Urban models for transportation and spatial planning

State-of-the-art and Future Challenges

October 2012

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Introduction

Urban transport is essential for citizens to perform their daily activities, but at the same time constitutes one of the major sources of urban pollution (GHG emissions, local air quality, noise), directly affecting citizens' health and well-being. Urban traffic produces 40% of CO_2 emissions and 70% of emissions of other pollutants (CO, NO_x, SO_x, particulate matter) produced by road traffic [Com07]. Traffic accidents are also increasing, with two thirds of the accidents and one third of the victims taking place in cities. The quest for environmentally sustainable urban transport, while ensuring competitiveness and addressing social concerns such as health problems or the needs of persons with reduced mobility, is a common and urgent challenge for all major cities in Europe.

Policy context

The European Commission's first policy proposal in the area of urban mobility launched a series of initiatives based upon a best practice approach [Com95]. The Commission's 2001 White Paper on Transport [Com01] aspired to change the direction of EU transport policy to deal with the increasing challenges of congestion, noise, pollution, and accidents, largely caused by excessive use of the private car. The White Paper aimed to break the link between transport and economic growth by urging a shift towards more sustainable transport modes and promoting the modernisation of public transport. With the continued rise in transport demand, the Commission's mid-term review of the White Paper [Com06] shifted the focus from curbing overall transport growth to decoupling transport growth from its negative effects, and emphasised the concept of comodality. The Green Paper Towards a New Culture for Urban Mobility [Com07] opened a broad consultation on the key issues of urban mobility. Following the consultation results, the European Commission Action Plan on Urban Mobility [Com09] proposed twenty measures to encourage and help local, regional, and national authorities in achieving their goals for sustainable urban mobility. With the Action Plan, the European Commission presents for the first time a comprehensive support package in the field of urban mobility.

Urban models for transportation and spatial planning

To tackle the challenge of sustainable urban mobility, urban planners need models, decision support tools, and input data allowing the assessment of policies and their resulting effects. Cities have been treated as systems for several decades, but only recently has the approach changed from aggregate equilibrium systems to complex, evolving systems of systems. Different types of urban models have been developed, from the static and aggregate land use-transportation interaction (LUTI) models first developed in the 1960s, to recent, bottom-up, activity-based microsimulation models which seek to represent cities in more disaggregate and heterogeneous terms [Bat76, Bat07, Hep12].

In recent years, quantitative models for transportation and spatial planning have received a renewed attention. Urban development along the last two centuries has been driven by an increasing mobility of people and goods facilitated by relatively cheap energy. The growth of urban areas, the increasing concerns about sustainable development, and the challenges posed by energy scarcity and climate change, raise new questions such as the influence of higher transport costs on mobility and location (e.g. will distances to workplaces, shops, services and leisure be reduced?) or the impact of new policies (e.g. promotion of more

efficient vehicles, transport demand management, anti-sprawl legislation) aiming at fostering a more sustainable mobility and location behaviour [Weg10]. In parallel, the emergence of new social media and electronic communications is leading to profound changes in social relationships, which is in turn modifying location and mobility patterns in cities. This new landscape makes it necessary to develop new models, tools, and methodologies enabling city governments and their citizens to design sustainable mobility policies.

Urban models serve various purposes. First, models help achieve an enhanced understanding of urban dynamics (in an explanatory role). Second, they enable virtual experimentation allowing the prediction of the impact of new infrastructures, technologies, or policies (in a predictive role). Finally, models are powerful tools to facilitate participatory processes for collaborative decision making (in policy and design roles). Despite significant effort carried out in the last two decades, urban models still require progress along several axes to fully satisfy these three objectives, and ultimately to support the assessment of urban mobility policies in terms of a comprehensive set of economic, social, and environmental sustainability indicators. Further research is needed in three main directions:

1. **Data collection**. Urban modelling is a data-intensive task. The development and validation of improved models critically relies on the availability of data. Despite significant progress in this area in recent years, the EC acknowledges that there are still big gaps in urban mobility statistics at the EU level [Com07], and that urban modelling research can greatly benefit from additional international effort in standardising, collecting, and sharing data. Data collection efforts have traditionally been focused on trip data (origin-destination, travel time, mode, etc.), but there is still a lack of appropriate data especially on non-motorised modes and on factors determining mobility behaviour, such as attitudes and lifestyle. There is also a need for further progress in the development of standard definitions, indicators, and data collection methods allowing comparative studies of urban transport planning throughout Europe [Eur07].

2. **Theoretical research**. In October 2007, the FP6-funded Coordination Action 'European Research Forum for Urban Mobility' (EURFORUM) presented a 'Strategic Research Agenda' for urban mobility [Eur07], highlighting a number of areas where further research is needed, from both the demand and supply perspective. On the transport demand side, many questions are still open, such as the social determinants of mobility behaviour, i.e. norms, social perception, age and demographic, personal security, or comfort; the activity patterns underlying human travel behaviour; the impact of information campaigns on user behaviour; the social acceptance of transport systems and mobility policies; the expectations that transport systems have to meet to be accepted and successful without inducing new travel needs; or the relationship between land use and transport demand. As for the transport supply side, research must be undertaken to investigate the potential of technology to supply integrated mobility services and transport systems. Particularly interesting are questions such as the impact of ICT-based services on the interaction between demand and supply; new services with the potential to improve urban mobility; the integration of transport systems and intermodality; or the alternatives to private, fossil fuel-based car such as electric and hybrid.

3. **Link between modellers, decision makers, and societal actors**. The use of system models in policy making and planning is very heterogeneous. Many cities do not use any quantitative models at all; among the cities using simulation models, traditional LUTI models are still the most applied [Bat76, Bat08]. The use of more advanced, state-of-the-art models—particularly of agent-based models—for policy-making purposes is still scarce, and in many cases the potential users do not have the skills to use such models or are not convinced of the benefits. To bridge this gap, the development of the models needs to be user-driven and account for the requirements of the policy makers [Bra08]. The use of system models in a policy decision context will only be successful if the development of these tools is accompanied by user-model interaction methodologies and procedures facilitating a smooth integration into the decision-making processes.

Smart cities: opportunities for improved planning and decision-making

The term 'smart city' has become widely spread in the last few years. While more technocentric concepts, such as 'digital cities', are built around ICT infrastructures, the concept of smart city—even if still not clearly delimited—is now generally understood as a holistic concept encompassing not only the use of modern technology (including modern transport or energy technologies, in addition to ICT), but also the investment in human, social, and environmental capital, to create sustainable development and high quality of life. Giffinger et al. [Gif07] define a smart city as a city performing well along six main axes or dimensions: smart economy, smart mobility, smart environment, smart people, smart living, and smart governance.

Though the smart city concept goes beyond ICT, it is clear that ICT remains a key element to enable sustainable urban development. When it comes to urban models and policy support tools, the increased penetration of ICT, the rise of the Big Data movement, and the emergent concept of smart cities open new opportunities to make progress in the three directions previously identified:

1. Modern ICT, such as smart phones, e-transactions, Internet social networks, or smart card technologies, allow the **automatic collection of spatial and temporal movement data** that can complement and enhance the data collected by using traditional methods (census data, travel surveys). Yet, the collected data have to be analysed, making it necessary to develop new data mining techniques in order to obtain useful knowledge about urban mobility patterns and improve our understanding of cities.

2. This improved understanding can in turn inform the modelling of the mechanisms behind observed mobility patterns, helping develop **new theory and better models** for the quantitative assessment of different scenarios and policy options.

3. Finally, ICT opens the door to the development of new tools which can help capture the inputs from societal actors (e.g. algorithms for reconstructing citizens' opinion from data resources distributed throughout the Internet), support an **increased participation of citizens** (e.g. through applications that allow citizens to monitor and report the system status in real time), and enable collaborative, multi-stakeholder policy assessment and decision making processes.

Spatial analysis of mobility patterns. The explosion of available data

For many networks, such as transportation systems, power grids, the Internet, or neural networks, space is relevant: their nodes are located in space and there is usually a cost associated with the length of the links. Such networks can be termed as 'spatial networks' and have specific properties due to the physical constraints existing in these systems [Bar11]. In particular, their degree distribution is peaked, clustering is large, the assortativity spectrum is flat, and the betweenness centrality of a node is not only a function of its degree, but it also depends on its geographical location.

The use of data obtained from online and mobile devices to better characterise human behaviour has recently been the focus of a lot of attention from the complex systems research community, and has been dubbed as one of the most promising venues for the development of quantitative approaches to social sciences in the XXI century [Wat07, Laz09, Ves09]. In the field of mobility and transport, the recent explosion of data availability on individual movement at all scales has triggered the emergence of studies on mobility networks, allowing a better understanding of the statistics of individuals movements, opening new directions for mobility modelling, and providing new insights into individual behaviour in the social, urban context. Mobility networks describe the statistics of movements of individuals between various locations. A simple way to formalise this problem is to divide the area of interest in different zones and to count the number of individuals going from one location to another. These flows constitute the origin-destination (OD) matrix, which is at the core of many transportation models and whose properties have been discussed in a large number of papers [Bar11]. The OD matrix describes a network, directed and weighted, and in the general case is time-dependent. These matrices are usually extremely difficult and costly to measure, and it is only recently, thanks to technological advances such as the GPS or the democratisation of mobile phones together with geosocial applications, that we can obtain precise measurements on large data sets, opening the door to an improved quantitative understanding of urban movements.

The first works focused on the traces left by the dollar bills registered by the "Where's George?" project site (http://www.wheresgeorge.com). The different cities, counties, and states where the same bill was recorded were used as a proxy for human mobility [Bro06] and also to evaluate the possible pathways of propagation of infectious diseases [Huf04].

Calls from cell phones are another source of mobility data. In large urban areas, the density of antennas for mobile phone network base stations is large enough so that triangulation gives a relatively accurate indication of the users' location (mobile phones are regularly in contact with the base station; triangulation allows to determine the location of the device at a resolution that depends on the local density of base stations). Mobile phone data has recently been used to detail individual trajectories [Aha05], to identify 'anchor points' where individuals spend most of their time [Aas08, Eag09, Son10b], or statistics of trip patterns [Onn07, Lam08, Gon08, Wan09, Kri09, Sev10, Que10, Sim11]. In [Gon08], González et al. used a set of mobile phone data at a national level and found that the distribution of displacement of all users can be fitted by a Levy law with an exponent of order 1.7. In a recent paper [Son10a], Song et al. propose a model of human mobility in order to reproduce this power law, and suggest that the dominant mechanisms of individual movements are based on the facts that the tendency to explore additional locations decreases with time and that there is a large probability of returning to a location visited previously.

GPS is another interesting tool in order to characterise individual trajectories. In [Baz10, Ram07], GPS data of private vehicles for the city of Florence (Italy) were used to show that the total daily length trip is exponentially distributed and seems to be independent of the structure of road network, pointing to the possible existence of more general principles governing human movements [Koe03].

At an intra-urban scale and even at the scale of social networks, Radio Frequency IDentification (RFID) might provide interesting insights. This technology is usually composed of a tag which can interact with a transceiver that processes all information contained in the tag. RFIDs are used in many different instances, from tagging goods or dynamical measures of social networks [Cat10], to the Oyster card system in London, which provides information about instantaneous flows of individuals in the subway system. These individual trajectories were analysed [Rot11], displaying evidence for a polycentric organisation of activity in this urban area. It was also found that the traffic is broadly distributed, in agreement with many other transportation networks, but also that the displacement length distribution is peaked.

Similarly to other electronic data, the information coming from interactions in online social networks can be used to understand the characteristics of user mobility and how factors such as distance can affect the relation between individuals. Online social media have received relatively less attention because it has been only recently that some of the most popular online social networks, e.g. Twitter, have included detailed geolocation for the origin of the messages interchanged by the users. However, an item that was systematically requested at new user registration is the city of residence. This is the information on which the first works on the relation between geographical distance and online relations were based, like [Lib05]. Later works in the area have also analysed the mobility patterns and features of the trajectories of the users of Twitter [Sce10, Kin11], FourSquare [Che11, Nou11, Sce11], or Facebook [Bac10]. Other works have also explored the connection between distances to acquaintances and mobility [Cho11], the probability of having a friendship given the distance between two users [Cra10], or the relation between belonging to social groups (communities) in the networks and distance [Onn11]. Online social networks show thus a high potential to study geolocation together with social interactions between the users [Gra11].

Urban simulation models

Urban models are mathematical representations of the 'real world'—typically implemented through computational simulation tools—that describe, explain, and forecast the behaviour and complex interactions between different elements of the urban system. As far as urban mobility is concerned, one can distinguish between transport-only models and land use-transport interaction (LUTI) models. Transport-only models require land-use inputs which are forecast exogenously, whereas LUTI models generate their own forecasts of land-use as a function of land-use policies and changes in the transport system.

Travel demand models

Trip-based and tour-based models

The need for travel demand models was recognised by urban and transport planners and researchers as early as the mid-19th century, with the development of the first macroeconomic models of the spatial flows of people and goods, such as the one proposed in [Car59]. For about a century, transport planners relied on various aggregate trip-based models, such as gravity-based models. The 1950s saw the development of a sequential process of estimating travel demand, known as the urban transportation modelling system (UTMS) or four-stage model. The process starts with the definition of the study area, which is typically divided into a number of zones, whose attributes are the levels of population and zonal activity (e.g. households, population, employment, shopping space, educational, and leisure facilities). The classic UTMS model comprises a sequence of four sub-models:

1. Trip generation. The trip generation model estimates the number of trips with origin or destination in each zone as a function of zonal activity.
2. Trip distribution. Trips by zone of origin are allocated to destination zones using trip distribution models, e.g. gravity models in which the trip flow for a given origin-destination (OD) pair is positively influenced by levels of activity contained in the two zones, and negatively influenced by the zone-to-zone impedance (travel time and/or cost). The output of the trip distribution model is an OD matrix which defines the number of trips from each zone to every other zone.
3. Modal split. Trips are allocated to different transportation modes based on modal and traveller attributes, e.g. by using some sort of factoring or more formally through a discrete choice model.
4. Route assignment. Each trip between an origin and destination by a particular mode is assigned to a route, e.g. by using equilibrium route assignment models. If the network is capacitated and congestion occurs, travel costs are changed and the four-step process is repeated until equilibrium occurs.

The simple four-step models of the 1950s and the 1960s have evolved greatly over the past 50 years, with diverse advances that have led to an increasing sophistication of individual stages and inter-stage feedback, such as the development of discrete choice methods based on utility maximisation [McF81], or the work in the field of deterministic (DUE) [War52] or stochastic (SUE) [Dag77] user equilibrium route assignment models. Advances in modelling techniques resulted in a shift towards more disaggregated trip-based models, which consider the individual (or household or firm) as the decision-making unit, thus taking into account the effects of individual characteristics on travel-related choices. A detailed discussion of the UTMS and the variety of modelling approaches to the different stages can be found in [Ort11]. A serious limitation of trip-based models is that they do not consider the linkages between trips. Tour-based models partially address this limitation by adopting the tour (or trip-chain) as modelling unit. Tour-based models typically

divide individual travel into home-based tours and non-home based trips, so they still neglect linkages between trips forming part of non-home based tours, as well as linkages between different tours [Siv07].

Trip-based and tour-based four-stage models remain the dominant framework for operational transportation planning and policy analysis. Four-step models perform reasonably well in representing and forecasting aggregate travel demand. However, as the problems under study become more disaggregated, they face several limitations. The fundamental weakness is that they are not based on a coherent theory of travel behaviour, and therefore are not suitable to capture travellers' responses to measures influencing travel behaviour, such as demand management policies. Also, they are essentially static in that they represent travel over a particular time period with a single state. As a consequence of these weaknesses, they fail to adequately represent aspects such as the time of day chosen for travel, e.g. time shifting in response to congestion or mobility pricing. For a discussion of these limitations, see e.g. [TRB07].

Activity-based models

In the 1970s and early 1980s, the work of different researchers [Hag70, Cha74, Jon83] set the basis for a paradigm shift in travel demand modelling, with the development of the activity-based approach, as a solution to the shortcomings of the trip and tour-based approaches. The main idea behind activity-based models is that the travel needs of an individual are driven by the desire or need to participate in activities at different locations, thus shifting the focus from the analysis of flows to the understanding of travel decisions. Activity-based models simulate the activities of individuals during a typical period of travel, often the working day or even over the entire week, with the time-budgets of travellers dictating the mode and means of travel, and accounting for various sequences of trips which bind together the activities undertaken during the day.

As opposed to the four-step approach, activity-based models include a consistent representation of time, a detailed representation of persons and households, time-dependent routing, and microsimulation of travel demand and traffic. Comprehensive activity-travel schedules contain information on what activities are performed, where, when and for how long, and which travel modes and routes are used for the trips between the activities. The differences between trip/tour-based and activity-based models are described in detail in [Bha03]. In comparison with the four-step model, the activity-based approach allows for a more realistic modelling of travel decisions. It provides an improved capability to model non-work and non-peak travel, to move beyond traditional explanatory variables (i.e. zone-based socio-economics, travel time and cost), and to deal with the effects of household interaction, lifestyle, etc. on travel behaviour [Fei09], making it possible to model trip chaining, car sharing, or interdependencies between household members.

Examples of state-of-the-art activity-based travel demand models are MATSim (www.matsim.org) and TRANSIMS (www.anl.gov/TRACC/Computing_Resources/transims.html).

Integrated land use-transport models

In parallel to the development of the four-step transportation model, urban planners began to recognise the complex interactions between the transport network and the rest of the urban system. Indeed, land use and transportation systems are closely intertwined: land use patterns influence travel needs, mobility patterns, and the evolution of transportation infrastructure; and the transportation system, in turn, influences where people engage in activities and how urban form changes.

Land use models intend to predict future changes in land use, socio-economic, and demographic data, based on economic theories and social behaviours. The term land use-transport interaction (LUTI) model describes

a model which brings together urban form and travel analysis[1]. LUTI models are also referred to as integrated land use-transport models or, more simply, as integrated urban models.

The first integrated mathematical models of urban land use and transport appeared in the United States in the early 1960s. Many of these early efforts failed in their goals due to technical restrictions: data collection, calibration and validation difficulties, and insufficient computing power [Weg10]. Additionally, there were also serious drawbacks in the conception of the models, which were essentially static and suffered from an excessive spatial aggregation [Siv07]. In 1973, Lee published a paper entitled Requiem for Large Scale Models [Lee73] where he pointed out the 'seven deadly sins' of large-scale models: hypercomprehensiveness, grossness, hungriness, wrongheadedness, complicatedness, mechanicalness, and expensiveness. After a near total abandonment in the 1970s and the 1980s, the 1990s and the 2000s brought a new boom in urban modelling research, boosted by the appearance of Geographical Information Systems (GIS) and simultaneous advances such as parallel computing, data mining, or agent-based modelling. The dominant trend has evolved towards disaggregation of population and employment groups by various socio-economic attributes, and there has been a shift towards bottom-up approaches (activity-based and agent-based models) relying on data of single households and their members, together with their daily activities and the resulting transportation needs, thus merging to an extent with the activity-based travel models described in the previous section. At the same time, other classes of land use models that we will not detail here have been developed based on physical evolution of locational patterns and morphologies in cities, in particular cellular automata models and various more ad hoc agent-based models of particular urban sectors such as residential location, housing markets, or retail choice [Bat08, Hep12]. The evolution of urban modelling suggests that the field is not converging to a unified modelling approach, but to the coexistence of a variety of models.

LUTI models can be classified into the following broad categories:

- **Spatial interaction (Lowry-type) models**. The first of these models to gain notice was Lowry's model of Metropolis in 1964 [Low64]. Spatial interaction models estimate flows between locations as a function proportional to the size and attraction of origins and destinations, and inversely proportional to the travel time and/or cost, as in the gravity model underlying many travel demand models. Inversely, population is concentrated in areas with high accessibility to employment, and employment is concentrated in areas with high accessibility to population. The land use model provides population and employment distributions based on assumed travel impedances to the travel model, which calculates updated impedances to be fed back into the land use model; the loop is iterated until reaching equilibrium. A widely use spatial interaction LUTI model is DRAM/EMPAL [Put95].

- **Spatial input-output models**. Spatial input-output models account for producers and consumers of goods and services and their interactions. Households are included as both producers and consumers: they supply labour to employers (resulting in work trips) and consume goods and services (resulting e.g. in shopping trips). Land is considered a non-transportable production factor. Production factors are allocated to zones according to zonal production costs (including land prices) and travel impedances to zones of consumption. Land prices are determined endogenously through an iterative procedure which aligns land demand (elastic to price) with land supply. Examples of models of this type are MEPLAN [Ech90], TRANUS [Bar05], and PECAS [Hun03].

- **Microeconomic-based, computable general equilibrium (CGE) models**. They have their roots in Alonso's bid-choice land use model [Alo64], which assumes that firms or households are willing to pay

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[1] The term LUTI model is sometimes used interchangeably with land use model. This is potentially confusing because, within the group of land use models, the degree of integration with travel demand models varies considerably. Some include, or are fully integrated with, transportation models, while others incorporate transportation-related measures in a much more indirect, static manner.

higher rents if they report larger benefits in terms of production and transport cost balance [Alo64]. Firms or households bid for space up to a maximum value, trying to maximise the difference between their willingness to pay and the rent they actually pay; and landlords rent to the highest bidder. The model assumes a static equilibrium in which supply equals demand. The land use model is typically connected with a four-stage travel model. An example of this type of model is MUSSA [Mar96].

- **Agent-based microsimulation models**. Microsimulation models of land use are activity-based models with the individual (or household, firm, or any other agent in the urban system) as the unit of analysis. They integrate naturally with agent-based transport models, allowing the exploration and simulation of the behaviour of urban systems at an extremely fine level of detail and fidelity. Activity patterns are modelled from the bottom up, generating emergent spatial and temporal patterns at more aggregate levels. Examples of models in this category are UrbanSim [Wad03], ILUTE [Sal05], or ILUMASS [Str05].

- **'Sketch' models**. With the development of web 2.0 technologies, there is also a parallel move to building simpler, faster, more visually accessible desktop tools. These tools are based on 'lightweight', less data-intensive and/or less theory-rich approaches (e.g. rule-based / GIS-based tools) and aim to support rapid scenario analysis, visualisation, and community engagement using state-of-the-art interactive graphics embedded in web-based interfaces. A review of this kind of tools, such as CUF, UPlan, Index, Community Viz, PLACE3S, or MetroQuest, can be found in [Con09].

Challenges and opportunities

Despite the close interrelationship between land use and transportation, and the profound effects of such interaction on quality of life and the environment, in most urban areas of the world land use and transportation have historically been planned separately. Urban transportation planning has been the most active application area of simulation models, while land use planning has to a large extent been based on qualitative considerations and urban planners' experience, with computational land use models being used to a lesser degree than in transportation planning.

Though transportation-only models are still widely used, the situation has progressively changed along the last two decades, and there is an increasing awareness about the importance of an integrated planning approach. This increasing awareness has even begun to influence legislation, such as the State of California SB 375 bill passed in 2008 [Cal08], which explicitly requires integration of planning processes for transportation, land-use, and housing. However, there is still a sense among practitioners that integrated land use-transportation models are immature with respect to institutional integration and operational policy decision support [Bra08, Koc09]. According to a recent survey of U.S. metropolitan planning organisations (MPOs) with more than 200,000 residents [Lee10], a few MPOs (7%) do not use any kind of modelling tool; 46% use transport-only models; and the remaining 47% use transport and land use models, though only 27% carries out an integrated planning. There have been various surveys in a European context, but the focus has been much less on models, and more on the use of ICT in planning agencies. This betrays the fact that most planning agencies are not engaged with the use of LUTI or related urban models in their policy deliberations.

Depending on the size of the urban area and the available skills at the local level, standard four-stage models including logit choice of mode and destination choice are commonly employed [Ort11, TRB07]. About 90% of the transportation demand models currently in use, either in an isolated manner or combined with land use models, are variations of the traditional four-step model; TRANSCAD, VISUM, and CUBE are the tools most widely spread. These models seem to satisfy the demands of the local and regional political processes, even if implemented less than optimally from a technical viewpoint [TRB07]. At the same time, agent-based models are finding increasing application in regions with more complex planning issues (New York, NY; Portland, OR; San Francisco, CA or now Los Angeles, CA). In these advanced regions, generally land use models are also considered or actively in use. In addition, agent-based models are the rule for fine-grained and spatially detailed models of traffic flow and traffic operations. Here a range of commercial software are available and in widespread use (e.g. VISSIM, PARAMICS, or AIMSUN, among others). The agent-based models of travel demand are generally one-off implementations (with the exception of MATSim), in most cases delivered by research groups. This lack of professional support is holding many cities and regions back.

Land use-transport models are in the same situation, i.e. between research and commercial software. The tool for integrated land use-transport planning most widely spread is UrbanSim, followed by commercially supported tools such as DRAM/EMPAL, DELTA, or MEPLAN. UrbanSim is probably the most advanced of the 'research tools', and its agent-based approach makes it a natural match to agent-based transport models.

Theoretical challenges

Activity-based microsimulation captures the interactions between land use and transport systems to the greatest extent possible, and represents the most advanced approach to land use and transport modelling. Although the state-of-the-art is fairly advanced, there are several areas where further research is needed:

- **Generation of artificial agent population**. Activity-based models require more detailed information about population demographics than is usually available from surveys or census data [TRB07]. The lack of easy tools to generate the artificial agent-population is an obstacle for their implementation. Current progress is lowering that hurdle, and 'population synthesisers' are being developed so that available data can be used to extrapolate synthetic populations that are statistically equivalent to actual populations. A review of current population synthesis tools can be found in [Mul11].

- **Generation of comprehensive all day activity-travel schedules**. The combinatorial size of the solution space for the schedule of an individual increases dramatically with the level of detail allowed for the agents' choice sets (number of activities, activity types, time intervals, location, tour/sub-tour/trip mode choice, etc.). As a consequence, modellers are usually forced to reduce the number of choice dimensions or the number of alternatives within each dimension. At the same time, the problem of multimodal choice and multipurpose trips remains a crucial issue which increases the complexity of travel decisions: new transport solutions become available, and intermodality (e.g. park & ride) is being promoted as a promising approach to solve today's mobility problems; people not only merge different purposes in single or multistage trips, but also use different modes.

  Scheduling in activity-based modelling follows three major lines of research: econometric models, which use systems of equations to capture relationships among attributes [Bha04] and tend to be difficult to operationalise [Joh04]; utility-based microsimulation, which applies a sequential decision making process and employs heuristic methods to search for a solution; and computational process models (CPMs), which replace the utility maximising framework by open-ended approaches based on behavioural principles of information acquisition and context-dependent decision making, typically through 'if-then' rules. Despite promising approaches such as the concept of schedule recycling, which significantly reduces the runtimes of utility-based microsimulations [Fei09], or the open-ended approach proposed in [Mar11], further research is still needed to deal with the huge magnitude of the solution space achieving acceptable computational costs without sacrificing behavioural validity.

- **Influence of social contacts on travel decisions**. Travel behaviour is nearly always modelled as a set of independent decisions across travellers. This approach provides satisfactory results for regularly-scheduled or very inelastic activities, like work trips, but ignores the fact that intra- and extra-household interactions play a key role in many other trips and activities (e.g. leisure trips) that are planned jointly and/or depend on the trips and activities of the social contacts. The concept of a 'full individual daily pattern', which constitutes the core of the original activity-based approach, needs to be expanded to account for the influence of the social network.

  Recent research has begun to develop the theoretical foundations to incorporate the social context into activity-based models [Axh07] and to model the mechanisms for information sharing—both face-to-face and through ICT—and coordination of activities in time and space [Hac09, Car09]. A key issue is incorporating realistic geographic social networks into agent-based models, which makes it necessary to characterise the form and statistical properties of the underlying social structures and the strengths of their influences. Empirical survey work [Axh08, Kow11, Ill11] needs to be expanded. In parallel, the analysis of new data sources, such as online social networks, can help improve the understanding of the interdependencies and co-evolution of the social networks and the activity-travel patterns.

- **Joint resource use**. Households and groups of friends, relatives, and acquaintances share resources, such as cars or bicycles. Existing models claim to reproduce such processes, e.g. being a car passenger, but do not verify that the vehicle and its driver are physically available for the specific trip. To overcome this deficiency, activity-travel models need to be enhanced to account for the availability of shared resources, as well as for interdependence between the decisions leading to the joint use.

- **Scalability, multiscale aspects, and granularity**. Urban dynamics exhibits multiple spatial and temporal scales. The increasing level of disaggregation and sophistication of microsimulation models comes at the expense of large amounts of computational resources and serious implications for the calibration, validation, and application of the models, e.g. the need to reduce the number of sensitivity tests to check the plausibility of model behaviour. The identification of the time horizons and spatial resolutions relevant for the analysis of different phenomena is still a very active research area, and the question of the right level of disaggregation remains open [Wad09]. In a recent paper [Weg09], Wegener calls for a 'theory of multi-level models', according to which for each question under investigation there is an appropriate level of conceptual, spatial, and temporal resolution.

Practical challenges

The transfer of models developed in an academic environment, where theoretical foundations receive the highest priority, to an operational, policy-making context, raises also practical and methodological issues that need to be addressed [Wad11]:

- **Data availability and quality**. Microsimulation models require a lot of input data to specify, calibrate, and validate them. Data requirements are not always met, which hinders their operational use. While the situation is still not optimal, GIS is being integrated with many models, and large scale systems are being developed for new data sources, opening promising venues: Open Data government initiatives, Open Street map, GSM traces, self-tracing apps employing GPS-enabled smart phones, etc.

- **Professional support**. The fact that most tools are still in a research and development phase and the lack of professional support is another barrier, especially for medium-sized cities with typically limited in-house capabilities. This situation is beginning to change, and agent-based models are being professionalised in collaboration with various software houses, e.g. the MATSim-VISUM interface recently created by PTV AG and senozon AG.

- **Transparency and ease of use**. Models will not have credibility in complex, controversial domains such as land use, transportation, and environmental planning, unless it can be explained in relatively simple terms what the models are doing, and why. The term 'black box' has often been used to criticise the lack of transparency. Models must also achieve a threshold of usability that makes it possible for staff within planning agencies to use them without excessive support.

  Although there are rapid developments in making urban simulation models more visual and in scaling them down to use in the policy context [Bra08], many sketch planning tools provide simplicity at the cost of sacrificing theoretical soundness and validity. Progress is still needed to conciliate transparency and ease of use with the necessary sophistication required for a realistic modelling of a system as complex as the city.

- **Flexibility**. Because of the continuous progress in theory, data collection, computational performance, or user-model interfaces, as well as of the fact that different users have different data and needs, modularity, adaptability, and scalability are mandatory requirements for a model to be widely used.

- **Uncertainty**. Complex systems are characterised by large—partly irreducible, partly unquantifiable—uncertainties. Policy modelling requires a comprehensive treatment of uncertainty; answers to policy questions can often only be given in probabilistic terms. However, uncertainty is a concept that has only recently come into the lexicon of policy makers, and it is still difficult to communicate.

- **Conflicting stakeholders and methodologies**. Sustainable urban development requires coordinated action in different areas (land use, transportation, environment). These policy areas are subject to distributed, multi-level decision processes—from infrastructures and regulation depending on local authorities, to national and European directives—and have a profound impact on a wide variety of stakeholders. Assessing these policies in terms of a comprehensive set of meaningful indicators and in relation to a set of shared objectives is a challenging task, which requires a continuous involvement of stakeholders [Wim11]. The increasingly widespread use of the design charrette in urban planning illustrates one response to this complexity [Kwa08]. A charrette can be defined as a policy formulation event that brings together diverse stakeholders to produce sustainable policies through collaborative interaction [Con07]. The theory underpinning charrettes is that sustainability requires a holistic integration of all relevant dimensions in a collaborative and interdisciplinary setting [Con09]. Recent practical experiences in some major European cities, such as the Madrid Mobility Round Table [Luc10, Luc11], have shown the potential of collaborative processes to increase the quality of policy evaluation and reach consensus on mobility policies. However, these processes are still based to a large extent on qualitative considerations and expert judgement. The challenge is to integrate state-of-the-art simulation tools in a form that fluidly intersects the multi-stakeholder decision-making process [Con09], bridging the gap between implicit and explicit knowledge [Bro10].

The EUNOIA project

The overall goal of the EUNOIA project is to take advantage of the opportunities brought by smart city technologies and the most recent advances in complex systems science to develop new urban models and ICT tools empowering city governments and their citizens to design better mobility policies.

The specific objectives of the project are the following:

- to investigate how new data available in the context of smart cities can be exploited to understand mobility and location patterns in cities;
- to characterise and compare mobility and location patterns in different European cities;
- to improve the understanding of the interdependencies between social networks and travel behaviour;
- to enhance urban land use and transportation models, by integrating the role of the social network and new models of joint trips and joint resource use into state-of-the-art agent-based models;
- to develop useful policy interfaces and appropriate methodological procedures for the use of simulation tools in multi-stakeholder, collaborative assessment of urban transport policies;
- to apply the new models and methodologies to several case studies of interest for policy makers.

Approach

Data

EUNOIA will analyse different sets of heterogeneous data, including traditional data sources—such as census data or travel surveys—as well as new data sources available through smart technologies.

Data from traditional well-proven sources will be accessible online or available upon request, such as population, employment, land uses, housing census data, or travel surveys. EUNOIA will rely on the direct involvement of the municipal authorities of Barcelona, London, and Zurich, which will support the project by providing additional data.

Data from Internet social networks (e.g. Twitter geolocated data, Foursquare, locational data from Flickr) will be also retrieved and mined. Internet social networks enclose a lot of information about activity-travel behaviour that can inform the modelling of travel decisions and trip purposes, as well as the interrelationship between the spatial distribution of social network and the mobility patterns.

The EUNOIA Consortium has reached an agreement with Banco Bilbao Vizcaya Argentaria, S.A. (BBVA) to analyse data on credit card payments in Barcelona. BBVA is the second largest bank in Spain and one of the biggest financial institutions in Europe. The Consortium has also reached an agreement with Telefónica, the biggest Spanish telecommunication company and one of the largest telecommunication companies in the world, to analyse data on mobile phone records for Barcelona. The data from BBVA and Telefónica will be anonymised and managed under the necessary precautions to protect their confidentiality.

The previous data will be complemented with two surveys specifically designed for the purpose of the project, which will be run in Barcelona as a joint survey: a survey on the spatial spread of the members of egocentric social networks, the frequency of contacts, and the modes chosen for them (egocentric survey); and a life course survey which will address the question of to what extent life style and mobility habits are passed on or modified from generation to generation. The egocentric survey and the life course survey will

be respectively similar to the ones documented in [Axh08, Kow11] and in [Bei11] for Zurich, which will allow the comparison of the two cities.

Characterisation of mobility patterns in different types of cities around the world

The data sets described above will be mined with a view to discern general and local basic features of urban mobility patterns, such as the existence and organisation of centres of activity in the cities. To extract useful knowledge from the data, EUNOIA will make use of standard statistical analysis and data mining methods, as well as new spatial analysis methods recently developed in the context of network theory [Bar11]. The study will be focused on the three cities that participate in the project: Barcelona, London, and Zurich. This will allow a wide comparative analysis of urban mobility patterns in cities with very different geographical, structural, political, institutional, socio-economic, and cultural characteristics.

Interaction between social networks and travel behaviour

Social interactions are of crucial importance for realistic modelling of travel decisions. The results of the egocentric surveys (the one run in Barcelona, as well as previous surveys such as the ones already available for Zurich) will be combined with the analysis of Internet social networks to extract new knowledge about the spatial spread of social contacts and the influence of social interactions on activity-travel behaviour. EUNOIA will investigate aspects that are still not well reproduced by existing transportation models, such as the influence of the social network on the planning of joint trips (mainly leisure trips, but also other joint trips, such as car pooling to go to work, or group day care trips for elderly people) and joint resource use; peer influence on travel behaviour; the changes in mobility induced by the changes in social relationships brought about by new ICT technologies (e.g. telecommuting); or the influence of the transport network on the spatial and topological features of the social network and the way social networks co-evolve with the activity-travel patterns of the individuals.

Improvement of urban transportation models

The analysis of urban mobility patterns in different types of city and their relation to the spatial structure and socio-economic characteristics, as well as the conclusions about the interrelationship between social networks and mobility patterns, will be the basis for the formulation, calibration, and testing of new models of location and travel behaviour. The new models will be integrated into comprehensive, state-of-the-art urban simulation tools. Tools currently being used and developed by Consortium members, in particular MATSim (http://www.matsim.org/), which originates from IVT and is also being developed for London by CASA, will be enhanced by plugging in the models developed by the project. The project will also link the patterns of travel acquired from the data analysis to SIMULACRA (http://www.simulacra.casa.ucl.ac.uk/), a more aggregate model of London developed by CASA. The new models will be later on validated against other data sets and evaluated through three case studies carried out in collaboration with the cities of London, Zurich, and Barcelona.

Policy interfaces and methodological procedures for collaborative assessment of urban transport policies

EUNOIA will aim at involving policy makers and other social stakeholders in the development of the models from its initial stages, with the purpose of reinforcing the credibility and usability of the model and fostering the application of state-of-the art transport models in policy decision contexts.

The project will identify the key stakeholders for urban mobility policy modelling (policy makers, interest groups, citizens' associations, etc.) and will carry out a consultation to identify the current practices and needs in different cities around the world. The consultation will help elicit stakeholders' expectations and requirements for collaborative generation of scenarios and policy options.

The analysis of stakeholders' expectations will be used to derive requirements for ICT tools enabling stakeholders' collaboration in policy assessment, in particular for the development of user-friendly analysis tools allowing interaction with the policy simulation results. This will include the development of visual interactive interfaces and data representations facilitating analytical reasoning.

These requirements will be refined in the specific context of the Barcelona case study. We will define a methodology for collaborative assessment of mobility policies supported by the demonstrative simulation and visualisation tools developed by EUNOIA. The proposed methodology will aim at the active participation of the policy makers and the main mobility stakeholders, and will be implemented and tested in close collaboration with the Barcelona City Council, through several workshops and policy formulation events. Experience of similar stakeholder involvement processes for location problems in which CASA is involved for the GLA in London will be available for comparison.

Case studies

The models and methodologies developed by EUNOIA will be iteratively evaluated, refined, and validated through three case studies conducted in cooperation with the cities of London, Zurich, and Barcelona. The case studies will be selected during project execution. Some examples of potentially interesting questions identified during proposal preparation are: mobility pricing (road tolls, parking, public transport), such as congestion charging in central London; policies to increase the attraction of urban hubs and activity centres (e.g. traffic calming), with a view to foster a polycentric urban structure with more sustainable mobility patterns; optimisation of new, emergent transport services around the idea of providing common access to resources at a lower cost and in a more energy-efficient manner, e.g. optimisation of the location of public bikes, optimisation of car sharing locations and fleet sizes, etc.; optimisation of the location of the charging infrastructure for electric vehicles; demand-side management policies to foster a sustainable use of electric vehicles; interactions between aging, migration, and travel behaviour, including intergenerational aspects.

Target outcomes

The EUNOIA project will deliver the following results:

- Improved methods and tools for collecting and mining urban data relevant for the study of mobility and location patterns in cities.
- Improved understanding of the factors determining mobility and location patterns in cities with different characteristics, focusing on the analysis of three exemplar cases: London, Zurich, and Barcelona.
- New theoretical models of the influences of social networks on travel behaviour.
- Improved urban simulation tools, which will enhance state-of-the-art microsimulation urban models by implementing the new theoretical models developed by the project, as well as innovative, user-friendly visual analytics tools.
- A methodology for the use of urban modelling tools in collaborative policy assessment processes involving policy makers and communities of stakeholders.
- An evaluation of the models, tools, and methodologies through their application to three case studies tackling relevant policy questions in the cities of London, Zurich, and Barcelona.

References

[Aas08]   Aasa A., Jarv O., Saluveer E., Slim S., and Ahas R. (2008). Methodology of determination of the anchor points based on passive mobile positioning database. Social Positioning Method (SPM) 2008.

[Aha05]   Ahas R., Mark U., Aasa A., and Kalle H. (2005). Mapping human behavior in Tallinn. In Litjens, A. et al., Tallinn, pp 222-233. TU Delft.

[Alo64]   Alonso W. (1964). Location and land use. Harvard University Press, Cambridge, MA.

[Are11]   Arentze T.A., Kowald M., and Axhausen K.W. (2011). A method to model population-wide social networks for large scale activity-travel micro-simulation. Arbeitsberichte Verkehrs- und Raumplanung, 698, IVT, ETH Zürich, Zurich.

[Axh07]   Axhausen K.W., Larsen J., and Urry J. (2007). Network society and networked traveller. Arbeitsberichte Verkehrs- und Raumplanung, 435, IVT, ETH Zürich, Zürich.

[Axh08]   Axhausen K.W. and Frei A. (2008). Contacts in a shrunken world. 86th Annual Meeting of the Transportation Research Board, Washington, D.C., January 2008.

[Axh11]   Axhausen K.W. (2011). Computational challenges for integrated micro-simulation models. Arbeitsbericht Verkehrs- und Raumplanung, 719, IVT, ETH Zürich, Zurich.

[Bac10]   Backstrom L., Sun E., and Marlow C. (2010). Find me if you can: Improving geographical prediction with social and spatial proximity. Proceedings of WWW 2010.

[Bar05]   de la Barra T. (2005). Integrated Land Use and Transport Modelling. Cambridge University Press, Cambridge.

[Bar11]   Barthélemy M. (2011). Spatial Networks. Physics Reports.

[Bat76]   Batty M. (1976, reissued 2009). Urban Modelling: Algorithms, Calibrations, Predictions. Cambridge University Press, Cambridge, UK.

[Bat07]   Batty M. (2007). Cities and Complexity: Understanding Cities with Cellular Automata, Agent-Based Models, and Fractals. The MIT Press, Cambridge, MA.

[Bat08]   Batty M. (2008). Urban Modeling. In R. Kitchin and N. Thrift (Eds) International Encyclopedia of Human Geography, Volume 12, Elsevier, Oxford, 51–58.

[Baz10]   Bazzani A., Giorgini B., Rambaldi S., Gallotti R., and Giovannini L. (2010). Statistical laws in urban mobility from microscopic GPS data in the area of Florence. Journal of Statistical Mechanics: Theory and Experiment P05001.

[Bei11]   Beige, S. and Axhausen, K.W. (2011). Interdependencies between turning points in life and long-term mobility decisions. IVT, ETH Zürich, Zurich.

[Bha03]   Bhat C.R., Guo J., Srinivasan S., and Sivakumar A. (2003). Guidebook on Activity-Based Travel Demand Modeling for Planners. Product 4080-P3, Texas Department of Transportation, October 2003.

[Bha04] Bhat C. R., Guo J.Y., Srinivasan S. and Sivakumar A. (2004). A comprehensive econometric microsimulator for daily activity-travel patterns. Transportation Research Record, 1894, 57-66.

[Bra08] Brail R. K. (Editor) (2008). Planning Support Systems for Cities and Regions. Lincoln Institute of Land Policy, Cambridge, MA.

[Bro06] Brockmann D., Hufnagel L., and Geisel T. (2006). The scaling laws of human traveling. Nature 439:462-465.

[Bro10] te Brömmelstroet M. and Bertolini L. (2010). Integrating land use and transport knowledge in strategy-making. Transportation, 37(1), pp. 85–104.

[Cal08] California State Senate. Senate Bill (SB) 375.

[Car59] Carey, H.C. (1859). Principles of Social Science. Philadelphia: J.B. Lippincott Company.

[Car09] Carrasco J.A. and Miller E.J. (2009). The social dimension in action: A multilevel, personal networks model of social activity frequency between individuals. Transportation Research Part A, Vol. 43, Iss. 1, pp 90–104.

[Cat10] Cattuto C., Van den Broeck W., Barrat A., Colizza V., Pinton J.-F., and Vespignani A. (2010). Dynamics of person-to-person interactions from distributed RFID sensor networks. PLoS ONE 5(7): e11596.

[Cha74] Chapin F.S. (1974). Human Activity Patterns in the City. Wiley and Sons, New York.

[Che11] Cheng Z., CaverleeJ., Lee K., and Sui D.Z. (2011). Exploring millions of footprints in location sharing services. Proceedings of ICWSM 2011.

[Cho11] Cho E., Mayers S.A., and Leskovec J. (2011). Friendship and mobility: User movement in location-based social networks. Proceedings of KDD 2011.

[Com95] Commission of the European Communities (1995). Green Paper 'The Citizens' Network - Fulfilling the potential of public passenger transport in Europe'. Communication COM(95) 601 Final, November 1995.

[Com01] Commission of the European Communities (2011). White Paper 'European transport policy for 2010: time to decide'. Communication COM(2001) 370 Final, September 2001.

[Com06] Commission of the European Communities (2006). Keep Europe moving - Sustainable mobility for our continent. Mid-term review of the European Commission's 2001 Transport White Paper. Communication COM(2006) 314 Final, June 2006.

[Com07] Commission of the European Communities (2007). Green Paper 'Towards a new culture for urban mobility'. Communication COM(2007) 551 Final, September 2007.

[Com09] Commission of the European Communities (2009). Action Plan on Urban Mobility. Communication COM(2009) 490 Final, September 2009.

[Con07] Condon, P.M. (2007). Design charrettes for sustainable communities. Island Press, Washington, DC.

[Con09] Condon P.M. , Cavens D., and Miller N. (2009). Urban Planning Tools for Climate Change Mitigation. Lincoln Institute of Land Policy, Cambridge, MA.

[Cra10] Crandall D., Backstrom L., Cosley D., et al. (2010). Inferring social ties from geographical coincidences. Proceedings of the National Academy of Sciences USA 107:22436-22441.

[Dag77] Daganzo C.F. and Sheffi Y. (1977). On Stochastic Models of Traffic Assignment. Transportation Science, 11, 253-274.

[Eag09] Eagle N. and Pentland S. (2009). Eigenbehaviors: Identifying structure in routine. Behavior Ecology Sociobiology, 63: 1057--1066.

[Ech90] Echenique M. H., Flowerdew A.D.J., Hunt J.D., Mayo T.R., Skidmore I.J., and Simmonds D.C. (1990). The MEPLAN models of Bilbao, Leeds and Dortmund. Transport Reviews 10, (4): 309-22.

[Eur07] European Research Forum for Urban Mobility (2007). Strategic Research Agenda. European Conference of Transport Research Institutes.

[Fei09] Feil M., Balmer M., Axhausen K.W. (2009). New approaches to generating comprehensive all-day activity-travel schedules. Arbeitsberichte Verkehrs- und Raumplanung, 573, IVT, ETH Zürich, Zurich.

[Fro09] Froehlich J., Neumann J., and Oliver N. (2009). Sensing and Predicting the Pulse of the City through Shared Bicycling. Twenty-First International Joint Conference on Artificial Intelligence (IJCAI-09), Pasadena, California, USA, 11-17 July 2009.

[Gif07] Giffinger R., Fertner C., Kramar H., Kalasek R., Pichler-Milanovic N., and Meijers E. (2007). Smart cities - Ranking of European medium-sized cities. Final Report of the EU project Smart Cities. Centre of Regional Science, Vienna UT.

[Gil05] Gilbert N. and Troitzsch K.G. (2005). Simulation for the social scientist. Maidenhead: Open University Press.

[Gon08] González M., Hidalgo C.A., and Barabasi A.-L. (2008). Understanding individual human mobility patterns. Nature 453:779-782.

[Gra11] Grabowicz P., Ramasco J.J., Moro E., et al. (2011). Social features of online social networks: the strength of intermediary ties in online social media. http://arxiv.org/abs/1107.4009 to appear in PLoS ONE.

[Hac09] Hackney J. (2009). Integration of Social Networks in a Large-Scale Travel Behaviour Microsimulation. PhD Thesis, ETH Zürich, Zurich.

[Hag70] Hägerstrand T. (1970). What about people in Regional Science? Papers of the Regional Science Association, 24(1), 6-21.

[Hep12] Heppenstall A., Crooks A., See L., and Batty M. (Editors) (2012). Agent-Based Models of Geographical Systems. Springer, Berlin and New York.

[Huf04] Hufnagel L., Brockmann D., and Geisel T. (2004). Forecast and control of epidemics in a globalized world. Proceedings of the National Academy of Sciences USA 101:15124-15129.

[Hun03] Hunt J. D. and Abraham J.E. (2003). Design and application of the PECAS land use modeling system. 8th Computers in Urban Planning and Urban Management Conference, Sendai, Japan.

[Ill11] Illenberger J., Kowald M., Axhausen K.W., and Nagel K. (2011). Insights into a spatially embedded social network from a larger-scale snowball sample. European Physical Journal B 84, 549-561.
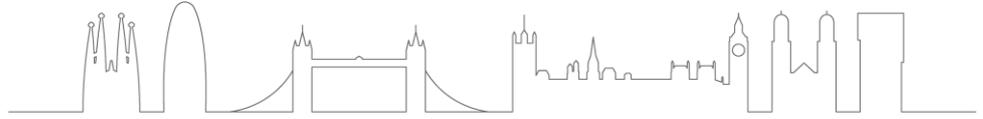
[Joh04] Joh C.-H. (2004). Measuring and predicting adaptation in multidimensional activity-travel patterns. PhD Thesis, Technical University Eindhoven, Eindhoven.

[Jon83] Jones P.M., Dix M.C., Clarke M.I., and Heggie I.G. (1983). Understanding Travel Behaviour. Gower, Aldershot.

[Kin11] Kinsella S., Murdock V., and O'Hare N. (2010). I am eating a sandwich in Glasgow: Modeling locations with tweets. Proceedings of SMUC 2011.

[Koc09] Kockelman K., Zhou B., and Tirumalachetty S. (2009). NCTCOG's land use modeling workshop: meeting minutes. University of Texas.

[Koe03] Koelbl R. and Helbing D. (2003). Energy and scaling laws in human travel behaviour. New Journal of Physics, 5:48.

[Kow11] Kowald M. and Axhausen K.W. (2011). Surveying data on connected personal networks, Arbeitsberichte Verkehrs- und Raumplanung, 722, IVT, ETH Zürich, Zurich.

[Kri09] Krings G., Calabrese F., Ratti C., and Blondel V. D. (2009). Urban gravity: A model for inter-city telecommunication flows. Journal of Statistical Mechanics: Theory and Experiment, L07003.

[Kwa08] Kwartler, M. and Longo G. (2008). Visioning and visualization: People, pixels, and plans. Lincoln Institute of Land Policy, Cambridge, MA.

[Lam08] Lambiotte R., Blondel V. D., de Kerchove C., et al. (2008). Geographical dispersal of mobile communication networks. Physica A 387:5317-5325.

[Laz09] Lazer D., Pentland A., Adamic L., Aral S., Barabasi A.-L. et al. (2009). Computational social science. Science 323:721-723.

[Lea03] O'Leary J. (2003). Modelling Urban Mobility within a Dynamic Spatial Microsimulation Model - Case Study: the MicroSim Model. Proceedings in Modelling our future, 2003.

[Lee73] Lee D.B. (1973). Requiem for large-scale models. Journal of the American Institute of Planners, Vol. 39, No. 3, pp. 163–178.

[Lee10] Lee, D.J-H. (2010). 2009 TMA/MPO modeling activity survey. Fredericksburg Area Metropolitan Planning Organization.

[Lib05] Liben-Nowell D., Novak J., Kumar R., Raghavan P., and Tomkins A. (2005). Geographic routing in social networks. Proceedings of the National Academy of Sciences USA 102:11623-11628.

[Low64] Lowry I.S. (1964). A Model of Metropolis. The Rand Corporation, Santa Monica.

[Luc10] Lucio A. (2010). Electric mobility: Madrid case. SIMBA project, Final Workshop, Brussels, 26 October 2010.

[Luc11] Lucio A. (2011). Mobility Round Table of Madrid 2006-2011. URBELAC Conference, Emergent Cities Platform, Cartagena (Colombia), 11 May 2011.

[Mar11] Märki F., Charypar D., and Axhausen K.W. (2011). A continuous simulation concept for daily travel. 11th Swiss Transport Research Conference, Ascona, Switzerland, 11-13 May 2011.

[Mar96] Martínez F. J. (1996). MUSSA: a land use model for Santiago City. Transportation Research Record, 1552, pp. 126–134.

[McF81] McFadden D. (1981). Econometric model of probabilistic choice. In C.F. Manski and D. McFadden (eds.), Structural Analysis of Discrete Data with Econometric Applications, 198-272, MIT Press, Cambridge.

[Mis10] Misuraca G., Broster D., Centeno C., Punie Y., Lampathaki F., Charalabidis Y., Askounis D., Osimo D., Szkuta K., and Bicking M. (2010). Envisioning Digital Europe 2030: Scenarios for ICT in Future Governance and Policy Modelling. European Commission JRC-IPTS.

[Moe03] Moeckel R., Spiekermann K., Schürmann C., and Wegene, M. (2003). Microsimulation of land use. International Journal of Urban Sciences 7 (1), 2003.

[Mul11] Müller K. and Axhausen K.W. (2011). Population synthesis for microsimulation: State of the art. Proceedings of the 90th Annual Meeting of the Transportation Research Board, Washington, D.C., January 2011.

[Nou11] Noulas A., Scellato S., Lambiotte R., Ponti M., and Mascolo C. (2011) A tale of many cities: universal patterns in human urban mobility. Proceedings of the National Academy of Sciences USA 104:20167-20172.

[Onn07] Onnela J.-P., Saramaki J., Hyvnen J., et al. (2007). Structure and tie strength in mobile communication networks. Proceedings of the National Academy of Sciences USA 104:7332-7336.

[Onn11] Onnela J.-P., Abesman S. et al. (2011). Geographic constraints on social network groups. PLoS ONE 6:e16939.

[Ort11] Ortúzar J.d.D. and Willumsen L.G. (2011). Modelling Transport. Fourth Edition, John Wiley & Sons Ltd, Chichester, UK.

[Put95] Putman S. H. (1995). EMPAL and DRAM location and land-use models: An overview. TMIP Land Use Modelling Conference, Dallas.

[Que10] Quercia N., Lathia L., Calabrese F., Di Lorenzo G., and Crowcroft J. (2010). Recommending social events from mobile location data. Proceedings of IEEE ICDM 2010.

[Ram04] Ramanath A.M. and Gilbert N. (2004). The Design of Participatory Agent-Based Social Simulations. Journal of Artificial Societies and Social Simulation, 7(4).

[Ram07] Rambaldi S., Bazzani A., Giorgini B., and Giovannini L. (2007). Mobility in modern cities: looking for physical laws. Proceedings of the ECCS 2007, 132.

[Rot11] Roth C., Kang S.M., Batty M., Barthélemy M. (2011). Structure of urban movements: polycentric activity and entangled hierarchical flows. PLoS One 6(1):e15923.

[Sal05] Salvini P. A. and Miller E. J. (2005). ILUTE: An Operational Prototype of a Comprehensive Microsimulation Model of Urban Systems. Networks and Spatial Economics, Vol. 5, No. 2, June 2005, pp. 217-234.

[Sce10] Scellato S., Mascolo C., Musolesi M., Latora V. (2010). Distance matters: Geo-social metrics for online social networks. Proceedings of WOSN 2010.

[Sce11] Scellato S., Mascolo C., Musolesi M., Crowcroft J. (2011). Track globally, deliver locally: Improving content delivery networks by tracking geographic social cascades. Proceedings of WWW 2011.

[Sev10] Sevtsuk A. and Ratti C. (2010). Does urban mobility have a daily routine? Learning from the aggregate data of mobile networks. Journal of Urban Technology, 17:41--60.

[Sim11]   Simini F., González M.C., Maritan A., Barabasi A.-L. (2011). A universal model of mobility and migration patterns. http://arxiv.org/abs/1111.0586

[Siv07]   Sivakumar A. (2007). Modelling Transport. A Synthesis of Transport Modelling Methodologies. Imperial College London.

[Son10a]   Song C., Koren T., Wang P., Barabasi A.-L. (2010). Modeling the scaling properties of human dynamics. Nature Physics 7:713.

[Son10b]   Song C. et al. (2010). Limits of Predictability in Human Mobility. Science 327:1018-1021.

[Str05]   Strauch D., Moeckel R., Wegener M., Gräfe J., Mühlhans H., Rindsfüser G., and Beckmann K.-J. (2005). Linking transport and land use planning: the microscopic dynamic simulation model ILUMASS. In: Atkinson P.M., Foody G.M., Darby S.E., Wu F. (Eds.): Geodynamics. Boca Raton, Florida: CRC Press, 295-311, 2005.

[TRB07]   Transportation Research Board (2007). Special Report 288: Metropolitan Travel Forecasting: Current Practice and Future Direction. National Research Council, Washington, D.C.

[Ves09]   Vespignani A. (2009). Predicting the behavior of techno-social systems. Science 325:425-428.

[Wad03]   Waddell P., Borning A., Noth M., Freier N., Becke M., and Ulfarsson G. (2003). Microsimulation of urban development and location choices: Design and implementation of UrbanSim. Networks and Spatial Economics 3, (1): 43-67.

[Wad09]   Waddell P. (2009). Parcel-Level Microsimulation of Land Use and Transportation: The Walking Scale of Urban Sustainability. Proceedings of the 2009 IATBR Workshop on Computational Algorithms and Procedures for Integrated Microsimulation Models.

[Wad11]   Waddell P. (2011). Integrated Land Use and Transportation Planning and Modelling: Addressing Challenges in Research and Practice. Transport Reviews, Vol. 31, No. 2, 209–229.

[Wan09]   Wang P., Gonzalez M., Hidalgo C.A., Barabasi A.-L. (2009). Understanding the spreading patterns of mobile phone viruses. Science 324:1071-1076.

[War52]   Wardrop, J.G. (1952). Some theoretical aspects of road traffic research. Proceedings of the Institute of Civil Engineers, 1 (2) 325-378.

[Wat07]   Watts D.J. (2007). A twenty-first century science. Nature 445:489.

[Weg09]   Wegener M. (2009). From Macro to Micro – How Much Micro is too Much? International Seminar on Transport Knowledge and Planning Practice at the University of Amsterdam, 14-16 October 2009.

[Weg10]   Wegener M. (2010). The future of mobility in cities: challenges for urban modelling. Proceedings of 12th World Conference on Transport Research.

[Wim11]   Wimmer, M.A. (2011). Open Government in Policy Development: From Collaborative Scenario Texts to Formal Policy Models. In Natarajan, R. and Ojo, A. (eds.): ICDCIT 2011. LNCS (# 6536), Springer Verlag: Berlin Heidelberg: 76–91.

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