schools, quality of area for raising children), site and utility costs (electricity costs and supply), and local tax rates. A question facing model developers, therefore, is how to better incorporate or recognize such nontransportation, nonaccessibility based factors within future urban models.

3.3.3.2 Spatial Agglomeration of Activities

Factors in New Urban Center Formation

As Berechman and Small (1988) point out, many of our newly emerging urban places are different in structure from the classical city containing a radial highway network focused on a centrally located CBD. As a companion, and apparently necessary, corollary to the automobile-induced urban sprawl, the location of suburban centers, their rates of growth, and their mix of traffic generating land uses now represent a central concern for urban land use planning (Orski, 1985; JHK Associates, 1989; Garreau, 1991; Southworth and Jones, 1995). Traffic congestion within and between industrial as well as commercial and mixed use suburban activity centers is now also a problem. The very benefits of location and agglomeration of activities offered by a city's CBD, and which led to its subsequent traffic congestion problems, are now causing the more peripheral urban subcenters to experience their own version of traffic related negative externalities; encouraging us to ponder what the solution to such agglomeration diseconomies might be and where this process is leading us (Cervero, 1989).

Such "polycentric" urban development appears to be occurring at a number of scales and is having effects on travel speeds, trip distances, and total travel mileage. What are today seen as an expanding metropolitan area's suburban centers may tomorrow become small satellite cities in their own right. It is possible also that the functional ties between these satellite cities and the long established CBDs will be fewer and different than they have been in past decades. What is currently lacking in our operational models is any in-depth analysis of how such subcenters originate, develop, and perhaps eventually become smaller cities in their own right.

Despite the now quite long and active history of urban economic analysis, current operational models shed little light on this process; using simple incrementalism or random event generation coupled with spatial accessibility measures to produce alternative development scenarios. Traffic congestion would here seem to be an important indicator of when, if not where, a new industrial park or mixed use urban activity center is likely to be needed. Just where they spring up, or which existing centers will continue to compete successfully, is currently much less obvious.

More effort appears warranted here in at least two directions. First, more work needs to go into understanding the locational influences on basic sector industries, including both heavy and light manufacturing industries. Second, a more in-depth understanding of both intraindustry and interindustry dynamics is required. To move this process forward properly requires that we recognize the influence of locationally induced economies of scale on the site selections of such "basic" industries. The POLIS model discussed previously has made one start in this area. More in-depth analysis is necessary.

Such economies of scale arise from placing relevant resources in close spatial proximity to each other, thereby improving the productivity of participating firms. Henderson (1988) distinguishes between scale economies internal to each industry and urbanization economies resulting from the general increases in economic activity which occur as a result of locating within a large city. Both are industrial production economies of the types discussed by Mills (1967), who suggests that cities form in an economy because of scale economies resulting from

1. communications among firms, which enhance the speed of adoption of new technological innovations and/or reactions to changing market conditions;
2. labor market economies for both workers and firms searching, respectively, for specific jobs and specific skill combinations;
3. greater opportunities for specialization in firm (and worker) activities; and
4. scale economies in the provision of intermediate common inputs (docking facilities, warehousing, power, etc.).

As Henderson points out, scale economies which result from the interactions between different but related industries are particularly difficult to identify, because spatial agglomeration may occur without their presence. Transportation cost savings have been cited in the past as the major reason for such spatial clustering.

More generally, locations sharing a number of traits desired in common by a variety of firms may lead to the formation of a mixed use suburban center. Such tendencies are evident in the commercial and retail as well as the industrial employment sectors. Within the retailing sector, what Berechman and Small (1988) term "shopping" agglomeration economies are clearly important. The development of multistore shopping malls recognizes the attraction to consumers of one-stop locations. These tendencies have been extensively modeled over recent years, notably by Wilson and colleagues (see, for example, Harris and Wilson, 1978; Wilson et al., 1981) whose experiments in applying quite rudimentary dynamics to spatial interaction models quickly throw up complex temporal shifts in the locational advantage of retail stores. The wider applicability of such ideas on dynamics to the commercial/office building sector (see Pivo, 1990, for example) or, with adaptations, to the manufacturing sector also needs to be looked into (see Wilson, 1987, for some ideas on this).

In addressing this question of how activity centers originate and subsequently grow, we also need to allow for the long recognized transition of our economy from manufacturing towards both service-based and, increasingly, information-based industries. In tomorrow's cities the never entirely satisfactory distinction between basic and nonbasic sectors is likely to become less useful. With many locationally footloose

industries emerging, just what constitutes the benefits of a particular locational choice may be quite different from what it was just twenty years ago. A search for better theories suggests a search of the wider literature on the nature of both intraindustry and interindustry contacts, their types, frequencies, and impacts on firms' locations. For example, the emergence of *network* forms of organization both within and between firms is discussed by Cooke and Morgan (1993), who consider it to be a significance development in terms of not only corporate strategy but also in terms of regional development potential.

Our urban system model-based explorations into these and industrial linkages have been largely theoretical to date, and our efforts to make urban center formation endogenous to the modeling process are still highly theoretical in nature (see Berechman and Small, 1988). Clapp (1984), for example, adapted the new urban economics bid-rent model to include the effects of business contacts by a single agent, such as the corporate headquarters of a single company, on the rise of suburban centers. However, much more work is needed in this area, with potentially significant payoffs in terms of model realism.

Factors Affecting Travel Within and Between Urban Centers

There is also a need for a more normative approach to the problem, which might lead eventually to more prescriptive modeling efforts. As Dyett (1991) points out, neither current urban economic nor locational accessibility based theories provide much insight into how to best configure land uses at the neighborhood and community scale. However, such designs may prove to be an important source of personal travel reduction. He suggests more work be done to establish whether suburban mixed use centers can be designed to take advantage of cost effective urban designs (or in older suburbs, redesigns) which support walk, cycle, park-and-ride, transit and paratransit options. The location of public buildings (police, fire, city hall) as well as urban parks and other open spaces would also be important components in such designs. We must also pay more direct attention to the role played by land developers within this process. They can become key players in the creation of effective private-public partnerships. For example, they have been active in the adoption of a range of trip reduction ordinances (TROs) through their participation on local Transportation Management Associations in states such as California (Ferguson, 1990). They have also been identified as important players in the development of employer-based rideshare-supporting schemes (Southworth, 1985a). However, our current land use models contain little if anything to reflect the actual role and motivations behind these developer activities (see Levy, 1990, for an interesting discussion).

Some useful research on practical design specifications for mixed use urban centers was recently sponsored by DOT (Snohomish County Transportation Authority, 1989; Middlesex Somerset Mercer Regional Council, 1993) and by the 1000 Friends of Oregon (Cambridge Systematics et al., 1992a). Each of these U.S. studies key their

discussions to a specific type of land use arrangement known as transit-oriented development (TOD), which is proposed as an integral part of a neighborhood or urban center's planned growth strategy.

Once urban centers have formed, movements between them will naturally become increasingly important. In doing urban center planning then, the type, location, and areal extent of the suburbs surrounding these commercial or mixed use centers, from which they draw their workers and customers, should be explicitly recognized and accounted for. According to the 1990 National Personal Transportation Survey (Hu and Young, 1994), while average personal trip lengths (one way, averaged over all purposes) increased from 8.7 to 9.5 miles between 1983 and 1990, increases in travel speeds kept average trip travel times relatively stable. A possible explanation for such increased speeds is the growth in intersuburb, as oppose to suburb-to-CBD, trips. Such intersuburban travel patterns are now an important component of urban development and should be further investigated.

A recent empirical study of the travel patterns of Chicago residents by Prevedouros and Schofer (1990, 1991) contains some interesting findings. Using aggregate census data to classify suburbs into growing versus stable suburbs, they surveyed 1420 respondents to compare two low-density, growing outer-ring suburbs with two suburbs selected for their higher density, stability, and inner-ring location. Among their findings (Prevedouros and Schofer, 1991): for both types of suburb, average speeds for automobile work trips were statistically similar for all but trips to the CBD. However, average trip distances were noticeably higher on average for those from the growing suburbs, resulting in residents from these suburbs staying in traffic some 25% longer than their counterparts from the stable areas. Among their other findings of interest were the high dependence of suburban females on the automobile, the substantial amount of off-peak travel being engaged in, and the possible, if not entirely clear, effects of an aging population on trip rates in the coming decade.

What the above suggests is that an integration of detailed, possibly design-oriented, models of suburban mixed use center formation with a more spatially extensive, and highly structured socioeconomic analysis of intersuburban linkages offers a useful approach to consider for further theoretical and empirical development.

3.3.4 Simulation of Urban Dynamics

As discussed in Sect. 2.5, the simulation of increasingly comprehensive urban dynamics is already quite evolved, and for multiyear forecasting the use of static-recursive approaches may be sufficient for most strategic policy making. However, further study of system dynamics is both warranted and arguably necessary for the following reasons. First, a number of studies indicate that failure to consider such dynamics explicitly may cause us to misinterpret the actual processes of urban change.

Second, intriguing possibilities for more direct representations of detailed traveler behavior now exist than at any time in the past. By making use of microsimulation methods in conjunction with massively parallel or vectorized computers its now possible to generate tens of thousands of daily activity patterns in a surprisingly short turnaround ("wall clock") time. To take advantage of this opportunity the travel activity analysts needs to develop explicitly dynamic equation sets when trying to represent the behavioral responses of travelers.

Over the past two decades a number of research efforts have addressed the issue of introducing dynamics more explicitly into our urban systems models. These include a number of efforts focussed on the evolution of all or parts of complete urban systems, notably (1) the work by the Leeds group in the United Kingdom based on catastrophe theory (Wilson, 1981), (2) the work by the Brussels Group in Belgium based on uses of self-organizing system's theory and micro-simulation (Allen, Engelen and Sanglier, 1986), and (3) a number of efforts, including research in France (Fournier, 1986) and Italy (Bertuglia et al., 1981), to adapt the urban dynamics approach proposed by Forrester (1969) to real world cities.

Wilson (see, e.g., Wilson, 1987) offers the following approach to tracking the change over time in the size of a facility at location j , W_j , as a function of profit accrued at that location. Let R_j = the revenue attracted to that location, then profit at j is given as:

$$R_j - k_j W_j \quad (53)$$

where k_j = the unit cost of floorspace in location j for the given facility type. Assuming a desire to maximize such profits among facility suppliers (e.g. developers) a suitable hypothesis for change in facility size is taken to be

$$dW_j/dt = \epsilon (R_j - k_j W_j) \quad (54)$$

for some constant ϵ . Spatial equilibrium is then assumed to be reached in a given time period t , when the value of Eq. (50) equals zero. A more general functional form is proposed for applications, as is the conversion from a differential to difference equation form for computational purposes, i.e.

$$W_{j,t+1} - W_{j,t} = \epsilon (R_{j,t} - k_{j,t} W_{j,t}) W_{j,t}^n \quad (55)$$

which for an exponent $n=1$ produces logistic growth. Rearrangement then gives:

$$W_{j,t+1} = (1 + \epsilon R_{j,t}) W_{j,t} - \epsilon k_{j,t} W_{j,t}^2 \quad (56)$$

Experiments with these sorts of equations for retail activity location systems (Harris and Wilson, 1978; Beaumont, Clarke and Wilson, 1981) show the potential for significant oscillations in facility sizes, including possible jumps back to zero floorspace in some W_j values when the value of $(1+\epsilon R_j)$ in Eq. (52) is greater than 2.

One conclusion from such findings is the need for caution in oversimplifying the assumptions involved in detailed travel pattern and associated land use forecasts. A more positive view of the picture is that such discoveries will allow us to experiment with the robustness of alternative urban land use and transportation infrastructure plans if we can find a way to bring them effectively into our operational models. Wilson (1987) describes a beginning in this process by formulating a dynamical version of the Lowry model based on the above ideas. These developments also help to tie the above described spatial interaction approach more closely to economic concerns. For example, consider the mathematical programming version of the shopping model discussed in section 2.4.2 above, and repeated here for convenience:

$$\text{Maximize } Z(S_{ij}, W_j) = \sum_{ij} S_{ij} \left(\frac{\alpha}{\beta} \ln W_j - c_{ij} \right) - \left(\sum_{ij} S_{ij} \ln S_{ij} \right) \quad (57)$$

subject to:

$$\sum_j S_{ij} = e_i P_i \quad \forall i \quad (58)$$

and

$$\sum_j W_j = W \quad (59)$$

where S_{ij} = the flow of shopping revenues from shoppers in zone i visiting shops in zone j , W_j = the size of shopping facilities in zone j in units of floorspace, and the two terms in the objective function measure consumer surplus and the spatial dispersion of destination choice (spatial entropy). Now if we let:

$$\sum_i S_{ij} = R_j = W_j k_j \quad (60)$$

Where the unit floorspace costs $k_j = \alpha/\psi$, and where ψ is the lagrangian multiplier associated with the total floorspace supply constraint (55) above, we have placed a supplier's floorspace requirement as a condition of the optimization. The resulting equilibrium pattern of W_j 's is therefore based on a supplier profit motive as well as on consumer benefits maximization.

To be of practical use such developments will need to incorporate the effects of a variety of other factors, notably the effects of spatially varying prices. A search for ways to bring such ideas of market driven, profit-induced change into modeling, via the use of

modern day highly computer intensive microsimulation techniques appears worth pursuing. Of particular interest are methods which can use difference equations to simulate the dynamics involved in mixed use urban activity center formation and decline. For example, can we use explicitly dynamic equations to microsimulate the alternative temporal paths available to individual (that is, synthetically constructed) companies as well as synthetically constructed travelers? In particular, can we simulate the effects of spatial agglomeration of activities based on the mutual locational benefits discussed above by microsimulating the passage of information as well as goods and people between such companies?

3.4 PRACTICAL ISSUES: TOWARDS MORE USABLE MODELS

A strong argument can be made that as far as land use-transportation modeling efforts to date are concerned, toolmaking is more advanced than theory. It would be difficult to find an area of research that has drawn on a greater variety of mathematical, statistical, and computational methods in its search for empirical validation and subsequent practical applicability. Yet the application of many of these techniques is much less widespread within the planning profession than might be expected. Few practicing regional or metropolitan planners calibrate their own multinomial logit models or experiment with alternative land availability or density constraints as part of a nonlinear mathematical programming exercise. Nor is the issue simply one of technical training. In order to encourage practicing planners to make greater use of the models which do exist, the models need to be made easier to use.

If planners from more than one jurisdictional level (local, metropolitan, statewide, or regional) can be brought together by use of a common, easy to use modeling, possibly game-playing software, then improved models could possibly be transformed into consensus building tools, rather than the seemingly arcane components of a planning process in which only one or possibly two experts within any metropolitan planning agency have anything to do with them directly.

Researchers have already developed a range of user interfacing capabilities, including graphical interfaces, for commercially available models such as MEPLAN. However, we can go much further here, as evidenced by the use of highly interactive, multimedia, decision-support aids in other fields. The emergence of reasonably priced and generally accessible geographic information system (GIS) software is the latest step in this development of decision-support tools. By linking a relational database management tool to software programs for manipulating spatial primitives (points, lines, polygons), adding the land use and transportation modeling subroutines themselves, and building around all of these an easy to use, map-based interface, we have the principal components of a spatial decision support system (an SDSS). Ongoing developments in the SDSS arena promise more effective manipulation of both spatial and nonspatial data

elements, in the short term through the more efficient selection of which computations to carry out via database manipulations and which to continue to model through the more context-specific algorithms (see, e.g., Lolonis, 1993). The field of urban transportation modeling is only now beginning to make use of such GIS tools (Prastacos, 1991; Hartgen et al, 1993; Anderson, Kanaroglou and Miller, 1994; Spiekermann and Wegener, 1994).

Current developments in database encapsulated software systems and object-oriented programming languages also suggest a move towards more flexible software systems (Stevens, Tonn, and Southworth, 1994). Again, we are just beginning to make use of such advances in the field. For example, the SUSTAIN model, an offshoot of the TOPAZ efforts at CSIRO in Australia, is currently being developed as an object-oriented programming approach specifically directed at the linkages between transport, urban form, and energy consumption (Roy and Marquez, 1993).

A key component of such decision-support systems will be their ability to help the planner resolve often competing energy, environmental, fiscal, social, and economic goals. Here the use of multicriteria decision-making methods are also worth further explorations. Three increasingly popular decision aides that have been applied recently to transportation project assessments include Saaty's Analytic Hierarchy Process (see Zahedi, 1986 for a review), Roy's ELECTRE III method (see Roy, Present, and Silhol, 1986 for an application to Paris metro station locations) and Concordance Analysis (see Giuliano, 1986b, for an application to the ranking of alternative highway, bus transit, ride sharing and commuter rail investment projects in Orange County, California).

Each of these approaches can be applied to, actually on top of, the outputs of any of the above reviewed land use-transportation models as a further aid to strategic as well as project specific decision making. In particular, they can enhance the evaluation of trade-offs between the costs of plan implementation and the energy savings, emissions reductions, and the economic and social impacts (including intercommunity equity impacts) of proposed travel reduction strategies. Any realist hope for the acceptance of transportation plans which significantly reduce petroleum based fuel use and greenhouse gas emissions will certainly require plans which also address such trade-off issues (see Bae, 1993).

There are a number of additional benefits to developing a highly interactive, multimedia approach to decision support. It's much easier to remain skeptical about a batch driven process in which the user's only interaction of note is data input than it is to feel the same way about a process in which he or she is an active component. Highly interactive user-centered planning tools can prove to be very powerful decision-support aids. This is particularly true for spatially explicit problems. Here an interactive game of consequence analysis is appealing; a game in which the analyst gets to experiment with different starting points, parameter values, land use controls, pricing schemes, fiscal and other constraints, and a range of differentially weighted plan objectives. A major benefit

from the use of such interactive systems is likely to be the knowledge both gained from and added back to the system by the analysts. Tomorrow's decision-support systems are likely to combine text, and geo-graphics with sound, and video, including animation (see Wiggins and Shiffer, 1990, for a discussion). Software which allows the user to place aerial photographs behind model constructs, such as network upgrades and new land use arrangements, can also serve the process of bringing the art of modeling closer to the planner. With the arrival of global communications in the form of the Internet and World Wide Web, a considerable increase in the use of interactive, map-based editing tools should be expected to inform the land use and transportation planning process.¹ Indeed, in coming years, whenever a major metropolitan planning proposal is transmitted in digital form its likely to encourage a significant number of similarly transmitted responses from a growing number of interested parties. This constitutes a type of information which our present models and supporting databases are perhaps ill-equipped to handle.

The development of such interactive, model-encapsulated analysis tools constitutes a challenging research and development task. Well-designed decision-support system require as much thought (and at least as much money to render operational) as do the computer models of land use and transportation interaction on which they are based. The tools now exist with which to build such software. However, current commercial GIS packages are still some way from being the spatial decision-support tools we need. Experience with such software in the field of urban and regional transportation modeling has been quite limited to date. Education in how to construct, adapt, and use such software tools is now required within the transportation planning profession.

¹ Early efforts in this area currently include those at the University of California at Davis (Johnston, 1995).

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