TRANSPORT AND SPATIAL ORGANISATION OF CITIES : SYNTHESIS OF THEORIES AND MODELS

Michael WEGENER

Institute of Spatial Planning
University of Dortmund
D-44221 Dortmund

Résumé

The spatial organization of contemporary cities is of bewildering complexity. Urban growth and decline, concentration and dispersal, polarisation and equalisation, prosperity and deprivation coexist in an intricate spatio-temporal web of partly interdependant and partly autonomous processes. In this paper an overview of classical and contemporary approaches to modelling the interface between spatial interaction and location in urban regions is given. Four paradigms are distinguished : technological, economic, social and political. In a second part of the paper an attempt to integrate components of the four paradigms in an unified theoretical framework and quantitative model of the transport and spatial organization in urban regions is presented.

Mots Clés

Urban regions - Transport and spatial organization - Theory and models

Introduction

The spatial organisation of contemporary cities is of bewildering complexity. Urban growth and decline, concentration and dispersal, and polarisation and equalisation interact in an intricate spatio-temporal web of panly interdependent and partly autonomous processes.

The urban sciences are still far from being able to explain the spatial evolution of cities by one comprehensive theory. There coexist a multitude of partly incompatible theories proposed by various disciplines that try to explain the same phenomena under different assumptions and using different explanatory variables.

However, there is a broad agreement that transport is one of the major factors determining the spatial organisation of cities. Medieval cities were built for walking, and this required that living and working were close together. The railway made spatial division of labour possible and so opened the way for the growth of cities. Rapid transit and the private car have facilitated the expansion of metropolitan areas over wider and wider territories. However, the growing separation of human activities demands ever longer trips and greater volumes of traffic with all their associated problems of congestion, traffic accidents, energy use, pollution and land consumption.

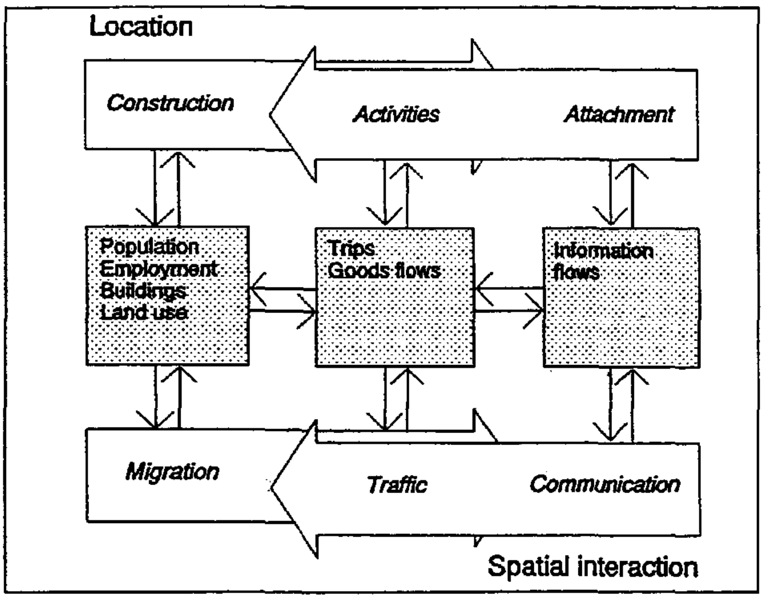
Despite the consensus about the importance of the transport-location interlace, there is no general theory of location and spatial interaction in cities. Again one finds a large number of divergent and sometimes contradictory explanations of spatial choices of firms, landlords, households, and travellers. These explanations are linked to specific disciplines. Engineers, economists and social scientists have independently developed ideas about how decisions about location or travel are made, and there have been only few attempts to bring these isolated approaches together in an integrated theory.

Such a synthesis will be suggested here. The paper first gives an overview of classical and contemporary approaches to modelling the interface between transport and location in urban regions. Three paradigms are distinguished : technological, economic and social. In a second part of the paper an attempt to integrate components of the three paradigms in a unified theoretical framework and in a quantitative model of transport and spatial organisation in urban regions is presented.

Location and Spatial Interaction in Cities

The review starts with a taxonomy of human behaviour in space. Two prineipal modes of spatial behaviour are distinguished : *location* and *spatial interaction* (see Figure 1) :

Figure 1 : Interrelationships between location and spatial interaction



– *Location is* the fixing of a relation between people and space. There are three levels of such relations : physical change through development (construction, rehabilitation, demolition, etc) ; utilisation of space for activities (living, working, shopping, education, recreation, etc) ; and attachment to space (familiarity, habits, social integration, etc).

– *Spatial interaction is* material or immaterial exchange between spaces. There are three levels of spatial interaction : permanent relocation (migration, change of job) ; daily mobility (travel, transport) ; and instantaneous communication (phone calls, fax messages, mail, data exchange, etc).

Figure 1 shows the interrelationships between location and spatial interaction via three types of stocks and flows : Land use, buildings, jobs and people represent the localised stocks of the urban system. Trips and flows of goods represent material exchanges between locations. Information flows between people and places represent immaterial exchanges. These stocks and flows are the main descriptors used to analyse and forecast urban systems.

In the following sections classical and contemporary approaches to modelling the interface between transport and location in cities are summarised. Three paradigms associated with the three academic disciplines engineering, economics and social science are distinguished.

Technical Theories : Urban Mobility Systems

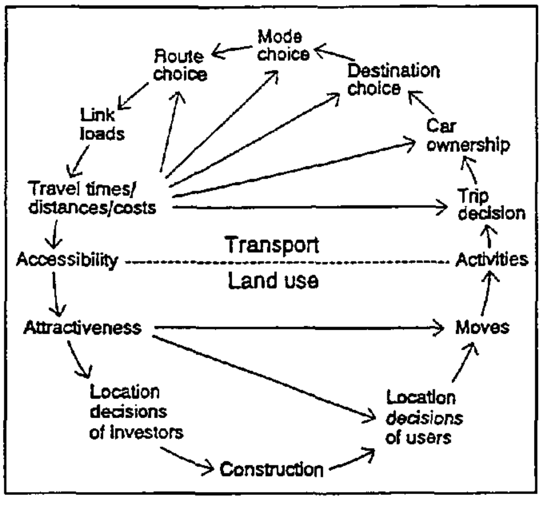
In the technical paradigm of urban development, mobility constraints determine the internal organisation of cities. The high density or crowdedness of the medieval city resulted from the need for fortification and from the fact that most trips had to be made on foot. When these two constraints disappeared in the 19th century, urban development largely became a function of transport technology.

The workers' housing areas of the early 19th century were still built in the immediate vicinity of the factories, and, after the introduction of the railways, «rent barracks» were the most efficient way to concentrate large numbers of workers around commuter railway stations. Consequently large cities expanded along the railway lines fanning out from the traditional city centre in a star-like pattern. With the diffusion of the private automobile, first in America and after World War II also in Europe, the areas between the railway lines could also be used for housing, and so the expansion of urban areas became less directed and more dispersed («urban sprawl»).

In the 1950s first efforts were made in the United States to study systematically the interrelationship between transport and location in cities. Hansen (1956) demonstrated for Washington, DC, that locations with good accessibility had a higher chance of being developed, and at a higher density, than remote locations («How accessibility shapes land use»). The recognition that trip and location decisions codetermine each other and that therefore transport and land use-planning needed to be coordinated, quickly spread among American planners, and the «land-use transport feedback cycle» became a commonplace in the American planning literature.

The set of relationships implied by the land-use transport feedback cycle can be briefly summarised as follows (see Figure 2) :

Figure 2 : The «land-use/transport feedback cycle»



– The distribution of *land uses* such as residential, industrial or commercial over the urban area determines the locations of human *activities* such as living, working, shopping, education or leisure.

– The distribution of human *activities* in space requires spatial interactions or trips in the *transport system* to overcome the distance between the locations of activities.

– The distribution of infrastructure in the *transport system* creates opportunities for spatial interactions and can be measured as *accessibility.*

– The distribution of *accessibility* in space codetermines location decisions and so results in changes to the *land-use* system.

The theories based on this paradigm start from observed regularities of certain parameters of human mobility, such as trip distance and travel time, and from these try to infer those trip origins and destinations that best reproduce the observed frequency distributions. Ravenstein (1885) and Zipf (1949) observed that the frequency of human interactions such as messages, trips or migrations between two locations (cities or regions) is proportional to their size, but inversely proportional to their distance. The analogy to the law of gravitation in physics is obvious.

The gravity model was the first *spatial interaction* (or in short SIA) model. Its straightforward physical analogy has later been replaced by better founded formulations derived from statistical mechanics (Wilson, 1967) or information theory (Snickars and Weibull, 1976). Yet even then the SIA model did not provide an *explanation* for spatial behaviour. Only later did it become possible (Anas, 1983) to link it via random utility theory (McFadden, 1973) to psychological models of human decision behaviour (Luce, 1959).

From the SIA model it is only a small step to its application as a location model. If it is possible to make inferences from the distribution of human activities to the spatial interactions between them, it must also be possible to identify that location of activities which gives rise to a certain trip pattern. Wilson (1970) distinguishes four types of urban *spatial interaction location models* (see Table 1) :

Table 1 : Wilson's four spatial interaction location models

Type	Constraints	Residence	Workplace
1	unconstrained	predicted	predicted
2	production-constrained	predicted	known
3	attraction-constrained	known	predicted
4	doubly constrained	known	known

Source : Wilson (1970)

Model type 1 deals with households having neither residence nor workplace, model type 2 with households looking for a residence and model type 3 with households looking for a job. Model type 4 is actually not a location model but the familiar transport model. The column «constraints» refers to the marginal totals of the interaction matrix, which act as constraints to its elements, if they are known.

Lowry's (1964) *Model of Metropolis* consists of two singly-constrained SIA location models, a residential location and a service and retail employment location model, nested into each other. The Lowry model stimulated a large number of increasingly complex modelling approaches such as the work by Goldner (1971), Echenique (Geraldes et al., 1978), Putman (1983, 1992), Mackett (1983) and Webster et al. (1988). Boyce et al. (1981) developed combined equilibrium models of residential location, mode and route choice.

The limits of location models based on the SIA paradigm lie on two levels :

– First, the SIA location model assumes equilibrium between transport and location. In reality, however, this equilibrium does not exist. Urban processes have very different speeds and response times. For instance, the behaviour of transport users adjusts very quickly to changing conditions in the transport system. Conversely, transport investment takes a long time from planning to final implementation. In a similar way the distribution of activities reacts only very slowly to changes in accessibility. Even a simple change of residence or workplace may take months or even years between planning and realisation, whereas the planning and implementation of housing, olfices or work-places as a rule requires several years (Wegener, 1985 ; 1986 ; Wegener et al., 1986). This kind of disequilibrium, however, cannot be represented by the SIA location model.

– Second, the SIA location model lacks economic content. The only variable explaining location behaviour in the model is transport cost, and even that only in so far as it is necessary to model the choice between mobility alternatives. In particular, there is no link between transport cost and other expenditure by households and firms. This makes the model incapable of considering wider choices than that between transport modes or destinations, such as choices involving trade-offs between transport and location or between housing and work-place location - unless it is embedded into a more comprehensive framework of factors determining the decision.

It is unfortunate that the mainstream of urban theory-building and modelling adopted this most restricted, engineering-based perception of the urban system as a system of movements. The spatial interaction model, after some twenty years of refinement and generalisation (Williams and Senior, 1978 ; Coelho and Williams, 1978 ; Leonardi, 1981 ; Anas, 1983), is essentially still the atemporal equilibrium model it always was, and with each advance in mathematical rigour and elegance seems to move farther away from reality.

In particular the spatial interaction paradigm itself (the myth that workers choose their place of residence on their way home from work) turned out to be a veritable straitjacket which forces things together which should be analysed separately, such as decisions to move, to choose a job, to make trips, etc, although of course these are interrelated, but only in a timelagged and indirect way. Moreover, there are no people in this paradigm, no households, no entrepreneurs, no landlords, no developers ; there are no distorted perceptions, no incomplete information, no uncertainty, no biases, no heuristics, no adaptation, no learning. There are no change processes, no construction, no upgrading, no demolition, no supply and demand variables, no rents and land prices, no markets, no market distortions such as oligopolies, price controls, legal constraints or public interventions.

Some of these issues have been taken up by more recent approaches. Their common characteristic is their interest in dynamics. The rediscovery of time was motivated partly by new results in the biosciences with respect to the behaviour of complex ecosystems, such as the theory of dissipative structures (Allen et al., 1981), and partly by the availability of new mathematical instruments such as catastrophe and bifurcation theory (Wilson, 1981 ; Dendrinos and Mullaly, 1985) or the theory of nonlinear dynamic systems (Weidlich and Haag, 1983 ; 1988 ; Nijkamp and Reggiani, 1992). However, the application of these new concepts to urban systems still faces serious empirical difficulties.

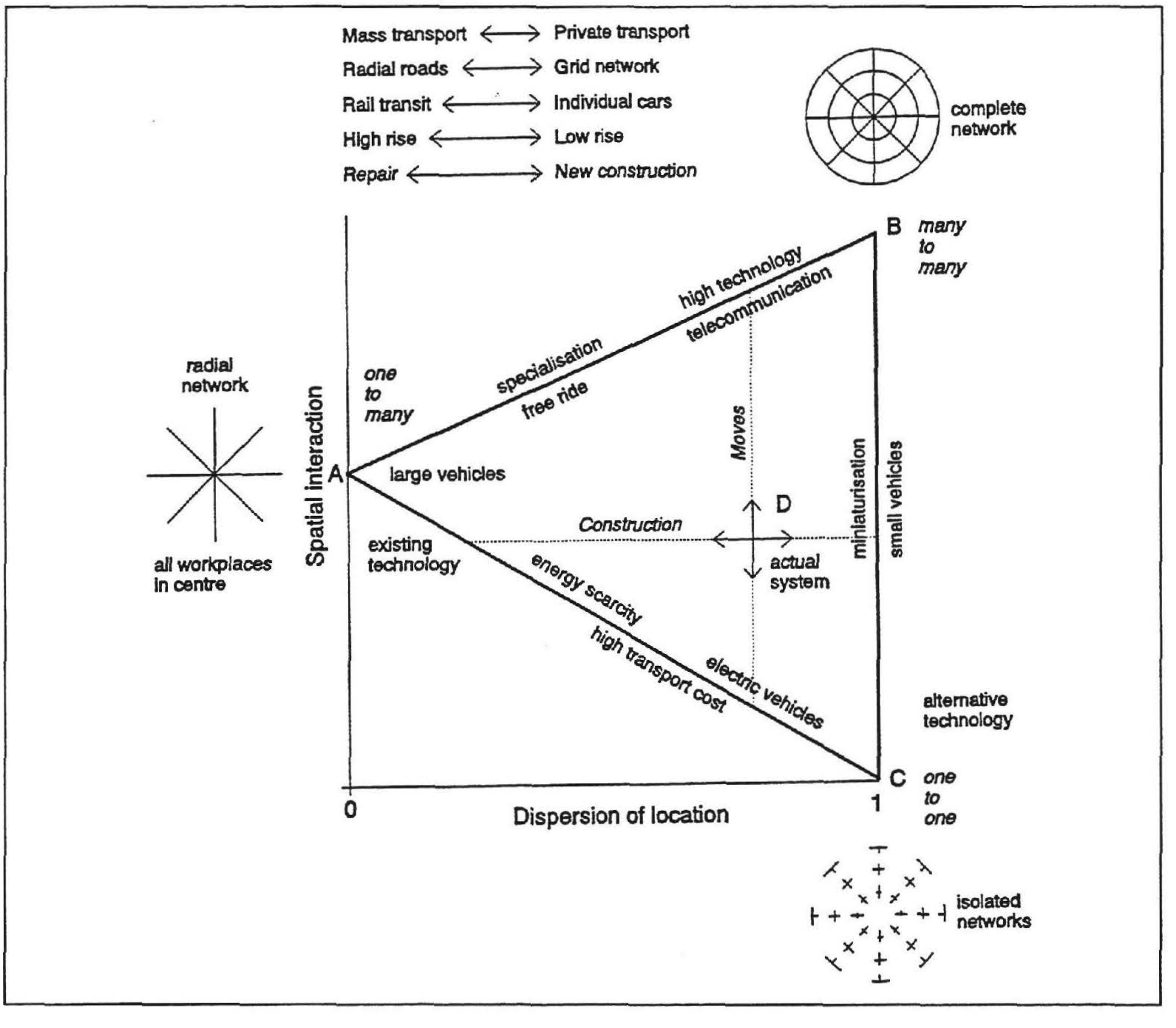
Nevertheless, the spatial interaction paradigm has led to a better understanding of important dimensions of individual mobility and location behaviour and their interrelationships. Figure 3 portrays these interrelationships in a format proposed by Brotchie (1984).

The «Brotchie Triangle» represents the universe of possible constellations of spatial interaction and spatial structure in an urban area. Spatial structure is represented on the horizontal axis as spatial dispersal (for instance, mean travel distance of employment from the centre of the region), spatial interaction on the vertical axis as some measure of total travel such as mean travel distance to work. Any city lies between three hypothetical points in the diagram : point A represents a situation in which all jobs are at the centre, i.e. dispersal of employment is zero. Both points B and C represent regions in which all jobs are as dispersed as the population. Point B represents a situation in which workers choose their residence without regard of distance, point C a situation in which they walk to work. The model answers the question in which direction the real city, point D, will shift : a shift up or down indicates reorganisation or *moves*, a shift to the left or right *construction*.

Economic Theories : Cities as Markets

A second set of theories focuses on the *economic* foundations of urban growth. Following this paradigm, the market function distinguishes the city from the countryside. If transport cost and location costs in the form of land prices are taken into account, firms look for the optimum constellation of size (economies of scale) and location (agglomeration economies) given the existing pattern of transport cost and land prices and their specific mix of products, production technology and pattern of suppliers and customers, whereas households try to match their housing space needs and location preferences with their budget restrictions. Both firms and households trade off accessibility (travel time) for space.

Figure 3 : The «Brotchie Triangle»



A fundamental assumption of all spatial economic theories is that locations with good accessibility are more attractive and have a higher market value than peripheral locations. Microanalytic approaches start from the locational behaviour of individual actors such as firms, landlords or households in the urban land or housing markets. Probably the most influential example of this kind is the model of the urban land market by Alonso (1964). The basic assumption of the Alonso model is that firms and households choose that location at which their bid rent, i.e. the land price they are willing to pay, equals the asking rent of the landlord, so that the land market is in equilibrium.

Alonso's model has been the point of departure for a multitude of urban economics model approaches (see Nijkamp and Mills, 1987). In more advanced variations of the model, restrictive assumptions such as perfect competition and complete information or the monocentric city have been relaxed (e.g. Anas, 1982). More recent extensions include models to deal with land speculation (Seo, 1989) or the behaviour of landlords in neighbourhoods undergoing gentrification (Smith, 1979 ; Smith and Williams, 1986). Another important development is the incorporation of intersectoral and interregional factor and commodity flows into the model (Williams and Echenique, 1978).

Another group of theoretical contributions have drawn attention to the importance of *innovation* for urban development. Today the most advanced industries are undergoing what is described as the transition from «Fordism» to «Post-Fordism» : Fordism indicates the era of mass production dominated by economies of scale. In the Post-Fordist economy a new flexibility of the production process is achieved in response to increasingly selective tastes in more and more saturated markets : economies of scale are complemented by «economies of scope», made possible by vertical integration of all steps of the production process from supply to delivery by computer control and telecommunications in «logistic chains». Earlier steps in the assembly chain are contracted out to outside suppliers, who have to synchronise their operations with the production schedule by «just-in-time» delivery, thus making inventories redundant.

This theory helps to explain the spatial polarisation observed within urban regions. Flexible production and distribution systems require extensive, low-density sites with good access to the regional and local road network, and this explains why new manufacturing firms prefer suburban locations. Retail facilities tend to follow their customers to the suburbs and similarly prefer large suburban sites with good road access. High-level services, however, continue to rely on face-to-face contacts and, despite fax machines and electronic data interchange, remain in the city centre. The result is the spatial dispersal of all economic activities except high-level services and the progressive erosion of activities in the city centre.

Social Theories : Society and Urban Space

In social-science theories of urban development, the spatial organisation of cities is the result of individual or collective appropriation of space. Since Durkheim and Simmel there are in sociology traditions in which the city is a fundamental dimension of human existence. Other authors have defined the city as the interface between public and private society (Bahrdt, 1969), the stage for social interaction and sell:expression (Goffman, 1959), the medium for the world of daily life (Lefebvre, 1968) or the field of action of social movements (Harvey, 1973 ; Castells, 1977). However, as a rule these approaches remained essentially social theories and failed to deal explicitly with the spatial and temporal dimensions of urban development.

The one exception is the Chicago school of urban sociologists, who between the wars looked more closely into processes of social change on the neighbourhood and urban levels. Based on an adaptation of evolutionist thoughts from philosophy (Spencer) and biology (Darwin), they interpreted the city as a multi-species ecosystem, in which social and economic groups fight for «ecological positions» (Park et al., 1925 ;1936). In spatial terms the ecological position is a territory such as a neighbourhood or a region. Appropriation of space takes place as invasion of different ethnic or income groups or tertiary activities into a residential neighbourhood and uses concepts of animal and plant ecology such as «invasion», «succession» or «dominance» to describe the phases of such displacement.

Social geography theories go beyond the macro perspective of social ecology by referring to age-, gender- or social-group-specific activity patterns which lead to characteristic spatio-temporal behaviour and hence to permanent localisations. Action-space analyses (Chapin, 1965 ; Chapin and Weiss, 1968) identify the frequency of activities reconstructed from daily space-time protocols as a function of distance to other activities and draw conclusions from this for the most appropriate allocation of housing, work-places, shopping and recreation facilities or the optimum level of spatial division of labour in cities.

Hägerstrand (1970) made these ideas operational through the introduction of «time budgets», in which individuals according to their social role, income and level of technology (e.g. car ownership) –subject to various types of constraints («capacity constraints», «coupling constraints» and «institutional constraints»)– command *action spaces* of different size and duration. Only locations within these action spaces can be considered for choice. It is the achievement of the «time geography» of the Hägerstrand school to have drawn attention to the various kinds of captiveness caused by a land-use and transport system designed for the needs of the affluent and able : the restricted mobility of women with children, the elderly and the handicapped.

Time geography has stimulated a new school of disaggregate models of urban travel. In these «behavioural» models, the mobility needs and mobility constraints and the resulting travel choices of individuals belonging to groups with homogenous travel behaviour are simulated using Monte-Carlo or microsimulation (Jones, 1979). These models are able to take account of non-standard forms of travel such as car sharing, park and ride or trip chains. Typically they do not rely on observations of travel behaviour («revealed preference») but on information about travel needs and constraints obtained in interviews («stated preference»).

A Theory of Spatial Choice

Each of the above theoretical approaches captures important aspects of the spatial organisation of cities, yet none of them is general enough to explain the coexistence of different patterns of spatial behaviour by a comprehensive and yet simple theory. In this section it is attempted to suggest how such a theory might be composed from the elements discussed in the previous section cutting across disciplinary boundaries and perspectives.

Actors

On a micro level of explanation, urban development is understood as a process of thousands or millions of human decisions, many small and some large, occurring over time as a broad stream of concurrent, unrelated or interrelated, individual or collective choices (Wegener, 1986). A microanalytic theory of urban transport and location therefore has to identify the main actors and their decision behaviour. The *actors* involved in choice processes of urban development may be either public or private :

– *Public actors* in urban development are governments and government agencies from the local to the national level. Public policy decisions relevant for urban development are direct investment or construction decisions of local governments or other public or semi-public bodies as well as indirect government policies implemented through legislation regarding taxation, land development, construction, transport or the environment. These public interventions constitute the *planning* component of urban development.

– *Private* actors in urban development are firms, households or individuals. Private decisions relevant for urban development are location, migration and travel decisions which cannot, or can only indirectly, be influenced by public planning. The private actors in urban development interact on spatial markets such as the land and construction market or the housing market. Hence the decisions of private actors constitute the *market* component of urban development.

Thus *planning* and *market* are two fundamental categories of urban development which are contingent upon each other. Public planning sets the framework for the behaviour of private actors or directly intervenes in the market. Conversely, public planning is often merely a reaction to prior market developments or becomes instrumental for the achievement of economically powerful market forces. In many cases the role of public planning has been reduced to the provision of compensatory measures to alleviate spatial disparities caused by market developments. Depending on the economic and social system, the relative importance of planning and market forces in urban development differ. Here the coexistence of market behaviour and public intervention characteristic for most west European countries is assumed, i.e. it is assumed that the majority of decisions relevant for urban development are made by private actors within a decision framework set by public decisions.

Choices and Transitions

Choices are selections between alternatives. A typical choice is for instance the behaviour of a household looking for a dwelling in the housing market (Wegener, 1984 ; 1985) : Its propensity to move depends on its satisfaction with its present dwelling. It first chooses a neighbourhood in which to look for a dwelling, and this is not independent of its present residence and work-place. The household then looks for a dwelling in that neighbourhood guided by the attractiveness and price of vacant dwellings there. Finally the household decides whether to accept an inspected dwelling or not. It accepts the dwelling if it can significantly improve its housing condition. If it declines, it enters another search phase.

However, not all changes in an urban system are decision-based. Some are simply transitions from one state to another. A typical transition is the evolution of a household during a certain time interval during which it is promoted to another household category with respect to nationality, age, income or size conditional on the relevant transition probabilities for events such as naturalisation, birth of child, ageing/death, marriage, divorce, relative joins or leaves household (Wegener, 1984 ; 1985). Also choice-based events such as marriage or divorce may be treated as transitions if the causal chain behind them is of no interest.

Preferences and Constraints

Both public and private actors pursue their possibly conflicting goals. Here mainly the behaviour of the private actors is of interest. The following basic assumptions about the choice behaviour of private actors are :
- Actors *attempt* to act *rationally*, i.e. to perceive and accomplish *their preferences*.
- In doing so, they are subject to group-specific economic, institutional and informational *constraints*.
- In response to these constraints, they act as «satisficers», i.e. are content with obtaining suboptimum *aspiration levels*.
- The aspiration levels of actors are determined by their socio-economic status and *experiences*.
- In particular actors with low income are likely to be forced to *reduce* their aspiration levels.

The *preferences* of actors are multi-attribute. For instance, the attractiveness of a dwelling for a household is a function of its quality and size, the quality of its neighbourhood, its proximity to work-places and to other activities in the region and of its rent or price in relation to the household's income. The attractiveness of a site as a location for a firm is a function of its size and zoning category, the quality of its neighbourhood, its location in the region and its land price. The attractiveness of a given route in the transport network for a traveller is a function of the corresponding travel time, travel distance and travel cost in relation to alternative routes and to the traveller's perceived time and money budgets. The preferences of different groups of actors are different because of their different needs and financial means such as housing or travel budgets.

Constraints are circumstances narrowing the decision margin of actors. Economic constraints are limits to the ability or willingness to pay. Institutional constraints are restrictions of access to services or facilities. Informational constraints are restrictions of the collection of decision information due to lack of time or money. Just like the preferences, the constraints are different for each group of actors because of their dilferent income, social status, education or occupation.

Preferences and constraints determine the behaviour of actors in *decision situations* in which they choose between action alternatives. It is assumed that actors in their daily decision-making use heuristic choice rules, which means that the results of their decisions are not normally optimum in terms of individual utility maximisation but represent systematic deviations from the optimum, the distribution of which can be estimated.

A Model of Spatial Choices

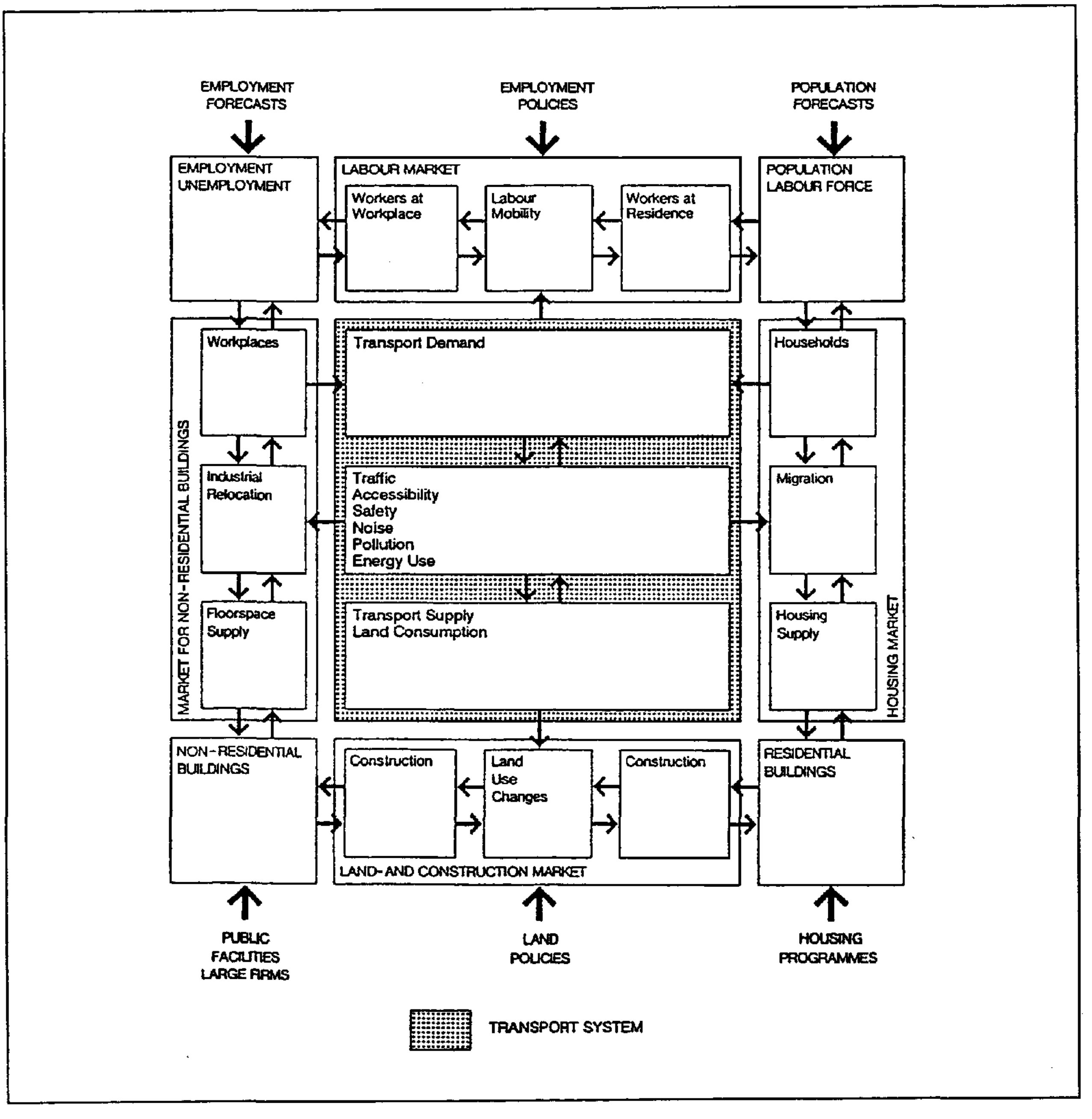
The theory of spatial choice outlined in the previous sections has been tested empirically by making it operational in the form of a quantitative mathematical computer simulation model and applying the model to the urban region of Dortmund in Germany in variety of projects concerned with issues of land use, housing, migration and transport. In this section the Dortmund model is briefly introduced. More detailed descriptions of the model are contained in Wegener (1983, 1984, 1985, 1993) and in Webster et al. (1988).

The Dortmund model is a model of intraregional location and mobility decisions in the metropolitan area of Dortmund. It receives its spatial dimension by the subdivision of the study region in thiny *zones* (urban districts or suburban communities) connected by transport networks containing the most imponant links of the public transpon and road networks coded as an integrated, multimodal network including walking and cycling and all past and future network changes. It receives its *temporal* dimension by the subdivision of time into periods of two or three years' duration.

Figure 2 is a schematic diagram of the major subsystems considered in the model and the interactions between them and of the most important policy instruments.

The four square boxes in the corners of the diagram show the major stock variables of the model : *population, employment, residential buildings* (housing) and *non-residential buildings* (industrial and commercial workplaces and public facilities). The actors representing these stocks are *individuals or households, workers, housing investors* and *firms.*

Figure 4 : Major subsystems of the Dortmund model



These actors interact on five *submarkets* of urban development. The submarkets and the market transactions occurring in them are :

- the *labour market* : new jobs and redundancies,
- the *market for non-residential buildings* : new firms and firm relocations,
- the *housing market* : immigration, outmigration, new households and moves,
- the *land and construction market* : changes of land use through new construction, modemisation or demolition.
- the *transport market* : trips and their consequences : changes of accessibility, road accidents, traffic noise, air pollution and energy use.

For each submarket, the diagram shows supply and demand and the resulting market transactions. Choice in the submarkets is constrained by supply (jobs, vacant industrial or commercial floorspace, vacant housing, vacant land, network capacity) and guided by attractiveness, which in general terms is an actor-specific aggregate of *quality* and *price*.

The large arrows in the diagram indicate exogenous inputs : these are either *forecasts* of regional employment and population subject to long-term economic and demographic trends or *policies* in the fields of industrial development, housing, public facilities and transport.

With this model structure the Dortmund model is one of the few operational urban models in which the two-way interaction between land use and transport in urban areas is explicitly modelled (Webster et al., 1988).

A Model Application

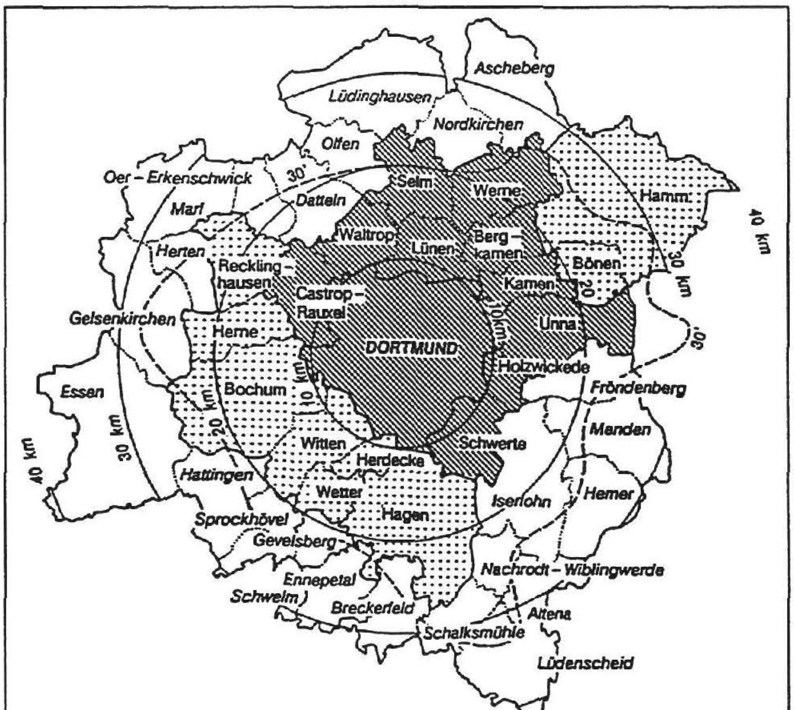
In this section a typical application of the model is presented, in which the model was used to explore possibilities to reduce energy consumption in cities by travel demand management.

Under conditions of growing affluence and low transport costs, market-driven land-use development has led to dispersed settlement patterns associated with high levels of mobility, congestion, pollution and energy consumption. In particular the high energy consumption of transport has become an issue of growing concern. The fear of diminishing fossil fuels and the threat of long-term climate changes due to greenhouse gases have sharpened the awareness that present energy prices do not nearly cover the environmental and social costs of energy use and that the level of energy consumption in affluent countries represents a gross unfairness against developing countries which can never be allowed to rise to the same standards. The German government pledged to reduce CO_2 emission from all sources by 30 percent compared with 1987 by 2005. As transport represents a major share of primary energy consumption, serious efforts to lower the energy use of urban transport are necessary to achieve this goal.

Most experts agree that a return to more compact urban development and the promotion of higher densities and mixed land use are the most effective ways to reduce the need for travel and to bring energy consumption of urban transport down. However, at the outset of the project, this popular opinion was put in doubt (cf. Breheny, 1992). The underlying hypothesis was that because of the slow turnover of physical stock land-use policies have only long-term impacts and that high density facilitates, but does not guarantee, short distances, and that therefore policies to influence travel behaviour would be the most efficient way to reduce the energy use of urban transport. In particular various policies to change the cost or speed of travel were to be investigated.

The Study Region

Figure 5 : The metropolitan area of Dortmund



The study region of the application was the urban region of Dortmund in Germany. Dortmund (615 000 population) is the most eastern of the cities of the Ruhr Area, the largest industrial region in Germany. It used to be one of the major centres of coal mining and steel manufacturing in Germany, but with the decline of the mining and steel industries it has been reduced to being the administrative, service and retail centre for a large metropolitan region which is partly suburban and partly still rural in character. The study region is the commuter catchment area of Dortmund containing Dortmund itself and eighteen neighbouring communities. The commuter catchment area was defined as communities with at least 200 daily commuters to Dortmund in 1970 (see Figure 5). The resulting urban area is relatively compact ; most of its settlements lie within the 30-minute travel-time isochrone by car from central Dortmund. The hatched area is the urban area of Dortmund in the narrower sense ; these municipalities are exclusively oriented towards Dortmund. The dotted areas are larger self-contained cities or communities oriented towards more than one centre. The whole region has a population of approximately 2,3 million.

The Scenarios

Three types of scenarios were simulated : scenarios of travel cost changes, scenarios of travel speed changes, and scenarios in which changes of both travel costs and travel speeds were combined. Table 1 shows the list of scenarios and their specification. The first two groups of scenarios are similar to the kinds of policy tests conducted by the International Study Group on Land-Use/Transport Interaction (ISGLUTI) (Webster et al., 1988) ; the combination scenarios go beyond ISGLUTI. Scenarios 30 and 40 were defined differently from their ISGLUTI counterparts. In Scenario 30 a much faster increase of petrol price was assumed (all price increases include inflation), but the scenario was made more realistic by assuming that car manufacturers would respond to significant increases of fuel price by offering more energy-efficient cars. In Scenario 40 public transport was not only made faster but also having more trains or busses to accommodate additional ridership.

Table 2 : Scenarios

Scenario		Specification
Base scenario :	00	Base scenario
Travel cost scenarios :	30	Increase petrol price to 5 DM/l by 2000 and 12 DM/l by 2015, reduce average petrol consumption to 5 l per 100 km by 2015.
	32	Increase inner-city parking charges, after 2000 quintupled.
	33	Reduce public transport fares, after 2000 free.
	35	Increase public transport fares, after 2000 doubled.
	37	Increase all transport costs, after 2000 doubled.
Travel speed scenarios :	40	Make public transport faster (25 %) and reduce headways (50 %) and make cars slower (40 %).
	46	Make public transport and cars faster (25 %).
	47	Make public transport and cars slower (40 %).
Combination scenarios :	53	«Promotion of public transport» : scenarios 30 + 32 + 40.
	54	«Reduction of mobility» : scenarios 30 + 32 + 35 + 47.

The results of the simulations are summarised in Figures 6 to 8. In each of them the evolution of the urban system between 1970 and 2015 is represented by trajectories of one variable for each of the simulated scenarios. Until the mid-1990s, all scenarios coincide because the policies specified in Table 1 are introduced after 1993 ; this part of the diagrams serves to visualise the development in the past. The trajectory of each scenario is indicated by its number as in Table l ; Scenario 00 is the «base scenario» defined as the trend scenario without policy changes.

Figures 6 (top) shows the effect of the various policies on average trip length. It can be seen that in the base scenario average trip length increases from 8 to 13 kilometres between 1970 and 2015, and that policies to reduce travel cost (Scenario 33) or increase travel speed (Scenario 46) result in longer trips. Increasing travel costs (Scenarios 30, 37) and making travel slower (Scenarios 40, 47) results in shorter trips, but this effect is diluted after 2000 by growing affluence and greater fuel efficiency of cars. The reduction effect is strongest in the combination scenario which penalises mobility altogether (Scenario 54), whereas in the combination scenario which promotes public transport (Scenario 53), the loss of mobility is smaller.

Figure 6 (bottom) shows that the impact of the combined policies is even stronger if only car travel is considered. Here Scenario 53 shows its superiority because it results in a much stronger reduction of car-km travelled than Scenario 54, in which no attractive travel alternatives by public transport exist. Indeed the total distance travelled by car in the region is reduced by two thirds in Scenario 53.

Figure 6 : Mean trip length (top) and car-km per capita per day (bottom)

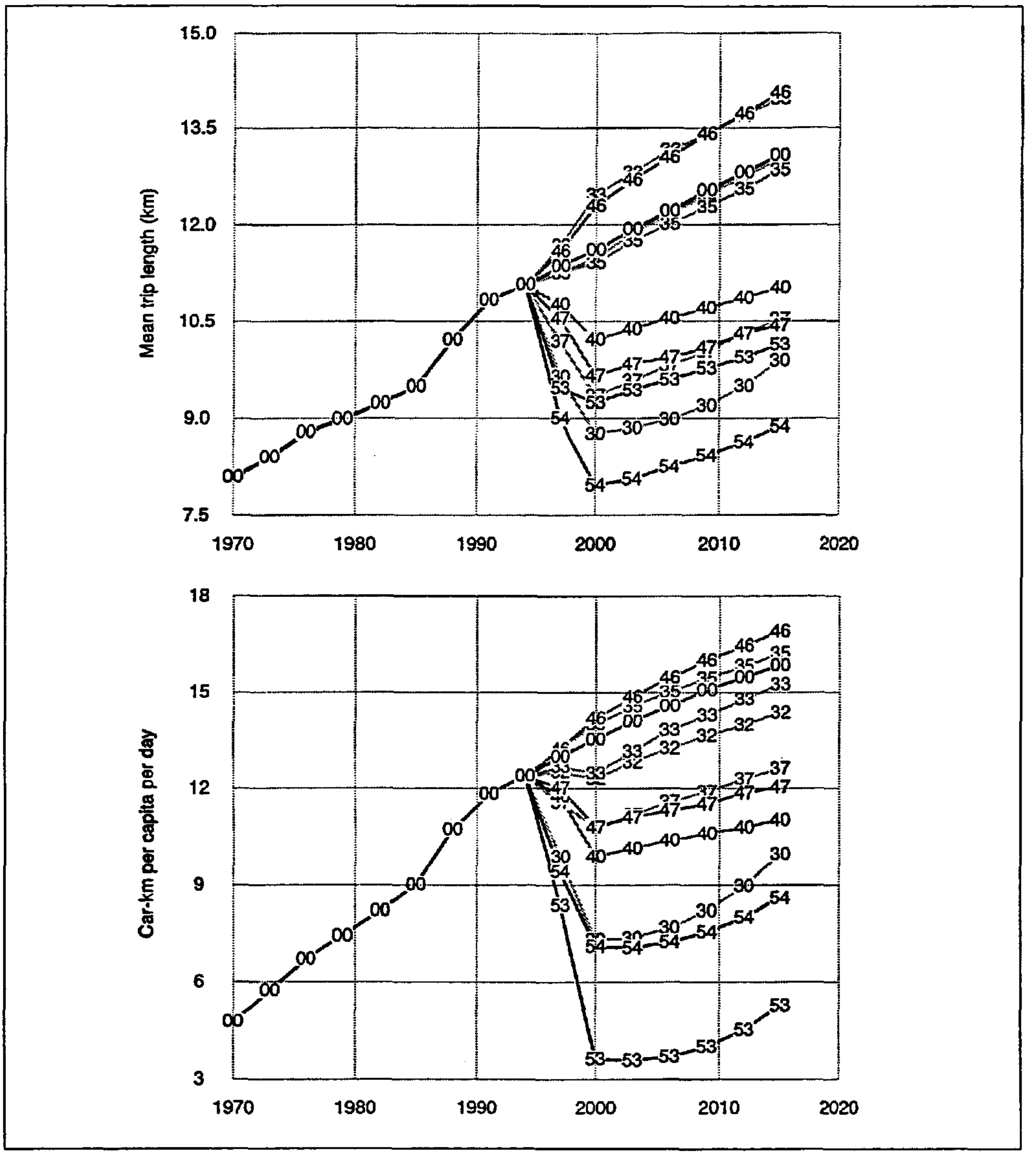
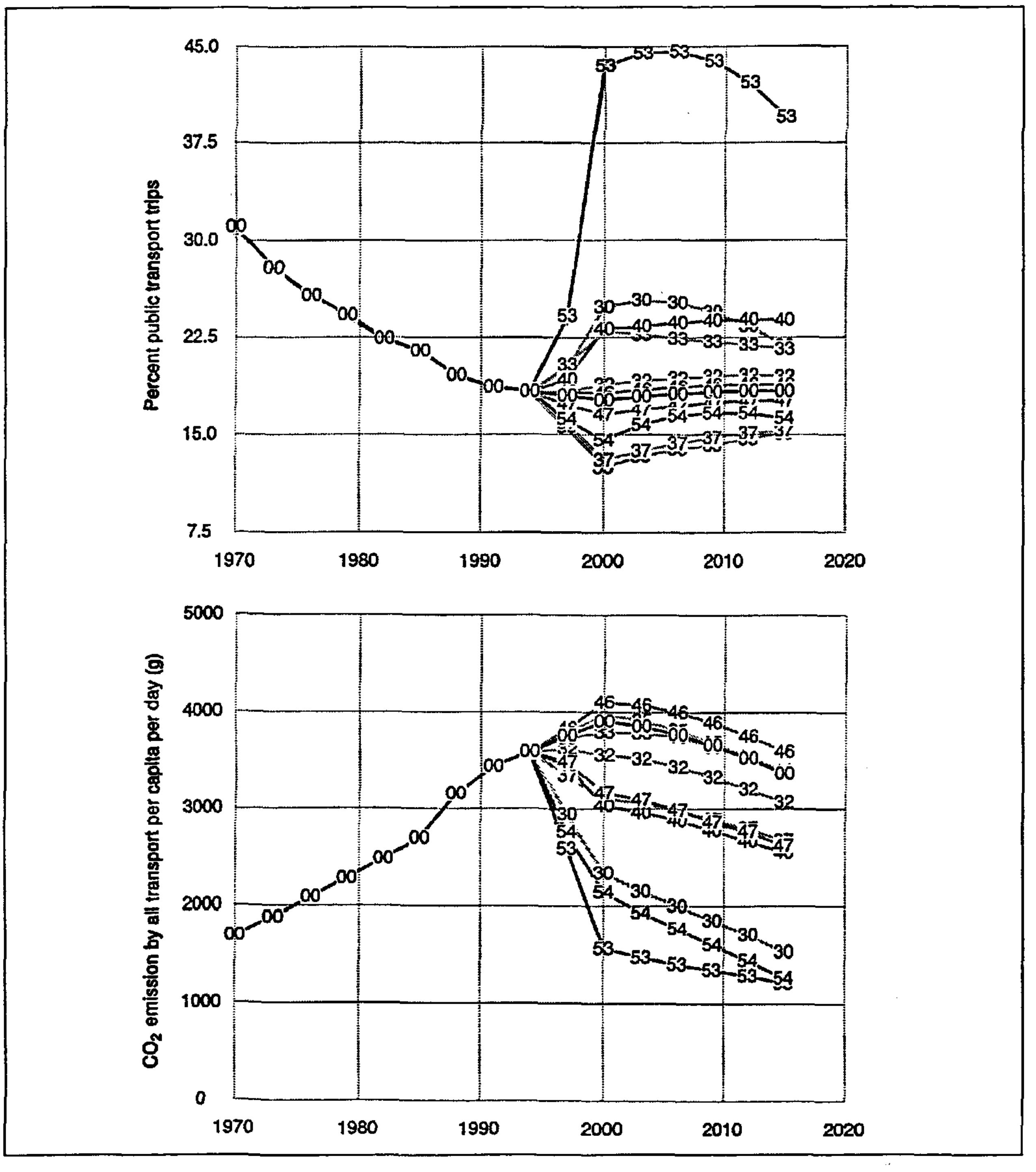


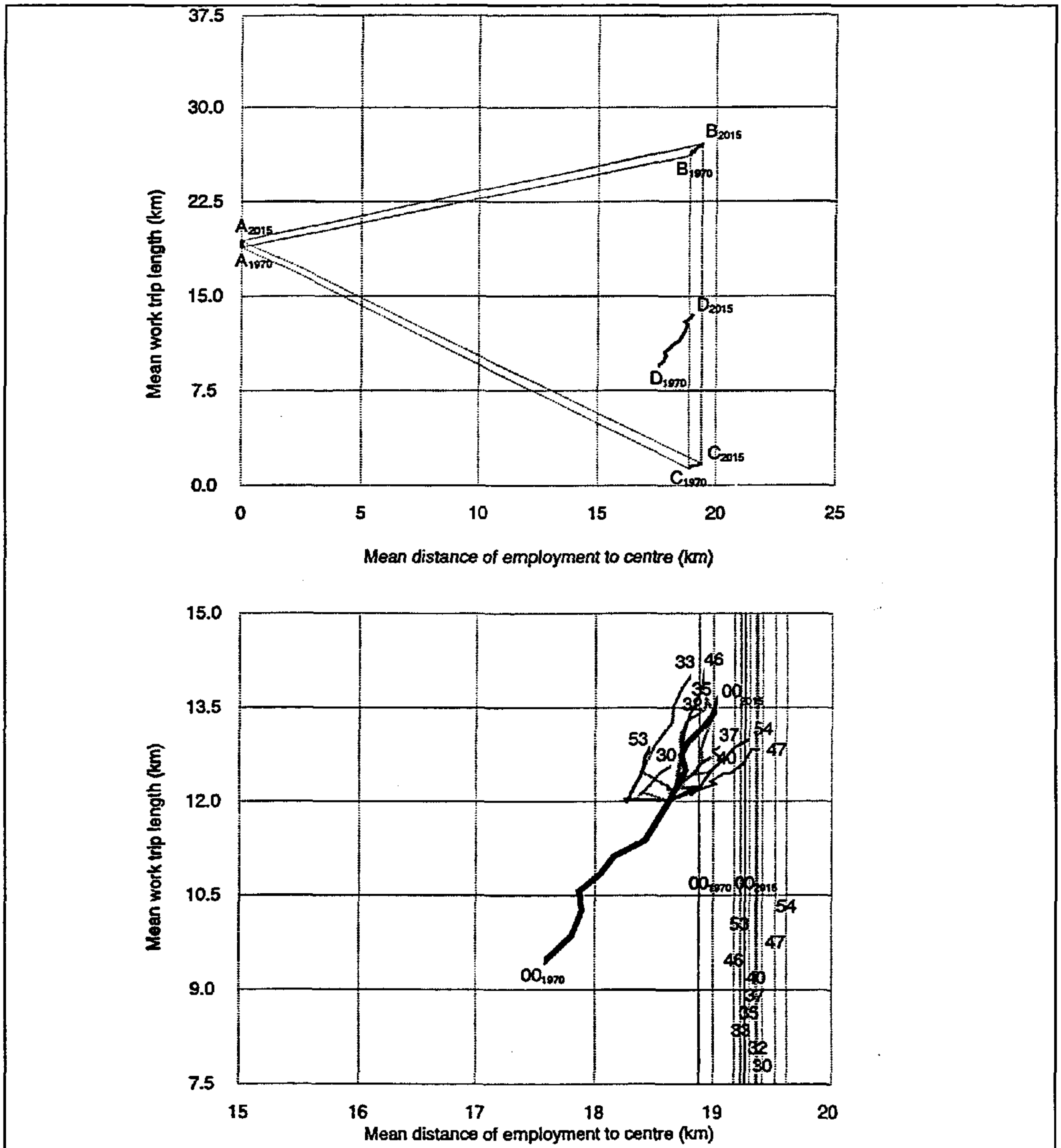
Figure 7 (top) shows that this is due to the substantial modal shift occurring in the region in that scenario. It can be seen that public transport has declined from 30 percent of all trips in 1970 to less than 20 percent today. One can see that neither massive investment in public transpon at the expense of car traffic (Scenario 40) nor making public transport free (Scenario 33) will result in substantial increases in ridership. Not even drastic increases in the out-of-pocket cost of car travel (Scenario 30) will help to revitalise public transport ; *in combination with increased fares (Scenario 54) it will even discourage public transport use.* However, if the improvement of public transport is combined with monetary disincentives to car travel (Scenario 53), the effect is a dramatic rise in public transport use to 45 percent of all journeys.

Figure 7 : Percent public transport (top) and CO2 emission of transport (bottom)



All this translates into significant savings in energy and C02 emission as shown in Figure 7 (bottom). The diagram shows the savings in energy use and CO2 emission by all transport, including the additional busses and trains necessary for the growing number of passengers. Despite the continued growth in car ownership and travel distances, total C02 emission per capita is likely to decrease after 2000 because of higher energy efficiency of cars. However, without intervention the goal to reduce C02 emission by 30 percent compared to its 1987 level cannot be achieved. In fact, none of the policies meets this target except those in which car travel is made significantly more expensive. Of these, however, Scenario *53* implies the smallest sacrifice in mobility.

Figure 8 : The «Brotchie Triangle» : base scenario (top) and all scenarios (bottom)



How much of this effect is due to changes in land use rather than travel behaviour ? Figure 8 gives some idea of this. The top diagram shows the «Brotchie Triangle» of the Dortmund urban region between 1970 and 2015. The top diagram shows how the region is drifting apart in the base scenario both in terms of employment and population. The lower diagram is a blow-up with the trajectories of the other ten scenarios added. The vertical lines indicate dispersion of population. In all scenarios the spatial structure of the region moves towards more dispersal and more travel. Changing the cost of travel has only little effect on location, but substantial effect on distance travelled. If travel speeds are changed, the impact on location is stronger. The direction of change is related to the share of public transport trips (see Figure 6, bottom). Higher shares of public transport (Scenarios 53, 30, 33) are associated with a more compact city, car-dependent cities (Scenarios 37, 40, 47, 54) tend to be more dispersed. Higher speeds (Scenario 46) lead to longer trips, whereas slower speeds (Scenarios 40, 47, 53, 54) result in energy savings. Because of their limited adjustment potential, the savings of worktrips are small compared with those of all trips (see Figure 6, top) ; this suggests that the largest savings are made with respect to «voluntary» trips to shopping and leisure.

It is frequently argued that increasing the fuel tax as in Scenario 53 would be socially unfair as it would restrict automobility to the rich. Figure 9 (left) looks into that issue. It shows car-km per household per day for four household income groups t'or Scenario 53. As one might expect, poor households (l) drive less than the middle-class (2) or the more affluent (3-4), but all households increase their distance travelled by car during the 1970s and 1980s. The drop in all four trajectories illustrates that all households are affected by the policies of Scenario 53, but that the more affluent households give up more in absolute terms, with the effect that after 2000 the ratio of car travel between the four household groups is about the same as in the 1970s and 1980s, though on a lower level.

Another concern frequently expressed is that significant increases in travel cost would lead to spatial segregation of social groups. Figure 9 (right) demonstrates that, according to the model, this is not the case. The diagram shows the development of segregation indices for the same four household income groups (1-4) and old people (5) and foreign residents (6). A segregation index of zero indicates perfect homogeneity of distribution of a group in all zones of the region, a value of 100 indicates its ghettoisation in one subregion. It can be seen from the diagram that spatial segregation in the region increases, in particular with respect to foreign residents, but that this is independent of the policies of Scenario 53, as there is no visible discontinuity at the time of their introduction.

A final argument against Scenario 53 might be that the money required to improve public transport as substantially as assumed in the scenario would be unaffordable to local governments. A simple calculation as the one shown in Table 2 demonstrates that, despite the decline in car-km travelled, the additional revenue from the increased fuel tax would be sufficient to more than double the annual expenditure of the regional public transport authority. In combination with the expected increase in fare revenue, this would allow them not only to accommodate the additional passengers by running more trains and buses, but also to significantly improve the quality of service.

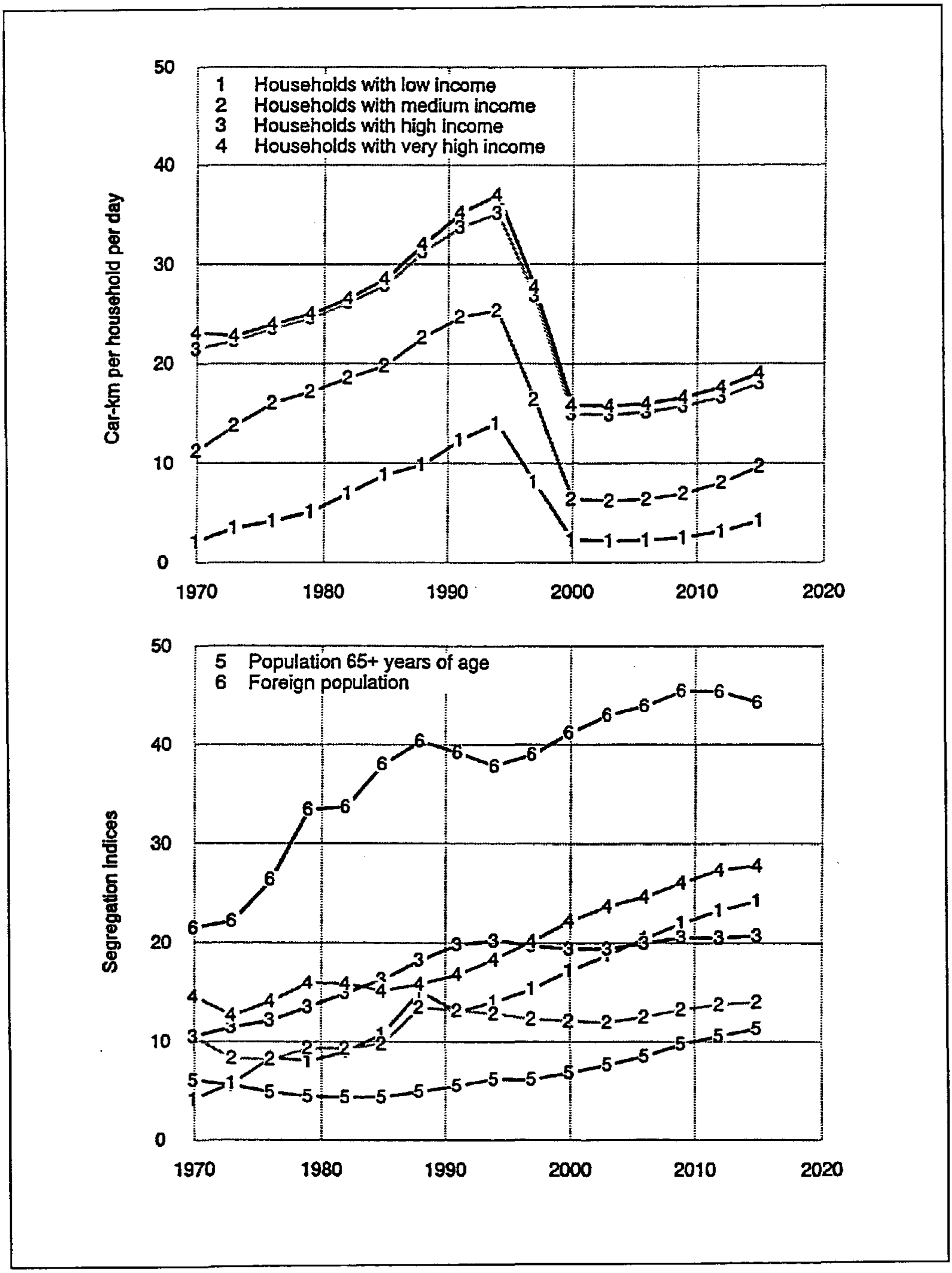
Table 3 : Financial impacts of Scenario 53

	Scenario 00 2015		Scenario 53 2015
Million car-km/year	7,748		2,578
Fuel price (DM/l)	2.7		12
Fuel tax revenue (million DM)	496		1,289
Difference (million DM)		793	
in DM 1990 (million DM)		380	
For comparison : VRR*			
Total revenues (million DM)		148	
Total expenditures (million DM)		367	
Deficit (million DM)		219	

* The Public Transport Authority Ruhr (VRR) is approximately five times as large as the study area. The numbers given were scaled down accordingly

The conclusion from these results is that a combination of policies to increase the cost of car travel and to improve the quality of public transpon would permit a significant reduction of energy use and C02 emission of urban transport without unacceptable losses of mobility, without aggravating social and spatial disparities, and without additional costs for the public authorities. Other factors not considered in the analysis, such as car sharing (increase of car occupancy), chaining of trips (reduction of number of trips), information and marketing and a potential change of values in the direction of growing environmental awareness, all work in the same direction and would contribute further to energy conservation. This implies that the present settlement system of European cities contains a huge unused potential tor reducing trip lengths and avoiding trips without fundamentally changing the physical layout of cities. This does not suggest that rebuilding our cities does not make sense, but for other, such as ecological, social or aesthetic reasons, and not for reasons of energy conservation.

Figure 9 : Social (top) and spatial (bottom) disparities in Scenario 53



Conclusions

The paper presented a theory of spatial choice synthesised from engineering, economic and social science theories about the interrelationship between transport and the spatial organisation of cities. The theory integrates ideas from spatial interaction modelling, random utility theory, bid-rent theory, social ecology and time geography into a consistent framework of actors, choices and transitions, and preferences and constraints.

Based on that theory, a mathematical simulation model of urban location and transport was presented. The model simulates intraregional location and mobility decisions of individuals or households, workers, housing investors and firms. The application of the model was demonstrated by a project in which the model was used to explore possibilities to reduce energy consumption in cities by travel demand management.

The conclusion drawn from the paper is that transport and spatial organisation in cities are closely interrelated, and that this relationship can be analysed and modelled combining theories from engineering, economics and the social sciences. The model application has shown that planning can influence both spatial organisation and transport, but that, because of the inherent inertia of the spatial organisation of cities, transport polices are much more effective, if energy consumption and emission of C02 by urban transpon are to be reduced.

References

ALLEN P.M., M. SANGLIER and F. BOON (1981) : *Models of Urban Settlement and Structure as Self-Organizing Systems.* Washington, DC : US Department of Transportation

ALONSO W. (1964) : *Location and Land Use: Towards a General Theory of Land Rent.* Cambridge, MA : Harvard University Press

ANAS A. (1982) : *Residential Location Markets and Urban Transportation.* New York : Academic Press

ANAS A. (1983) : Discrete choice theory, information theory and the multinomial logit and gravity models. *Transportation Research* 178, 13-21

BAHRDT H.-P. (1969) : *Die moderne GroBstadt.* Hamburg : Wegner

BOYCE D.E., L.J. LEBLANC, K.S. CHON, Y.L. LEE and K.T. LIN (1981) : *Combined Models of Location, Destination, Mode and Route Choice :* An *Unified Approach Using Nested Entropy Constraints.* Publication N° 3. Transportation Planning Group, Department of Civil Engineering. Urbana, IL : University of Illinois

BREHENY M.J., ed. (1992) : *Sustainable Development and Urban Form.* European Research in Regional Science 2. London : Pion, 1-23

BROTCHIE J.F. (1984) : Technological change and urban lorm. *Environment and Planning A 16,* 583-596

CASTELLS M. (1977) : *The Urban Question.* London : Edward Arnold.

CHAPIN F.S. (1965) : *Urban Land Use Planning.* Urbana, IL : University of Illinois Press

CHAPIN F.S. and S.F. WEISS (1968) : A probabilistic model for residential growth. *Transportation Research* 2, 375-390

COELHO J.D. and H.C.W.L. WILLIAMS (1978) : On the design of land use plans through locational surplus maximisation. *Papers of the Regional Science Association 40, 71-85*

DENDRINOS D.S., MULLALY H. (1985) : *Urban Evolution: Studies in the Mathematical Ecology of Cities.* Oxford : Oxford University Press

GERALDES P., M.H. ECHENIQUE and I.N. WILLIAMS (1978) : *A Spatial Economic Model for Bilbao.* Proceedings of the PTRC Summer Annual Meeting. London : PTRC, Stream M, 75-94

GOFFMAN E. (1959) : *Behavior in Public Places: Notes on the Social Organization of Gatherings.* New York : The Free Press

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

HAGERSTRAND T. (1970) : What about people in Regional Science ? *Papers of the Regional Science Association 24,* 7-21

HANSEN W.G. (1956) : How accessibility shapes land use. *Journal of the American Institute of Planners 25,* 73-76

HARVEY D. (1973) : *Social Justice and the City.* London: Edward Arnolds.

JONES P.M. (1979) : New approaches to understanding travel behaviour: the human activity approach. In : Hensher, D.A., P.R. Stopher, ed. (1979) : *Behavioral Travel Modeling,* London : Croom Helm, 55-80

LEONARDI G. (1981) : A general accessibility and congestion-sensitive multi-activity spatial interaction model. *Papers of the Regional Science Association 47,* 3-17

LEFEBVRE H. (1968) : *La vie quotidienne dans le monde moderne.* Paris : Gallimard

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

LUCE R.D. (1959) : *Individual Choice Behavior.* New York : J. Wiley

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

MCFADDEN D. (1973) : Conditional logit analysis and qualitative choice behavior. In : P. Zarembka, ed. (1973) : *Frontiers in Econometrics*. New York : Academic Press, 105-142

NIJKAMP P. and E.S. MILLS, eds. (1987) : *Handbook of Regional and Urban Economics*. Amsterdam : North Holland, Vol. 2

NIJKAMP P. and A. REGGIANI (1992) : Interaction, Evolution and Chaos in Space. Berlin/Heidelberg/New York : Springer Verlag

PARK R.E., F.W. BURGESS and R.D. MACKENZIE (1925) : *The City*. Chicago : Chicago University Press

PARK R.E. (1936) : Human Ecology. *The American Journal of Ecology 42*, 1-15

PUTMAN S.H. (1983) : *Integrated Urban Models*. London : Pion

PUTMAN S.H. (1992) : *Integrated Urban Models 2*. London : Pion

RAVENSTEIN E.G. (1885) : The laws of migration. *Journal of the Royal Statistical Society* 43 : 167-235

SEO F. (1989) : A Neoclassical Approach to Treating the Land Price Formation in a Great Metropolitan Area. Paper presented at the 11th Pacific Regional Science Conference, Singapore, 3-6 July 1989

SMITH N. (1979) : Toward a theory of gentril;cation: a back to the city movement by capital, not people. *Journal of the American Planning Association 4*, 538-548

SMITH N. and P. WILLIAMS, eds. (1986) : *Gentrifrication of the City*. London : Winchester

SNICKARS F. and J.W. WEIBULL (1976) : A minimum information principle. *Regional Science and Urban Economics* 7, 137-168

WEBSTER F.V., P.H. BLY and N.J. PAULLEY, eds. (1988) : *Land-Use Transport Interaction : Policies and Models*. Aldershot : Avebury

WEGENER M. (1983) : *Description of the Dortmund Region Model*. Arbeitspapier 8. Dortmund : Institut fur Raumplanung, Fachbereich Raumplanung der Universität Dortmund

WEGENER M. (1984) : Raumliches Wahlverhalten unter ökonomischen und informationellen Restriktionen: ein mikroanalytisches Modell des Wohnungsmarkts. *Bremer Beitrage zur Geographie und Raumplanung 5*, 92-136

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

WEGENER M (1986) : Integrated forecasting models of urban and regional systems. *London Papers in Regional Science 15, Interated Analysis of Regional Systems*, 9-24

WEGENER M., F. GNAD and M. VANNAHME (1986) : The time scale of urban change. In : B. Hutchinson and M. Batty, eds. (1986) : *Advances in Urban Systems Modelling*. Amsterdam : North Holland, 145-197

WEGENER M. (1993) : *The End of the Industrial City*. Berichte aus dem Institut für Raumplanung 37. Dortmund : Institut für Raumplanung.

WEIDLICH W. and G. HAAG (1983) : *Concepts and Models of a Quantitative Sociology - the Dynamics of Interacting Populations*. Berlin/Heidelberg/New York : Springer Verlag

WEIDLICH W. and G. HAAG (1988) : *Interregional Migration, Dynamic Theory and Comparative Analysis*. Berlin/ Heidelberg/New York : Springer Verlag

WILLIAMS H.C.W.L and M.L. SENIOR (1978) : Accessibility, spatial interaction and the spatial benefit analysis of land-use transportation plans. In : A. Karlqvist, L. Lundqvist, F. Snickars and J.W. Weibull, eds. (1978) : *Spatial Interaction Theory and Planning Models*. Amsterdam : North-Holland, 253-287

WILLIAMS I.N. and M.H. ECHENIQUE (1978) : *A Regional Model Jor Commodity and Passenger Flows*. Proceedings of the PTRC Summer Annual Meeting. London : PTRC, Stream F, 121-128

WILSON A.G. (1967) : A statistical theory of spatial distribution Models. *Transportation Research 1*, 253-269

WILSON A.G. (1970) : *Entropy in Urban and Regional Models*. London : Pion

WILSON A.G. (1981) : *Catastrophe Theory and Bifurcation. Applications to Urban and Regional Systems.* London : Croom Helm

ZIPL G.K. (1949) : *Human Behaviour and the Principle of Least Effort*. Carnbridge, MA : Addison Wesley