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Current Operational Urban Land-use–Transport Modelling Frameworks: A Review

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ABSTRACT *Various alternative frameworks are available for modelling urban land-use–transport interaction. This paper provides a detailed review of six of these frameworks that have been or are currently being used to develop operational models. The intention is to indicate what is the general nature of the current state of practice and what is now available for practical modelling work in the area. The intention is also to compare the current state of practice with what might be the ideal in various respects. The six frameworks reviewed (ITLUP, MEPLAN, TRANUS, MUSSA, NYMTC-LUM and UrbanSim) are considered in terms of their representations of physical systems, decision-makers and processes, along with various more general modelling and implementation issues. None matches the ideal as envisaged here in all respects. However, a wide range of policy considerations can be handled explicitly with what is available, and more recent developments show an encouraging trend towards expansion in the scope of what can be considered. Further strengthening of the behavioural basis and relaxation of some of the more restrictive assumptions would appear to be both appropriate and likely in the future.*

Introduction

The purpose of this paper is to review a representative range of operational, comprehensive, integrated, urban land-use–transport modelling frameworks both as a guide for practitioners to the current state of practice and as a benchmark against which researchers might assess research needs for improving the integrated urban modelling state of the art. Keywords in this statement of the paper's purpose include: 'operational' (the model must be used in one or more practical urban planning applications), 'comprehensive' (the model must include a—reasonably—complete range of spatial processes, notably land development, location choices by both households and businesses, and travel), and 'integrated' (meaning that feedback exists between the transport and urban activity systems, so that the short- and long-run interactions between transport network perfor-

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mance and land development/location choice behaviour are captured appropriately within the model). Implicit in stressing the operational nature of these models is the assumption that these models must be useful in assessing the impacts over time of a range of transport and land-use policies on both transport system performance/travel demand and the spatial, economic and environmental evolution of the urban region being analysed.

Finally, a fundamental assumption in constructing this review is that urban spatial processes play out within *markets* (for land, floor space, travel, goods and services, etc.), within which production/consumption (supply/demand) processes interact to determine system outcomes. In particular, these market interactions both determine the *prices* at which goods/services are exchanged and are, in turn, influenced by these prices. Thus, the ability of a model to capture market demand–supply interactions and to determine market prices endogenously is viewed as an issue of fundamental importance in assessing a given model's capabilities.

This review has four sections (excluding this brief introduction). The next section defines the set of six models to be reviewed and the rationale underlying their selection. This is followed by a relatively brief introduction to each model in turn. The six models are then compared in detail with another with respect to a range of criteria. Finally, the models are evaluated against a hypothetical 'benchmark' or 'ultimate' model. While this ultimate model obviously reflects the authors' own views on how integrated urban models should evolve, it is hoped it provides a useful starting point for considering the strengths and weaknesses of current models and for defining promising directions for further research and development in this area.

Detailed descriptions of the mathematical formulation of each model are beyond the scope of this review and are available from the cited material included with each introduction.

Modelling Frameworks Selected

A reasonable number of urban land-use–transport-modelling frameworks currently exist, in varying degrees of completeness and usability. Wegener (1994) identifies 20 active urban modelling centres, 12 of which have produced models used for actual research and/or policy analysis. Southworth (1995) identifies a further three frameworks.

The intent of the present paper is to build on the reviews of Wegener and Southworth by focusing on a limited number of representative models and by assessing these models in greater detail than is possible in a more typical, more broadly defined review. Six such frameworks for urban modelling are considered:

- ITLUP (also often referred to as DRAM/EMPAL).
- MEPLAN.
- TRANUS.
- MUSSA.
- NYMTC-LUM.
- UrbanSim.[1]

The six frameworks fall into two main categories. The first three are operational, commercially available 'packages' with an established history of use. In particular, ITLUP (DRAM/EMPAL) is the most widely used urban modelling package used in the USA, while MEPLAN and TRANUS have been extensively applied in Europe and South America (with more limited application in North America). Thus, for many agencies, these packages collectively define current operational practice.

The second group of three (MUSSA, NYMTC-LUM, UrbanSim) are also currently operational, or very close to being operational, in one or more practical settings. Each is also noteworthy in that it contains a significant and interesting approach to land market representation, incorporating an explicit treatment of prices in land use and development.

A range of other urban modelling frameworks exists. Noteworthy examples include microsimulation models (Wegener, 1982a; Miller *et al.*, 1987; Mackett, 1990; Oskamp, 1997; Miller and Salvini, 1998); optimization models (Brotchie *et al.*, 1980; Dickey and Leiner, 1983; Kim, 1989; Caindec and Prastacos, 1995); land accounting-type models (Landis, 1994); and other European, Japanese and Australian models (Wegener 1982a, b; Mackett, 1983, 1985; Nakamura *et al.*, 1983; Anderstig and Mattsson, 1991; Gu *et al.*, 1992; Eliasson and Mattsson, 1997). While each modelling framework is of potential interest in one or more ways, they are not included here for a variety of reasons. The authors view microsimulation models as an extremely promising approach to large-scale modelling, but they are not yet in operational practice. Optimization models are useful for exploring what optimal urban configurations might look like (among perhaps other uses), but are generally not of direct use in the assessment of the impacts of transport and land-use policies on the evolution of existing urban areas. Land-accounting models are in widespread use but do not generally include land-use–transport interactions (indeed, the transport sector is typically absent from such models), and so these models are neither integrated nor comprehensive in their design. Finally, many of the other models listed above (and/or reviewed by Wegener) are either not comprehensive (many are housing market models, but do not deal with the full set of urban land uses and land development processes), not fully operational (i.e. more research tools than working models) and/or bring little new to the discussion relative to the models selected for review in this paper.

Thus, the six models listed above are selected for detailed review because they provide a good representation of the range of approaches used in current operational practice for comprehensive, integrated urban modelling, where the intent is to simulate/predict the evolution over time of urban systems (and various elements within these systems) for land-use–transport policy analysis purposes.

General Descriptions

General descriptions of the six frameworks are given below.

Integrated Transportation and Land Use Package (ITLUP)

The ITLUP framework has been developed and applied by Professor Stephen Putman at the University of Pennsylvania, Philadelphia, USA, over 25 years. It includes a number of sub-models, the best known of which are DRAM (Disaggregate Residential Allocation Model) and EMPAL (Employment Allocation Model). It uses a Lowry-derivative form (Lowry, 1964) to allocate households (usually by four income categories, though further categorizations are possible), employment (usually by four types, though more detailed Standard Industrial Classification (SIC) groupings are possible) and travel patterns (public and private modes). Exogenous study area forecasts of employment, population and trips, activity rates and household types are inputs. Detailed documentation of the model is provided by Putman (1983, 1991, 1994), with useful summary descriptions also available (Webster *et al.*, 1988; Wegener, 1994; Southworth, 1995; Putman, 1996). Notable features of ITLUP are as follows:

- ITLUP (more specifically, DRAM and EMPAL) is the most widely used spatial allocation framework in the USA today. A recent count indicates over a dozen active US applications (Putman, 1997), although over 40 calibrations have been performed across the USA and elsewhere.
- It contains a multinomial logit modal split sub-model, as well as a trip assignment sub-model that can support various network assignment algorithms. Trip generation and distribution are developed within DRAM, simultaneously with household location. However, DRAM and EMPAL often are used separately and have been linked in actual applications with other commercial travel demand forecasting models (including EMME/2, TRANPLAN and UTPS). Thus, considerable detailing of travel demand and travel costs can be provided through exogenous links.
- Compared with other frameworks, it has relatively parsimonious data requirements. Southworth (1995) notes that an important advantage of DRAM/EMPAL is its basis in generally available data (i.e. related to population, households and employment). However, it is also noted that this reflects a weakness of the approach; namely, that the framework does not account for land market clearing processes (or, it follows, other market clearing processes).
- A recent development is METROPILUS, which is aimed at improving linkages with geographic information system (GIS) databases and in revising the framework towards greater system modularity. It operates within an ArcView shell, which supports linkages with an ArcView GIS database, and is Windows compatible (Putman, 1997).

MEPLAN

The MEPLAN framework is contained in proprietary software developed by Marcial Echenique and Partners Ltd in the UK, a private consulting firm. It draws on 25 years of experience in practical integrated urban modelling, with work on the software package itself beginning in 1985. It has been applied to over 25 regions throughout the world, including Sacramento, California and the Cross-Cascades Corridor in the US. Detailed documentation can be found in various sources (Echenique *et al.*, 1969, 1990; Echenique and Williams, 1980; Echenique, 1985; Hunt and Echenique, 1993; Hunt and Simmonds, 1993; Hunt, 1994).

MEPLAN is an aggregate model: space is divided into zones, quantities of households and economic activities (called ‘factors’ or ‘sectors’) are allocated to these zones, and flows of interactions among these factors in different zones give rise to flows of transport demand. The heart of the framework is a spatially disaggregated input–output matrix, or social accounting matrix, extended to include variable technical coefficients, labour sectors and space sectors. All economic activities, including households, are treated as producing and consuming activities, with consumption patterns expressed using technical coefficients. Spatial disaggregation is accomplished by having the further production arising to satisfy consumption allocated among the spatial zones according to discrete choice models reacting to the prices for such production. The resulting interactions among zones gives rise to the demand for travel.

Temporal change is simulated by considering sequential points in time. Space (both land and floor space) is 'non-transportable' and must be consumed in the zone where it is produced. The supply of space in each zone is fixed at a given point in time. The technical coefficients for the consumption of space are elastic with respect to price, and prices for space that ensure demand equates with supply in each zone are established endogenously as part of an equilibrium solution established for each point in time considered. Prices for the outputs of other sectors are established endogenously running back along the chains of production–consumption. Travel demands arising for a given point in time are allocated to a multimodal network using logit functions representing mode and route choice, taking account of congestion. Transport disutilities feed back into the next time period, representing lags in response to transport conditions. Exogenous demand, which is analogous to the 'Lowry' (1964) basic sector, provides the initial impetus for economic activity. Changes in study-wide exogenous demand and in the quantity of space in each zone from one time period to the next fuel economic change, with these changes allocated among zones.

Modelo de Uso de Suelo de SAntiago (MUSSA)

MUSSA is an operational model of urban land and floor space markets developed by Professor Francisco Martínez for Santiago, Chile. It is 'fully connected' with a thorough four-stage model (known as ESTRAUS); together, the combined models are referred to as 5-LUT, and provide equilibrated forecasts of land use and travel demand for Santiago. The model has been used to examine various transportation and/or land-use policies, usually involving transit as a central component of the policy. Documentation of the model is provided by Martínez (1992a, b, 1996, 1997, 2000) and Martínez and Donoso (1995). Notable features of MUSSA include the following:

- Consistently based throughout on an extremely rigorous and compelling application of microeconomic theory.
- Equilibrium model of building stock supply and demand. Demand for building stock (whether by households or firms) is based on their willingness to pay (WP). Buyers attempt to maximize their surplus (WP less price actually paid), while sellers attempt to maximize the price paid. Building stock is supplied by developers so as to maximize profits, given the apparent demand. Building stock prices are endogenously determined within the equilibration process.
- Solves for a static equilibrium in the forecast year by adjusting the amount of building stock supplied, a supply response, and consumers' expectation levels (expected utility to be obtained from their housing), a demand response, until demand and supply balance. The model end state is path independent and does not require solution for intermediate year results, although such intermediate results can also be generated.
- Uses traffic analysis zones as its spatial unit of analysis, thereby providing a relatively fine level of spatial disaggregation. In addition, extensions to more micro-levels of spatial analysis are being investigated (Martínez, 1997).

- Highly disaggregated relative to most other currently operational models. The Santiago implementation has 65 household types and could be run using a large weighted sample of observed households (and their associated detailed attributes) in essentially a 'static microsimulation' format.
- Extensions are being investigated to incorporate zone-level environmental impact (emissions) calculations into the modelling system (O'Ryan *et al.*, 1996).

NYMTC-LUM

The NYMTC-LUM framework has been developed by Professor Alex Anas on behalf of New York Metropolitan Transit Commission (MTC), New York, USA (Anas, 1998). It is a simplified version of METROPOLIS, and the most recent of a series of land use and housing market models developed by Anas over the last two decades (Anas, 1982, 1992, 1994, 1995; Anas and Arnott, 1993, 1994; Anas and Brown, 1985). Notable features of NYMTC-LUM include the following:

- Consistently based throughout on microeconomic theory.
- Simultaneously models the interactions between residential housing, commercial floor space, labour and non-work travel markets, with explicit representations of demand and supply processes in each case.
- Housing prices, floor space rents and workers' wages are all endogenously determined within the model and are used to mediate between demand and supply processes within their relevant markets.
- Solves for a static equilibrium in the forecast year by finding the prices and wages that cause demand and supply in the markets being modelled to balance. The model end state is path independent and does not require solution for intermediate year results.
- Uses traffic analysis zones as its spatial unit of analysis (up to 3500 zones in the New York application), thereby providing a very fine level of spatial disaggregation relative to many other current models.
- In its current state of implementation, the model does not contain much disaggregation of its main behavioural units (households, employment, buildings).
- In its current implementation, the land-use component is not integrated with a travel demand model. Rather, it is 'connected' to the existing MTC travel demand model in terms of receiving as inputs model utilities from the MTC mode choice model. This is similar to the case for DRAM/EMPAL, MUSSA and UrbanSim.

Features of the model that facilitate its application by a transit property include: use of small traffic zones as the spatial unit of analysis; access to detailed transit network representations and mode choice models in the MTC travel demand model; and the microeconomic structure of the model that permits a range of economic evaluation measures to be computed (property values, consumers' surplus, producers' surplus, etc.). Earlier models have similarly been applied to the evaluation of the impacts of the proposed South Corridor rapid transit line in Chicago, Illinois (Anas and Duann, 1986), and the assessing the impacts of a range of road and transit service changes in New York (using NYSIM) (Anas, 1998).

TRANUS

The TRANUS package is proprietary software developed by Modelistica in Venezuela, a private firm run by Dr Tomas de la Barra. It draws on much the same modelling experience as MEPLAN, with the elements of the package first coming together in the early 1980s. A key feature of TRANUS is the use of a somewhat more restricted set of functional forms and modelling options within the framework allowing a more set approach to model development relative to MEPLAN. It has been applied to a number of regions in Central and South America, and in Europe. TRANUS models of the Sacramento and Baltimore, Maryland, USA, regions and Oregon have been completed or are under development. For detailed documentation, see De la Barra (1982, 1989), De la Barra *et al.* (1984) and Modelistica (1995).

UrbanSim

UrbanSim is an operational model of urban land and floor space markets developed by Professor Paul Waddell for Hawaii, Oregon and Utah, USA. A prototype has been completed in Eugene-Springfield, Oregon. The model is designed to work in conjunction with a traditional four-stage model in Eugene-Springfield, and is being connected to a new activity-based travel model in Honolulu, Hawaii. Although the initial development of the model was undertaken through the consulting firm of Urban Analytics, further development and support of the model is being done at the University of Washington. The model and software has been placed in the public domain by the Oregon Department of Transportation, and the University of Washington will support its release and dissemination through the Internet as part of an NCHRP Project 8-32(3), 'Integration of Land-use Planning and Multimodal Transportation Planning'. For documentation of the model, see Waddell (1998a–c) and Waddell *et al.* (1998). Access to documentation and to the model is available at www.urbansim.org.

Notable features of UrbanSim include the following:

- Uses a 'WP' framework similar in concept to that used in MUSSA, but differing in significant aspects such as in not assuming equilibrium.
- Disequilibrium model of building stock supply and demand with annual time increments. Demand for building stock (whether by households or firms) is based on their WP, or bid (observed prices paid rather than hypothetical WP, which is difficult to observe). Buyers attempt to maximize their surplus (WP less price paid), while sellers attempt to maximize the price paid. Building stock is supplied by developers so as to maximize profits, given the apparent demand. Building stock prices are determined within the market clearing process, which occurs at the submarket level of the traffic analysis zone and property type.
- Model operates as a dynamic disequilibrium in each year, with the supply component developing and redeveloping individual land parcels on the basis of expected profits (expected revenue less costs). Expected revenue is based on prices lagged by one year, and new construction choices are not assumed to be available for occupancy until the subsequent year. Demand is based on lagged prices and current supply, and prices are adjusted based on the balance of demand and supply in each submarket in each year. The model end state is path dependent and requires a solution for each intermediate year.
- Demand side of the model uses traffic analysis zones as its spatial unit of analysis (271 zones in the Eugene-Springfield application, 761 in Honolulu, over 1000 in Salt Lake City, Utah), thereby providing a very fine level of spatial disaggregation relative to many other current models. On the supply side, the

model uses the individual land parcel as the unit of land development and redevelopment, making this the only model to date to use the parcel as the fundamental unit of analysis.

- Model is highly disaggregated relative to most other currently operational models. The Eugene-Springfield implementation has 111 household types and could be run using a large weighted sample of observed households (and their associated detailed attributes) in essentially a static microsimulation format.
- Model is based on the analysis of policy scenarios that include comprehensive land-use plans, growth management regulations such as urban growth boundaries, minimum and maximum densities, mixed-use development, redevelopment, environmental restrictions on development, and development pricing policies, as well as the range of transportation infrastructure and pricing policies handled by the linked travel demand models.

Detailed Considerations

In this section, the six selected models are compared in terms of their representation of the following:

- Physical system being modelled (time, space, building stock, transport system).
- Decision-makers (actors/agents) whose actions/choices determine the evolution of this physical system over time.
- Decision processes used by these actors.

To streamline what might otherwise be a very extended discussion, a series of tables is used to summarize the attributes of each model. These contain a considerable amount of information, much of which is not explicitly discussed in the main body of the paper.

Table 1 presents some very general facts about the operational history and availability of each of the six frameworks as packages for implementation. The extent of operational experience varies dramatically. The packages run on a variety of platforms, although most are now typically PC based. Most are supported by (at best) a small consulting group, which typically depends heavily on the model developer. One exception is MEPLAN, which is supported by a fair-sized consulting firm.

Table 2 summarizes how the six frameworks deal with the primary physical entities within urban areas: time, land and developed space (buildings). In this and subsequent tables, MEPLAN and TRANUS are grouped together due to their common conceptual structures (with differences between the two models indicated where necessary).

Five of the six are static equilibrium models, which either jump directly to the end-year equilibrium state or are moved from one equilibrium point to the next in typically 5-year steps. The exception is UrbanSim, which operates on a 1-year step and which does not assume equilibrium. While equilibrium is a powerful and convenient concept for modelling complex systems (since it provides the criteria needed to solve for a future year system state), the assumption that urban areas are in a state of equilibrium at any point in time is a very strong one. It is more likely that urban systems are in a constant state of inertial adaptation, with actors' decisions being based on both past system states/performance and anticipated

Table 1. General facts

Software	Developer	Operational history	Platform	Commercial availability	Support
ITLUP	S. H. Putman	Developed over the last 25 years; operationally applied in many US cities plus selected overseas (40 plus calibrations)	Originated in FORTRAN for mainframe/work-station. PC version (METROPILUS) in ArcView shell, which provides linkage to ArcView GIS (Windows compatible)	Yes	Consulting firm, with commercial documentation and technical support (user's manual, newsletter, user group)
MEPLAN	M. Echenique	Much shared history over 25-year development. Operational applications throughout the world, including the USA (Sacramento for both; Washington State for MEPLAN; Oregon State and Baltimore for TRANUS)	MEPLAN originated in FORTRAN for mainframe; now PC based	Yes	Consulting firm, with commercial documentation and technical support (user's manual, newsletter)
TRANUS	T. de la Barra		TRANUS developed directly for PC (Windows orientation)	Yes	Consulting firm, with commercial documentation and technical support (user's manual)
MUSSA	F. Martinez	Operational in Santiago, Chile. Developed over last 8–10 years	PC based; runs under Windows. Interfaces with a relational database management system (Access). GUI and GIS	Yes	University-based research team in collaboration with the Government of Chile
NYMTC-LUM	A. Anas	Currently being implemented in New York City. Based upon previous models (CATLAS, CPHMM, NYSIM) developed in Chicago and New York over the last 20 years	PC or workstation. FORTRAN program	Yes	Alex Anas & Associates (a small firm). Limited documentation
UrbanSim	P. Waddell	Currently being implemented in Honolulu, Eugene/Springfield and Salt Lake City. Historical validation performed in Oregon	Platform independent, written in Java. Viewer currently implemented in MapObjects GIS on Windows 95/NT	Yes; public domain via website (www.urbansim.org)	University of Washington. Limited documentation currently. Reference manual, user guide, software available at website (www.urbansim.org)

Table 2. Treatment of time, land and space

	Time	Land	Developed space
ITLUP	Equilibrium established at each time step (normally 5 years). Information lags exist from a previous time step Transportation costs at time *t* are the basis of the employment allocation at time $t + \Delta T$, although both sets of costs are used in the household allocation at time	Zone-based (typically large zones due to data constraints, although no theoretical difficulty in using smaller zones, e.g. 291 zones used in San Francisco Bay Area model) Developable land is specified exogenously No micro-scale representation	No explicit representation of buildings/floor space (Lowry-like representation), although tests have been conducted with proxies (e.g. age of housing stock, location of retirement households, single versus multifamily dwelling units)
MEPLAN TRANUS	Equilibrium established at each time step. Information lags exist from previous time steps Transportation disutilities at time *t* are the basis of the allocation at time $t + \Delta T$. $(\text{Prices/capacities})_t$. → . $(\text{development})_{t+\Delta t}$ Note: Δt is set during calibration (often 5 years, due to data)	Zone-based (typically large zones). Technical coefficients for production/consumption become 'unrepresentative' for small zones Land categorization essential to the model Developable land is specified exogenously No micro-scale representation	Framework is sufficiently flexible to include and usually does Chain of demand: land . → . buildings . → . activity . → . explicit representation: floor space, density, prices, etc In TRANUS, in the GUI, there is a limitation of 25 floor space categories
MUSSA	Direct step to static equilibrium solution for a horizon year. Can be used with multiple time steps (e.g. 5-year steps), in which case the equilibrium at each time step is found. Some explanatory variables are lagged from a previous time step. Building stock supply function dynamic is in its theoretical development	Small-zone based (i.e. traffic zones). A total of 264 zones used in Santiago. Developable land per zone an explicit, exogenous constraint. Currently working on extensions to the micro-scale	Number of units by type (residential and firm) explicit and endogenously determined. Six housing types and five commercial unit types currently used in the Santiago model. Endogenous prices

Table 2. *Continued*

	Time	Land	Developed space
NYMTC-LUM	Direct step to equilibrium solution for a horizon year (New York City) implementation. Can be used with multiple time steps (e.g. 5-year steps), in which case equilibrium at each time step is found	Small zone based (i.e. traffic zones). A total of 3500 zones used in the New York City implementation. Land area categorized by housing type, basic industry (exogenously determined), non-basic (endogenously determined) and vacant. No micro-scale representation	Housing by category (New York City implementation: two categories, i.e. single- and multifamily): number of units and floor space by zone; basic and non-basic floor space by zone. Number of categories limited by data availability, although computational size goes up with number of categories (equilibrium solution requires solving $(H + \mathrm{NB})N$ simultaneous equations, where H is the number of housing categories, NB is the number of non-basic categories and N is the number of zones. Prices explicit
UrbanSim	Dynamic disequilibrium. One-year time step. Lagged responses to price signals	Demand side uses traffic analysis zones and property types. Supply side uses parcel level for land development/ redevelopment. Land-use plans, regulations, environmental constraints integrated at the parcel level. Developable land is specified exogenously	Explicit representation of housing by type, non-residential floor space by type, density, price and age of development

future conditions. Thus, the UrbanSim approach of dynamically evolving the urban system over a series of finer time steps in an incremental, adaptive process possesses considerable intuitive appeal. Relatively little experience exits, however, in integrated urban modelling (and, indeed, within all of transport modelling) with disequilibrium-based, dynamic modelling, and more experimentation with models of this sort would appear to be warranted.

All six frameworks are zone based, with the three older models (ITLUP, MEPLAN, TRANUS) typically being implemented using a very coarse zone system (e.g. 50–100 zones for very large urban areas). MUSSA and NYMTC-LUM, on the other hand, operate at the traffic zone level. UrbanSim uses two levels of spatial detail: the traffic zone level for travel demand calculations, and the individual parcel for land supply and demand calculations. The developers of MUSSA are also experimenting with more micro-scale analysis capabilities, but these are not operational at the time of writing.

The issue of spatial/demographic aggregation is, of course, important since it affects: the extent of aggregation bias within the models (in the face of considerable heterogeneity within the actors being modelled); the ability of the model to represent road and transit systems and their usage adequately (very large zones do not provide an adequate basis for modelling transit system performance and patronage); data requirements (greater disaggregation obviously implies increased data needs); and computational effort (more, smaller zones require greater computational resources to store and process the system state). In four of the six models, the choice of spatial/demographic aggregation level generally reflects design tradeoffs among these four issues. In the case of MEPLAN/TRANUS, however, the spatially disaggregated input–output matrix tends to impose limitations on the level of disaggregation which can be operationally achieved, since the technical coefficients in the spatial input–output model become unrepresentative/unreliable at the small zone level.

Five of the six models explicitly represent developed space in one way or another. The exception is ITLUP, in which households consume land directly, with no explicit representation of the built environment being maintained. In the other models, developed space is represented through some combination of 'units' (i.e. housing units are used in MUSSA, NYMTC-LUM and UrbanSim) and floor space (non-residential developed space is represented by floor space in all five models, while MEPLAN/TRANUS also use floor space to describe residential housing as well).

Table 3 considers the representation of the transportation system. All six frameworks use some form of multimodal transportation network model. MEPLAN and TRANUS have built-in network modelling capabilities; MUSSA, NYMTC-LUM and UrbanSim are 'connected' to stand-alone four-stage modelling systems; and ITLUP can function either way. In addition, at the time of writing, UrbanSim is being developed to run with an activity-based travel model in Honolulu.

In all cases, information passed from the network model to the land-use component takes the form of various composite utility values derived from random utility theory. These values are so-called 'log-sum' or 'inclusive value' terms taken from the logit models used in the travel demand model. MEPLAN/TRANUS are more 'integrated' than the others in that composite utilities derived from mode choice models are input to the land-use model, and the land-use model simulates the spatial economic flows that are used to determine trip

Table 3. Treatment of transportation networks and services

<table>
<tr><th rowspan="2"></th><th rowspan="2" colspan="2">Transportation networks</th><th colspan="3">Transportation supply (infrastructure + services)</th></tr>
<tr><th>Transit representation</th><th>Goods movement</th><th>Other transportation services</th></tr>
<tr><td>ITLUP</td><td colspan="2">Uses road network for assignment of ‘private’ vehicle trips (and determination of travel costs)

Accessibilities specified exogenously to DRAM/EMPAL: can be endogenous (within ITLUP) or via link to exogenous travel demand-forecasting model

Since ITLUP is a composite model, iterations between the transportation and land-use models require data transfer between independently structure submodels. Links also exist with several exogenous travel demand-forecasting models (EMME/2, TRANPLAN, UTPS)

Population/employment distribution independent of work trip distribution developed in travel demand model</td><td>Inherent in general accessibility term (depends on the travel demand model being used; not explicitly considered in the endogenous travel demand model)

Commonly (though not always), auto-only accessibility is used.</td><td>Not present</td><td>Inherent in general accessibility term (depends upon the travel demand model being used; not explicitly considered in the endogenous travel demand model).</td></tr>
<tr><td>MEPLAN</td><td rowspan="2">Multimodal networks used

Integrated interactions between land-use, modal split/assignment

Assignments static, not dynamic

Coarse networks relative to usual travel demand models. Can interface with external travel demand models and networks, but different zone systems are an issue. Fully integrated with travel demand-forecasting, i.e. these do trip distribution—only trip-generation, assignment done in travel demand-forecasting side</td><td>Nested logit for modal split. Stochastic assignment (SUE)</td><td rowspan="2">Explicit transit representation exists; sub-modes (rail, bus); including transit capacity representation; links can carry different modes

Coarse network restricts the level of detail at which transit can be represented</td><td rowspan="2">Explicit goods movement by all relevant modes in considerable detail, albeit on a coarse network (truck, rail, etc.)

Terminal costs explicit

Shipping costs included

TRANUS also includes deadheading</td><td rowspan="2">Taxis have been included in some applications

Flexibility exists to expand the set of modes and to trace/allocate costs to users</td></tr>
<tr><td>TRANUS</td><td>Modal split by ‘scaled logit’ as part of path enumeration

Assignment (SUE)</td></tr>
</table>

Table 3. *Continued*

		Transportation supply (infrastructure + services)		
	Transportation networks	Transit representation	Goods movement	Other transportation services
MUSSA	Linked via the DBMS to a very good four-stage travel demand model (ESTRAUS). Accessibility terms taken from ESTRAUS, population and land-use are passed from MUSSA to ESTRAUS. Combined MUSSA–ESTRAUS system called 5-LUT; full static equilibration between transportation and land use is obtained. Models are connected rather than integrated: place of residence—place of work linkages determined by trip distribution model in ESTRAUS	Detailed transit representation in ESTRAUS (11 modes, road, transit and mixed modes included). Detailed disaggregate logit mode choice model. Used to analyse transit projects	Not present	Dependent upon the modal split model used; incorporated inaccessibility terms
NYMTC-LUM	Accessibilities imported from a separate four-stage travel demand model (NYMTC-TDM). Feedback from LUM to TDM is possible, but it is not clear this will be done. METROSIM intended to have an integrated travel demand model	Depends on the travel demand model used (NYMTC-TDM contains full transit system representation). Transit effects enter via the mode choice model log-sum terms. Small zone system provides good transit system sensitivity. CATLYS, NYSIM both used to assess the impacts of transit projects, as is the intention for NYMTC-LUM	Not present	Dependent upon the modal split model used; incorporated in accessibility terms
UrbanSim	Connected with travel demand models (activity-based in Honolulu; four-step elsewhere). Uses composite utility to develop access measures to activities as part of business and household location models. Workplace choice predicted within the travel model	Depends on travel demand model being used (full transit system representation used in all three current applications). Transit effects enter via mode choice model log-sum terms. Small zone system provides good transit system sensitivity	Implicit in use of car accessibility terms as a proxy for congestion/costs of shipping) on employment location decisions. (Note: does not model flows of goods)	Dependent upon modal split model; incorporated in accessibility terms

origin–destination tables. ITLUP also shares this feature, if run in 'fully integrated' a fashion (although in most implementations, the DRAM/EMPAL components are only used, 'connected' to a stand-alone four-stage travel model in a fashion similar to the other models). The others (MUSSA, NYMTC-LUM, UrbanSim) use the composite utilities derived from destination choice models, either explicitly or implicitly, as inputs to the land-use model, and simulate trip origin–destination tables within the transportation model. In general, the ability of the integrated model system to analyse transportation policy impacts (on travel or land use) depends on the quality and capabilities of the four-stage travel demand model being used, rather than on the integrated modelling system per se.

As indicated above, a 'fully integrated' model is one in which the origin–destination trip linkages are determined within the land-use/spatial economic side of the modelling system. Thus, for example, in TRANUS, place of residence–place of work linkages are explicitly determined within the housing market model (i.e. households are allocated to residential locations conditional upon their known place of work). As a result, no work trip distribution model exists on the transport side of the modelling system, which only has to deal with work trip generation, mode choice and route assignment. In a 'connected' model, on the other hand (e.g. MUSSA), households are allocated to residential locations based on (among other factors) inclusive value-type employment accessibility terms, but the actual place of work for a given household is not determined until a trip distribution model is run within the transport side of the system.

Both approaches possess strengths and weaknesses. The fully integrated approach possesses a certain amount of theoretical rigour/elegance. It also ensures internal consistency between the land-use and transport components of the modelling system. At the same time, the 'connected' approach is very practical, in that it means that an urban area can develop a land-use modelling component that can be 'bolted onto' an existing travel demand model for the region. In addition, the connected approach is not without its behavioural rationale. It implies that residential location processes are relatively long run in nature and depend upon a variety of factors, accessibility to work being only one. While the fully integrated approach does not contradict this observation, it might be argued that the connected approach facilitates more flexible approaches to modelling residential location choices, perhaps among others.

All six frameworks can include transit explicitly, although the large-area zones typically used in the older models (ITLUP, MEPLAN, TRANUS) clearly limit the sensitivity of these models to transit system impacts; also, the internal travel demand model with ITLUP does not include a transit assignment capability. MEPLAN and TRANUS are the only frameworks that explicitly model goods movements. Other modes (such as high-occupancy vehicle/car-pooling and paratransit) typically are not represented; although, again, this is primarily a function of the travel demand model used in a particular application.

Table 4 addresses treatment of the four types of actors of interest within an integrated urban model: persons, households, private establishments (firms) and public authorities. Private establishments are further subdivided into general, developers and carriers, with the latter two categories being explicitly identified due to the special roles that they play within the land-use–transport interaction.

None of the frameworks deals explicitly with individual persons, except to the extent that individual trips are eventually generated on the transportation networks: all six of the models are household based. An explicit representation of

Table 4. Treatment of actors

			Private establishments			
	Persons	Households	General	Developers	Carriers	Public authorities
ITLUP	Not explicit, although exogenous total population is used as a control total	Household-based Categorization, typically by four income bands, is used as a proxy for social aggregations, although further sub-groups (e.g. income by household structure) also have been used Aggregate number of households/zone	Aggregate number of jobs/zone Typical categorization is by four basic industry groups, but other SIC classification also possible No explicit representation of firms	Not explicit	n/a	Exogenous policy inputs re: transportation (road) system (via accessibility terms), developable land (which is also a proxy for zoning and planning regulations and policies) No taxation effects considered (except in terms of travel costs and developable land indicators) Some of the aggregate jobs/zone will be public sector (although no distinction is made between public and private-sector jobs) No endogenous public-sector responses
MEPLAN TRANUS	Person-trips generated by households No explicit representation of persons or their attributes	Household-based User-specified categorization (e.g. income, occupation of head of household) Aggregate number of households/type/zone	Explicit outputs of production processes Represented by various proxies; sometimes employment, sometimes just dollars	Space is developed and/or redeveloped as a function of prices, availability Redevelopment can occur (demolition/new construction) Developers implicitly represented in the process (Note: total space by type to be developed/redeveloped exogenously for each period (in practice))	Implicit in multimodal network representation Cost structure explicit	Exogenous policy inputs re: serviced land, zoning, transportation networks and supply, land taxes, value added taxes, transportation taxes (e.g. carbon tax)

Table 4. *Continued*

	Persons	Households	Private establishments			Public authorities
			General	Developers	Carriers	
						No endogenous public sector response (except some implicit transit network frequencies change in response to demand) 'Government' typically is a separate category in the production process (since it consumes labour, etc. and generates employment, etc.)
MUSSA	Not explicit. Number of persons per household by household type known, along with various attributes of these persons (see Households in this table)	Household-based. Detailed representation of households; currently 65 household types used in Santiago model. Capability exists to use every household from a sample, with each household being appropriately weighted (weights derived from aggregate exogenous inputs) in a 'static	'Firms' explicit as occupiers of building stock. Five firm types currently used in the Santiago model	Explicit building supply sub-model attempts to reproduce profit-maximizing behaviour of developers	n/a	Exogenous inputs of alternative policies. Sensitive to a wide range of transport and land-use policies

Table 4. *Continued*

	Persons	Households	Private establishments: General	Private establishments: Developers	Private establishments: Carriers	Public authorities
		microsimulation' or 'sample enumeration' framework, wherein detailed characteristics of each household member are maintained within the DBMS and the model				
NYMTC-LUM	Not explicit. NYSIM includes an adjustment to equations to account for multi-worker households	Household-based. No apparent categorization by household type (although some earlier versions included categorizations). Average household income in each zone is determined by the allocation of workers from their place of work (with a known average income) to residential zones	No explicit representation of firms. Employment explicit by zone. Lowry concept of basic (exogenously specified) and non-basic (endogenously determined) used. In New York City implementation, basic employment broken down into office and industry; non-basic categorized by non-office/industry (e.g. retail), institutional and other non-residential. Not clear how this	Supply of building stock (non-basic sector floor space; residential housing units and floor space by type) in each zone responds to market values for buildings by type by zone, subject to available land	n/a	Transportation network or service changes are exogenous inputs. Currently no sensitivity to zoning or other land-use controls (proposal exists to extend the model in this regard). Some land-use policy sensitivity on a scenario basis implicit in exogenous basic sector inputs, plus exogenous inputs of total population and non-basic employment totals

Table 4. *Continued*

	Persons	Households	Private establishments			Public authorities
			General	Developers	Carriers	
			segmentation is used within the model, since it appears that only a single, general non-basic category is used for keeping track of land use and floor space			
UrbanSim	Not explicit at present; planned for a future microsimulation version which includes workplace choice	Detailed representation of households: currently 111 household types in Eugene-Springfield, more in Honolulu and Salt Lake City. Extension planned to maintain full household sample. Model predicts births/deaths, moves, building type and location choices. Uses synthetic population generated from Public Use Microdata, Summary Tape Files and parcel data	Business establishments explicit, user classified by industry and number of employees. Model predicts births/deaths, moves, building type and location choices. Major businesses may be exempted from simulation due to low mobility and lack of information. Known events such as major business relocations may be accommodated explicitly	Developers explicit as a decision-maker. Currently simulates development/redevelopment at the parcel level, based on expected profitability. Land-use plan, density constraints, development charges, environmental constraints, urban growth boundaries considered in determining feasibility and cost. Revenue estimated from current market price, before construction. Implementing extension to accommodate delayed start and multi-year construction timetables for large development projects	n/a	Explicit policy inputs include land-use plans, density constraints, urban growth boundaries, environmental constraints, development charges, transportation infrastructure, pricing and service levels

persons (in addition to households), however, would appear to be advantageous, since many processes of interest within the urban system (in addition to travel) are inherently person based (birth, death, labour force participation, etc.).

All six models treat public authorities as essentially exogenous generators of public policy inputs to the model—transportation network changes, zoning changes, etc. The partial exceptions are MEPLAN/TRANUS, which generally have 'Government' as an explicit category in the input/output production process and, hence, an endogenous supplier/demander of goods, services and travel.

With respect to private establishments, most frameworks deal directly with the location of employment, not firms. The exceptions are MUSSA and UrbanSim, both of which explicitly model firms. All have some form of explicit representation of the building supply/development process, with the exception of ITLUP, which has no supply-side representation. Carriers are not explicitly represented in any of the models, except for MEPLAN and TRANUS, in which carrier cost functions are explicit components of the production functions being modelled.

Table 5 summarizes the treatment of various markets of potential interest within the land-use–transport system. Points to note concerning these markets include the following:

- Housing market. All frameworks include explicit representation of housing demand–supply interactions with price signals, except ITLUP. ITLUP models the demand side only, without endogenous prices.
- Commercial floor space market. In general, the frameworks treat the demand–supply of commercial floor space similarly to housing, making due allowances for differences in the two types of space. Again, ITLUP is the only framework without explicit supply–price components.
- Goods and services market. MEPLAN and TRANUS are the only frameworks that explicitly consider the production and consumption of goods and services. MUSSA obtains activity totals by sector from an external input–output model, while UrbanSim somewhat similarly accepts exogenous inputs concerning business growth and decline.
- Job market. In MUSSA and UrbanSim, worker–job linkages are determined by the travel demand work trip distribution model. Labour markets are explicitly modelled in MEPLAN, TRANUS and NYMTC-LUM. The labour market is implicit in the ITLUP procedure. In ITLUP, MEPLAN and TRANUS, very little distinction actually exists between the labour and housing markets (i.e. workers are allocated from known employment locations to residences in essentially a joint labour–housing market model).
- Personal transportation market. In MEPLAN and TRANUS, work, personal business and other types of travel arise out of the spatial production–consumption process. In ITLUP, three trip purposes (home-to-work; home-to-shopping; work-to-shopping) are generated and distributed simultaneously with the spatial allocation of households, i.e. all within the household allocation model (DRAM). All other models use a conventional four-stage travel demand model.
- Goods movement market. MEPLAN and TRANUS are the only frameworks with explicit goods movement representation.
- Transportation infrastructure market. All frameworks treat the supply of transportation infrastructure and services as exogenous inputs. Demands for infrastructure and services are implicit in the travel demand models.

Table 5a. Motivational framework (Part I)

	Housing market	Floor space market	Goods and services market*
ITLUP	Demand for land is explicit (Lowry logit formulation), allocating households to zones by type Supply is implicit, although it is defined by exogenous constraints, i.e. developable land; density constraint processes under development in METROPILUS No price mechanism/signal—static equilibrium: most likely entropy solution	Supply implicit No price mechanism/signal	n/a
MEPLAN	Supply function : developers allocate from (i.e. given) the exogenous total. In practice, housing by type to zones = f (prices$_{t+\Delta T}$, current capacity) dynamic, lagged response → note link to lagged step	Same as housing market, except with production processes (other than households) producing labour	Explicit. Based upon input–output framework Variable technical coefficients (e.g. elastic with respect to price; logit-style substitutions (e.g. 'oak' versus 'pine') based on relative prices) Households maximize utility subject to a budget constraint (actually using the dual problem)
TRANUS	Demand function: amount of space consumed per household is elastic with respect to price/zone In a period, prices are adjusted in zones until the amount of space consumed per household and distribution of households among zones such that the market clears that all space is consumed → no explicit vacancies. There is a 'within time step' equilibrium		
MUSSA	Heart of the model. Explicit demand–supply equilibrium found with endogenous prices. Demand is based on willingness-to-pay (WP); consumers are assumed to try to maximize their surplus (WP less price). Sellers are assumed to maximize price. Developers control supply, attempting to maximize profits. Martinez' 'bid choice' model is derived from Ellickson's 'bid rent' model. The model has an elegant, rigorous theoretical micro-economic foundation. If working with	Identical to and integrated with the housing market model. Households and firms compete for use of the same land	Regional input–output (I/O) model is run externally to 5-LUT to generate activity totals and total population. No goods flows are generated; however, nor is there any other direct links between the I/O model and 5-LUT Extension of the model to include a goods and services market is feasible, if the transport model can support goods movement (ESTRAUS does not)

Table 5a. *Continued*

	Housing market	Floor space market	Goods and services market*
	a static equilibrium, is a very compelling model; it is disaggregate, stochastic, policy sensitive, computationally efficient, possesses demonstrated methods for parameter estimation with reasonable data requirements, and is very sound theoretically		
NYMTC-LUM	Supply of housing by type by zone is a function of its market value (which, in turn, is a function of housing price, interest rates and development costs). Demand for housing by type by zone is determined by a logit model of worker joint choice of workplace and place of residence. This choice is a function of the wage rate in the employment zone, the price of housing in the residential zone, accessibility terms, and other explanatory variables. Housing prices are determined by assumption of equilibrium (i.e. demand = supply) in each zone	Similar to the housing market, except that the demand for non-basic floor space is a function of the price (rent) of the floor space and the demand for non-basic services located in a given zone, as determined by the residence–non-work linkage model (see Table 5b, 'Personal Transportation Market')	n/a
UrbanSim	As with MUSSA, derived from Ellickson's 'bid-rent' model, but does not impose equilibrium assumption. Demand is based on willingness to pay (Bid function); consumers are assumed to try to maximize their surplus (Bid – price). Households are considered price-takers, with prices adjusting between 1-year time steps based on aggregate relationship of demand and supply within each submarket (traffic zone and property type). Developers produce supply, attempting to maximize profits based on current market conditions. Supply assumed inelastic within 1-year time step, but becomes available in subsequent year (with extension to multi-year construction currently underway). Short time steps make model equilibrium-seeking, while retaining rigorous micro-economic foundation	Identical to and integrated with the housing market model. Land parcels developed into most profitable use that regulations allow, providing a realistic representation of competition between residential and commercial land uses within the constraints of land policy	Exogenous levels of employment by sector, endogenous mobility and location of businesses. Location choice incorporates access to labour market, localization and inter-industry linkages. Strength of locational influence of inter-industry linkages and localization is determined empirically during calibration for each sector

Table 5b. Motivational framework (Part II)

	Job market	Personal transportation market	Goods movement market
ITLUP	Implicitly modelled (i.e. job and housing markets are really one process): ● Demand for labour is determined exogenously to the submodel, i.e. employment per zone is known (Lowry) ● Spatial distribution of supply (i.e. where those employees live) determined by spatial allocation model ● No price mechanism (i.e. wages)	Endogenous (within ITLUP) or exogenous linkages to external travel demand models. In practice: a no feedback to activity system if not iterated. Otherwise, instantaneous ('equilibrium') feedback if iterated	n/a
MEPLAN TRANUS	Labour is supplied by households, as demanded by production activities Typically, labour costs paid by employers are the costs faced by households (which need to get these payments in order to survive). Framework is sufficiently flexible to allow simulation of a market process, where labour prices are established endogenously (but it is never done in practice; it is sufficiently difficult to get the other system to work)	Origin–destination demands arise from spatial distributions of flows from production to consumption. Includes work, personal business (non-work, i.e. including recreation, shopping) and in course of employer's business travel Includes all modes. Flows assigned to networks, with congestion (SUE, static) Feedback to travel decisions is instantaneous; feedback to activity locations is lagged one period	Same as, and integrated with, personal transportation market
MUSSA	Total numbers of jobs per workers by type determined exogenously. Locations of jobs and workers determined as household and firm location choices within MUSSA. Job market demand–supply interactions implicit in the ESTRAUS trip distribution model	ESTRAUS. Full, joint equilibrium model of trip distribution, modal choice and route assignment. Working on elastic trip generation. Full equilibration of transportation and land use	n/a
NYMTC-LUM	Demand for labour in each zone is a function of wages, rent and possibly other factors. The supply of labour is determined by the logit model discussed under 'Housing Market'. Wages are chosen to equilibrate labour demand and supply	External travel demand model. If feedback between LUM and TDM is implemented, then instantaneous equilibrium between travel and land-use would occur. Place of residence–place of work linkages and residence–non-work activity location linkages are determined within the model, but are not currently used in the TDM	n/a

Table 5b. *Continued*

	Job market	Personal transportation market	Goods movement market
UrbanSim	Locations of jobs and workers determined as household and firm location choices, with firm location influenced by access to labour market and household location influenced by access to jobs. Direct linkage of individual workers to individual jobs is not modelled in the current software; this is envisioned for a microsimulation version of the model	External travel demand model. Instantaneous feedback within the travel model; lagged feedback to the household and business location choice model	n/a

Table 5c. Motivational framework (Part III)

	Transportation infrastructure market	Car (vehicle) market
ITLUP	Exogenous supply, from public authorities (or other providers of transportation infrastructure) Demand is implicit in the travel demand-forecasting models	Not considered explicitly in ITLUP, although could be reflected in DRAM trip-generation rates, modal split model and vehicle occupancy rates. However, an exogenous travel demand model (if used) could include an explicit car ownership choice sub-model
MEPLAN	Exogenous supply Demand is implicit in the travel demand-forecasting models	Can have categorization of households by car ownership level, with exogenous transition among categories
TRANUS		
MUSSA	Exogenous supply Demand is implicit in ESTRAUS	Implicit in the demographic inputs, which include forecasts of households by car ownership level
NYMTC-LUM	Exogenous supply Demand is implicit in the travel demand-forecasting models	Exogenous travel demand model could include car ownership choice sub-model
UrbanSim	Exogenous supply Demand is implicit in the travel demand-forecasting models	Can have categorization of households by car ownership level, with exogenous transition among categories or could have an car choice sub-model in the travel demand model

- Car market. The car market is treated exogenously and implicitly in all frameworks. However, indirect mechanisms could be used to account, at least partially or approximately, for car ownership. For example, households could be categorized by car ownership level (with exogenous definitions of total households by category), or the travel demand model could have an endogenous car ownership sub-model (in principle, usually not currently in practice).

One other noteworthy difference between the models concerns the mechanism used to determine prices within a given market (in particular, the housing market). In MEPLAN, TRANUS and NYMTC-LUM, prices within a given (sub-) market are adjusted so that short-run supply and demand balance within a given time step are using a classical Walrasian equilibrium structure. UrbanSim uses hedonic price functions to determine prices at each time step. MUSSA, on the other hand, employs a ‘bid choice’ approach in which consumers bid for housing in an attempt to maximize their consumer surplus, while suppliers accept bids in an attempt to maximize profits. In this last, conceptually very attractive approach, prices in each time step depend only on the outcome of this competitive, multi-agent game, and not on an explicit balancing of supply and demand (Martínez, 1992b, 1997). Housing supply then changes as a longer-run, lagged response to housing prices in the previous time period (a similar lagged supply response occurs within UrbanSim).

Table 6 provides additional detail concerning these market processes in terms of the allocation processes used to determine the spatial distributions of demand

Table 6a. Spatial allocation processes (Part I)

	Housing supply	Housing demand		Floor space supply	Floor space demand
ITLUP	Implicit; allows for zone/ sector-specific constraints that correspond to zoning and planning regulations and other land-use policies. Density constraint process being tested in METROPILUS	Logit allocation model for households, given known workplaces		Implicit	Implicit
MEPLAN	Total development is exogenous in each period and is allocated among zones as a function of price in the previous period and of availability of space (uses Cobb–Douglas formulation for utility function)	Households containing workers demanded in zone j are allocated among zones i, according to logit functions; where utility functions includes costs of locating in zone i + travel disutility i . →. j + alternative-specific constants. Set of explanatory variables can be expanded, although rarely done in practice	Housing type: can include alternative-specific constants Costs of locating in zone i include costs of consumption to produce in zone i (in this case, a household)	Same as housing supply	Same as housing demand
TRANUS			Housing type: 'scaled logit' without alternative-specific constants Nested logit is allowed		
MUSSA	Developers add units by type (residential and commercial) based on lagged prices, attempting to maximize profits. Supply function is empirically derived from observed market data	Logit model, probability of a given household being the maximum bidder for a given location, given the household's willingness-to-pay function		Same as housing supply	Same as housing demand

Table 6a. *Continued*

	Housing supply	Housing demand	Floor space supply	Floor space demand
NYMTC-LUM	Number of housing units per zone a function of market value = f (price, interest rates, development cost)	Logit model, function of household income, housing price, accessibility (to work and goods/services), and (optionally) other variables	Same as housing supply	Function of demand for non-basic services and rent
UrbanSim	Developers convert vacant parcels or redevelop parcels with existing development based on expected profits, using current market prices and development costs. Housing supply is inelastic within 1 year, but elastic from year to year. Price changes trigger changes in the profitability of development	Household choices of moving, building type and location may be modelled as connected choices in a nested logit, or may be separated into mobility choice and joint choice of building type and location. Location choice is a function of consumer surplus, and bids are a function of housing type, density, access to jobs and shopping, age of housing, housing supply, and zonal income distribution, land-use characteristics, and proximity to the central business district (CBD) (other variable may be specified)	Same as housing supply	Same formulation as housing demand, with bids a function of access to labour; localization effects; inter-industry linkages; building type, density, and age; zonal land-use mix, presence of highway, and proximity to the CBD (other variables may be specified)

Table 6b. Spatial allocation processes (Part II)

	Goods and services supply	Goods and services demand	Labour (workers) supply/demand	Demographic processes
ITLUP	Implicit in non-work (home shopping) person-trip attraction model	Implicit in non-work (home shopping) person-trip production model	Treats job and housing markets effectively as one and the same, without differentiating between the two, i.e. housing location choice decisions conditioned on workplace location decisions—very 'workplace driven' (starts with the workplace location, then determines household location on this basis)	Exogenously specified total households by income category (which then are allocated by zone) in each period; other processes have been tested (e.g. isolation of retirement households; age of housing units)
MEPLAN TRANUS	Explicit in production–consumption process as modelled in an input–output framework	Same as supply (supply-demand chains throughout)	Same as ITLUP	When households are demanded (for labour), households are created. In practice, little or no demographics. Unemployed/retired households exogenously specified or are implicit in labour-to-household ratios. (Note: this is why the job market is simplified in its representation.)
MUSSA	Implicit in ESTRAUS non-work trip attraction model. Aggregate supply and demand determined by exogenous I/O model	Implicit in ESTRAUS non-work trip production model. Aggregate levels of supply and demand determined by exogenous I/O model	Total employment and workers determined by exogenous I/O model. Linkages determined by ESTRAUS trip distribution model	Not explicit in the model. Exogenous forecasts determine the aggregate total of households by type. The model structure permits very detailed representation of households. In the limit, it can be run using a weighted sample of observed households, where the weights are derived so that the weighted sample reproduces the aggregate distributions. As such, MUSSA can be classified as a static microsimulation model

Table 6b. *Continued*

	Goods and services supply	Goods and services demand	Labour (workers) supply/demand	Demographic processes
NYMTC-LUM	Implicit in non-basic employment, which is determined by residential demand for these services	Residence–non-work linkages submodel estimates the number of non-work trips from each residential zone to each non-basic employment zone as a function of travel impedances, accessibilities, incomes and other socio-economic attributes	Supply of labour jointly determined with workers' household residences using a logit model. Model is a function of wage rate by zone, travel impedances, etc. Demand for non-basic labour a function of wages, rent, and demand for non-basic goods, as determined by the residence–non-work linkage model	No explicit demographic processes within the model structure. Total population for the forecast year is an exogenous input, as are, presumably, any other demographic attributes. Not clear how these, if entered, would be stored or used in the model
UrbanSim	Implicit in non-work trip attraction model	Implicit in non-work trip production model	Household and business location processes modelled independently, but with information about the lagged access to jobs or labour market. Linkages determined by trip distribution model. Unlike ITLUP, model is not 'workplace driven'	Full range of demographic transitions is envisaged (birth, death, ageing, household formation, household dissolution, in/out migration). Current: static transition probabilities

and supply in each market. Demand functions are generally logit or nested logit models. Supply functions vary in nature, but generally are based on some concept of profit maximization. All models except UrbanSim solve for some form of equilibrium in each time step. Of these equilibrium-based frameworks, all except ITLUP use some form of endogenous price mechanism to equilibrate supply and demand.

Note that across all integrated models (both the ones reviewed here and others), housing/floor space supply models are probably the least well developed of any component of the entire modelling system. Many reasons for this exist, including the following:

- A lack of good data, which has limited the quality of the analysis/modelling that could be achieved.
- Complexity of the supply process and, hence, the difficulty of developing strong theoretical insights into the process.
- Relatively few decision-makers involved in the building stock supply process, which makes developing statistically reliable models difficult.

This last point is of particular importance. Relative to most processes of interest (which typically involve thousands, if not millions, of individual decision-making units, e.g. persons, households, businesses), the development industry in even a large urban area may well consist of only a few hundred serious actors, of which perhaps a few dozen (or less) are the dominant players in the industry. Under such conditions, developing general models of building stock supply can be problematic, given the larger role that idiosyncratic factors may play in the observed outcomes. This problem is further compounded by the very long-run nature of the development process (which often stretches out over decades for large projects) and its very open-ended nature (a large developer may be considering projects in several urban areas, not just the one being modelled).

Table 6 also discusses the treatment of demographic processes. In general, none of the frameworks handles demographic processes endogenously, although UrbanSim appears to be moving in this direction. Demographics tend to enter in terms of the nature and extent of household categorization, with control totals by household category generally being exogenously determined. MUSSA and UrbanSim are particularly noteworthy in this regard, since they support a very high level of household disaggregation, in the limit including use of a weighted observed sample of actual households in a virtual microsimulation framework. Demographics play a major role in determining housing demand, labour supply, travel demand, etc., and so an enhanced treatment of demographics within integrated urban models would be welcome. In particular, the inability of many planning agencies to generate detailed forecasts of future year demographics often limits their ability fully to exploit the capabilities of currently available disaggregate travel models. If integrated urban models were available that could generate credible future year demographic forecasts, this could provide a significantly improved capability for generating estimates of travel demand.

Table 7 summarizes the abilities to respond to the typical range of policies that might be of interest within an urban area. For each policy, a tick (✓) indicates that the policy can (at least in principle) be represented and tested explicitly, whereas a cross (✗) indicates that the structure/specification of the framework precludes testing the given policy. A star (✶) indicates that the policy can be 'implicitly' addressed (either through a proxy variable or through straightforward extensions to the current modelling system). Finally, a diamond (♦) indicates that the only way in which the framework can be made to respond to a given policy is through user-defined, exogenous changes to model parameters.

Integrated urban models, in general, are intended to analyse policies relating to land use, transport or other policies that might have significant impacts on either land use or transport. Table 7 is divided into three sections, each corresponding to these broad policy types. At the same time, regardless of type, policies can also be categorized by the mechanism employed, namely pricing, infrastructure and services (which involves both the supply of new infrastructure/services and the operation of existing facilities), regulatory and education/marketing. These generic policy categories define the rows of Table 7, with representative (but not necessarily exhaustive) examples of specific policies being shown for each category and type of policy.

In general, models developed using the frameworks reviewed here can respond to a fair range of pricing and infrastructure/service-related policies. This is not surprising given that these represent the traditional types of policies motivating model development over the years. There are three important caveats to this general observation. First, because ITLUP does not model land-use demand–supply interactions explicitly, relative to the other models it is limited in its ability to address land-use pricing and infrastructure policies. Second, while ITLUP, MEPLAN and TRANUS are all shown as being able to address transit infrastructure and service policies, the large zone system typically used in these models limits the sensitivity that these models can have with respect to transit. Third, the extent to which a given model is sensitive to transportation policies depends critically on the specific travel demand model being used: and the full set of ticks shown in Table 7b is appropriate only if a best-practice travel demand model is used.

All the frameworks are much less able to address regulatory policies, especially with respect to transportation. TDM and ITS impacts are generally not well addressed. These limitations primarily reflect well-known weaknesses in the four-stage travel demand modelling system, upon which these integrated models heavily rely, rather than any fundamental problem with land-use models per se. Thus, as operational travel demand models continue to improve (through the efforts of TMIP and other research and development initiatives), such integrated models can be expected to directly benefit as well.

Land-use regulation (zoning, urban growth boundaries, etc.) represents a particularly important type of policy to be analysed by integrated urban models. All six models can, in principle, deal with land-use regulation through the exogenous imposition of constraints on development of certain types in given zones. As noted above, ITLUP is less suited to analysing this type of policy than the others. This is because different types/levels of regulatory constraints on land development might have different impacts on prices (e.g. it is often argued that an urban growth boundary might inflate housing prices compared with the no-boundary case), and hence alter supply–demand outcomes within the urban area—something ITLUP will not be able to address due to its lack of an explicit supply side and price determination process.

Not surprisingly, all the frameworks can reflect education/marketing policies aimed at changing people's values/attitudes only through exogenous changes in the model parameter values, where these parameters are intended to capture

Table 7a. Policy capabilities of current models: land use

Policy category	Specific policy	ITLUP	MEPLAN/ TRANUS	MUSSA	NYMTC-LUM	UrbanSim
Pricing	• Taxation: property taxes	✗	✓	✓	✓	✓
	• Subsidies: Business Redevelopment Zones	✗	✓	✓	✓	✓
	• Development charges	♦	✓	✓	✓	✓
Infrastructure and services	• Public housing	✗	✓	✓	✓	✓
	• Servicing land (excluding transportation, e.g. sewers, waters, wired city)	♦	✓	✓	✓	✓
	• Government buildings/other not-for-profit institutions (i.e. location of these as 'seeds'/cores for development)	✗	✓	✓	✓	✓
Regulatory	• Zoning (uses, densities)	♦	✓	✓	✓	✓
	• Micro-design building/neighbourhood issues ('shadowing,' pedestrian-scale massing, neo-traditional design, etc.)	✗	✗	✓	✗	✓
Education/ marketing	• Changing/how to change attitudes and sensitivities (e.g. traveller 'value of time' as opposed to deeply held values)	♦	♦	♦	♦	♦

✓, Explicit and normally/could be done; ✗, no; ✶, implicit; ♦, can respond, but only through exogenous change in parameters.

Table 7b. Policy capabilities of current models: transportation

Policy category	Specific policy	ITLUP	MEPLAN/ TRANUS	MUSSA	NYMTC-LUM	UrbanSim
Pricing	• Road tolls/congestion pricing	✶	✓	✶	✶	✶
	• Gas taxes	✶	✓	✶	✶	✶
	• Subsidies (capital, operating)	✗	✗	✗	✗	✗
	• Transit fares	♦	✓	✶	✶	✶
	• Parking pricing	♦	✓	✶	✶	✶
Infrastructure and services	• Build roads, high-occupancy vehicles	✓	✓	✓	✓	✓
	• Build rail/dedicated transitways	♦	✓	✓	✓	✓
	• Operate transit services	♦	✓	✓	✓	✓
	• ITS (i.e. infrastructure technology; system optimization, transportation	✗	✗	✗	✗	✗
	system management (TSM), etc.)	✗	✗	✗	✗	✗
	• Parking					
Regulatory (see note below)	• Parking provision regulations (off-street)	✗	✗	✗	✗	✗
	• Rules of the road (speed limits, on-street parking, high-occupancy vehicle	♦	✓	✓	✓	✓
	lanes, traffic operations, etc.)	✗	✗	✗	✗	✗
	• Non-pricing TDM (e.g. employer trip reduction programmes, etc.)	♦	✗	✗	✗	✗
	• Vehicle/driver licensing (i.e. granting of access to the transportation system)	✗	✗	✗	✗	✗
	• Inspection/maintenance programmes					
Education/marketing	• Changing/how to change attitudes and sensitivities (e.g. traveller 'value of time' as opposed to deeply held values)	♦	♦	♦	♦	♦

The ability to address any or all of the specific regulatory policies listed above depends on the travel demand-forecasting model used. Also, whereas pricing can be considered somewhat dynamically (therefore, an 'implicit' ✶ designation), the same cannot be said for infrastructure or regulation (therefore, mostly 'no' ✗).
✓, Explicit and normally/could be done; ✗, no; ✶, implicit; ♦, can respond, but only through exogenous change in parameters.

Table 7c. Policy capabilities of current models: other

Policy category	Specific policy	ITLUP	MEPLAN/ TRANUS	MUSSA	NYMTC-LUM	UrbanSim
Pricing	• Car purchase tax	✗	✗	✗	✗	✗
	• Licence charges	✗	✗	✗	✗	✗
	• Income redistribution (e.g. progressive taxation, welfare, etc.)	♦	✓	✓	✓	✓
Infrastructure and services	n/a	n/a	n/a	n/a	n/a	n/a
Regulatory (see note below)	• Air quality standards (area wide)	✗	✗	✗	✗	✗
	• Emissions standards (vehicle-specific)	✶	✓	✓	✶	✶
	• Noise	✶	✶	✶	✶	✶
	• Safety (accidents)	✶	✶	✶	✶	✶
	• Vehicle technology standards (e.g. must have 10% electric vehicles in CA, etc.)	✗	✗	✗	✗	✗
Education/marketing	• Changing/how to change attitudes and sensitivities (e.g. traveller 'value of time' as opposed to deeply held values)	♦	♦	♦	♦	♦

Air quality is designated as 'no' (✗), while some other policies are designated as 'implicit' (✶) because air quality tends to be addressed as a post-travel demand model analysis.
✓, Explicit and normally/could be done; ✗, no; ✶, implicit; ♦, can respond, but only through exogenous change in parameters.

decision-makers' tastes and preferences. All models are calibrated against observed, historical data. Given this, at best, they capture the behavioural preferences manifested in the historical data. To use these models in a forecasting mode, it must be assumed that these behavioural preferences will also hold in the future. While the increasing availability of time-series data (both panel and repeated cross-sections) is beginning to provide the opportunity to study the evolution of tastes and preferences over time, such research is a long way from providing operational models of parameter formation and evolution.

Finally, Table 8 summarizes much of the previous discussion in terms of the operational characteristics of the frameworks. Some key points to note are as follows:

- Historically, operational urban land-use–transport models have tended to be quite aggregate spatially. The current trend among newer models is towards a finer spatial scale, typically the traffic zone level. UrbanSim is the most disaggregate of the frameworks reviewed, modelling land development at the parcel level and travel demand at the traffic zone level.
- Most frameworks are based on strong equilibrium assumptions. UrbanSim is a noteworthy exception to this rule.
- Most applications of the frameworks are still very aggregate temporally, using up to 5-year time steps. Again, UrbanSim is the exception to this rule in that a 1-year time step has been used in applications.
- Data requirements and implementation effort obviously vary, depending on model complexity. But the development of any integrated urban land-use–transport model requires significant investment in time and money.
- Significant on-going technical support is required to operate models developed using these frameworks.

The bottom line for all integrated models is the extent to which they assist in the evaluation of alternative urban policies. To do this, they must generate useful and credible measures of system benefits and costs. As indicated in Table 8, all systems reviewed provide considerable capability in this regard. The random utility framework that underlies most of the model components is a major help in this regard in that it readily permits the calculation of consumer surplus terms. In addition, real estate prices (in all but ITLUP), land consumed by land-use type, travel times and costs, roadway congestion levels, transit patronage, etc. are all 'standard' outputs from these models and provide useful measures of the effectiveness for policy/project evaluation purposes. None of the models reviewed explicitly computes atmospheric emissions, but, as with conventional travel demand models, the travel outputs from an integrated model can be used to provide inputs to a suitable vehicle emissions model. As also shown in Table 8, the packages in general have, or are rapidly developing, graphical, GIS-based user interfaces for the convenient retrieval, display and analysis of model results (as well as input data preparation).

Summary of the State of Practice

Miller *et al.* (1998) present an extended discussion of integrated urban modelling needs and design criteria. Emerging from this discussion is one vision for an 'ideal', 'ultimate' or 'fully evolved' modelling system. This conceptual modelling

Table 8a. Performance of current models: applicability

<table>
<tr><th rowspan="2"></th><th rowspan="2">Scope</th><th rowspan="2" colspan="2">Theoretical consistency</th><th colspan="2">Precision</th><th rowspan="2">Validation</th><th rowspan="2">Transit representation/sensitivity</th></tr>
<tr><th>Spatial</th><th>Temporal</th></tr>
<tr><td>ITLUP</td><td>Partially integrated/partially connected with transport model(s)

Spatial distribution only of exogenously specified totals

No supply, no prices</td><td colspan="2">Over reliance on equilibrium; at best quasi-dynamic</td><td>Spatial precision is determined by data availability; in practice, this means that large zones tend to be used (although the 291 zone San Francisco Bay Area model is an obvious exception)</td><td>Five-year step

Smaller increments are possible if supported by data</td><td>History of validation work (e.g. through ‘backcasting’ starting from a historical base year)</td><td>Typically, no *direct* land-use sensitivity to transit (although the Chicago model has composite costs). Typically, only car trips are considered

Transit trip-making representation depends on the travel demand model used</td></tr>
<tr><td>MEPLAN</td><td rowspan="2">Integrated with the transport model

Full market representation (production and consumption)

Fully endogenous prices</td><td rowspan="2">Over reliance on equilibrium; at best quasi-dynamic

Can question use the of input–output framework at such a small spatial scale . →. **</td><td></td><td rowspan="2">→. ** Use of aggregate input–output coefficients restricts how small zones can be, while maintaining a reasonable representation of economic processes</td><td rowspan="2">Five-year step

Smaller increments *might* possible if supported by data

At least one period lag, possibly with more of a land-use response to transportation</td><td rowspan="2">Some validations have occurred with MEPLAN</td><td rowspan="2">Explicit representation of transit services

Accessibilities include transit effects and influence land use
Conversion of transit origin–destination times/costs to larger land-use zones an issue</td></tr>
<tr><td>TRANUS</td><td>Scaled’ form of logit used departs from random utility theory

Appears to be an over reliance on trip-generation elasticities to fit trip lengths</td></tr>
</table>

Table 8a. *Continued*

	Scope	Theoretical consistency	Precision		Validation	Transit representa-tion/sensitivity
			Spatial	Temporal		
MUSSA	'Fully connected' rather than integrated	Over reliance on equilibrium. However, given the equilibrium assumption, the theoretical model is rigorous, complete and very attractive	Developed at the traffic zone level (264 zones in the Santiago application). Currently working to extend the modelling system to accommodate more microscopic design issues (rail station location impacts, etc.)	Static equilibrium model. Can be run by a time step	Calibrated using 1986 and 1991 data; validated against independent observed 1991 and 1997 data. Year 2005 base forecasts have good face validity	Detailed transit network and mode choice models used. Traffic zone level of analysis is currently used; finer resolution may be achievable
NYMTC-LUM	Connected, not integrated currently. METROSIM is intended to be a fully integrated model	Over reliance on equilibrium. Consistent application of micro-economic concepts throughout	Developed at the traffic zone level (3500 zones in New York City implementation)	Current implementation: one step to forecast the end-year equilibrium. Could use 5-year steps, with full equilibrium at each step, although it is not clear whether this would change the end-year result	None for current version since it is still being implemented. Some empirical experience with previous model versions	Transit trip-making and land-use sensitivity to transit depends on the travel demand model used. Small zone structure beneficial

Table 8a. *Continued*

	Scope	Theoretical consistency	Precision		Validation	Transit representation/sensitivity
			Spatial	Temporal		
UrbanSim	Connected, not integrated with transport model	Only model reviewed to use non-equilibrium, dynamic framework with 1-year increments. Relies on solid theoretical foundation similarly to MUSSA, but relaxing the equilibrium assumption	Demand side is implemented at the traffic zone level (271 in Eugene-Springfield, 761 in Honolulu, 1000 plus in Salt Lake City). Supply side is implemented at the parcel level	One-year steps. Interaction with travel model may be annual or, more likely, as needed to represent significant changes in the transportation system	Historical validation process underway in Eugene-Springfield using 1980–95 data	Transit trip-making representation and land-use sensitivity to transit depend on the travel demand model used. Models in Eugene-Springfield, Honolulu and Salt Lake City have detailed transit network and mode choice models. Given the parcel-level data used in the model, significant improvement in the characterization of transit-oriented land-use patterns is possible

Table 8b. Performance of current models: feasibility/usability

	Data requirements/implementation	Technical support requirements	Output/presentation capabilities	
ITLUP	Simpler model structure; generally implies relatively modest data requirements and calibration effort Semi-automated calibration process exists METROPILUS (ArcView shell) provides direct links to ArcView GIS database and to Windows analytical software	Set-up: consultant support generally required On-going support: advertised as capable of being run by the owner alone, without outside help	METROPILUS: ArcView shell provides presentation capabilities plus a link to external analytical and graphical display capabilities via Windows	
MEPLAN	Much more general than TRANUS. Complex model structure; generally has significant data requirements and calibration effort MEPLAN (note: 'Mentor', a 'MEPLAN Lite' version, is trying to include some default parameters)	Set-up: major undertaking by consultants; not done in house (expert system for supporting set-up recently developed) On-going support: difficult for in-house staff to operate; strong consulting backup available	Full economic evaluation module (prices, consumer surplus, flow volumes, times, etc.)	Has plotting capabilities
TRANUS	Somewhat simpler model structure than MEPLAN; less general. Significant data requirements, but calibration effort generally is somewhat less than that of MEPLAN	Set-up: slightly less than MEPLAN but still major On-going support: not quite so difficult as MEPLAN; consulting backup is an issue		GUI for input–output manipulations
MUSSA	Relatively moderate data requirements for calibration; can be calibrated from a single year's data (except for the building supply function, which requires data for two points in time). Data for a sample of zones can be sufficient. Some price data are required. Data requirements are probably similar overall to NYMTC-LUM. Resources, obstacles to	Transport Research Group, University of Chile	All data stored in and retrievable from a Windows-based relational DBMS (Access), thereby providing good access to model results and easy interface with other analysis/display software. Built-in graphical display capabilities. Full range of economic evaluation measures on both land-use and transportation sides	

Table 8b. Performance of current models: feasibility/usability

	Data requirements/implementation	Technical support requirements	Output/presentation capabilities
	implementation in another city not completely clear. The model assumes the existence of a good four-stage travel demand model and a regional I/O model. In Santiago, the model represents an on-going research and development effort, but is also an operational planning tool		
NYMTC-LUM	Since it is a static equilibrium model, data for one point in time are sufficient for calibration. At a minimum, census journey to work and income data, employment data by zone, and non-work trip linkages required for calibration. Housing/floor space price data do not appear to be essential for calibration. Still under implementation, so overall level of effort required not yet well defined	Unknown at this time	Population and employment distributions by zone; residence–work and residence–non-work trip linkages; wages, rents, average incomes by zone; consumers' and producers' surpluses for economic evaluation. Presentation capabilities cannot be verified
UrbanSim	Requires the following data: parcels (with land and improvement values, area, housing units and non-residential square footage), business establishment inventory, census data, land-use plans, environmental constraints. Calibration requires use of standard regression techniques for bid functions, and multinomial or nested logit for the location choice models	Supported by the University of Washington. Will be able to assess extent of support requirements once implementation is completed in the three locations now underway	Model outputs include household and business distributions by zone, land use, property values, housing and non-residential floor space. Results written into database or comma-delimited files. A GIS viewer based on MapObjects provides visualization capabilities. Reports and evaluation measures under development

system is based on the set of axioms shown in Table 9 that the authors argue are model properties towards which any integrated urban model should aspire. In advancing these axioms as the basis for an ultimate model design, the authors are not arguing that one model fits all, or insisting that all modelling efforts must conform to this particular vision to be useful or acceptable. Indeed, Miller *et al.* explicitly argue that many models (which differ in spatial and temporal detail, modelling complexity, etc.) are required to address planning issues across the wide range of urban areas that exist worldwide, and that different urban areas can and should follow different development paths in improving their integrated modelling capabilities, many of which may/should not end with this ultimate model. In particular, these axioms imply a strong preference for a microsimulation approach to modelling urban systems, which, while many researchers argue appears to be an attractive approach to the problem, is not necessarily the only expansion path for model development.[2]

Nevertheless, to provide some form of benchmark against which the current state of operational models might be compared, it is felt that this ultimate model provides a useful point of comparison. Table 10 attempts this comparison by summarizing the general state of integrated urban modelling practice (as defined by this review) with what might be viewed as an ultimate model with respect to the modelling axioms of Table 9.

In Table 10, the ultimate in each aspect of model design is printed in italics, followed by a summary of current practice in normal type. This format allows current operational practice to be compared with an ideal, towards which the discipline might reasonably be striving as it advances in understanding and improvements in computing power become available. The exact nature of this ideal is, of course, open for further consideration. Again, the point here is merely

Table 9. Integrated urban systems: modelling axioms

1. In referring to the urban system, the focus is on those elements that influence and/or interact with the transportation system. Notwithstanding, the model should be extensible as appropriate
2. Urban system consists of *physical elements*, *actors* and *processes*. The modelling representation of this urban system must contain all three of these
3. Transportation system is inherently multimodal and involves the flows of both *people* and *goods*
4. Markets represent the basic organizing principle for most interactions of interest within the urban area, providing price and time signals to producers (suppliers) and consumers (demanders) of housing, transportation services, etc.
5. Flows of people, goods, information and money through time and space arise as a derived demand from market interactions that are distributed in time and space
6. Urban areas are open, dissipative systems subject to external forces. As such, they never achieve a state of equilibrium
7. Future is path dependent. To generate a forecast year end state, the model must explicitly evolve the system state over time
8. Model must address both short- (activity/travel) and long-run (land development, transportation infrastructure, etc.) processes. There must be feedback/interaction between both processes
9. Some factors and processes are clearly exogenous to the urban system per se. Others may be treated as exogenous as a modelling strategy
10. Some activities within the urban area are 'basic' in the sense that they arise in response to external demand
11. Ideal model should be conceptualized at a very fine level of representation (i.e. analytical units) so as to maximize 'behavioural fidelity' in the representation of actors and processes, recognizing that any practical implementation probably will occur at higher levels of aggregation

Table 10. Summary of current modelling capabilities relative to an 'ultimate' model

Physical systems

- Time: *dynamic evolution of the system state in 1-year time steps. System state generally not in equilibrium. Interactions between long- and short-run processes are 'properly' accounted for*. Most models are static equilibrium models with large time steps (5 years or more). One-year time steps certainly feasible, as demonstrated by UrbanSim
- Land: *basic unit of land is the individual lot*. All models are zone based, often with very large zones. Recently developed/emerging models tend to use traffic zones. UrbanSim uses individual parcels for modelling land use. MUSSA experimenting with micro-level analysis capabilities
- Building stock: *building stock is explicitly represented. Each lot has a certain amount of floor space characterized by type, price, etc.* Building stock explicit in most models. Small number of building types usually used
- Transportation networks: *full, multimodal representation of the transportation system used to move both people and goods. Sufficient spatial and temporal detail properly to model flows, network performance, emissions, etc. Ideally, a dynamic, 24-hour network model to be used*. All models involve use of a multimodal network. Spatial detail often could be improved. Static, temporally aggregate representation of flows. Goods movement only represented in MEPLAN/TRANUS
- Services: *sufficient representation of other services for the purpose of modelling land development decisions*. Non-transportation services generally not explicitly represented in the models

Decision-makers

- Persons and households: *both persons and households are explicitly maintained (with appropriate 'mappings' between the two entities) in sufficient detail to model the various processes of interest*. All models are household based, with very little explicit representation of individuals are separate decision-makers. Households are grouped into relatively homogeneous categories, often using a relatively small number of categories. MUSSA and UrbanSim provide examples of a high level of household disaggregation, in the limit approaching a totally disaggregated 'microsimulation' approach
- Firms: *explicitly represented. Firms at least as important as households in the overall system: they occupy land/floor space; they employ workers; and they buy/sell goods and services from/to themselves and households. Firms are modelled in sufficient detail to capture adequately their behaviour within these various roles*. Older models typically model employment directly, rather than firms. More recently developed/emerging models model firms explicitly, usually using a small number of firm types
- Public authorities: *represented within the model to the extent they generate purely endogenous effects (employer of workers; demander/supplier of services, etc.). Will remain largely represented by exogenous inputs to the model*. Public authorities are almost entirely exogenous the models. The only exception is MEPLAN/TRANUS, which include 'government' as an explicit sector in their regional I/O models

Processes

- Markets: *land development, residential housing, commercial floor space and labour all occur within economic markets which possess demand and supply components and price signals that mediate between demand and supply. These economic markets must be explicitly modelled if their behaviour over time is to be captured properly*. Most models have explicit supply–demand market interaction models for land development and building stock allocation. Some model the job market explicitly; some use work trip distribution models to link workers with jobs. Some link housing demand and job allocation processes so closely together that these two processes are essentially treated as one. Strong static equilibrium assumptions are generally imposed to balance demand and supply in each time step (UrbanSim is the one example considered of a 1-year time step, non-equilibrium-based model)
- Demographics: *Demographic processes should be modelled endogenously so as to ensure that the distribution of population attributes (personal and household) are representative at reach point of time being modelled and are sufficiently detailed to support the behavioural decision models being used*. No model currently includes a significant demographic component. Households typically categorized by type, often with only a few household types used. Totals by household type typically supplied by exogenous inputs

Table 10. *Continued*

- Regional economics: *components of urban production/consumption processes that are endogenous to urban areas should be modelled endogenously. The model should also be sensitive to macro exogenous factors such as interest rates, national migration policies, etc.* MEPLAN and TRANUS are built around a regional input–output (I/O) model. MUSSA takes output totals from a regional I/O model. Otherwise, regional economic data are all exogenously generated
- Activity / travel: *the travel demand component of the integrated model should be activity-based and sufficiently disaggregated so as to capture properly trip-makers' responses to a full range of transportation policies, including ITS and TDM*. All models use variations on conventional four-stage modelling systems and so are susceptible to all the usual criticisms of these models. UrbanSim is being integrated with an activity-based travel model in Honolulu
- Automobile holdings: *household car holdings (number of vehicles, by type) should be endogenously determined within the model*. All models essentially ignore car holdings. At best, the household categorization scheme may include number of vehicles as one of its dimensions

to characterize current operational practice against some ultimate in order to develop a further appreciation of this current practice.

In assessing Table 10, as well as its predecessors, it must be recognized that an attempt has been made to characterize the attributes and performances of models based on the frameworks as they are typically implemented in practice. Any specific application may either exceed or fall short of what has been depicted here. Further, it has not been the objective of this review to pick 'winners' and 'losers'; nor has it been the objective to appear to criticize what has been done previously by comparing it against an ultimate (that is perhaps still unattainable). Rather, the objective has been to achieve an assessment of current modelling practice that is as objective as possible. It is felt that the general state of practice is of much more direct interest than the strengths/weaknesses of any particular model. In any case, it would appear that the vast bulk of previous work on and using these frameworks has been exemplary: progressive, fit to purpose and more than appropriate under the circumstances.

Summarizing even further from Table 10, as well as from the discussion in the previous section, several key points emerge, including the following:

- All currently operational frameworks fall short of the ultimate by varying degrees. Areas of significant shortfall in most models include:
  - excessive spatial aggregation;
  - excessive reliance on static equilibrium assumptions (with associated assumptions of large time steps and lack of path dependencies);
  - overly aggregate representations of households and firms, as well as a lack of representation of individuals as decision-making units separable from their households;
  - lack of endogenous demographic processes;
  - lack of endogenous car ownership processes; and
  - reliance on four-stage travel demand modelling methods.
- At the same time, current frameworks individually and collectively display many strengths and generally provide a solid basis for further evolutionary improvements. Strengths include:
  - generally strong microeconomic formulations of land and housing/floor space market processes;
  - coherent frameworks for dealing with land-use–transport interactions;
  - multimodal transportation network analysis capabilities; and
  - experience with developing and using large-scale urban land-use–transport models.
- Despite the scope for significant evolutionary development among existing frameworks, a new generation of integrated urban land-use–transport-modelling frameworks will need to be developed in order to realize the ideal. While newer models such as MUSSA and UrbanSim point the way to more disaggregate and/or more dynamic models, much research and development must be undertaken to realize models based on the ideal framework. This will include development of and experimentation with model structures that are explicitly designed to operate in a more disaggregate, dynamic, non-equilibrium framework.

It is arguable that integrated urban modelling has not progressed as far over the past decades as one might expect, given the potential importance of these models for urban policy analysis (Timmermans, 2003). Many possible reasons for this exist (Miller *et al.*, 1998; Timmermans, 2003). Interest in integrated urban modelling, however, appears to be on the rise in recent years, and next-generation modelling efforts such as ILUTE in Canada (Salvini and Miller, 2003; www.ilute.com), ILUMASS in Germany (Moeckel *et al.*, 2003), the TLUMIP work in Oregon, USA (http://www.odot.state.or.us/tddtpau/modeling.html), RAMBLAS in the Netherlands (Veldhuisen *et al.*, 2000), as well as continuing evolution of existing models such as UrbanSim (Waddell, 2002; www.urbansim.org) and MUSSA (Martínez and Donoso, 2001; www.mussa.cl), hold significant promise for future developments in this regard.

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Notes

1. The names of these frameworks and the software packages embodying them may be asserted by others to be proprietary terms or trade marks. The use of these names here does not imply that they have acquired for legal purposes any non-proprietary or general significance, nor is any other judgement implied concerning their legal status.
2. A detailed discussion of the relative merits of microsimulation models relative to other modelling approaches is well beyond the scope of this paper. Miller (2003), among others, presents an in-depth discussion of the method and its strengths and weaknesses.

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