OVERVIEW OF LAND-USE TRANSPORT MODELS

Michael Wegener
Spiekermann & Wegener Urban Regional Research
Lindemannstrasse 10, D-44137 Dortmund, Germany
E-mail: mw@spiekermann-wegener.de

The previous chapters in this Handbook have shown that spatial development, or land use, determines the need for spatial interaction, or transport, but that transport, by the accessibility it provides, also determines spatial development. However, it is difficult to empirically isolate impacts of land use on transport and vice versa because of the multitude of concurrent changes of other factors. This poses a problem if the likely impacts of integrated land-use and transport policies to reduce the demand for travel are to be predicted.

There are principally three methods to predict those impacts. The first is to ask people how they would change their location and mobility behaviour if certain factors, such as land use regulations or transport costs, would change ('stated preference'). The second consists of drawing conclusions from observed decision behaviour of people under different conditions on how they would be likely to behave if these factors would change ('revealed preference'). The third method is to simulate human decision behaviour in *mathematical models*.

All three methods have their advantages and disadvantages. Surveys can reveal also subjective factors of location and mobility decisions, however, their respondents can only make conjectures about how they would behave in still unknown situations, and the validity of such conjectures is uncertain. Empirical studies based on observation of behaviour produce detailed and reliable results; these, however, are valid only for existing situations and are therefore not suited for the assessment of novel yet untested policies. In addition it is usually not possible to associate the observed changes of behaviour unequivocally with specific causes, because in reality several determining factors change at the same time.

Mathematical models of human behaviour are also based on empirical surveys or observations. The difference is that the conclusions to be drawn from the survey and observation data are quantified. Strictly speaking, the results of mathematical models are no more universally valid than those of empirical studies but are only valid for situations which are similar to those for which their parameters were estimated. Nevertheless it is possible to transfer human behaviour represented in mathematical models within certain limits to still unknown situations. In addition, mathematical models are the only method by which the effects of individual determining factors can be analysed by keeping all other factors fixed.

In this chapter recent developments in the field of operational integrated land-use transport models will be reviewed with special emphasis on their ability to test both land use and transport policies and to assess their impacts.

Chapter 9 in David A. Hensher and Kenneth Button (Eds.): *Transport Geography and Spatial Systems*. Handbook 5 of the *Handbook in Transport*. Pergamon/Elsevier Science, Kidlington, UK, 2004, 127-146.

.

EXISTING URBAN LAND-USE TRANSPORT MODELS

The models reviewed here are integrated, i.e. incorporate the most essential processes of spatial development in urban regions. This implies that they forecast urban land use, where land use denotes a range of land uses such as residential, industrial and commercial. This excludes partial models addressing only one subsystem such as housing or retail. It is essential that the links from transport to land use are considered; transport itself may be modelled either endogenously or by an exogenous transport model. The models are operational in the sense that they have been implemented, calibrated and used for policy analysis for at least one metropolitan region.

The number of real-world applications of models falling under the above definition has increased steadily over the last two decades. There has been a continuous reflection of purpose, direction and theoretical basis of land-use transport modelling as witnessed by volumes edited by Hutchinson et al. (1985); Hutchinson and Batty (1986), Webster et al. (1988) and Webster and Paulley (1990) and by reviews by Harris (1985), Mackett (1985a), Wegener (1986b, 1987), Kain (1987), Boyce (1988), Berechman and Small (1988), Aoyama (1989), and Batty (1994), Harris (1994), Southworth (1995), Wilson (1997), Wegener (1994, 1995, 1998a), Wegener and Fürst (1999) and EPA (2000).

To assess the current state of the art in urban modelling, in this section first a framework for the classification and evaluation of urban models is established.

Urban Change Processes

For the evaluation of operational urban models, the urban change processes to be modelled are identified. Eight types of major urban subsystem are distinguished. They are ordered by the speed by which they change, from slow to fast processes:

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

There is a ninth subsystem, the *urban environment*. Its temporal behaviour is more complex. The direct impacts of human activities, such as transport noise and air pollution are immediate; other effects such as water or soil contamination build up incrementally over time, and still others such as long-term climate effects are so slow that they are hardly observable. All other eight subsystems affect the environment by energy and space consumption, air pollution and noise emission, whereas only locational choices of housing investors and households, firms and workers are co-determined by environmental quality, or lack of it. All nine subsystems are partly market-driven and partly subject to policy regulation.

In the 1950s first efforts were made in the USA to study the interrelationship between transport and the spatial development of cities systematically. Hansen (1959) demonstrated for Washington, DC that locations with good accessibility had a higher chance of being developed, and at a higher density, than remote locations ("How accessibility shapes land use"). The recognition that trip and location decisions co-determine each other and that therefore transport and land use planning needed to be co-ordinated, quickly spread among American planners, and the 'land-use transport feedback cycle' became a commonplace in the American planning literature. The set of relationships implied by this term can be briefly summarised as follows (see Figure 1):

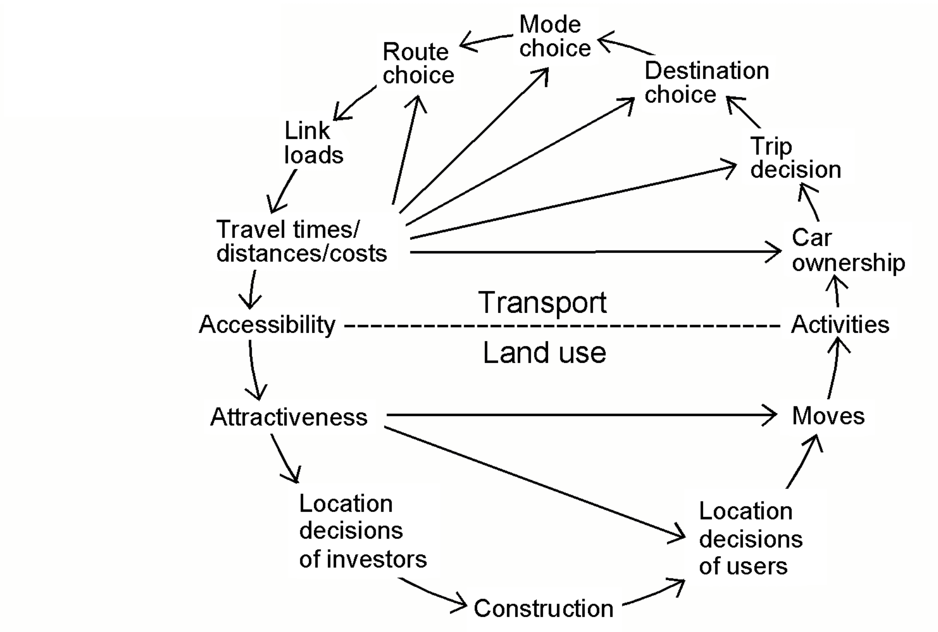

Figure 1. The 'land-use transport feedback cycle'.

- The distribution of *land uses*, such as residential, industrial or commercial, over the urban area determines the locations of human *activities* such as living, working, shopping, education or leisure.
- The distribution of human *activities* in space requires spatial interactions or trips in the *transport system* to overcome the distance between the locations of activities.
- The distribution of infrastructure in the *transport system* creates opportunities for spatial interactions and can be measured as *accessibility*.
- The distribution of *accessibility* in space co-determines location decisions and so results in changes of the *land use* system.

This simple explanation pattern is used in many engineering-based and human-geography derived urban development theories (see chapters by Haynes and Thisse).

Lowry's (1964) *Model of Metropolis* was the first attempt to implement the urban land-use transport feedback cycle in an operational model. The Lowry model essentially consists of a residential location model and a service and retail employment location model nested into each other (see chapter by Horowitz and Putman). The Lowry model stimulated a large number of increasingly complex modelling approaches, such as the work by Goldner (1971), Echenique (Geraldes et al., 1978), Putman (1983, 1991) and Mackett (1983). Boyce et al. (1981) developed combined equilibrium models of residential location, mode and route choice. From these pioneering efforts, a wide range of different approaches to model urban land use and transport have evolved. The following section provides an overview.

Twenty Urban Models.

For this overview, twenty contemporary urban land-use transport models were selected for a comparative review. The twenty models represent the current state of the art of urban modelling – though it cannot be excluded that promising new approaches in this rapidly moving field were overlooked.

BOYCE the combined models of location and travel choice developed by Boyce (Boyce et al. 1983, 1985; Boyce and Mattsson, 1991; Boyce et al. 1992);

CUFM the California Urban Futures Model developed at the University of California at Berkeley (Landis 1992, 1993, 1994; Landis and Zhang, 1998a, 1998b);

DELTA the land-use/economic modelling package by Davids Simmonds Consultancy, Cambridge, UK (Simmonds and Still, 1998; Simmonds, 2001);

ILUTE the Integrated Land Use, Transportation, Environment modelling system under development at several Canadian universities (Miller and Salvini, 2001);

IMREL the Integrated Model of Residential and Employment Location developed at the Royal Institute of Technology, Stockholm by Anderstig and Mattsson (1991, 1998);

IRPUD the model of the Dortmund region developed at the University of Dortmund (Wegener, 1982a, 1982b, 1985, 1986a; Wegener et al. 1991; Wegener, 1996, 1998b);

ITLUP the Integrated Transportation and Land Use Package by Putman (1983, 1991, 1998) consisting of the residential location model DRAM and the employment model EMPAL;

KIM the non-linear urban equilibrium model developed at the University of Illinois at Urbana by Kim (1989) and Rho and Kim (1989);

LILT the Leeds Integrated Land-Use/Transport model developed at the University of Leeds by Mackett (1983, 1990c, 1991a, 1991b);

MEPLAN the integrated modelling package developed by Marcial Echenique & Partners (Echenique et al., 1969; Echenique and Williams, 1980; Echenique, 1985; Echenique et al., 1990; Hunt and Echenique, 1993; Hunt and Simmonds, 1993, Williams 1994; Hunt 1994);

METROSIM the microeconomic land-use and transport model developed for the New York Metropolitan Area by Anas (1992, 1994, 1998);

MUSSA	the '5-Stage Land-Use Transport Model' developed for Santiago de Chile by Martinez (1991, 1992a,1992b; Martinez and Donoso, 1995; Martinez, 1996, 1997a, 1997b);
PECAS	the Production, Exchange and Consumption Allocation System developed at the University of Calgary (Parsons Brinckerhoff Ohio et al., 1999; Hunt and Abraham, 2003);
POLIS	the Projective Optimization Land Use Information System developed by Prastacos for the Association of Bay Area Governments (Prastacos, 1986; Caindec and Prastacos, 1995);
RURBAN	the Random-Utility URBAN model developed by Miyamoto (Miyamoto et al., 1986; Miyamoto and Kitazume, 1989; Miyamoto and Udomsri, 1996);
STASA	the master-equation based transport and urban/regional model developed for the metropolitan region of Stuttgart by Haag (1990);
TLUMIP	the land-use transport model of the US State of Oregon developed in the Oregon Transport and Land Use Model Integration Program (ODOT, 2002);
TRANUS	the transport and land-use model developed by de la Barra (de la Barra, 1982; de la Barra et al. 1984; de la Barra 1989, 1998);
TRESIS	the Transportation and Environment Strategy Impact Simulator developed at the University of Sydney by Hensher and Ton (2001);
URBANSIM	the microeconomic model of location choice of households and firms by Waddell (1998a, 1998b, 2002; Waddell et al., 1998).

These twenty models are now compared in terms of the criteria *comprehensiveness*, *model structure*, *theoretical foundations*, *modelling techniques*, *dynamics*, *data requirements*, *calibration and validation*, *operationality* and *applicability*.

<u>Comprehensiveness</u>. All twenty models are comprehensive in the sense that they address at least two of the eight subsystems identified above. Only ILUTE, MEPLAN, STASA, PECAS, TLUMIP and TRANUS encompass all eight subsystems. IRPUD, LILT, METROSIM and TRESIS address all subsystems except goods transport and KIM models goods movements but not physical stock and land use. Half of the models make no distinction between activities (population and employment) and physical stock (housing and workplaces). Six models (DELTA, CUFM, MUSSA, POLIS, RURBAN and URBANSIM) do not in themselves model transport but rely on interaction with existing transport models. Only DELTA, ILUTE, IRPUD, LILT and URBANSIM model demographic change and household formation. Table 1 shows the urban subsystems that are modelled with each model.

<u>Model structure</u>. With respect to overall model structure, two groups can be distinguished. One group of models searches for a unifying principle for modelling and linking all subsystems; the others see the city as a hierarchical system of interconnected but structurally autonomous subsystems; The resulting model structure is either tightly integrated, 'all of one kind', or consists of loosely coupled submodels, each of which has its own independent internal structure. The former type of model is called 'unified', the latter 'composite' (Wegener et al. 1986). Nine of the twenty models (BOYCE, MUSSA, KIM, MEPLAN, METROSIM, PECAS, RURBAN, TRANUS and STASA) belong to the unified category, the remaining eleven are composite. The distinction between unified and composite model designs has important implications for the modelling techniques applied and for the dynamic behaviour of the models (see below).

Table 1. Urban subsystems represented in land-use transport models

Models	Speed of change							
	Very slow		Slow		Fast		Immediate	
	Networks	Land use	Work-places	Housing	Employ-ment	Popula-tion	Goods transport	Travel
BOYCE	+				+	+		+
CUFM	(+)	+	+	+	+	+		(+)
DELTA	(+)	+	+	+	+	+		(+)
ILUTE	+	+	+	+	+	+	+	+
IMREL	+	+	+	+	+	+		+
IRPUD	+	+	+	+	+	+		+
ITLUP	+	+			+	+		+
KIM	+				+	+	+	+
LILT	+	+	+	+	+	+		+
MEPLAN	+	+	+	+	+	+	+	+
METROSIM	+	+	+	+	+	+		+
MUSSA	(+)			+	+	+		(+)
PECAS	+	+	+	+	+	+	+	+
POLIS	(+)	+			+	+		(+)
RURBAN	(+)	+			+	+		(+)
STASA	+	+	+	+	+	+	+	+
TLUMIP	+	+	+	+	+	+	+	+
TRANUS	+	+	+	+	+	+	+	+
TRESIS	+	+	+	+	+	+		+
URBANSIM	(+)	+	+	+	+	+		(+)

(+) provided by linked transport model

Theoretical foundations. In the last thirty years great advances in theories to explain spatial choice behaviour and in techniques for calibrating spatial choice models have been made. Today there is a broad consensus about what constitutes a state-of-the-art land use model: Except for one (CUFM), which uses allocation rules, all models rely on random utility or discrete choice theory to explain and forecast the behaviour of actors such as investors, households, firms or travellers. Random utility models predict choices between alternatives as a function of attributes of the alternatives, subject to stochastic dispersion constraints that take account of unobserved attributes of the alternatives, differences in taste between the decision makers or uncertainty or lack of information (Domencich and McFadden 1975). Anas (1983) showed that the multinomial logit model resulting from random utility maximisation is, at equal levels of aggregation, formally equivalent to the entropy-maximising model proposed by Wilson (1967, 1970); he thus laid the foundation for the convergence and general acceptance of formerly separate strands of theory. The STASA model is based on the master equation approach and may be seen as a dynamic and decision based multi-agent system (Haag, 1990). Underneath that uniformity, however, there are significant differences between the theoretical foundations of the models:

- Eleven models (DELTA, IMREL, KIM, MEPLAN, METROSIM, MUSSA, PECAS, RURBAN, TLUMIP, TRANUS and TRESIS) represent the land (or floorspace or housing) market with endogenous prices and market clearing in each period; three (ILUTE, IRPUD and URBANSIM) have endogenous land and housing prices with delayed price adjustment. These models are indebted to microeconomic theory, in particular to Alonso's (1964) theory of urban land markets or bid-rent theory. The models without market equilibrium rely on random utility maximisation; however, three of the microeconomic models (MUSSA, RURBAN and STASA) are hybrids between bid-rent and random utility theory. All models with transport submodels use random utility or entropy theory for modelling destination and mode choice, except the STASA model.

- Only KIM and METROSIM determine a general equilibrium of transport and location with endogenous prices. Other models are equilibrium models of transport only (ILUTE, IRPUD, ITLUP and TLUMIP), of transport and activity location separately (IMREL, MEPLAN, PECAS, TRESIS and TRANUS), or of transport and location combined but without endogenous prices (BOYCE and LILT). Five models apply concepts of locational surplus (IMREL, POLIS), random utility (DELTA, IRPUD and ITLUP) or profitability (CUFM) to locate activities. ITLUP may be brought to general equilibrium, but this is not normally done; METROSIM may produce a long-run equilibrium or converge to a steady state in annual increments. STASA describes the short-term redistribution of population during a day due to transport events.
- IMREL uses its equilibrium mechanism to determine the distribution of housing that maximises locational surplus and so is a true optimisation model, whereas all other models in the sample simulate one particular scenario only. Despite earlier attempts at optimisation in urban models (e.g. Brotchie et al., 1980), optimisation approaches in urban models have all but disappeared (a recent exception is described in Pfaffenbichler and Shepherd, 2002).
- Several other theoretical elements are built into some models. MEPLAN, METROSIM, PECAS and TRANUS use export base theory to link population and non-basic employment to exogenous forecasts of export industries. DELTA, ILUTE, IRPUD, LILT, TLUMIP and URBANSIM apply standard probabilistic concepts of cohort survival analysis in their demographic and household formation submodels. IRPUD also utilises ideas from time geography, such as time and money budgets, to determine action spaces of travellers in its transport submodel.

<u>Modelling techniques</u>. In all twenty models, the urban region is represented as a set of discrete subareas or zones. Time is typically subdivided into discrete periods of one to five years. This classifies all models except IMREL (which is static) as recursive simulation models:

- STASA uses a one-year period for the urban/regional modelling and a one-hour period for redistribution effects due to transport events. In nine models (BOYCE, IMREL, KIM, LILT, MEPLAN, METROSIM, PECAS, RURBAN and TRANUS) transport and location are simultaneously determined in spatial-interaction location models in which activities are located as destinations of trips; in the remaining models (and in the employment location model of IMREL) transport influences location via accessibility indicators. In the models with network representation, state-of-the-art modelling techniques are applied, with network equilibrium the dominant trip assignment method despite its weakness of collapsing to all-or-nothing assignment in the absence of congestion. Only ITLUP, MEPLAN, STASA and TRANUS have multiple-path assignment allowing for route-choice dispersion, and only ILUTE and TLUMIP use activity-based trip generation.
- For representing flows of goods, spatial input-output methods are the standard method. DELTA, KIM, MEPLAN, PECAS and TRANUS use input-output coefficients or demand functions for intersectoral flows and random utility or entropy models for their spatial distribution. MEPLAN, PECAS and TRANUS incorporate industries and households as consuming and producing 'factors' resulting in goods movements or travel.

- With the exception of CUFM, all models are aggregate at a meso level, i.e. all results are given for medium-sized zones and for aggregates of households and industries. CUFM, ILUTE and TLUMIP are disaggregate, i.e. apply microsimulation techniques. CUFM uses detailed land information in map form generated by a geographical information system. IRPUD starts with aggregate data but uses microsimulation in its housing market submodel; work is underway to make more submodels microscopic (Salomon et al., 2002). ILUTE and URBANSIM apply zones but use smaller spatial units such as grid cells or parcels in some submodels.

Dynamics. The discussion on dynamics is related to the issue of equilibrium (see above). Equilibrium models are based on the assumption that interdependent model variables, such as prices, supply and demand, adjust to equilibrium with zero delay or, if adjustment is delayed, equilibrium is eventually reached. Dynamic models, on the other hand, are based on the assumption that some changes, e.g. changes in demand, are faster than others, e.g. responses of supply, and that these differences in speed of adjustment are so large that urban systems are normally in disequilibrium. All but three (BOYCE, IMREL, KIM) of the twenty models are recursive simulation models. Recursive simulation models are called quasi-dynamic because, although they model the development of a city over time, within one simulation period they are in fact cross-sectional. This is however only true for strictly unified models. Composite models consist of several interlinked submodels that are processed sequentially or iteratively once or several times during a simulation period. This makes composite models well suited for taking account of time lags or delays due to the complex superposition of slow and fast processes of urban development (cf. Wegener et al., 1986). However, this feature is insufficiently used by some models, because their simulation period of five years has the effect of an implicit time lag – a too long time lag in most cases. This problem is likely to disappear as faster computers will make shorter simulation periods of one or two years more feasible.

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

Calibration and Validation. All twenty models of the sample have been (or could have been) calibrated using observed data, using readily available computer programmes and following well-established methods and standards. In particular, maximum-likelihood estimation of the ubiquitous logit model has become routine. Yet, while calibration has become easier, the limits to calibrating a model with data of the past have become visible. Calibration of cross-sectional models, as it is practised today, provides the illusion of precision but does little to establish the credibility of models designed to look into the far future. There has been almost no progress in the methodology to calibrate dynamic or quasi-dynamic models. In the face of this dilemma, the insistence of some modellers on 'estimating' every model equation appears almost an obsession. It would probably be more effective to concentrate instead on model *validation*, i.e. the comparison of model results with observed data over a longer period. In the future, the only real test of a model's performance should be its ability to forecast the essential dynamics of the modelled system over a past period at least as long as the forecasting period.

Operationality. All models in the sample are operational in the sense that they have been applied to real cities. However, there are differences. Some models have remained primarily research models applied to one particular study area. Other models have been applied to only a few cities. Some models are actually families of models each specifically tailored to the needs of a particular urban area or client. Only few models are on their way to become standard software for a wider market. ITLUP has been applied by a large number of metropolitan planning agencies in the United States. TRANUS stands out as a particularly advanced and well documented software with an attractive user interface in Spanish or English. MEPLAN is applied in more and more cities all over the world and DELTA to an increasing number of UK cities. The time seems not far when any planning office will be able to buy a complex and versatile urban model with full documentation, default values and test data sets for less than a thousand dollars.

Applicability. If one considers the enormous range of planning problems facing a typical metropolitan area in industrialised countries today, the spectrum of problems actually addressed with the twenty urban models in the sample is very narrow. The majority of applications answer traditional questions such as how land use planning or housing programs would affect land use development and transport, or how transport improvements or changes in travel costs would shift the distribution of activities in an urban area.

FUTURE URBAN LAND-USE TRANSPORT MODELS

Today there are many urban modelling projects underway all over the world. In the United States, environmental legislation, such as the Clean Air Act amendments of 1990, the Intermodal Surface Transportation Efficiency Act (ISTEA) of 1991 and the Transportation Equity Act for the 21st Century (TEA-21) of 1998, gave a boost to the development and application of urban land-use transport models. ISTEA required cities to consider the likely effect of transportation policy decisions on land use development. In Europe, the European Commission has funded a number of studies employing land-use transport models. The SPARTACUS project applied MEPLAN to three urban areas and connected the model with spatially disaggregate environmental submodels, the PROSPECTS project applied several models DELTA and IMREL, and the PROPOLIS applied MEPLAN, TRANUS and IRPUD in seven urban regions in six European countries. There is an increasing number of applications of DELTA, MEPLAN and TRANUS.

Nevertheless, there remain challenges to be met. The transport submodels used in most existing land-use transport models do not apply state-of-the-art activity-based modelling techniques but the traditional four-step travel demand model sequence which is not suitable to model behavioural responses to many travel demand management policies presently discussed. Moreover, the spatial resolution of existing land-use transport models is too coarse to model activity-based travel behaviour or neighbourhood-scale travel demand management policies.

Their insufficient spatial resolution is also one of the reasons why only very few land-use transport models are linked to advanced environmental submodels of air quality, traffic noise, land take and biotopes (Wegener, 1998a). Environmental issues are certain to play a more prominent role in the future when the manifest unsustainability of present urban lifestyles and mobility patterns will increasingly come under scrutiny. However, most present efforts to link environmental submodels to transport or land-use transport models are content with modelling emissions where actually air quality, i.e. local impacts of emissions occurring elsewhere, should be forecast.

This leads to issues of spatial equity. Most land-use transport models are utilitarian in that they favour solutions yielding the greatest aggregate social benefit. However, urban societies are increasingly becoming socially and spatially fragmented and polarised, which means that distributional issues, both in social and spatial terms, are becoming more prominent. Distributional issues are particularly relevant in environmental conflicts where polluters and those affected by pollution tend to come from different social groups or neighbourhoods of a city. Most present land-use transport models are insensitive to issues of social exclusion and spatial equity – one notable exception is the PROPOLIS project in which different concepts of equity are explored with the results of land-use transport models (LT et al., 2002).

The future of land-use transport modelling will largely depend on whether emerging new models will live up to these challenges.

From a technical point of view, the prospects are excellent. More powerful computers will remove former barriers to increasing the spatial, temporal and substantive resolution of models. The wealth of publicly available high-resolution spatial data will reduce aggregation error in spatial models. Geographic information systems will become the mainstream data organisation of urban models. Spatial disaggregation of land use and transport network data in raster GIS will permit the linkage between land-use transport models and air quality and noise propagation models. Multiple representation of spatial data in raster and vector GIS will combine the advantages of spatial disaggregation (raster) and efficient network algorithms (vector). Aggregate probabilistic approaches (e.g. entropy maximising) will be replaced by disaggregate stochastic (microsimulation) approaches.

Microsimulation was first used in social science applications by Orcutt et al (1961), yet applications in a spatial context remained occasional experiments without deeper impact, though covering a wide range of phenomena such as spatial diffusion (Hägerstrand, 1968), urban development (Chapin and Weiss, 1968), transport behaviour (Kreibich, 1979), demographic and household dynamics (Clarke *et al.*, 1980; Clarke 1981; Clarke and Holm 1987) and housing choice (Kain and Apgar, 1985; Wegener, 1985). Only recently microsimulation has found new interest because of its flexibility to model processes that cannot be modelled in the aggregate (Clarke, 1996). In the last two decades, several microsimulation models of urban land use and transport have been developed (Hayashi and Tomita 1989; Mackett 1985b, 1990a, 1990b; Landis, 1992, 1993, 1994; Landis and Zhang, 1998a, 1998b; Waddell, 1998a, 1998b, 2002; Wegener and Spiekermann, 1996; Salomon et al., 2002, Miller and Salvini, 2001).

A different approach emerged from the theory of cellular dynamics. Cellular automata (CA) are objects associated with areal units or *cells*. CA follow simple stimulus-response rules to change or not to change their *state* based on the state of adjacent or near-by cells. By adding random noise to the rules, surprisingly complex patterns that closely resemble real cities can be generated (White and Engelen, 1994; Batty and Xie, 1994; Batty, 1997). More complex stimulus-response behaviour is given to CA models in multi-reactive agents models. Multi-reactive agents are complex automata with the ability to control their interaction pattern; they can change their environment but also their own behaviour, i.e. are able to learn (Ferrand, 2000). The distinction between the behaviour of multi-reactive agents and the choice behaviour generated in microsimulation models is becoming smaller.

Probably the most advanced area of application of microsimulation in urban models is travel modelling (see Handbook 1). Aggregate travel models are unable to reproduce the complex spatial behaviour of individuals and to respond to sophisticated travel demand management measures. As a reaction, disaggregate travel models aim at a one-to-one reproduction of spatial behaviour by which individuals choose between mobility options in their pursuit of activities during a day (Axhausen and Gärling, 1992; Ben Akiva et al., 1996). Activity-based travel models start from interdependent 'activity programmes' of household members of a 'synthetic population' (Beckman et al., 1995) and translate these into home-based 'tours' consisting of one or more trips. This way interdependencies between the mobility behaviour of household members and between the trips of a tour can be modelled as well as intermodal trips that cannot be handled in aggregate multimodal travel models. Activity-based travel models do not model peak-hour or all-day travel but disaggregate travel behaviour by time of day, which permits the modelling of choice of departure time. There are also disaggregate traffic assignment models based on queuing or CA approaches, e.g. in the TRANSIMS project (Barrett et al., 1999; Nagel et al., 1999), which reproduce the movement of vehicles in the road network with a level of detail not known before.

However, it will take some time until the first urban land-use transport models fully based on microsimulation will be operational. Miller et al. (1998) presented a matrix in which the past and future evolution of urban land-use transport model was charted. The following diagram is an adaptation in which a sixth row L6 was added (Figure 2).

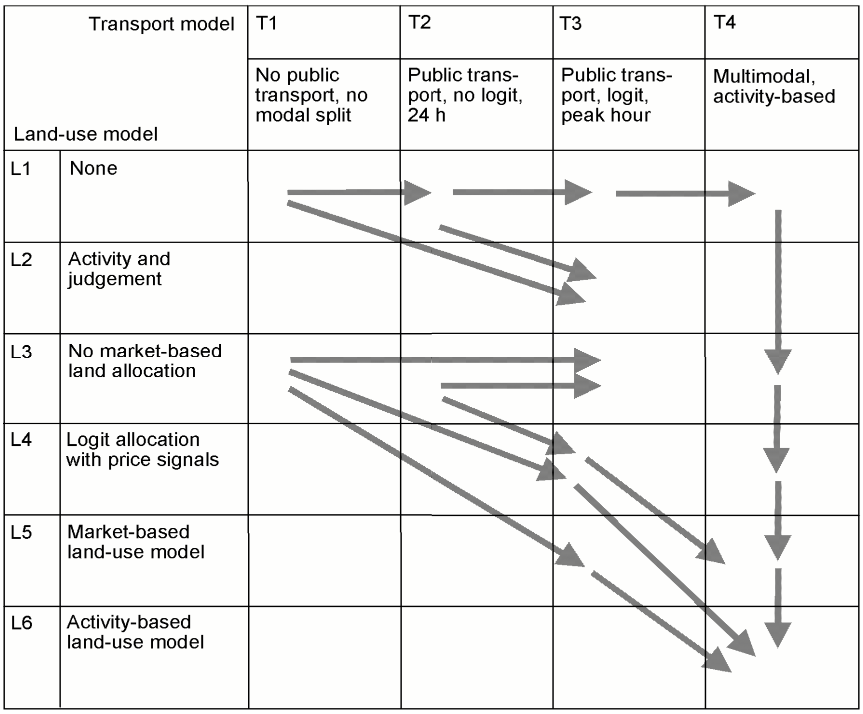

Figure 2. Evolution of urban land-use transport models (adapted from Miller et al., 1998)

In Figure 2, the rows correspond to different levels of levels of land-use modelling capability:

L1 No land use model.
L2 Activities are allocated to zones by professional judgement.
L3 Non-market-based land allocation model.
L4 Land allocation with price signals.
L5 Fully integrated market-based model
L6 Activity-based land-use model using microsimulation

Similarly, the columns in Figure 2 represent different levels of travel demand modelling capability:

T1 Only roads and auto travel are modelled.
T2 Public transport with simplified (non-logit) modal choice.
T3 Logit-based modal choice, peak-period assignment.
T4 Activity-based travel model using microsimulation.

Each cell in the figure therefore represents a land-use transport modelling combination. The arrows indicate incremental paths local governments can take to develop their land-use transport modelling capability.

CONCLUSIONS

Predicting the impacts of integrated land-use transport policies is a difficult task due to the multitude of concurrent changes of pertinent system variables. In general, there are three groups of methods to predict those impacts. The first one is to ask people about their anticipated reaction to changes such as increased transport costs or land use restrictions ('stated preference'). The second possibility is to draw conclusions from empirically observed behaviour of people ('revealed preference'). The third group of methods comprises mathematical models to simulate human decision making and its consequences. While all three possibilities have shortcomings, mathematical models are the only method to forecast still unknown situations and to determine the effect of a single factor while keeping all other factors fixed.

Urban land-use transport models incorporate the most essential processes of spatial development including all types of land uses. Transport may be modelled either endogenously or by an exogenous transport model. Urban systems represented in land-use transport models can be divided into nine subsystems according to the speed by which they change. The urban fabric consisting of infrastructure networks and land use patterns are subject to very slow change over time. Workplaces and housing change relatively slow while the employment and residential population adjust their spatial behaviour fairly quickly to changing circumstances. Goods transport or travel destinations are the most flexible phenomena of urban spatial development. They can be modified almost instantly according to changes in congestion or fluctuations in demand. There is a ninth subsystem, the urban environment, which is more complex regarding its temporal behaviour.

A number of integrated land-use transport models are in use today. There are significant variations among the models with respect to comprehensiveness, model structure, theoretical foundations, modelling techniques, dynamics, data requirements and calibration and validation. Despite the achievements in developing these models further, there remain some challenges to be met. The transport submodels used in most current land-use transport models do not apply state-of-the-art activity-based modelling techniques but the traditional four-step travel demand model sequence which is inadequate for modelling behavioural responses to many currently applied travel demand management policies. The most promising technique for activity-based land use and transport modelling is microsimulation which makes it possible to reproduce the complex spatial behaviour of individuals on a one-to-one basis.

In addition, the spatial resolution of present models is still too coarse to model neighbourhood scale policies and effects. In the future, the integration of environmental submodels for air quality, traffic noise, land take and biotopes are likely to play a prominent role. Issues of spatial equity and socio-economic distributions are expected to gain similar importance in model building.

ACKNOWLEDGMENT

The permission of Eric Miller and colleagues to use their matrix of model evolution as the basis for Figure 2 is gratefully acknowledged.

REFERENCES

Alonso, W. (1964) *Location and Land Use* Harvard University Press, Cambridge, MA

Anas, A. (1983) Discrete choice theory, information theory and the multinomial logit and gravity models *Transportation Research*, **17 B**, 13-23

Anas, A. (1992) NYSIM (The New York Area Simulation Model): A Model for Cost-Benefit Analysis of Transportation Projects. Research Report, Regional Plan Association, New York

Anas, A. (1994) *METROSIM: A Unified Economic Model of Transportation and Land-Use* Alex Anas & Associates, Williamsville, NY

Anas, A. (1998) *NYMTC Transportation Models and Data Initiative: The NYMTC Land Use Model* Alex Anas & Associates, Williamsville, NY

Anderstig, C., Mattsson, L.-G., (1991) An integrated model of residential and employment location in a metropolitan region *Papers in Regional Science*, **70**, 167-84.

Anderstig, C., Mattsson, L.-G. (1998) Modelling land-use and transport interaction: evaluations and policy analysis. In: *Network Infrastructure and the Urban Environment: Recent Advances in Land-Use/Transportation Modelling* (L. Lundqvist, L.-G. Mattsson, T.J. Kim, eds.), 308-328. Springer, Berlin/Heidelberg/New York

Aoyama, Y. (1989) A historical review of transport and land-use models in Japan *Transportation Research*, **23 A**, 53-61.

Axhausen, K.W., Gärling, T. (1992) Activity-based approaches to travel analysis: conceptual frameworks, models and research problems *Transport Reviews*, **12**, 324-341.

Barrett, C.L. et al. (1999) *TRansportation ANalysis SIMulation System (TRANSIMS)*. Version TRANSIMS-LANL-1.0. Volume 0: Overview. LA-UR 99-1658. Los Alamos National Laboratory, Los Alamos, NM. http://transims.tsasa.lanl.gov/PDF_Files/Vol0-jmhF_990602_.pdf

Batty, M. (1994) A chronicle of scientific planning: the Anglo-American modeling experience *Journal of the American Planning Association*, **60**, 7-16

Batty, M. (1997) Cellular automata and urban form: a primer *Journal of the American Planning Association*, **63**, 264-274.

Batty, M. and Xie, Y. (1994) From cells to cities *Environment and Planning B: Planning and Design*, **21**, 31-48

Beckman, R.J., Baggerly, K.A., McKay, M.D. (1995) *Creating Synthetic Baseline Populations*. LA-UR-95-1985. Los Alamos National Laboratory, Los Alamos, NM

Ben-Akiva, M.E., Bowman, J.L., Gopinath, D. (1996) Travel demand model system for the information era. *Transportation*, **23**, 241-166

Berechman, J., Small, K.A. (1988) Research policy and review 25: modeling land use and transportation: an interpretive review for growth areas *Environment and Planning A*, **20**, 1283-1422

Boyce, D.E. (1988) Renaissance of large-scale models *Papers of the Regional Science Association*, **65**, 1-10

Boyce, D.E., Chon, K.S., Ferris, M.E., Lee, Y.J., Lin, K.T., Eash, R.W. (1985) *Implementation and Evaluation of Combined Models of Urban Travel and Location on a Sketch Planning*

Network Working Paper. Department of Civil Engineering, University of Illinois and Chicago Area Transportation Study, Urbana-Champaign/Chicago, IL
Boyce, D.E., Chon, K.S., Lee, Y.J., Lin, K.T., LeBlanc, L. (1983) Implementation and computational issues for combined models of location, destination, mode, and route choice. *Environment and Planning A*, **15**, 1219-30
Boyce, D.E., LeBlanc, L.J., Chon, K.S., Lee, Y.L., Lin, K.T. (1981) *Combined Models of Location, Destination, Mode and Route Choice: A Unified Approach Using Nested Entropy Constraints* Publication No. 3. Transportation Planning Group, Department of Civil Engineering, University of Illinois, Urbana, IL
Boyce, D., Mattsson, L.-G. (1991) Modeling residential location choice in relation to housing location and road tolls on congested urban highway networks: *Transportation Research* **B 33**, 581-591
Boyce, D.E., Tatineni, M., Zhang, Y. (1992) *Scenario Analyses of the Chicago Region with a Sketch Planning Model of Origin-Destination Mode and Route Choice* Report to Illinois Department of Transportation. Urban Transportation Center, University of Illinois, Chicago, IL
Brotchie, J.F., Dickey, J.W., Sharpe, T. (1980) TOPAZ Planning Techniques and Applications. Lecture Notes in Economics and Mathematical Systems Series. Vol 180. Springer Verlag, Berlin
Caindec, E.K., Prastacos, P. (1995) *A Description of POLIS. The Projective Optimization Land Use Information System* Working Paper 95-1. Association of Bay Area Governments, Oakland
Chapin, F.S., Weiss S.F. (1968) A probabilistic model for residential growth *Transportation Research*, **2**, 375-390
Clarke, G.P., ed. (1996) *Microsimulation for Urban and Regional Policy Analysis* European Research in Regional Science 6. Pion, London
Clarke, M. (1981) A first-principle approach to modelling socio-economic interdependence using microsimulation *Computers, Environment and Urban Systems*, **6**, 211-227
Clarke, M., Holm, E. (1987) Microsimulation methods in spatial analysis and planning *Geografiska Annaler*, **69B**, 145-164
Clarke, M., Keys, P., Williams, H.C.W.L. (1980) *Micro-Analysis and Simulation of Socio-Economic Systems: Progress and Prospects* School of Geography, University of Leeds, Leeds
de la Barra, T. (1982) Modelling regional energy use: a land use, transport and energy evaluation model *Environment and Planning B: Planning and Design*, **9**, 429-443
de la Barra, T. (1989) *Integrated Land Use and Transport Modelling* Cambridge University Press, Cambridge
de la Barra, T. (1998) Improved logit formulations for integrated land use, transport and environmental models. In: *Network Infrastructure and the Urban Environment: Recent Advances in Land-Use/Transportation Modelling* (L. Lundqvist, L.-G. Mattsson, T.J. Ki, eds.), 288-307 Springer, Berlin/Heidelberg/New York
de la Barra, T., Pérez, B. Vera, N. (1984) TRANUS-J: Putting large models into small computers *Environment and Planning B: Planning and Design*, **11**, 87-101
Domencich, T.A., McFadden, D. (1975), *Urban Travel Demand: a Behavioral Analysis* North Holland, Amsterdam
Echenique, M.H. (1985) The use of integrated land use transportation planning models: the cases of Sao Paulo, Brazil and Bilbao, Spain. In: *The Practice of Transportation Planning* (M. Florian, ed.) Elsevier, The Hague

Echenique, M.H., Crowther, D., Lindsay, W. (1969) A spatial model for urban stock and activity *Regional Studies*, **3**, 281-312

Echenique, M.H., Flowerdew, A.D.J., Hunt, J.D., Mayo, T.R., Skidmore, I.J., Simmonds, D.C. (1990) The MEPLAN models of Bilbao, Leeds and Dortmund *Transport Reviews*, **10**, 309-322

Echenique, M.H., Williams, I.N. (1980) Developing theoretically based urban models for practical planning studies *Sistemi Urbani*, **1**, 13-23

EPA (US Environmental Protection Agency) (2000) *Projecting Land-Use Change: A Summary of Models for Assessing the Effects of Community Growth and Change on Land-Use Patterns* EPA/600/R-00/098 US Environmental Protection Agency, Office of Research and Development, Cincinnati, OH. http://www.epa.gov/ecocommunity/tools/reportfinal3.pdf

Ferrand, N. (2000) Multi-reactive agents paradigm for spatial modelling. In: *Spatial Models and GIS: New Potential and New Models* (A.S. Fotheringham, M. Wegener, eds.), 176-184. Taylor & Francis, . London

Geraldes, P., Echenique, M.H., Williams, I.N. (1978) A spatial economic model for Bilbao. In: *Proceedings of the PTRC Summer Annual Meeting*,75-94. PTRC, London

Goldner, W. (1971) The Lowry model heritage *Journal of the American Institute of Planners*, **37**, 100-110

Haag, G. (1990) Master equations. In: *Urban Dynamics. Designing an Integrated Model* (C,S. Bertuglia, G. Leonardi, A.G. Wilson, eds.), 69-83. Routledge, London/New York.

Hägerstrand T. (1968) *Innovation Diffusion as Spatial Process* University of Chicago Press, Chicago, IL

Hansen, W.G. (1959) How accessibility shapes land use *Journal of the American Institute of Planners*, **25**, 73-76

Harris, B. (1985) Urban simulation models in regional science *Journal of Regional Science*, **25**, 545-567

Harris, B. (1994) Science in planning: past, present, future *Journal of the American Planning Association*, **60**, 31-34

Hayashi, Y., Tomita, Y. (1989) A micro-analytic residential mobility model for assessing the effects of transport improvement. In: *Transport Policy, Management and Technology - Towards 2001*, Selected Proceedings of the Fifth World Conference on Transport Research, Yokohama, 91-105 Western Periodicals, Ventura, CA

Hensher, D., Ton, T. (2001) TRESIS: A transportation, land use and environmental strategy impact simulator for urban areas. Paper presented at the 8th World Conference on Transport Research, Seoul.

Hunt, J.D. (1994) Calibrating the Naples land-use and transport model. *Environment and Planning B: Planning and Design* **21**, 569-90

Hunt, J.D., Abraham, J.E. (2003) Design and application of the PECAS land use modelling system. Paper presented at the 8th International Conference on Computers in Urban Panning and Urban Management, Sendai, Japan.

Hunt J.D., Echenique, M.H. (1993) Experiences in the application of the MEPLAN framework for land use and transport interaction modeling. In: *Proceedings of the 4th National Conference on the Application of Transportation Planning Methods*, 723-754 Daytona Beach, FL

Hunt, J.D., Simmonds, D.C. (1993) Theory and application of an integrated land-use and transport modelling framework. *Environment and Planning B: Planning and Design*, **20**, 221-44

.

Hutchinson, B., Batty, M. (eds.) (1986) *Advances in Urban Systems Modeling* North Holland, Amsterdam

Hutchinson, B., Nijkamp, P., Batty, M. (eds.) (1985) *Optimization and Discrete Choice in Urban Systems* Springer, Berlin/Heidelberg/New York

Kain, J.F. (1987) Computer simulation models of urban location. In: *Handbook of Regional and Urban Economics* (E.S. Mills, ed.), Vol. II, 847-75. Elsevier, . Amsterdam

Kain, J.F. and Apgar, W.C. Jr. (1985) *Housing and Neighborhood Dynamics: A Simulation Study*Harvard University Press, Cambridge, MA

Kim, T.J. (1989) *Integrated Urban Systems Modeling: Theory and Applications* Kluwer, Dordrecht

Kreibich, V. (1979) Modelling car availability, modal split, and trip distribution by Monte Carlo simulation: a short way to integrated models *Transportation*, **8**, 153-166

Landis, J.D. (1992) *BASS II: A New Generation of Metropolitan Simulation Models.* Working Paper 573 Institute of Urban and Regional Development, University of California, Berkeley, CA

Landis, J.D. (1993) *CUF Model Simulation Results: Alternative Futures for the Greater Bay Area Region*. Working Paper 592 Institute of Urban and Regional Development, University of California, Berkeley, CA

Landis, J.D. (1994) The California Urban Futures Model: a new generation of metropolitan simulation models *Environment and Planning B: Planning and Design*, **21**, 399-422

Landis, J.D., Zhang, M. (1998a) The second generation of the California urban futures model. Part 1: Model logic and theory *Environment and Planning B: Planning and Design*, **25**, 657-666

Landis, J.D., Zhang, M. (1998b) The second generation of the California urban futures model. Part 2: Specification and calibration results of the land-use change submodel *Environment and Planning B: Planning and Design*, **25**, 795-824

Lowry, I.S. (1964) *A Model of Metropolis*. RM-4035-RC. Rand Corporation, Santa Monica, CA

LT, IRPUD, ME&P, MECSA, STRATEC, TRT, UCL (2002) *PROPOLIS (Planning and Research of Policies for Land Use and Transport for Increasing Urban Sustainability)*. http://www.ltcon.fi/propolis

Mackett, R.L. (1983) *The Leeds Integrated Land-Use Transport Model (LILT)*. Supplementary Report SR 805 Transport and Road Research Laboratory, Crowthorne, Berkshire

Mackett, R.L. (1985a) Integrated land use transport models *Transport Reviews*, **5**, 325-343

Mackett, R.L. (1985b) Micro-analytical simulation of locational and travel behaviour. In: *Proceedings of the PTRC Summer Annual Meeting, 175-188.* PTRC, London

Mackett, R.L. (1990a) *MASTER Model (Micro-Analytical Simulation of Transport, Employment and Residence)*. Report SR 237 Transport and Road Research Laboratory, . Crowthorne, Berkshire

Mackett, R.L. (1990b) Comparative analysis of modelling land-use transport interaction at the micro and macro levels. *Environment and Planning A*, **22**, 459-75

Mackett, R.L. (1990c) The systematic application of the LILT model to Dortmund, Leeds and Tokyo *Transport Reviews*, **10**, 323-38

Mackett, R.L. (1991a) A model-based analysis of transport and land-use policies for Tokyo *Transport Reviews*, **11**, 1-18

Mackett, R.L. (1991b) LILT and MEPLAN: a comparative analysis of land-use and transport policies for Leeds *Transport Reviews*, **11**, 131-54

Martinez, F.J. (1991) Transport investments and land values interaction: the case of Santiago City. In: *Proceedings of the PTRC Summer Annual Meeting*, 45-58. PTRC, London

Martinez, F.J. (1992a) Towards the 5-stage land-use transport model. In: *Land Use, Development and Globalisation*, Selected Proceedings of the Sixth World Conference on Transport Research, 79-90 Lyon, St.-Just-la-Pendue: Presse de l'Imprimerie Chirat

Martinez, F.J. (1992b) The bid-choice land-use model: an integrated economic framework *Environment and Planning A*, **24**, 871-85

Martinez, F.J. (1996) Analysis of urban environmental policies assisted by behavioural modelling. In: *Transport, Land Use and the Environment* (Y. Hayashi, J. Roy, eds.), 233-257. Kluwer, Dordrecht

Martinez, F.J. (1997a) Towards a microeconomic framework for travel behavior and land use interactions. Paper presented at the 8th Meeting of the International Association of Travel Behavior Research, Austin, TX.

Martinez, F.J. (1997b) *MUSSA: A Land Use Model for Santiago City* Department of Civil Engineering, University of Chile, Santiago

Martinez, F.J., Donoso, P.P. (1995) MUSSA model: the theoretical framework. In: *World Transport Research. Proceedings of the 7th World Conference on Transportation Research* (D.A. Hensher, J. King, eds.), Vol. 2. Pergamon, Oxford

Miller, E.J., Kriger, D.S., Hunt, J.D., Badoe, D.A. (1998) *Integrated Urban Models for Simulation of Transit and Land-Use Policies*. Final Report, TCRP Project H-12. Joint Program of Transportation, University of Toronto, Toronto

Miller, E.J., Salvini, P.A. (2001) The Integrated Land Use, Transportation, Environment (ILUTE) Microsimulation Modelling system: Description and current status. In: *The Leading Edge in Travel Behaviour Research* (D.A. Henscher, ed.), Selected Papers from the 9th International Association for Travel Behaviour Research Conference, Gold Coast, Queensland, Australia.

Miyamoto, K., Kitazume, K. (1989) A land-use model based on random utility/rent-bidding analysis (RURBAN). In: *Transport Policy, Management and Technology - Towards 2001*, Selected Proceedings of the Fifth World Conference on Transport Research, Yokohama, Vol. IV, 107-21. Western Periodicals, Ventura, CA

Miyamoto, K., Nakamura, H., Shimizu, E. (1986) A land use model based on disaggregate behavioral analyses In: *Proceedings of the Fourth World Conference on Transport Research*, 1535-50.

Miyamoto, K., Udomsri, R. (1996) An analysis system for integrated policy measures regarding land use, transport and the environment in a metropolis. In: *Transport, Land Use and the Environment* (Y. Hayashi, J. Roy, eds.), 259-280. Kluwer, Dordrecht

Nagel, K., Beckman, R.J., Barrett, C.L. (1999) *TRANSIMS for Transportation Planning*. LA-UR 98-4389. Los Alamos National Laboratory, Los Alamos, NM. http://transims.tsasa.lanl.gov/PDF_Files/LAUR98-4389.pdf

ODOT - Oregon Department of Transportation (2002) http://www.odot.state.or.us/tddtpau/modeling.html

Orcutt, G., Greenberger, M., Rivlin, A., Korbel, J. (1961) *Microanalysis of Socioeconomic Systems: A Simulation Study* Harper and Row, New York

Parsons Brinckerhoff Ohio and Hunt Analytics (1999) *Ohio Statewide Travel Demand Model Final Report* PID 17803. Ohio Department of Transportation Office of Technical Services, Columbus, OH

Pfaffenbichler, P.C., Shepherd, S.P. (2002) A dynamic model to appraise strategic land-use and transport policies. *European Journal of Transport and Infrastructure Research*, **2**, 255-283

Prastacos, P. (1986) An integrated land-use-transportation model for the San Francisco region. *Environment and Planning A*, **18**, 307-322 and 511-528

.

Putman, S.H. (1983) *Integrated Urban Models: Policy Analysis of Transportation and Land Use* Pion, London

Putman, S.H. (1991) *Integrated Urban Models 2. New Research and Applications of Optimization and Dynamics* Pion, London

Putman, S.H. (1998) Results from implementation of integrated transportation and land use models in metropolitan regions. In: *Network Infrastructure and the Urban Environment: Recent Advances in Land-Use/Transportation Modelling* (L. Lundqvist, L.-G. Mattsson, T.J. Kim, eds.), 268-287. Springer, Berlin/Heidelberg/New York

Rho, J.H., Kim, T.J. (1989) Solving a three-dimensional urban activity model of land use intensity and transport congestion *Journal of Regional Science*, **29**, 595-613

Salomon, I., Waddell, P., Wegener, M. (2002) Sustainable life styles? microsimulation of household formation, housing choice and travel behaviour. In: *Social Change and Sustainable Transport* (W.R. Black, P. Nijkamp, eds.), 125-131. Indiana University Press, Bloomington, IN

Simmonds, D.C., Still, B.G. (1998) DELTA/START: Adding land use analysis to integrated transport models. Paper presented at the 8th World Conference on Transport Research, Antwerpen.

Simmonds, D.C. (1999) The Design of the DELTA land-use modelling package *Environment and Planning B: Planning and Design*, **26**, 665-684.

Simmonds D (2001) The objectives and design of a new land-use modelling package: DELTA In: *Regional Science in Business* (G.P. Clarke, M. Madden, eds.), 159-188. Springer, Berlin/Heidelberg

Southworth, F. (1995) *A Technical Review of Urban Land Use-Transportation Models as Tools for Evaluating Vehicle Travel Reduction Strategies*. ORNL-6881. Oak Ridge National Laboratory, Oak Ridge, TN. http://tmip.fhwa.dot.gov/clearinghouse/docs/landuse/compendium/ornl_toc.stm

Waddell, P. (1998a) An urban simulation model for integrated policy analysis and planning: residential location and housing market components of UrbanSim. Paper presented at the 8th World Conference on Transport Research, Antwerpen.

Waddell, P. (1998b) UrbanSim Overview: http://urbansim.org.

Waddell, P. (2002) UrbanSim: Modeling urban development for land use, transportation and environmental planning *Journal of the American Planning Association*, **68**, 297-314

Waddell, P., Moore, T., Edwards, S. (1998) Exploiting parcel-level GIS for land use modeling. In: *Proceedings of the ASCE Conference on Transportation, Land Use and Air Quality: Making the Connection*. ASCE, Portland, OR

Webster, F.V., Bly, P.H., Paulley, N.J. (eds.) (1988) *Urban Land-Use and Transport Interaction: Policies and Models*. Report of the International Study Group on Land-Use/-Transport Interaction (ISGLUTI). Avebury, Aldershot

Webster, F.V., Paulley, N.J. (1990) An international study on land-use and transport interaction *Transport Reviews*, **10**, 287-322

Wegener, M. (1982a) A multilevel economic-demographic model for the Dortmund region *Sistemi Urbani*, **3**, 371-401

Wegener, M. (1982b) Modeling urban decline: a multilevel economic-demographic model of the Dortmund region *International Regional Science Review*, **7**, 21-41

Wegener, M. (1985) The Dortmund housing market model: A Monte Carlo simulation of a regional housing market. In: *Microeconomic Models of Housing Markets* (K. Stahl, ed.), Lecture Notes in Economic and Mathematical Systems 239, 144-191. Springer, Berlin/Heidelberg/New York

Wegener, M. (1986a) Transport network equilibrium and regional deconcentration *Environment and Planning A*, **18**, 437-56
Wegener, M. (1986b) Integrated forecasting models of urban and regional systems. In: *Integrated Analysis of Regional Systems* (P.W.J. Batey, M. Madden, eds.). London Papers in Regional Science 15, 9-24.
Wegener, M. (1987) Transport and location in integrated spatial models. In: *Transportation Planning in a Changing World* (P. Nijkamp, S. Reichman, eds.), 208-225. Gower, Aldershot
Wegener, M. (1994) Operational urban models: state of the art *Journal of the American Planning Association*, **60**, 17-29
Wegener, M. (1995) Current and future land use models. In: *Travel Model Improvement Program Land Use Modeling Conference Proceedings* (G.A. Shunk, P.L. Bass, C.A. Weatherby, L.J. Engelke, eds.), 13-40. US Department of Transportation, Washington, DC
Wegener, M. (1996) Reduction of CO_2 emissions of transport by reorganisation of urban activities. In: *Transport, Land Use and the Environment* (Y. Hayashi, J. Roy, eds.), 103-124. Kluwer, Dordrecht
Wegener, M. (1998a) Applied models of urban land use, transport and environment: state-of-the-art and future developments. In: *Network Infrastructure and the Urban Environment: Recent Advances in Land-Use/Transportation Modelling* (L. Lundqvist, L.-G. Mattsson, T.J. Kim, eds.), 245-267. Springer, Berlin/Heidelberg/New York
Wegener, M. (1998b) *The IRPUD Model: Overview*. http://irpud.raumplanung.uni-dortmund.de/irpud/pro/ mod/mod.htm
Wegener, M., Fürst, F. (1999) *Land-Use Transport Interaction: State of the Art*. Berichte aus dem Institut für Raumplanung 46. Institut für Raumplanung, Universität Dortmund, Dortmund. http://www.inro.tno.nl/ transland/Deliverable%202a.pdf.
Wegener, M., Gnad, F. and Vannahme, M. (1986) The time scale of urban change. In: *Advances in Urban Systems Modelling* (B. Hutchinson, M. Batty, eds.), 145-197. North Holland, Amsterdam
Wegener, M., Mackett, R.L., Simmonds, D.C. (1991) One city, three models: comparison of land-use/transport policy simulation models for Dortmund *Transport Reviews*, **11**, 107-29
Wegener, M., Spiekermann, K. (1996) The potential of microsimulation for urban models. In: *Microsimulation for Urban and Regional Policy Analysis* (G. Clarke, ed.), 146-163. European Research in Regional Science 6. Pion, London:
White, R., Engelen, G. (1994) Cellular dynamics and GIS: modelling spatial complexity *Geographical Systems*, **1**, 237-253
Williams, I.W. (1994) A model of London and the South East *Environment and Planning B: Planning and Design*, **21**, 535-53
Wilson, A.G. (1967) A statistical theory of spatial distribution models. *Transportation Research*, **1**, 253-69
Wilson, A.G. (1970) *Entropy in Urban and Regional Modelling*. Pion, London
Wilson, A.G. (1997) Land use/transport interaction models - past and future *Journal of Transport Economics and Policy*, **32**, 3-23