14 Applied Models of Urban Land Use, Transport and Environment: State of the Art and Future Developments

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14.1 Introduction

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

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

This new interest in land use models presents new challenges to land use modelling. A new generation of travel models such as activity-based travel demand models require more detailed information on household demographics and employment characteristics. New neighbourhood-scale transport planning policies to promote the use of public transport, walking and cycling require more detailed information on the precise location of activities. In addition, the models need to be able to predict not only economic but also environmental impacts of land-use and

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transport policies, and this requires small area forecasts of emissions from stationary and mobile sources as well as of immissions in terms of affected population.

Today there exist operational urban land-use/transport models that have the potential to respond to these challenges. There is a growing number of university laboratories, public agencies or private firms on five continents where research and development in urban and regional modelling is actively being conducted, and of urban/regional models of varying degrees of comprehensiveness and sophistication that have been and are being applied to real-life metropolitan regions for purposes of research and/or policy analysis. Rapid advances in information and computing technology have removed technical barriers besetting earlier generations of land-use/transport models. At the same time there exist exciting opportunities to incorporate new theoretical developments and methodologies into the field.

This chapter reviews the current state of the art of operational integrated urban models. In the first section an overview is given on existing land-use/transport (LT) models. The remaining sections explore how these models might be extended to become land-use/transport/environment (LTE) models and to what degree this has been achieved in pioneering modelling approaches.

14.2 Existing Land-Use/Transport Models

This section presents a brief overview on the state of the art in operational integrated urban land-use/transport models based on Wegener (1994). The term model is used here to indicate mathematical models implemented on a computer and designed to analyse and forecast the development of urban or regional land use systems. The models must be integrated, i.e. must incorporate the most essential processes of spatial development; this implies that they must include 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 must be operational in the sense that they have been implemented, calibrated and used for policy analysis for at least one metropolitan region.

The number of real-world applications of models falling under the above definition has increased steadily over the last decade. There 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) and Webster et al. (1988) and by reviews by Harris (1985), Wegener (1986b; 1987), Kain (1987), Boyce (1988), Berechman and Small (1988), Aoyama (1989), and Batty (1994), Harris (1994) and Wegener (1994).

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. Then fourteen contemporary operational urban models are compared using as criteria comprehensiveness, overall structure, theoretical foundations, modelling techniques, dynamics, data requirements, calibration and validation, and operationality and applicability. This section is an updated summary of more detailed information presented in Wegener (1994).

14.2.1 A Model of Urban Models

For the evaluation of operational urban models, an idealised urban model is first sketched out as a benchmark by which existing models are classified and evaluated. Eight types of major urban subsystem are distinguished. They are ordered by the speed by which they change, from very slow to very fast (cf. Wegener et al., 1986):

- *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 housing consumption and location to their changing needs; this determines the distribution of *population.*
- *Immediate change: goods transport, travel.* The location of human activities in space gives rise to a demand for spatial interaction in the form of *goods transport* or *travel*. These interactions are the most volatile phenomena of spatial urban development; they adjust in minutes or hours to changes in congestion or fluctuations in demand.

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.

14.2.2 Fourteen Urban Models

Fourteen models were selected for the comparison. The selection does not imply a judgement on the quality of the models, but was based on the availability of information. These are the fourteen models:

- *BOYCE*: the combined models of location and travel choice developed by Boyce (Boyce et al., 1983; 1985; Boyce, 1986; Boyce et al., 1992).
- *CUFM*: the California Urban Futures Model developed at the University of California at Berkeley (Landis, 1992; 1993; 1994).
- *MUS*: the '5-Stage Land-Use Transport Model' developed by Martinez for Santiago de Chile (1991; 1992a; 1992b).
- *HUDS*: the Harvard Urban Development Simulation developed by Kain and Apgar (1985).
- *IMREL*: the Integrated Model of Residential and Employment Location by Anderstig and Mattsson (1991; 1998).
- *IRPUD*: the model of the Dortmund region developed by Wegener (1985; 1986a; Wegener et al., 1991).
- *ITLUP*: the Integrated Transportation and Land Use Package developed by Putman (1983; 1991; 1998).
- *KIM*: the non-linear version of the urban equilibrium model developed by Kim (1989) and Rho and Kim (1989).
- *LILT*: the Leeds Integrated Land-Use/Transport model developed by Mackett (1983; 1990c; 1991a; 1991b).
- *MEPLAN*: the integrated modelling package developed by Marcial Echenique & Partners (Echenique et al., 1990; Hunt and Simmonds, 1993, Echenique, 1994; Williams, 1994; Hunt 1994).
- *METROSIM*: the microeconomic land-use and transport model developed by Anas (1992).
- *POLIS*: the Projective Optimization Land Use Information System developed by Prastacos for the Association of Bay Area Governments (Prastacos, 1986).
- *RURBAN*: the Random-Utility URBAN model developed by Miyamoto (Miyamoto et al., 1986; Miyamoto and Kitazume, 1989).
- *TRANUS*: the transport and land-use model developed by de la Barra (de la Barra et al., 1984; de la Barra, 1989; 1998).

These fourteen models are now compared with respect to the criteria listed above.

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

Model Structure. With respect to overall model structure, two groups can be distinguished. One group of models searches for a unifying principle for 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). Five of the fourteen models (BOYCE, MUS, KIM, METROSIM and RURBAN) belong to the unified category, the remaining nine 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).

Theory. In the last twenty 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), 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-maximizing model proposed by Wilson (1967; 1970); he thus laid the foundation for the convergence and general acceptability of formerly separate strands of theory.

Underneath that uniformity, however, there are significant differences between the theoretical foundations of the models. Eight models (MUS, HUDS, IMREL, KIM, MEPLAN, METROSIM, RURBAN and TRANUS) represent the land (or floorspace or housing) market with endogenous prices and market clearing in each period; one (IRPUD) has endogenous land and housing prices with delayed price adjustment. These models are indebted to microeconomic theory, in particular to Alonso's (1964) theory of urban land markets or bid-rent theory. The six models without market equilibrium rely on random utility maximisation; however, two of the microeconomic models (MUS and RURBAN) 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.

Only KIM and METROSIM determine a general equilibrium of transport and location with endogenous prices. The other models are equilibrium models of transport only (IRPUD, ITLUP), of transport and activity location separately

(IMREL, MEPLAN 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 (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.

Several other theoretical elements are built into some models. MEPLAN and TRANUS use export base theory to link population and non-basic employment to exogenous forecasts of export industries. HUDS, IRPUD and LILT 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.

Modelling Techniques. In all fourteen models, the urban region is represented as a set of discrete subareas or zones. Time is typically subdivided into discrete periods of between one and five years. This classifies all models except IMREL (which is static) as recursive simulation models.

In seven models (BOYCE, IMREL, KIM, LILT, MEPLAN, 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 ten models with network representation state-of-the-art modelling techniques are applied with network equilibrium the dominant trip assignment method despite its well-known weakness of collapsing to all-or-nothing assignment in the absence of congestion. Only ITLUP, MEPLAN and TRANUS have multiple-path assignment allowing for true route-choice dispersion.

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

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

Dynamics. All but one of the fourteen 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 most models, because the typical simulation period of five years has the effect of an implicit time lag – a too long time lag in most cases.

Data Requirements. The data collection for a model of a large metropolis has remained a major effort. However, in many cases the introduction of computers in local government has generated a pool of routinely collected and updated data that can be used as the information base for a model, in particular in the fields of population, housing, land use and 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 fourteen models of the sample have been (or could have been) calibrated using observed data, using readily available computer programs and following well-established methods and standards. In particular, maximum-likelihood estimation of the ubiquitous logit model has become routine. Yet, while calibration has become easier, the limits to calibrating a model with data of the past have become visible. Calibration of cross-sectional models, as it is practised today, provides the illusion of precision but does little to establish the credibility of models designed to look into the far future. There has been almost no progress in the methodology required to calibrate dynamic or quasi-dynamic models.

In the face of this dilemma, the insistence of some 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. There are only two models in the sample following this philosophy, IRPUD and MEPLAN. These models are partly calibrated not by statistical estimation, but by manual fine-tuning in a long, interactive process.

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

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

14.3 Modelling the Urban Environment

The new interest in land-use models has its origin in the imperative to make cities more sustainable. Therefore future urban models need to be able to model the urban environment.

Ecological modelling has been an established field of scientific work long before the present debate about environmental sustainability. Important pioneering insights into the nature of complex dynamic systems originated in ecology (Lotka, 1920; Volterra, 1931; see Nijkamp and Reggiani, 1992).

Urban modellers have for a long time ignored ecological aspects of the processes simulated in their models and have only recently been prompted to redirect their attention from economic to environmental impacts of land use and transport policies. The main reason for this is the threat of long-term climate change due to production of greenhouse gases by the burning of fossil fuels for heating and transport. A major additional thrust to include environmental impacts into urban models has come from the United States Intermodal Surface Transportation Efficiency Act (ISTEA) which shifts the criteria for new transport investment from travel time savings to environmental benefits such as air quality or reduction of single-occupancy vehicle trips. To demonstrate these benefits requires different models.

Therefore all over the world urban modellers are turning their attention to the urban environment. Existing land-use/transport (LT) models are being augmented by environmental submodels to become land-use/transport/environment (LTE) models. However, today there exist no full-scale urban LTE models. In this section it will be attempted to identify the environmental aspects a model deserving that name would have to contain.

For this the field 'urban environment' will be classified into sub-fields using criteria such as policy relevance, quantifiability, data availability, availability of theory and relationship with other submodels. Table 14.1 summarises the interactions among the sub-fields and between them and land use and transport.

In particular the relationship to land use and transport can be used to exclude environmental aspects which may be important in their own right but are only little

Table 14.1. Cross-impact matrix: land use, transport and environment

Cause \ *Effect*	Land use	Transport	*Resources*: Energy	Water	Land	Vegetation	Wildlife	Microclimate	*Emissions*: CO_2 emission	Air pollution	Water quality	Soil contamination	Solid waste	Noise	*Immissions*: Air dispersion	Noise propagation	Surface/ground water flows
Land use	●	●	●	●	●	●	●	●	●	●	○	●	○	●	●	●	●
Transport	●	●	●	·	●	*a*	*b*	*a*	●	●	○	○	·	●	●	●	○
Energy	○	○	●	·	·	·	·	*a*	●	●	·	·	·	·	●	·	·
Water	·	·	·	●	·	*c*	*c*	*c*	·	·	·	·	·	·	·	·	●
Land	●	·	·	●	●	●	●	●	·	·	·	·	·	·	·	○	●
Vegetation	○	·	·	○	·	●	●	●	●	·	·	·	·	·	·	●	·
Wildlife	·	·	·	·	·	·	●	·	·	·	·	·	·	·	·	·	·
Microclimate	○	·	·	·	·	○	○	●	·	·	·	·	·	·	·	·	·
CO_2 emission	·	·	·	·	·	·	·	·	●	·	·	·	·	·	·	·	·
Air pollution	*d*	·	·	·	·	*d*	*d*	●	·	●	*d*	·	·	·	●	·	*d*
Water quality	*c*	·	·	●	·	●	●	·	·	·	●	·	·	·	·	·	●
Soil contamination	●	·	·	·	●	●	●	·	·	·	·	●	·	·	·	·	·
Solid waste	○	·	·	○	○	·	·	·	·	·	·	●	●	·	·	·	●
Noise	*e*	·	·	·	·	·	*e*	·	·	·	·	·	·	●	·	●	·
Air dispersion	●	·	·	·	·	●	○	●	·	·	○	○	·	·	●	·	○
Noise propagation	●	·	·	·	·	·	●	·	·	·	·	·	·	·	·	●	·
Surface/ground water flows	·	·	·	●	·	●	●	●	·	·	·	·	·	·	·	·	●

· *no impact* ○ *weak impact* ● *strong impact*
a via air dispersion and land consumption
b via air dispersion, noise propagation and land consumption
c via surface/ground water flows
d via air dispersion
e via noise propagation

affected by the processes dealt with in the models from the analysis. It is useful to remember that the models discussed here are intended for forecasting the impacts of land use and transport policies. Therefore only those environmental impacts are relevant for them which result from changes in the spatial distribution of activities. For instance, the sewerage system and efficient waste water treatment are important for a sustainable city; however, while the cost of the sewerage system depends on the topography and physical layout of the city, the cost of the treatment plant probably does not. In Table 14.1 urban environmental impacts are classified under the headings of *resources*, *emissions* and *immissions*.

14.3.1 Resources

Most human activities consume resources. Some of them are global resources which are brought into the region such as energy, some are local resources such as water. Sustainable development aims at using non-renewable resources as little as possible in the interest of future generations. From the point of view of urban modelling the most important resources are energy, water and land:

- *Energy*. Energy is a global resource which is imported to the urban region in the form of non-renewable fossil fuel or electricity. Renewable kinds of energy such as solar or wind energy presently play a minimum role. Energy is consumed for process heat, for the heating of buildings and for transport. Energy use for heating is affected by type of building and density. Transport energy consumption is affected by modal choice, number and length of trips, travel speed, vehicle occupancy and energy efficiency of vehicles. Choice of building type and density as well as travel and shipping behaviour are influenced by energy cost, however, today this effect is diluted by underpriced fuel. Energy consumption of land use and transport are therefore candidates for being included in urban models; the relationships to be modelled are straightforward.
- *Water*. Water cannot be easily transported over great distances and is therefore consumed close to the source. Modern agriculture, manufacturing techniques and life styles all tend to higher water consumption. Water supply has therefore become a serious problem for many cities. There is a relationship between urban density and water consumption as suburban gardens and swimming pools tend to consume large quantities of water. There is no significant effect of urban transport on water consumption. However, both land use and transport affect water supply by sealing off land through buildings, pavings and roadways and so impeding rainfall from reaching the ground water. Because of this higher urban densities with smaller land coverage and less roads are environmentally preferable over disperse suburbs with one-storey buildings and a high percentage of paved road area. The effects of ground coverage on ground water supply can be modelled; so can the effect of policies to reduce water consumption by utilisation of rainfall.
- *Land*. Land is the ultimate resource of cities. With growing affluence and increasing substitution of (renewable) human labour by (non-renewable) mechanical energy, all human activities, from housing, manufacturing and services to transport

tend to consume more land. The amount of open space in and around cities is therefore continuously declining. This not only reduces ground water supply (see above) but has also negative effects on vegetation, wildlife and microclimate. Research on the impact of size, shape and interconnectedness of open spaces on the variety of plant and animal species and the microclimate in adjacent areas is still underway, but there are sufficient results available to include these effects in urban models.

14.3.2 Emissions

Most human activities give rise to metabolisms producing obnoxious emissions. Emissions are produced locally but have local, remote and global effects. From the point of view of urban modelling the most important emissions are gases, waste water, soil contamination, solid waste and noise:

- *Gases.* Most gaseous emissions originate from chemical or combustion processes in stationary or mobile sources. In cities stationary sources are chemical or manufacturing plants, power stations and residential areas; mobile sources are cars, lorries and buses. Pollutants such as CO, NO_x, HC, SO_2 and dust particles affect the well-being of humans at points of immission, whereas CO_2 is a greenhouse gas with global effects. It is therefore sufficient to predict CO_2 emissions for the whole urban region irrespective of where they occur, whereas for other pollutants air dispersion models calculating immissions from emissions are required (see below). To predict the magnitude and composition of industrial emissions requires information about the type and quantity of processes and the efficacy of emission abatement technology. Reasonable assumptions about the emissions by residential heating given a certain level of insulation and heating technology are possible. Gaseous emissions of cars are a well researched field; it is possible to predict them as a function of link traffic volumes, composition of flow, vehicle duty cycles and prevailing emission abatement technology with any desired detail. However, fuel consumption and emission characteristics of commercial vehicles still need more attention.
- *Water quality.* The amount of waste water produced in a city is a function of water consumption (see above), rainfall and irrigation; however, reasonable assumptions about waste water per capita or per worker by industry can be made. As indicated above, the amount of ground coverage through buildings and pavements affects the volume of rain water in the sewerage system and hence the required capacity of water treatment plants. Urban density affects the length and cost of sewerage networks. Intensive use of fertilisers or untreated industrial or domestic effluents lead to the degradation of ground water or streams and rivers and to the degeneration of aquatic habitats. However there is no causal relationship between type of land use or density and water quality. Therefore water quality is not a likely topic of urban models. Urban transport contributes to water pollution by oil and particles washed from roadways. This effect can be modelled, but is not likely to be significant compared with other sources of water contamination.

- *Soil.* Soil contamination through chemicals and obnoxious liquids by former manufacturing or extraction activities is a serious problem in old industrial or mining regions, but should soon become a thing of the past through stricter enforcement of emission standards. However, existing contamination can be a strong deterrent for potential residential or industrial investors.
- *Solid waste.* The generation of solid waste is not a function of land use type or density or urban transport, but of manufacturing and packaging technologies and personal life styles and recycling legislation. Solid waste disposal generates traffic and requires land for disposal sites or incineration plants and so affects urban transport and land use. These effects might be modelled but are likely to be relatively insignificant compared with those of other urban activities. Faulty disposal sites may be the cause of soil contamination, and incineration plants are suspected to emit dioxin, but these effects are not caused by land use or transport and are therefore not likely to be considered in urban models.
- *Noise.* Like air pollution, noise is emitted from stationary and mobile sources. Fixed sources are industrial processes and construction sites, mobile sources are vehicles. Noise from stationary sources (except construction sites) has been reduced by encapsulation of machinery and physical separation between industry and residences. Traffic noise, in contrast, is increasing and has become the most obnoxious and ubiquitous kind of emission in cities. Like industrial air pollution, industrial noise is difficult to predict without information about the processes at work. Traffic noise can be simulated as a function of traffic volume, composition of flow and speed. Noise propagation declines rapidly with distance, so calculation of noise emissions without calculation of noise immissions is not sufficient (see below).

14.3.3 Immissions

Air pollution, noise and water contamination are environmental impacts of which emission and immission points differ. As their effect is felt at immission points, calculation of immissions from emissions is critical for these kinds of impacts. Three types of emission-to-immission models are candidates for being included in urban models:

- *Air dispersion.* Air pollution can be carried over long distances, as the phenomenon of acid rain thousands of kilometres from the emission source has demonstrated. Also photochemical ozone-generating processes are known to occur far away from emission sources. Within urban areas air streams are important not only for the dispersal of pollutants but also as carriers of cool air from the countryside or mountains in the summer. Air dispersion models calculate immissions from emissions as a function of location and elevation of sources, topography and prevailing wind direction and speed. The use of these models can suggest which parts of the urban area should be left undeveloped as cold air ventilation corridors.
- *Noise propagation.* For the assessment of noise intrusion it is necessary to know the number of people affected by different noise levels. There exist several

methods of calculating noise immissions from simple distance buffers around point or line sources to sophisticated sound propagation models taking account of multiple reflection of noise from roadways, topography, buildings and the effects of sound protection measures such as protective dams or walls. The latter methods, however, require spatially disaggregate information on topography, built form and distribution of population.

– *Surface/ground water flows*. Hydrological modelling includes surface water models such as rainfall-runoff or streamflow simulation models and groundwater models such as groundwater flow and groundwater contamination transport models. Hydrological modelling is a complex field requiring extensive information on rainfall probability, land cover and the geological formation and the river system of the urban region. However, with imminent depletion of water resources in many cities, this type of model may become more prominent in the future. Rainwater management policies designed to reduce water consumption and sewerage volumes require site-specific information on roof areas and ground coverage and appropriately spatially disaggregate models.

14.4 Implications for LTE Models

Modelling the urban environment in integrated urban models presents new challenges as new subsystems with different dynamics and spatial resolution need to be incorporated into the models.

14.4.1 Dynamics

Most operational urban land-use/transport models are quasi-dynamic in the sense that their transport or land-use submodels or both are cross-sectional equilibrium models. In addition they have relatively long simulation periods of five or more years. The rationale behind this is that adjustment processes in urban areas are slow.

Environmental processes, however, have a different time scale. Some processes such as air dispersion and noise propagation are very rapid and can be dealt with in cross-sectional submodels. However, some processes such as the impacts of development on water supply, vegetation, wildlife and water quality have very long response times between several years and one or more generations.

The problems arising from this for the temporal organisation of the models may be fundamental. The longer time perspective necessary for environmental analysis is likely to make equilibrium approaches less appropriate and to favour dynamic approaches allowing for a variety of different speeds of adjustment in different parts of the modelled system.

14.4.2 Spatial Resolution

Urban models have always been spatially aggregate with zones of varying size such as boroughs or statistical districts as units of spatial reference. As the internal distribution of activities and land uses within a zone is not known, a homogenous distribution across the area of the zones has to be assumed. However, even though the number of zones of some models has increased substantially in recent years, the spatial resolution of zone-based models is much too coarse to appropriately deal with environmental processes. In particular emission-immission algorithms such as air dispersion, noise propagation and surface and ground water flows, but also microclimate analysis, require a much higher spatial resolution:

- Air distribution models typically work with raster data of emission sources and topographic features such as elevation and surface characteristics such as green space, built-up area, high-rise buildings and the like.
- Noise propagation models require spatially disaggregate information on emission sources, topography and sound barriers such as dams, walls or buildings as well as the three-dimensional location of population.
- Surface and ground water flow models require spatially disaggregate data on the river system and geological information on ground water conditions in the region.
- Microclimate analysis depends on small-scale mapping of green spaces and built-up areas and their features.

In all four cases the information needed is configurational. This implies that not only the attributes of the components of the modelled system such as quantity or cost are of interest but also their physical location. This suggests a fundamentally new organisation of data of urban models.

A data organisation in which topological and other attributes of spatial systems are integrated is called a geographic information system (GIS). Geographic information systems, in particular raster-based GIS, therefore promise to have great importance for future integrated urban models. The tendency away from zonal to spatially disaggregate raster-based data structures suggested by environmental modelling is not only in line with the enormously increased memory and computing capacity of modern computers but also conforms with the trend to disaggregate activity-based models in urban transport planning and the current revival of microsimulation approaches in urban modelling (Wegener and Spiekermann, 1996).

14.5 LTE Models: A Survey

Because the increased attention of urban modellers for environmental aspects is a relatively recent phenomenon, it is difficult to get an overview of the state of the art in this rapidly developing field. Therefore a quick, ad-hoc mini survey among some of the authors of urban models was conducted. The survey does not attempt to provide a comprehensive inventory of urban LTE models existing in the world today. It can be assumed that in the United States under the impression of the

ISTEA legislation numerous new modelling activities are being launched by local governments of all sizes. However, the modellers surveyed belong to the small group of researchers who have developed operational urban land-use/transport models, so it is likely that they represent the forefront of urban LTE modelling.

Altogether 24 models or model versions were named as LTE models by their authors. Some of them have not yet been published, so no reference can be given; in some cases the references refer to the original models and not to their yet unpublished environmental extensions. The 24 models are, in alphabetical order, ARCTRAN-AIR (Kim et al.), CODMA (Lundqvist, 1989; 1996; 1998), IMREL (Anderstig and Mattsson, 1991; 1998), IRPUD (Wegener, 1996), ITLUP (Putman, 1983; 1991; 1998), LAND (Gu et al., 1992; Young and Gu, 1993; 1996), LET (Anjomani), LILT (Mackett, 1983; 1990b; 1990c; 1991a; 1991b), MAPLE (Hayashi and Tomita, 1989), MASTER (Mackett, 1990a), MEPLAN Edmonton (Hunt), MEPLAN Helsinki/London/Santiago/Vicenza (Echenique et al., 1990; Hunt and Simmonds, 1993, Echenique, 1994; Williams, 1994; Hunt, 1994), MOUSE (Diappi et al.), MUS (Martinez, 1996), PSS (Anjomani), RURBAN (Miyamoto and Udomsri, 1996), SALOC (Lundqvist, 1996; 1998), START/DSCMOD (Simmonds, 1995), SUSTAIN (Roy et al., 1996; 1998), TRANUS (de la Barra et al., 1984; de la Barra, 1989; 1998), TRANUS/CUFM (by de la Barra and Landis, adapted by Johnston).

Table 14.2 summarises the main results of the survey. It shows the environmental indicators presently being calculated in urban models or being considered for inclusion in the near future. There are clear priorities. Of the 24 models included in the survey fifteen calculate (or are considering to calculate) land consumption, as might be expected from land use models. Sixteen models calculate (or plan to calculate) energy consumption and CO_2 emission of transport. Air pollution of transport is modelled by thirteen models. All other indicators are listed much less frequently. Energy consumption and CO_2 emissions and air pollution of land use are considered by only seven models. Surprisingly, only four models calculate traffic noise. Only between one and three models deal with water supply, vegetation, wildlife, microclimate, waste water, soil contamination, solid waste and industrial noise. Only seven models have (or will shortly have) an air dispersion submodel. Other immissions are almost absent in present LTE models. Only one model deals with noise propagation and two with surface and ground water flows. Another question asked in the survey was whether the environmental indicators are calculated only as output for later exogenous evaluation or are fed back into the land use or transport parts of the models. The purpose was to find out whether the models recognise a two-way relationship between land use and environment, and transport and environment, respectively, in the same way as they take account of the two-way interdependency between land use and transport.

A look at the cross-impact matrix of Table 14.1 shows that in the real world the relationships between the environment and land use and transport are not symmetric. Land use and transport affect almost all environmental indicators but the reverse is not the case. Only land use changes, i.e. location decisions by

Table 14.2. Environmental impacts modelled by urban LTE models

	Resources							*Emissions*									*Immissions*		
Models *(Authors)*	Energy consumption by land use	Energy consumption by transport	Water supply	Land consumption	Vegetation	Wildlife	Microclimate	CO_2 emission by land use	CO_2 emission by transport	Air pollution by land use	Air pollution by transport	Water quality	Soil contamination	Solid waste	Industrial noise	Traffic noise	Air dispersion	Noise propagation	Surface/ground water flows
ARCTRAN-AIR	·	·	·	·	·	·	·	●	●	●	●	·	·	·	·	·	●	·	·
CODMA	·	·	·	·	·	·	·	·	●	·	●	·	·	·	·	●	●	·	·
IMREL	.	●	·	○	·	·	·	.	●	.	○	·	·	·	·	.	·	·	·
IRPUD	·	●	·	●	·	·	·	·	●	·	·	·	·	·	·	·	·	·	·
ITLUP	·	·	·	●	·	·	·	·	*a*	·	*a*	·	·	·	·	·	·	·	·
LAND	·	·	·	·	·	·	·	·	·	·	●	·	·	·	·	●	·	·	·
LET	·	●	●	●	●	○	·	·	·	·	·	·	●	·	·	·	·	·	·
LILT	·	●	·	●	·	·	·	·	·	·	·	·	·	·	·	·	·	·	·
MAPLE	·	●	·	·	·	·	·	·	●	●	·	·	·	·	·	○	○	·	·
MASTER	·	·	·	●	·	·	·	·	·	·	·	·	·	·	·	·	·	·	·
MEPLAN Edmonton	○	●	·	●	·	·	·	○	●	○	○	·	·	·	·	·	·	·	·
MEPLAN Helsinki	·	●	·	●	·	·	·	·	·	·	·	·	·	·	·	·	·	·	·
MEPLAN London	·	●	·	●	·	·	·	·	●	·	●	·	·	·	·	·	·	·	·
MEPLAN Santiago	·	●	●	●	●	·	·	·	●	·	●	·	·	·	·	·	·	·	·
MEPLAN Vicenza	·	●	·	·	·	·	·	·	●	·	●	·	·	·	·	·	●	·	·
MOUSE	○	●	·	●	·	·	·	○	●	·	·	·	·	·	·	·	○	○	·
MUS	●	●	·	·	·	·	·	●	●	●	●	·	·	·	·	·	●	·	·
PSS	·	·	●	●	●	○	·	·	·	·	·	·	●	·	·	·	·	·	·
RURBAN	●	·	·	·	·	·	·	○	·	·	·	●	·	●	·	·	●	·	●
SALOC	●	●	·	●	·	·	·	·	·	·	·	·	·	·	·	·	·	·	·
START/DSCMOD	·	●	·	·	·	·	·	·	●	·	·	·	·	·	·	·	·	·	·
SUSTAIN	·	○	·	●	·	·	·	·	○	·	○	·	·	·	·	·	·	·	·
TRANUS	●	●	·	●	·	·	·	○	○	○	○	·	·		○	○	·	·	·
TRANUS/CUFM	●	●	·	·	·	○	○	○	○	○	○	○	·		·	·	·	·	○

· not modelled ○ *under development or planned* ● *applied or operational*
a links to standard EPA emission models (MOBIL5)

firms and households, are strongly affected by land availability, soil contamination, air pollution and noise; all other feedbacks from the environment are weak or potentially strong only in the case of a major change in the decision framework such as a substantial change in energy cost. Transport decisions are not affected by environmental indicators at all, except potentially by rising fuel costs. Nevertheless, as a minimum, feedback from environment to land use, i.e. the impact of environmental indicators on location decisions, should be included in any LTE model. However, in only 10 of the 24 models environmental indicators enter the attractiveness functions of land use location decisions. In two models transport decisions are affected by environmental indicators, mainly by energy cost. Changes in trip generation through changes in location of activities listed as feedback from environment to transport by one author are in fact indirect via land use. Policies to reduce energy consumption and CO_2 emissions by transport planning can also not be counted as endogenous feedback.

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

14.6 Conclusions

This paper has been an attempt to review the current state of the art of operational land-use/transport models in the light of the new challenges presented by the environmental debate. It has been shown that there have been immense achievements in land use and transport modelling during the last two decades. There exist operational land use and transport models which have been and are being used for real-life applications in cities all over the world. There is a growing number of active urban modelling centres on five continents in which new approaches are being developed and tested.

However, the review has also exposed deficiencies of current models. Many land-use/transport models are still too aggregate in space, time and substance for state-of-the-art environmental modelling. Most zone-based land-use/transport models lack the spatial resolution, required for modelling environmental impacts such as air dispersion or noise propagation, and surface and ground water flows. Some models have remained captive in the tradition of cross-sectional equilibrium poorly suited to cope with the complex temporal structure of environmental processes. Because of the limited number of environmental aspects addressed, only few current models qualify as full-scale land-use/transport/environment (LTE) models, though efforts to incorporate more environmental indicators in the models are increasing. Only very few models have yet implemented feedback from environment to land use.

These deficiencies suggest the agenda for modelling research in the next decade to make future land-use/transport models more responsive to environmental issues:

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

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

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

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

Finally, more efforts will be necessary to make land-use/transport/environment models a routine tool for a widening range of institutions and individuals, including non-experts. This must be supported by the development of attractive and efficient user interfaces for interactive model calibration, scenario formulation and inspection of results. The Windows-based user shell of TRANUS, Young's gaming simulation LAND (Gu et al., 1992; Young and Gu, 1993; 1996) and Batty's GIS-based model visualisation system (Batty, 1992) are leading the way in this direction.

The greatest challenge, however, seems to keep urban modelling open for new problems. Urban models have in the past been applied mainly to a very narrow set of planning problems, and have repeatedly failed to adapt to changing problem perceptions. The next decade will confront cities and regions in the developed world with complex new problems. Increasing social and spatial inequity, an ageing infrastructure and the need to significantly reduce energy consumption and CO_2 emission will require innovative solutions if social conflict is to be avoided. Only if the models prove that they are able to give meaningful answers to the urgent questions facing cities and regions can they establish for themselves a firm position in the planning process of the future.

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