DISSERTATION
Doctoral Thesis

The strategic, dynamic and integrated urban land use and transport model MARS (Metropolitan Activity Relocation Simulator)

Development, testing and application

ausgeführt zum Zwecke der Erlangung des akademischen Grades
Doktor der technischen Wissenschaften

am

Institut für Verkehrsplanung und Verkehrstechnik, E231
Technische Universität Wien

unter der Leitung von

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Wien, im September 2003

ABSTRACT

Sustainability is one of today's major public concerns. There is evidence that transport and land use systems of cities all over the world are unsustainable. Indicators backing up this hypothesis are among others: urban sprawl, pollution and consumption of non-renewable resources. As urban planning has become increasingly complex, decision support tools are essential to help to achieve the overall objective of sustainability. Recent research has shown that any single policy instrument cannot achieve sustainability. Policy strategies employing several instruments are needed to be successful. The use of formal models and optimisation methods is suggested to be used to identify the best performing strategy.

Research of the last decades has shown that land use and transport form a closely linked dynamic system. Therefore integrated land use and transport models are needed to assess the performance of urban policy strategies. A literature review has shown that a variety of operational transport and/or land use models exists. The current trend in land use and transport modelling is characterised by an extreme dis-aggregation even down to individual household level. This extremely detailed modelling approach is, independently from its theoretical appeal, inappropriate for identifying sustainable policy strategies. Despite the ever-increasing computational power, model runs take too long to be able to consider a reasonable number of instruments. Additionally data needs are very high. Even synthetic data have to be produced to match the level of model dis-aggregation. Data requirements might be one of the reasons why the use of integrated land use and transport models is still not widespread.

A different approach was therefore chosen for the work presented here. The rather high aggregated integrated, dynamic urban land use and transport model MARS (**M**etropolitan **A**ctivity **R**elocation **S**imulation) was developed as the core of a sustainability assessment framework. The underlying hypothesis is that cities are self-organising systems and that the principles of synergetics can be applied to describe collective behaviour.

A qualitative model was developed based on Viennese research. The method of causal loop diagrams was used for this task. From this basis a quantitative model was built and written into code. MARS was calibrated for the city of Vienna. An extensive model-testing program was carried out using observed data from 1981 to 2001. A back casting exercise and sensitivity tests have proven the usability of MARS. Nevertheless some weak points were identified. It was possible to find explanations for them. Potential fields for future improvements were identified and ranked.

A case study with the Vienna MARS model was carried out. Transport projects currently planned and under construction were assessed towards their contribution to official Viennese city planning objectives. An appropriate policy strategy to achieve these goals was identified using formal optimisation procedures.

KURZFASSUNG

Nachhaltigkeit wird von der Öffentlichkeit als wichtige Herausforderung wahrgenommen. Es gibt zahlreiche Befunde, die zeigen, dass weltweit städtische Verkehrssysteme und städtische Flächennutzung nicht nachhaltig sind. Indikatoren, die diese These unterstützen, sind z.B.: Zersiedelung, Luftverschmutzung und der Verbrauch nicht erneuerbarer Ressourcen. Stadtplanung wurde und wird immer komplexer. Um das übergeordnete Ziel Nachhaltigkeit zu erreichen, ist der Einsatz formaler Werkzeuge zur Unterstützung der Entscheidungsfindung sinnvoll. Forschungsarbeiten haben gezeigt, dass Nachhaltigkeit nicht durch die Umsetzung einer einzelnen Maßnahme erreicht werden kann. Um erfolgreich zu sein, ist es vielmehr notwendig Strategien, bestehend aus einer Kombination von Maßnahmen, anzuwenden. Um die beste Strategie zu finden, wird der Einsatz von Modellen und Optimierungsmethoden vorgeschlagen.

Die Forschung der letzten Jahrzehnte hat gezeigt, dass die Flächennutzung und der Verkehr ein eng gekoppeltes dynamisches System bilden. Integrierte Flächennutzungs- und Verkehrsmodelle sind daher notwendig, um die Leistungsfähigkeit städtischer Planungsstrategien zu beurteilen. Eine Literaturrecherche hat gezeigt, dass eine Bandbreite an einsatzfähigen Verkehrs- und/oder Flächennutzungsmodellen existiert. Der Trend geht dabei in Richtung extremer Disaggregierung bis hin zur modellhaften Abbildung der einzelnen Personen und Haushalte. Dieser radikale Modellansatz ist, unabhängig von seinem theoretischen Reiz, wenig geeignet, um komplexe Strategien zu identifizieren. Trotz der ständig steigenden Computerleistung sind die Laufzeiten zu lang, um eine ausreichende Zahl möglicher Kombinationen zu untersuchen. Zusätzlich sind die Anforderungen an die Daten sehr hoch. Um den angestrebten räumlichen Detailgrad zu erreichen, müssen teilweise künstliche Daten produziert werden. Die Datenanforderungen sind einer der Gründe dafür, dass integrierte Flächennutzungs- und Verkehrsmodelle noch immer wenig in Verwendung sind.

In der hier präsentierten Arbeit wurde ein anderer Ansatz gewählt. Das aggregierte, integrierte, dynamische Flächennutzungs- und Verkehrsmodell MARS (**M**etropolitan **A**ctivity **R**elocation **S**imulation) wurde als Kernstück eines Systems zur Beurteilung der Nachhaltigkeit entwickelt. Die zugrundeliegende Hypothese ist, dass Städte selbstorganisierende Systeme sind und daher die Prinzipien der Synergetik zur Beschreibung des kollektiven Verhaltens anwendbar sind.

Aufbauend auf Wiener Forschungsergebnissen wurde zuerst ein qualitatives Modell erstellt. Dabei kam die Methode der Causal-Loop-Diagramme zur Anwendung. Auf dieser Basis wurde ein quantitatives Modell entworfen und in Computercode transformiert. MARS wurde mit Daten der Stadt Wien kalibriert. Ein umfangreiches Testprogramm wurde unter Verwendung von Daten der Periode 1981 bis 2001 durchgeführt. Die Simulation der Periode 1981 bis 2001 und Sensitivitätsanalysen haben die Anwendbarkeit von MARS nachgewiesen. Dabei wurden aber auch einige Schwachpunkte aufgezeigt. Es war möglich, für alle Punkte Erklärungen zu finden. Gereihte Vorschläge für mögliche zukünftige Verbesserungen wurden gemacht.

Eine Fallstudie der Stadt Wien wurde ausgeführt. Verkehrsprojekte, die in Planung oder bereits in Umsetzung sind, wurden hinsichtlich ihres Beitrags zu offiziellen Zielen untersucht. Unter Verwendung einer formalen Optimierungsmethode wurde eine Strategie ermittelt, welche diese Ziele erreichen kann.

CONTENTS

1. INTRODUCTION

1.1 Background and rationale

Sustainability is one of today's major concerns. Sustainability can be defined by two characteristics (May, A. D. et al., 2003) p. 12:

- it includes both the welfare of the present society and of the society of the very distant future and
- it implies conservation of natural resources.

Urban agglomerations grow rapidly, causing severe transport and environmental problems. Decision makers and planners try hard to achieve the overall goal of sustainable development. But cities all over the world are still in an unsustainable state.

Interaction between transport planning, land-use planning and regional economy is highly complex. The numerous feedback loops within and between transport, land use and economy are effective on different temporal and spatial levels. As a result even effects caused by the change of a single policy instrument can be difficult to predict. Especially as, in reality, most decision-making processes have to take into account a combination of different policy instruments. In addition numerous different protagonists are involved on different administrative and legislative levels. Politicians as well as planners make their decisions under these circumstances (Figure 1.1). Negotiation and participation processes are necessary at the forefront of strategy implementation. A tool, which predicts effects caused by different possible actions, is highly welcome in this context.

Formal models are appropriate to be used as such a tool[1]. The use of transport models has a rather long tradition in planning. But the assumption that land use is constant is state of the practice in most transport modelling. In contrast to this practice it is common knowledge amongst planners that land use and transport are parts of a dynamic system that are linked together by time lagged feedback loops[2]. Although this fact has been recognised at least in the early Seventies of the last century[3], operational **L**and **U**se and **T**ransport **I**ntegrated (LUTI) models are still

[1] *The goal of modelling, and of scientific endeavor more generally, is to build shared understanding that provides insight into the world and helps to solve important problems. ... Experienced modelers likewise recognise that the goal is to help their clients make better decisions, decisions informed by the best available model.*
Sterman, J. D. (2000). Business Dynamics - Systems Thinking and Modeling for a Complex World; McGraw-Hill Higher Education, p. 850.

[2] *That urban land use and transport are closely inter-linked is common wisdom among planners and the public.* Wegener, M. (2003). Overview of land-use and transport models. CUPUM03 - The 8 th International Conference on Computers in Urban Planning and Urban Management, Sendai, Japan, Center for Northeast Asian Studies, Tohoku University.

[3] E.g.: *The overall system "settlement" is therefore a dynamic system with feedback loops.* (My paraphrase, original in German: Wermuth, M. (1973). Genauigkeit von Modellen zur Verkehrsplanung. Veröffentlichungen des Instituts für Stadtbauwesen, Technische Universität Braunschweig. Braunschweig, O. Prof. Dipl. Ing. H. Habekost. **12**. p. 62).

not widespread. But in line with increasing computational power their number is increasing[4].

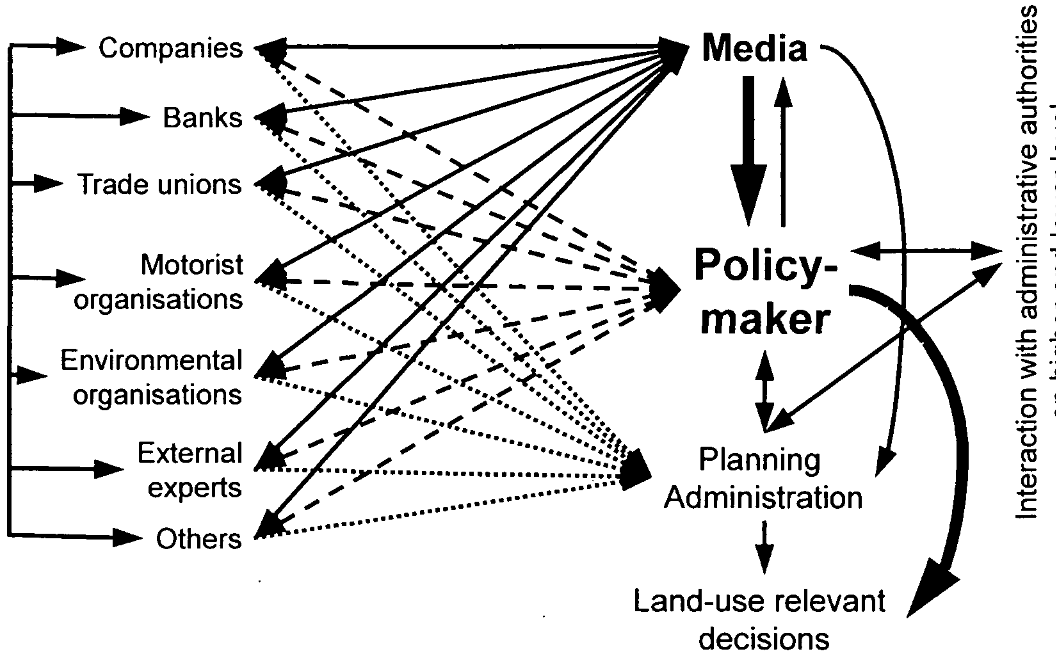

Figure 1.1: Interaction between different players involved in urban land-use and transport decision making processes (Knoflacher, H. et al., 2000)

Sustainability is a long term, strategic objective. To assess long-term effects of numerous competing possible strategic decisions, extreme accuracy of the predictions is not the crucial matter. Characteristics like availability of necessary data, low expenditure to set up the model and a short run time are more essential for the suitability as a tool to support strategic urban decision making processes. Therefore it was decided to develop a strategic, dynamic and integrated land use and transport model. This model should take into account the essential links and feedbacks within and between land use and transport and fulfil the other requirements described above. Furthermore the model should be able to be used in a sustainability appraisal framework[5].

[4] *The number of real-world applications of models falling under the above definition has increased steadily over the last two decades.* Wegener, M. (2003). Overview of land-use and transport models. CUPUM03 - The 8 th International Conference on Computers in Urban Planning and Urban Management, Sendai, Japan, Center for Northeast Asian Studies, Tohoku University.

[5] May, A. D., Karlstrom, A., Marler, N., Matthews, B., Minken, H., Monzon, A., Page, M., Pfaffenbichler, P. C. and Shepherd, S. P. (2003). Developing Sustainable Urban Land Use and Transport Strategies - A Decision Makers' Guidebook; Institute for Transport Studies, University of Leeds, Leeds.and
Minken, H., Jonsson, D., Shepherd, S. P., Järvi, T., May, A. D., Page, M., Pearman, A., Pfaffenbichler, P. C., Timms, P. and Vold, A. (2003). Developing Sustainable Land Use and Transport Strategies - A Methodological Guidebook; *TOI Report*, **619**; Institute of Transport Economics, Oslo.

Substantial part of the work presented in this thesis is based on the experience gained in several European research projects[6]. In these projects the basic strategic modelling concept as well as the assessment framework was applied on and tested in several European cities[7].

1.2 Objectives and methodology

The background objective of this thesis is to contribute to the achievement of the overall goal of sustainability. Transport and land use related problems are most severe in cities; therefore this thesis focuses on the urban scale. The aim is to develop a strategic, dynamic and integrated urban land use and transport model. The resulting model is named MARS (**M**etropolitan **A**ctivity **R**elocation **S**imulator). MARS is intended to form the core part of a decision support tool. MARS is embedded in a sustainability appraisal framework.

A literature review was performed to analyse existing approaches in land use and transport modelling. The next step was basic research of the behaviour of urban systems with a special focus on urban sprawl. The qualitative method of **C**ausal **L**oop **D**iagramming (CLD) was used in this analysis. The cause-effect-relations found in the qualitative analysis were quantified by using results from the literature review and various regression analyses with observed data from the city of Vienna. **V**isual **B**asic for **A**pplications (VBA)[8] was used to transform the quantified cause-effect relations into code. Microsoft Excel spreadsheets are used as in- and output interface. A MARS model for the city of Vienna was set up and calibrated. An extensive model-testing programme was performed. In a back-casting exercise the MARS simulation results were compared with empirical data. Different statistical methods and indicators were used to measure the ability of MARS to reproduce the historical Viennese developments. Sensitivity tests for different policy instruments were carried out. A case study was performed to illustrate the possibilities to use the MARS model.

1.3 Structure of the thesis

This thesis can be subdivided into five broad parts. Chapter 2. Review of land use and transport modelling is the first part which summarises theoretical approaches in land use and transport modelling, gives an overview about the history and tradition of land use and transport modelling and presents a selection of operational land use and transport models.

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[6] 4th RTD framework. OPTIMA (**O**ptimisation of **P**olicies for **T**ransport **I**ntegration in **M**etropolitan **A**reas), FATIMA (**F**inancial **A**ssistance for **T**ransport **I**ntegration in **M**etropolitan **A**reas), SAMI (**S**trategic **A**ssessment **M**ethodology for the **I**nteraction of Common Transport Policy Instruments). 5th RTD framework: PROSPECTS (**P**rocedures for **R**ecommending **O**ptimal **S**ustainable **P**lanning of **E**uropean **C**ity **T**ransport **S**ystems).

[7] The model presented here stems from a model developed in the 5th framework project PROSPECTS. A description of this version is given in Pfaffenbichler, P. and Shepherd, S. P. (2002). "A Dynamic Model to Appraise Strategic Land-Use and Transport Policies." *European Journal of Transport and Infrastructure Research* **2** (3/4): 255-283.

[8] VBA is the property of Microsoft Corp.

Part 2 is formed by the chapters 3. Qualitative Description of the Dynamic Transport and Land Use Interaction Model MARS and 4. Quantitative description of the Dynamic Transport and Land Use Interaction Model MARS and describes the MARS model in a qualitative and quantitative way.

Part 3 consists of the chapters 5. Calibration of the Viennese MARS model and 6. Model Testing. Part 3 presents the results of the Vienna model calibration and testing.

Part 4 comprises of chapter 7. A framework for finding optimal policy packages and 8. Vienna Case study. Part 4 shows how MARS is embedded in a sustainability assessment and optimisation framework and illustrates its application and use with a Viennese case study.

Part 5 (chapter 9. Conclusions) sums up the results of the parts 1 to 4. Conclusions concerning the position of MARS within the variety of existing models, the performance of MARS, policy recommendations from the case study and future need for research are drawn.

An extensive annex (chapter 11) presents summaries of basic underlying principles and theories as well as a compilation of the data used to set up and test the Vienna MARS model.

2. REVIEW OF LAND USE AND TRANSPORT MODELLING

2.1 Introduction

The aim of this section is first to clarify the meaning of the terms "model" and "simulation" as they are understood in the context of this thesis. Furthermore a brief overview about theories, history, state of practice, state of art and future developments in transport, land use and integrated transport land use modelling will be given. Finally the position of MARS within the land use and transport modelling framework will be shown and conclusions will be drawn.

2.2 What is a "model"?

The term "model" can have a wide range of different meanings in different contexts, from model airplanes to fashion models, from software tools to small-scale buildings. This section therefore aims at clarifying what the term "models" stands for in the context of this thesis. If the term "model" is used as a noun, the "New Shorter Oxford English Dictionary" ("Oxford University Press", 1997) gives the following definitions. The three major semantic divisions are:

I. *Representation of structure.*

II. *Type of design.*

III. *An object of imitation.*

The term "model", as it is used here, belongs to point I. "*Representation of structure*". The most suitable definition under this heading is:

2 e A simplified description of a system, process, etc., put forward as a basis for theoretical or empirical understanding; a conceptual or mental representation of something. E20. ("Oxford University Press", 1997)

As long as nothing else is stated, the term "model" stands for a transport or a transport and land use integrated model in this thesis. Transport is: *"3 A system or means of transportation or conveyance of people, goods, etc.; spec. (Mil.) a ship, aircraft, etc., used to carry soldiers or supplies (also transport-ship, transport-plane, etc.). L17."* ("Oxford University Press", 1997) and the term "transport model" as used in this work is defined as:

"A transport model is the simplified description of a system transporting goods and/or people, put forward as a basis for theoretical and empirical understanding and especially designed to facilitate predictions."

In philosophy of science models are linked very closely with scientific theories and vice versa. To draw a clear line between the two is sometimes impossible. A distinctive feature is that models refer to a limited sector of reality whereas theories cover a wider part of reality (full arrows in Figure 2.1). Models can be a preliminary stage in the development of a scientific theory. This is represented in Figure 2.1 by the dotted arrows from models (M) to theories (T). On the other side theories can become input into models. A theory from one discipline can be used as a model in another discipline, e.g. the analogy to the law of gravity applied to transport modelling. This is represented in Figure 2.1 by the dashed arrow from T to M. If a comprehensive theory is available, models become (strictly speaking) unnecessary. But for practical reasons it can still be sensible to use a model. E.g. if only a certain sector of reality is of interest or the calculation of all aspects would exceed the available resources. Transport planning and traffic engineering should deal with the whole range of human activities. The involvement of autonomous deciding human beings makes it impossible to find one comprehensive theory covering all aspects of transport. Therefore supportive use of models is and will be necessary.

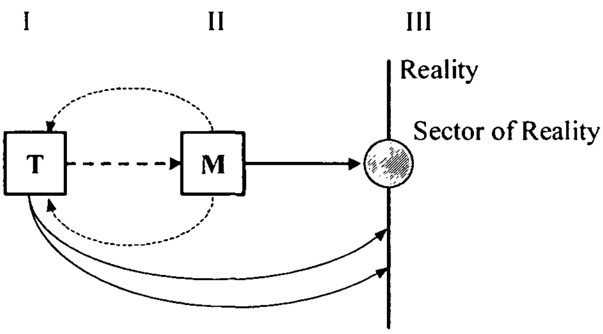

Figure 2.1: Relationship scientific theory - model

Legend:

T .... Scientific theory

M .... Model

As stated above, models cover a limited sector of reality, which is in our case the transport and/or land use sector. The focus of transport and/or land use models can vary in a wide range. The term "transport (and land use) model" includes numerous different model classes. The classification can follow different aspects. Obvious sub-divisions are that into freight and passenger transport models or into residential and workplace location models. Models can be qualitative or quantitative. They can be aggregated or disaggregated. A list of possible model classification is given in Table 2.1.

Table 2.1: Possible classifications of models

Physical	Abstract
Quantitative	Qualitative
Static	Dynamic
Causal	Correlative
Aggregate	Disaggregate
Transparent	Black box
Predictive	Prescriptive
Empirical	Synthetic

The model MARS which is the subject of this thesis is an abstract model. It is as well a quantitative as a qualitative model. Furthermore MARS is a dynamic model. Whether it is a causal or a correlative model depends on the viewpoint. The calculations are causal, but the results should be interpreted as probabilities. In line with its strategic nature MARS is an aggregated model. This thesis tries to present MARS as transparent as possible and therefore to avoid being a black box type model. MARS can be used as well in a predictive as in a prescriptive way.

Nevertheless it is mainly intended to be used to predict what will happen in a do-minimum scenario and/or in the case of the application of different policy strategies. But it can also be used in a prescriptive way, i.e. to define what has to happen to reach a certain objective[9]. MARS is based on empirical data rather than on synthetic ones.

2.3 What is a "simulation"

According to the "New Shorter Oxford English Dictionary" (Oxford University Press, 1997) "to simulate" is to:

3 Imitate the conditions of (a situation or process), esp. for the purpose of training etc.; spec. produce a computer model of (a process). M20.

MARS as a computer model is used to simulate the process of the development of urban land use and transport over a period of time. It is designed to simulate the effects of different interventions in the urban system and to compare the results with the option of doing nothing.

2.4 A brief review of transport modelling

2.4.1 From first qualitative analogies to first quantitative transport models

The analogy to the law of gravity could be seen as the first transport model in history (Erlander, S. and Stewart, N. F., 1990) p. 27:

"Carey (1858) was probably the first one to state the idea underlying the gravity model, i.e. that the number of trips is proportional to the attractive forces and inversely proportional to the distance. Similar ideas were used by Ravenstein (1885) in his study of migration. Carey and Ravenstein presented their arguments in prose without using any formulae."

The law of gravity (Equation 2.1) was first published by Sir Isaac Newton in the year 1687 (Philosophiae Naturalis Principa Mathematica).

$$F = \gamma * \frac{m_1 * m_2}{R^2}$$

Equation 2.1: Law of gravity

Legend:

F................Force of attraction [N]

γ................Constant factor ($6.67*10^{-11}$ Nm^2/kg^2)

m_1................Mass 1 [kg]

m_2................Mass 2 [kg]

r................Distance between mass 1 and 2 [m]

Eduard Lill, an Austrian railway engineer, formulated his law of travel in the year 1889. It is obvious that Lill's law is formal equivalent to Newton's law of gravity and is one of the first quantitative transport models (Equation 2.2).

[9] Both ways of using MARS are demonstrated in the case studies in chapter 8. Vienna Case study.

$$r = \frac{M}{k^2}$$

Equation 2.2: Travel Law by Lill (Lill, E., 1889) p. 700

Legend:

r .... Number of travellers arriving at a railway station from a certain origin

M .... Travel value of the origin

k .... Distance between origin and destination

2.4.2 From the first quantitative models to the state of the practice

Today the state of the practice in passenger transport modelling is a four stage, sequential algorithm (Figure 2.2). Figure 2.2 shows a "Trip-Interchange-Model". In a "Trip-End-Model" the order of calculations of the stages distribution and mode choice would be changed.

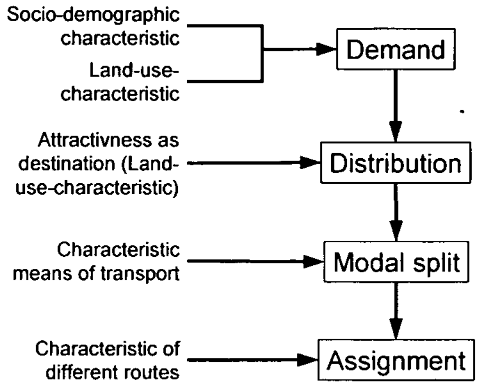

Figure 2.2: Four stage, sequential transport modelling approach

Existing literature provides a comprehensive overview about different state of the practice modelling approaches[10]. Therefore only a brief overview is given here. Table 2.2 summarises modelling approaches used in the four stages of today's common transport models.

[10] E.g.: Dorfwirth, J. R., Gobiet, W. and Sammer, G. (1980). Verkehrsmodelle - Theorie und Anwendung; *Straßenforschung*, **137**; Bundesministerium für Bauten und Technik, Wien.
Mensebach, W., Corell, C., Gordan, P. and Wilhelmy, T. (1994). Straßenverkehrstechnik, **3. Auflage**; Werner-Verlag, Düsseldorf.
Schnabel, W. and Lohse, D. (1997). Grundlagen der Straßenverkehrstechnik und der Verkehrsplanung, **Band 2: Verkehrsplanung**; Verlag für Bauwesen, Berlin.
Hensher, D. A. and Button, K. J., Eds. (2000). Handbook of Transport Modelling. Handbooks in Transport, Pergamon.
Köhler, U., Zöllner, R., Wermuth, M. and Emig, J. (2001). Analyse der Anwendung von Verkehrsnachfragemodellen; *Forschung Straßenbau und Straßenverkehrstechnik*, **Heft 804**; Bundesministerium für Verkehr, Bau- und Wohnungswesen, Abteilung Straßenbau, Straßenverkehr, Bonn.

Table 2.2: Summary transport modelling approaches

Stage	Sub-model
Demand	• Expansion factor method • Trip rate methods • Regression method
Distribution	• Growth factor methods (Fratar) • Gravity model • Intervening opportunities • Competing opportunities
Mode choice	• Linear probability model • PROBIT model • LOGIT model

Assignment	• All or nothing assignment
	• Congested assignment methods
	    o Repeated all or nothing methods
	    o Incremental methods
	    o Iterative methods
	    o Equilibrium assignment
	• Stochastic methods
	    o Monte-Carlo based methods
	    o Proportional methods

It is worth mentioning that in principle most of the modelling approaches already exist for a quite long time[11]. They became operational with increasing availability of computational power. E.g. gravity models are still state of the practice as distribution sub-models. Gravity models can be written in general form as follows:

$$F_{ij} = k * Q_i * A_j * f(w_{ij})$$

Equation 2.3: General form of the gravity model, (Köhler, U. et al., 2001) p. 21

Legend:

F_{ij}................Number of trips from source i to destination j

k..................Constant factor

Q_i................Trip production at source i

A_j.................Attractiveness of destination j

w_{ij}................Mobility impedance for a trip from i to j

For the special case of Newton's law of gravity the mobility impedance has the following form:

$$f(w_{ij}) = \frac{1}{w_{ij}^2}$$

Equation 2.4: Mobility impedance to fulfil Newton's law of gravity

[11] See e.g.: Hensel, H. (1978). Wörterbuch und Modellsammlung zum Algorithmus der Verkehrsprognose; *Stadt - Region - Land, Berichte Institut für Stadtbauwesen*, **4**; Institut für Stadtbauwesen RWTH Aachen, Aachen.

Currently maximising the subjective utility is seen as the most adequate principle behind individual decision making... (Köhler, U. et al., 2001) p. 32[12]. Therefore the multinominal LOGIT model is the state of the practice in today's mode choice mode choice modelling.

$$P_m = \frac{e^{\beta * u_m}}{\sum_m e^{\beta * u_m}}$$

Equation 2.5: Multinominal LOGIT model

Legend:

P_m .... Probability that mode m is chosen

β .... Parameter

u_m .... Utility using mode m

For a long period of time random utility maximisation and entropy-maximisation (gravity models) were seen as competing theories. In 1981 Alex Anas proved that, at equal levels of aggregation, multinominal LOGIT and gravity models are formally equivalent[13]. This finding laid the foundation for the convergence of the formerly separated theory strands random utility maximisation and entropy-maximisation.

Numerous commercial transport modelling software products are available on the market today. Some examples of available transport modelling are shown in Table 2.3.

[12] Own transcription. Original: *In neuerer Zeit wird die Maximierung des subjektiven Nutzens als das adäquateste Prinzip der Entscheidungsfindung angesehen...*

[13] Anas, A. (1983). "Discrete Choice Theory, Information Theory and the Multinominal LOGIT and Gravity Models." *Transportation Research B* **17** (1): 13-23.: p. 14: "*It is also shown in this paper that the traditional spatial gravity model (1), rederived by Wilson (1967) as an entropy model, is identical to a multinominal logit model of joint origin destination choice derived from stochastic utility maximisation.*"

Table 2.3: Examples available transport modelling software

Name of software product	Some characteristics
CUBE (TP+, TRANPLAN, TRIPS, MINUTP)	*Comprehensive demand modelling including pedestrian and freight, diversion curves, discrete choice and activity based approaches, dynamic traffic assignment, discrete choice multipath transit assignment with timetabling.* Source: (The Urban Transportation Monitor, 2002)
EMME/2	Integrated multi-modal approach, flexible modelling capabilities, theoretical sound models, interactive calculator for matrix and network data. Source: (The Urban Transportation Monitor, 2002) Webpage: www.inro.ca
QRSII	Elastic demand assignment methods, multipath transit assignment delays from intersection simulation, point-to-point traffic assignment, internal land use model, feedback options. Source: (The Urban Transportation Monitor, 2002) Webpage: www.execpc.com/~ajh
START, TRAM	Strategic transport model, aggregated network approach, links to detailed network models with TRIPS package, TRAM addresses especially parking restraint measures. Source: (Skinner, A. and Bradley, R., 1999) Webpage: www.mva-group.com
TMODEL	Separate delay functions for nodes and links, integral distribution and assignment with Multi-Point-Assignment (MPA) and Upstream Queuing Propagation (UPQ). Source: (The Urban Transportation Monitor, 2002) Webpage: www.tmodel.com
TransCAD	Numerous transit pathfinding, skimming and assignment methods, integrated with GIS, relational database manager. *Source: (The Urban Transportation Monitor, 2002)*
VENUS 2	Modular demand and assignment model, freight included, capacity restraint assignment. Source: http://ivv-aachen.de/produkte/venus/inhalt.htm
VISUM	Multi modal concept, highway and transit modes integrated into one network, integrated GIS objects, links and nodes/turnings have capacities and volume/delay functions, relational data base model, can operate a data base system, integrated with the simulator VISSIM. Source: (The Urban Transportation Monitor, 2002) Webpage: www.ptv.de

Note: The information cited from (The Urban Transportation Monitor, 2002) was supplied by the vendors of the software packages listed. (The Urban Transportation Monitor, 2002) cannot vouch for the accuracy of this information.

2.5 A brief review of land use modelling

Similar to transport modelling the analogy to the law of gravity from physics was the starting point in modelling land use[14]. First quantitative land use models were developed in the Sixties of the last century. There are three main theories in land use modelling (Still, B. G., 1997) p. 7:

- based upon micro-economic theory
- based upon spatial-interaction/entropy modelling and
- a fusion of these two incorporating random utility theory.

2.5.1 Urban economic theory

The history of theories trying to explain land uses by transport costs started in the 19th century (Still, B. G., 1997) p. 9ff. The main intra urban work started in the early sixties [e.g. (Alonso, W., 1964)]. The theory aims at predicting the rents and distribution of land uses for competing socio-economic groups and land uses within the city.

The basic theory makes a lot of simplifying assumptions about the city structure. The city is assumed to be circular with all employment in the city centre and workers living around it. Transport costs are uniform around the centre, increasing with distance from the centre. The basic principle is that activities trade their desire for space (positive utility) against transport costs to the city centre (negative utility). If no other goods are consumed, then the sum of rents and transport costs must be constant across the city. This principle is called complementarity (Figure 2.3 left part). If another category of expenditure "all other goods and services" is considered, then the households are assumed to maximise their utility of the two goods and minimise their consumption on transport, subject to a budget constraint. The right part of Figure 2.3 shows the typical pattern of land use which emerges from "bid auction" behaviour, i.e. utility maximisation locators in combination with profit maximisation of land owners. This pattern will lead to concentric land use pattern. Businesses (B) outbid residents close to the city centre. Poor households (P) have outbid wealthier households (W) by accepting to live at higher densities to reduce transport costs.

[14] Erlander, S. and Stewart, N. F. (1990). The Gravity Model in Transportation analysis - Theory and Extensions; *Topics in Transportation*, Utrecht. p. 27: *"Carey (1858) was probably the first one to state the idea underlying the gravity model, i.e. that the number of trips is proportional to the attractive forces and inversely proportional to the distance. Similar ideas were used by Ravenstein (1885) in his study of migration. Carey and Ravenstein presented their arguments in prose without using any formulae."*

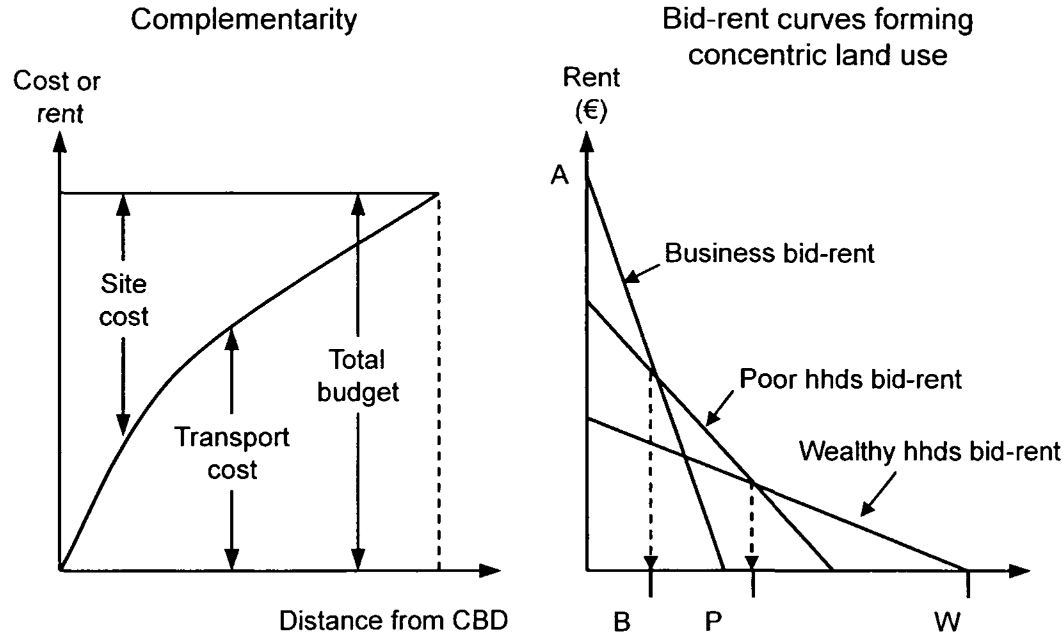

Figure 2.3: Graphs showing basics of urban economic theory (Still, B. G., 1997) p. 10

Given bid-price preferences of individuals and transport costs, the distribution of land uses and the rents, which lead to such a distribution, can be calculated. The theory focuses upon market mechanisms, land prices and behaviour and the role of accessibility. (Still, B. G., 1997) p. 11f highlights the following drawbacks of urban economic theory:

- The many simplifying assumptions are restrictive.
- Transport is given a pivotal role in being the key determinant of land value.
- The model represents individual behaviour, which quickly becomes difficult if large urban systems should be modelled.
- The equilibrium nature of the model is open to question.
- There is a lack of operational models following this theory.

2.5.2 Spatial interaction models

The term "model" is used for this approach as there is no explicit underlying theory that relates the phenomena studied. It is rather a statistical interpretation of system organisation (Still, B. G., 1997) p. 12ff. Space is divided into discrete zones. Activities locate in each zone and zones interact via linkages. The interactions traditionally decline with increasing distance.

Gravity theory was the first to be applied to the description of urban systems. Most common derivations of this model type use "entropy maximisation". The model finds the most "probable" final state. Entropy is the degree of likelihood that the final state of a system is reached. The "singly constrained" version is appropriate to model location choices. Equation 2.1 shows the example of a population location model. Considering vacant land L_i ensures that there are no people allocated if there is no land. The dispersion parameter β is determined in the calibration. Calibration is usually undertaken cross-sectional for the base year. It is assumed that the found relationships hold for future years. The most well known model of spatial interaction type is the Lowry model which is presented and discussed in more detail in section 2.6.3.

$$dP_i = dP^t * \frac{L_i * \left(\sum_j W_j * e^{-\beta * c_{ij}} \right)}{\sum_i L_i * \left(\sum_j W_j * e^{-\beta * c_{ij}} \right)}$$

Equation 2.6: Population location model (Still, B. G., 1997) p. 13

dP_i................ Increment in population allocated to zone i

dP^t................ Total population

L_i.................. Land vacant in zone i

W_j................. Attractiveness of destination j

β.................. Dispersion parameter

c_{ij}.................. Transport costs from zone i to zone j

(Still, B. G., 1997) p. 14 identifies the following drawbacks of the spatial interaction approach:

- There is a lack of a behavioural framework, which means that no causal relationships can be established.
- There is a lack of an economic framework, which means that the role of markets is ignored.
- The study area has to be subdivided into discrete zones.

The lack of economic or behavioural theory is also the main point of criticism in other references (Berechmann, J. and Small, K. J., 1988) p. 1290. A strength is that the spatial allocation mechanisms can mimic the results of randomness in individual decisions[15].

2.5.3 Random utility theory (RUT)

The use of this theory in location choice modelling is the state of the art. *In fact, RUT is a merging of utility maximisation and spatial interaction modelling, hence providing a behavioural base for zonal location choice* (Still, B. G., 1997) p. 14. The result is a discrete choice model. The central concept is that individual perception of utilities can be aggregated under the assumption that the group utility will vary around a mean value, reflecting the variability of the population. Equation 2.7 shows the aggregated utility function for a population group.

[15] *Indeed, in several the papers by Anas,..., this strength is capitalised upon by formulating stochastic-choice models of individual behaviour in order to provide microeconomic interpretations of the gravity functions.* Berechmann, J. and Small, K. J. (1988). "Research policy and review 25. Modeling land use and transportation: an interpretive review for growth areas." *Environment and Planning A* **20**: 1285-1309.p. 1290.

$$u^{gk} = U^g(X^k, \varepsilon)$$

Equation 2.7: Aggregated utility function for a population (Still, B. G., 1997) p. 14

u^{gk}................ Utility that group g obtains from choice k

U^g................ Utility function for the group g

X^k................ Measurable attributes of option k

ε.................... Random variation in the utility function

A distribution function is needed to represent the randomness. If a Weibull distribution (S-shaped plot) is used, then the LOGIT model can derived.

$$P^{gk} = \frac{e^{\beta^g * V^k}}{\sum_k e^{\beta^g * V^k}}$$

Equation 2.8: LOGIT model (Still, B. G., 1997) p. 15

P^{gk}................ Probability that group g chooses option k

V^k................ Deterministic attribute of choice k

β^g................ Parameter by group g

(Still, B. G., 1997) p. 15 states the following weaknesses of the random utility approach:

- The abstract concept of "utility", which the locator seeks to maximise, cannot be directly measured.
- The Weibull distribution produces a conveniently simple model, but there is not much evidence that real distributions of stochastic terms are of that form.

2.5.4 Other approaches

An additional approach not considered in (Still, B. G., 1997) is presented by (Berechmann, J. and Small, K. J., 1988): agglomeration economics. At the aggregate level agglomeration economics are a type of economy of scale. A larger cluster produces more efficiently than a smaller one. At the micro level, agglomeration economics are a type of positive externalities. The activity of one party benefits another parties more than is reflected in monetary payments. Most models of agglomeration economics are based on central places theory. In (Allen, P. M., 1997) a model of Brussels based on the principles of self organising systems is presented.

2.6 A brief review of operational land use and land use and transport integrated models

2.6.1 Introduction

(Wegener, M., 2003) reviews 20 land-use transport models which are operational. Urban change processes are analysed to classify the models. Eight types of urban subsystems are considered and ordered by the speed of their change (Table 2.4). The review in this chapter presents 17 operational land use and/or transport land use models in more detail. Eleven of them are part of Wegener's review. The others are older operational models added to the review to give an historical overview. The models are ordered approximately by the time of their development starting with the oldest ones. The review does not claim for completeness. The purpose is to give a broad overview to be able to define the position of MARS within the range of operational models.

Table 2.4: Urban subsystems represented in land use-transport models

Models	Speed of change								Section
	Very slow		Slow		Fast		Immediate		
	Net-works	Land use	Work-places	Hous-ing	Employ ment	Popula-tion	Goods transp.	Travel	
BOYCE	+				+	+		+	
CUFM		+	+	+	+	+			2.6.13
DELTA		+	+	+	+	+			2.6.15
HUDS				+	+	+			
ILUTE	+	+	+	+	+	+	+	+	
IMREL	+	+	+	+	+	+		+	2.6.10
IRPUD	+	+	+	+	+	+		+	2.6.11
ITLUP	+	+			+	+		+	2.6.9
KIM	+				+	+	+	+	
LILT	+	+	+	+	+	+		+	2.6.6
MEPLAN	+	+	+	+	+	+	+	+	2.6.5
METROSIM	+	+	+	+	+	+		+	2.6.7
MUSSA					+	+			2.6.11
POLIS		+			+	+			
RURBAN		+			+	+			
STASA	+	+	+	+	+	+	+	+	
TLUMIP	+	+	+	+	+	+	+	+	
TRANUS	+	+	+	+	+	+	+	+	2.6.6
TRESIS	+	+	+	+	+	+		+	
URBANSIM		+	+	+	+	+			2.6.17
MARS	(+)	+	+	+	+	+		+	

Source: (Wegener, M., 2003), MARS added by the author

2.6.2 The Herbert-Stevens model

The Herbert-Stevens model is a deterministic economic equilibrium model. It was the first model based on economic principles to be applied to data for a real metropolitan area (Berechmann, J. and Small, K. J., 1988) p. 1293. The structure of the Herbert-Stevens model is as follows (Herbert, J. D. and Stevens, B. H., 1960). The endogenous variables are X^K_{ih}, the number of households of type i choosing residential bundle h in area K. The task is to maximise aggregate site rents paid by households, given total land availability and the need to accommodate the entire population (Equation 2.9 to Equation 2.12).

$$\max \sum_{K=1}^{U} \sum_{i=1}^{n} \sum_{h=1}^{m} X_{ih}^{K} * \left(b_{ih} - c_{ih}^{K}\right)$$

Equation 2.9: The Herbert-Stevens model (Herbert, J. D. and Stevens, B. H., 1960) p. 27

$$\sum_{i=1}^{n} \sum_{h=1}^{m} s_h * X_{ih}^{k} \leq L^{K}$$

Equation 2.10: Boundary condition availability of land (Herbert, J. D. and Stevens, B. H., 1960) p. 27

$$\sum_{K=1}^{U} \sum_{h=1}^{m} X_{ih}^{K} = N_i$$

Equation 2.11: Boundary condition need to accommodate all population (Herbert, J. D. and Stevens, B. H., 1960) p. 27

$$X_{ih}^{K} \geq 0$$

Equation 2.12: Boundary condition to avoid negative population (Herbert, J. D. and Stevens, B. H., 1960) p. 27

U .... Areas which form an exhaustive subdivision of the region, indicated by superscripts $K = 1, \ldots, n$

n .... Household types; indicated by subscripts $i = 1, \ldots, n$

N_i .... Households of type i

m .... Residential bundles (each described by observable characteristics of a site, house, lot, and set of trips including work trips), indicated by superscripts $h = 1, \ldots, m$

b_{ih} .... Is the bid-rent by a household of type for residential bundle h

c^{K}_{ih} .... Is the annual cost to a type household of the residential bundle h in area K, exclusive of site cost, that is, it includes costs of travel and of construction and maintenance of the building

s_h .... Is the lot size included in the residential bundle h

L^{K} .... Is the number of acres of land available for residential use in the areas K

X^{K}_{ih} .... Is the number of households of type i choosing residential bundle h in area K

2.6.3 The original Lowry model

One of the first operational and widespread used land use models is the Lowry model (Berechmann, J. and Small, K. J., 1988). It was developed by Lowry in 1964 to simulate spatial patterns of residential and service development in Pittsburgh (Lowry, I. S., 1964). The original Lowry model is a spatial activity distribution model (Van Est, J., 1979) p. 222 ff. The Lowry model distributes residential, employment and service activities to the zones of the studied region (see Figure 2.4). Employment is divided into the two categories, basic and non-basic (i.e. service)[16]. The first group will be allocated to the zones exogenously. By application of multipliers, the pertinent labour force and services (shopping facilities) can be determined. The services are divided into three groups of service levels: neighbourhood, local and metropolitan. The size of those shopping centres is assumed to be dependent on a minimum size and the potential of the surrounding population. The population is not divided into socio-economic groups: therefore the model is an aggregated one. The characteristics of types of houses and the housing environment are lacking; the zones are assumed to be homogenous and can be distinguished only by housing density. The size of zones and their housing densities are the only constraints. The allocation rules of the model are based on the potential of each zone, and not on interaction between them. The population and services will be allocated to the zones according to rules of allocation (distance behaviour). Supply plays no significant role; the supply of housing and services is completely elastic, which means an automatic adaptation to the demand for such activities. The execution of the model is iterative; basic employment, population and services in sequence until all population and services have been allocated. There are no policy variables in the model, except for density constraints.

The amount and distribution of basic employment has to be defined exogenously (Figure 2.4). The total population is calculated by multiplying the total basic employment with a labour participation rate. The total population is allocated to residential zones. After a maximum density constraint is checked, the amount of service employment necessary to serve the population is calculated and allocated. A minimum service business size constraint is checked and the land use for service employment is calculated. The condition that the calculated and inputted population has to be equal is checked. If the condition is not fulfilled, calculated population and employment is substituted and the next iteration is started. If the condition is fulfilled, the output is population, employment and land use per zone.

The original Lowry model consists of a set of nine simultaneous equations (Equation 2.13 to Equation 2.21) and three inequalities (Equation 2.22 to Equation 2.24; (Lowry, I. S., 1964) p. 9 ff).

$$A_j = A_j^U + A_j^B + A_j^R + A_j^H$$

Equation 2.13: Areas by land use (Lowry, I. S., 1964) p. 9

j ....Sub-area of bound region, called tract

A_j.................Area of land of tract j

A^U_j...............Area of unusable land in tract j

A^B_j...............Area of land for the basic sector employment in tract j

A^R_j...............Area of land for the retail sector employment in tract j

A^H_j...............Area of land for the household sector in tract j

[16] Basic employment is employment which cannot solely be explain by local markets. Non basic (service) serves the local residents and follows population distribution. See Echenique, M., Crowther, D. and Lindsay, W. (1969). "A Spatial Model of Urban Stock and Activity." *Regional Studies* **3**: 281-312.

$$E^k = a^k * N$$

Equation 2.14: Retail employment (Lowry, I. S., 1964) p. 10

k................Class of establishment within the retail sector

E^k................Retail employment (number of persons)

a^k................Coefficient retail employment per household in class k

N................Population (number of households)

$$E_j^k = b^k * \left[\sum_{i=1}^{n} \left(\frac{c^k * N_i}{T_{ij}^k} \right) + d^k * E_j \right]$$

Equation 2.15: Spatial distribution of retail employment (Lowry, I. S., 1964) p. 10

E^k_j................Retail employment class k in tract j (number of persons)

b^k................Scale factor to adjust retail employment in each tract to the regional total determined in Equation 2.14

c^k, d^k................Coefficients to measure the relative importance of home and workplace as origin for shopping trips[17]

N_i................Population (number of households) in tract i

T^k_{ji}................Trips from tract i to tract j with a retail business of class k as destination

E_j................Employment (number of persons) in tract j

$$E^k = \sum_{j=1}^{n} E_j^k$$

Equation 2.16: Total retail employment by class (Lowry, I. S., 1964) p. 11

E^k................Total retail employment by class k (number of persons)

E^k_j................Retail employment class k in tract j (number of persons)

$$E_j = E_j^B + \sum_{k=1}^{m} E_j^k$$

Equation 2.17: Total employment by tract (Lowry, I. S., 1964) p. 11

E_j................Total employment in tract j (number of persons)

E^B_j................Basic employment in tract j (number of persons)

E^k_j................Retail employment class k in tract j (number of persons)

$$A_j^R = \sum_{k=1}^{m} e^k * E_j^k$$

Equation 2.18: Area of land retail sector (Lowry, I. S., 1964) p. 11

A^R_j................Area of land used in the retail sector in tract j

e^k................Employment density coefficient in class k

E^k_j................Retail employment class k in tract j (number of persons)

[17] In the original Lowry model it is assumed that shopping trips with the workplace as origin are only short pedestrian trips.

$$N = f * \sum_{j=1}^{n} E_j$$

Equation 2.19: Region's population (Lowry, I. S., 1964) p. 11

N .... Population of the studied region (number of households)

f .... Coefficient for labour participation rate (households per employee)

E_j .... Total employment in tract j (number of persons)

$$N_j = g * \sum_{i=1}^{n} \frac{E_i}{T_{ij}}$$

Equation 2.20: Spatial distribution of population (Lowry, I. S., 1964) p. 11

N_j .... Population in tract j (number of households)

g .... Scale factor to ensure that the sum of the tract population is equal to the total population (Equation 2.21)

E_j .... Total employment in tract i (number of persons)

T_{ij} .... Index of trip distribution

$$N = \sum_{j=1}^{n} N_j$$

Equation 2.21: Total population (Lowry, I. S., 1964) p. 11

N .... Total population (number of households)

N_j .... Population in tract j (number of households)

$$E_j^k \geq Z^k \ else \ E_j^k = 0$$

Equation 2.22: Minimum size constraint retail sector (Lowry, I. S., 1964) p. 12

E^k_j .... Retail employment class k in tract j (number of persons)

Z^k .... Minimum size constraint class k

$$N_j \leq Z_j^H * A_j^H$$

Equation 2.23: Maximum density constraint household sector (Lowry, I. S., 1964) p. 12

N_j .... Population in tract j (number of households)

Z^H_j .... Maximum density constraint household sector tract j

A^H_j .... Area of land used in the household sector in tract j

$$A_j^R \leq A_j - A_j^U - A_j^B$$

Equation 2.24: Constraint on land set aside for retail establishments (Lowry, I. S., 1964) p. 12

A^R_j .... Area of land for the retail sector employment in tract j

A_j .... Area of land of tract j

A^U_j .... Area of unusable land in tract j

A^B_j .... Area of land for the basic sector employment in tract j

Some points of criticism of the original Lowry model are:

- Strictly it is only valid if a free market economy for housing exists and the supply is total elastic. (Van Est, J., 1979) p. 226
- There is a lack of underlying economic or behavioural theory (Berechmann, J. and Small, K. J., 1988) p. 1290

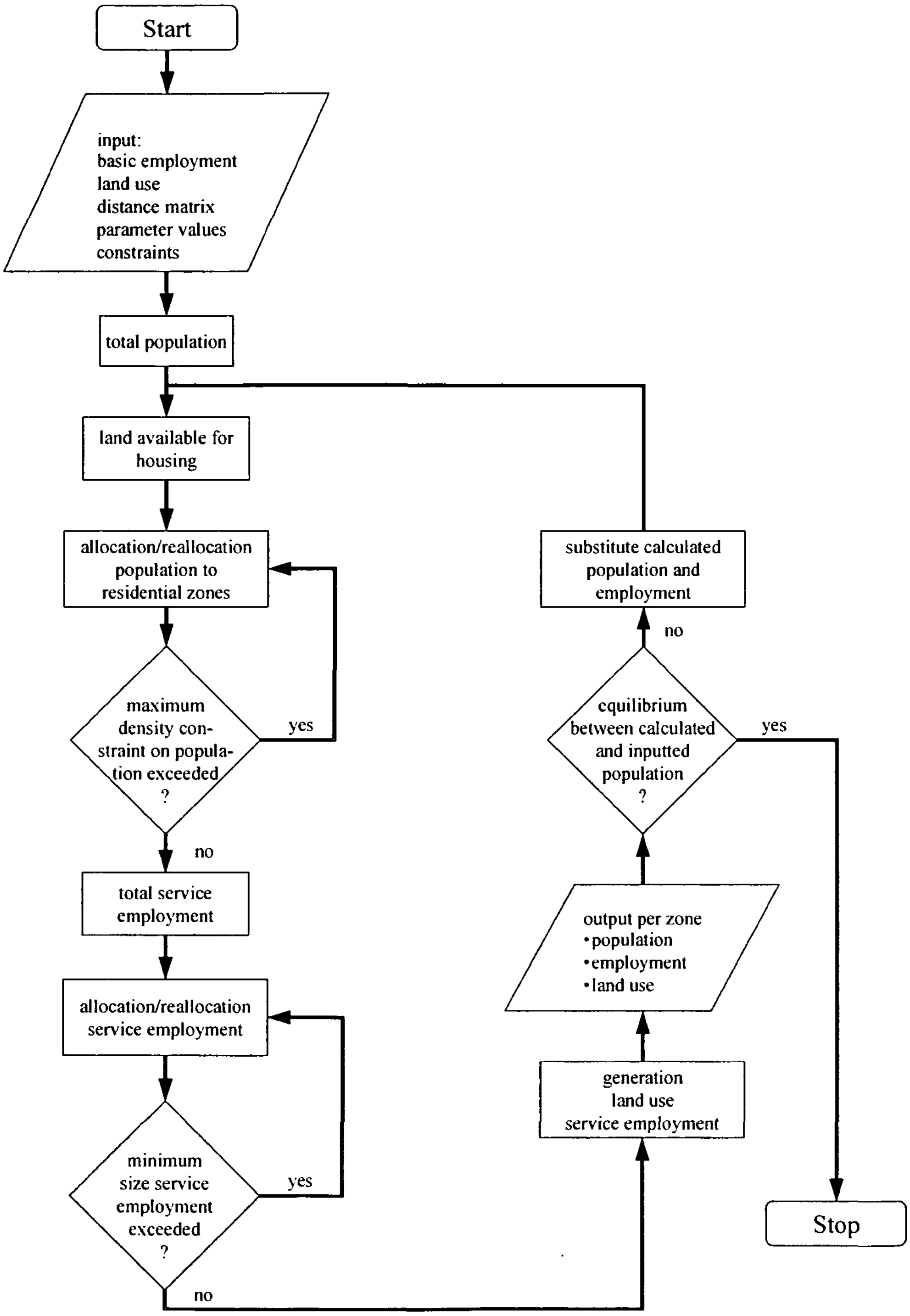

Figure 2.4: The original Lowry model (Van Est, J., 1979)

2.6.4 The Garin-Lowry model

Several extensions and improvements of the original Lowry model were made. One of the extended versions is the Garin-Lowry model (Berechmann, J. and Small, K. J., 1988) p. 1288. The Garin-Lowry model uses explicit interaction sub-models (containing the gravity formulae) that distribute all activities at each iteration of the calculation. The entire Garin-Lowry model is in matrix notation (Garin, R. A., 1966). The basic structure of the Garin-Lowry model is shown in Figure 2.5. The input data include zonal basic employment, interzonal travel cost matrices for home to work and home to shopping trips, zonal attractiveness as residential and service employment location and control parameters of economic-base mechanism. First the workers in the basic sector are allocated to residential zones. The incremental residential population and the resulting incremental service sector employment are calculated next. This increment of employment is distributed to zones of workplace. A corresponding increment of population is calculated and allocated to spatial zones of residence. This iterative process continues until a convergence criteria is fulfilled.

The Garin-Lowry model has been used successfully in replicating observed spatial distribution of land use activities and in analysing the impacts of regional changes. An advantage of the Garin-Lowry model is its simple structure. Another strength is that the spatial allocation mechanism mimics the result of randomness in the decision of individuals. The main disadvantage is the lack of an underlying economic or behavioural theory (Berechmann, J. and Small, K. J., 1988).

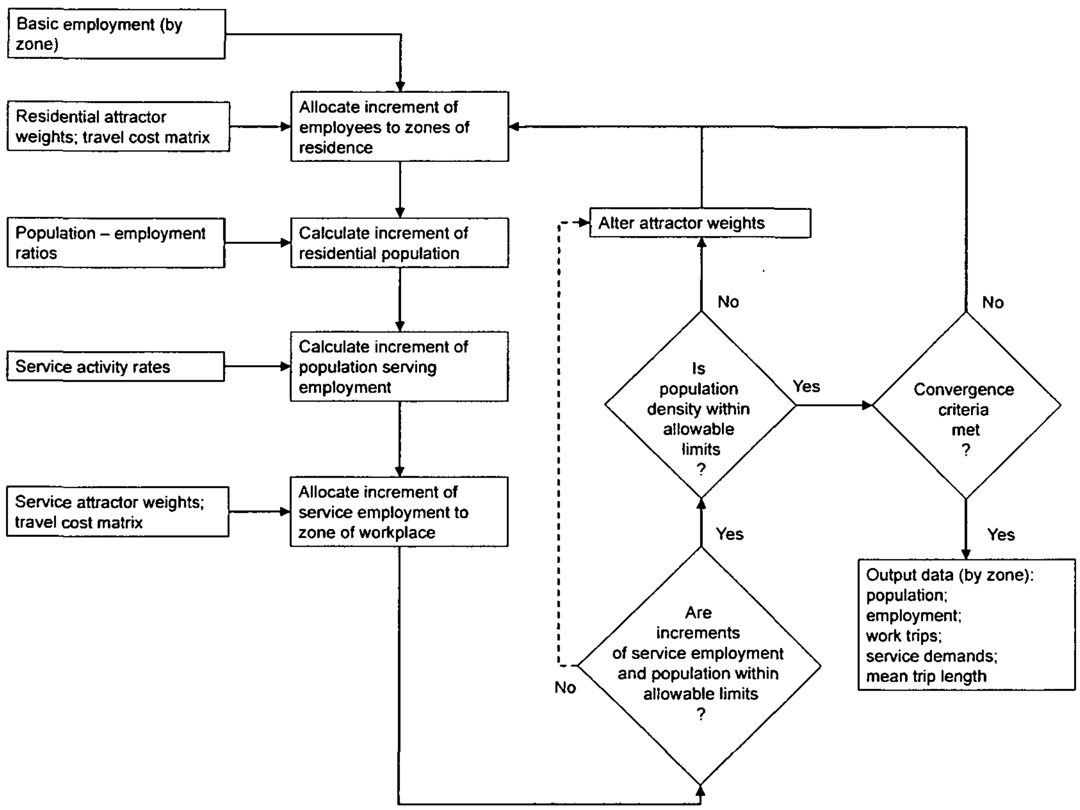

Figure 2.5: The modified Garin-Lowry model (Berechmann, J. and Small, K. J., 1988)

2.6.5 Martin centre models

In the Sixties a static model of the urban spatial structure was developed at the Martin Centre for Architectural and Urban Studies, University of Cambridge (Echenique, M. et al., 1969). This model, applied for the city of Reading, was *one of the earliest models of urban spatial development to be made operational in the United Kingdom* (Hunt, J. D. and Simmonds, D. C., 1993) p. 222. Fundamental parts of this model are Lowry type. The model consists of two sub-models: a stock model and an activity model. The model differentiates three types of activity groups: basic employment[16], residential and service employment activities; and two physical structures: an undifferentiated quantity of floor space and the transportation network. The stock model simulates the location of built floor space throughout an urban area. Road distance is used as a measure of accessibility. The structure of the activity model is of Lowry type. This basic modelling framework was embodied in a general software package, called MEPLAN[18], in 1984 to 1985 (Hunt, J. D. and Simmonds, D. C., 1993) p. 231. A description of the MEPLAN package and its application is given in (Williams, I. N., 1994).

The basic structure of the static model of the urban spatial structure is shown in Figure 2.6. Once the location of basic employment is established, the number of residents at the place of basic employment location is calculated by multiplying the number of basic workplaces with the labour participation rate. The population is then distributed to residential locations using journey to work distributions. The required floor space is calculated by multiplying the number of residents with the average residential space standard. This is checked against the existing stock of floor space in each zone. The overflow is distributed back to the place of employment and re-distributed in the next iteration. Once the location of residents is established, the number of service employment is calculated by multiplying the number of residents with the service employment to population ratio. The service employment is located using a journey to service distribution. External economics of clustering are considered in this stage. The floor space required by service employment is calculated by multiplying the number of service workplaces with the average service employment space standard. The floor space requirements are checked against the existing stock. Residents might be displaced by service employment. Displaced residents are added to the overflow and re-distributed in the next iteration. This process is repeated until the system approaches a state of equilibrium.

[18] The MEPLAN software package is the property of Marcial Echenique and Partners Limited of Cambridge, England. http://www.meap.co.uk/meap/Policy.pdf

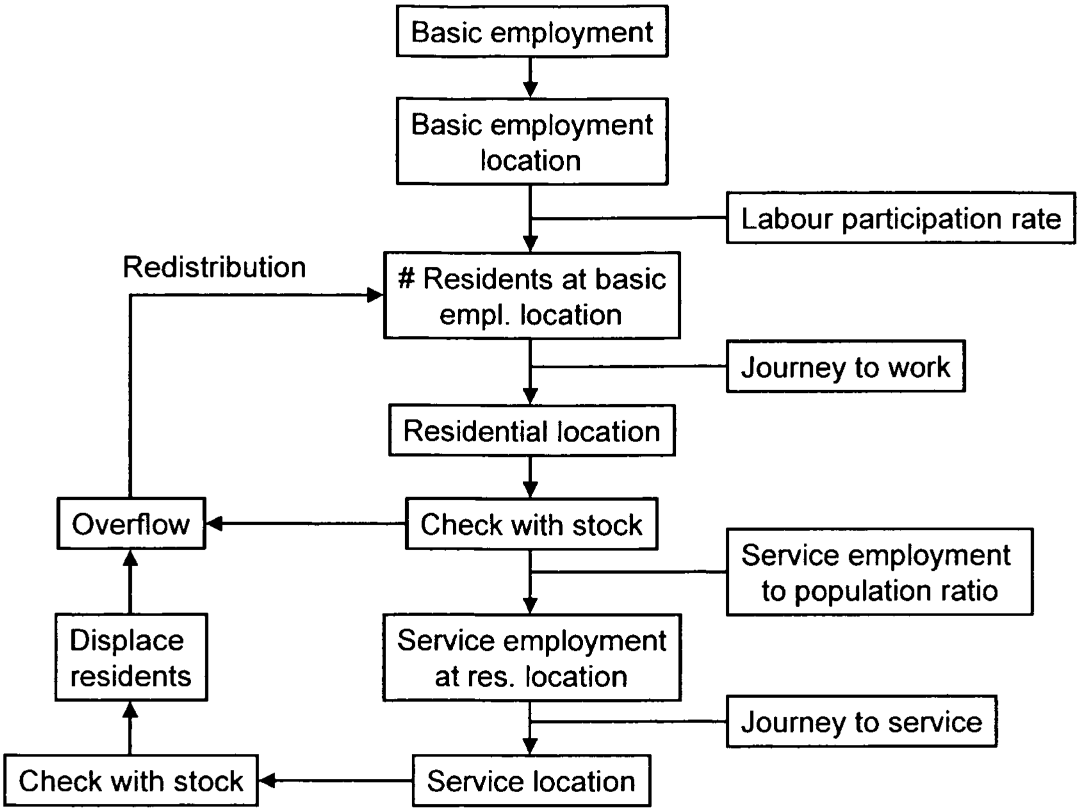

Figure 2.6: Simplified flowchart of the static model of the urban spatial structure (Echenique, M. et al., 1969)

2.6.6 LILT (Leeds Integrated Land-use Transport) model

LILT was developed in the late Seventies and early Eighties at the University of Leeds (DSC & MEP, 1999) p. 84ff. The LILT model represents the relationships between transport supply (or costs) and the spatial distribution of population housing, employment, jobs, shopping and land utilisation (Mackett, R. L., 1990). LILT is an allocation model which locates net change in population, housing and jobs from exogenous forecasts. It links the trip distribution and mode split stage of a four stage transport model with a Lowry type land use model. Three types of employment are considered:

- Primary, which is allocated in proportion to the existing distribution.
- Secondary (manufacturing, transport and communications etc.) are allocated on the basis of the previous employment distribution, but also with reference to the ratio of accessibility to the supply of labour and to other economic activity at the current time to previous time points. I.e. increasing accessibility in a zone will increase the activities and vice versa.
- Tertiary sector jobs respond to population distribution, taking into account the relative travel costs by each mode.

Floor space development is modelled, with dwelling development and demolition, which can be influenced by planning policies. New dwellings are allocated according to land availability and accessibility. The basic structure of LILT is shown Figure 2.7

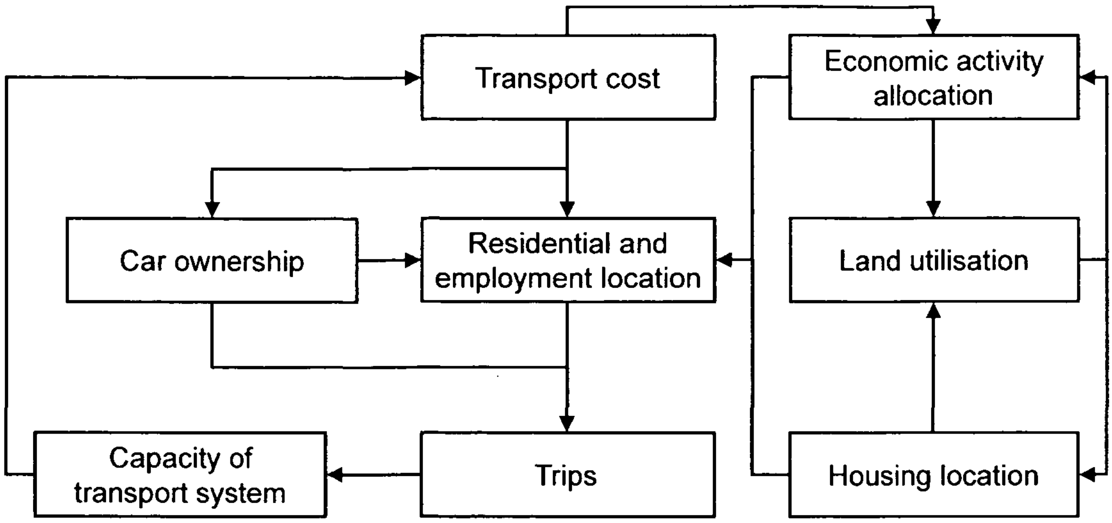

Figure 2.7: Schematic diagram of the LILT model (Mackett, R. L., 1990)

2.6.7 METROSIM

The METROSIM package is the outcome of many years of theoretical research and practical model building by Alex Anas (DSC & MEP, 1999). METROSIM is designed to forecast the interdependence effects of transport and land use at the metropolitan level for US Metropolitan Planning Organisations. The structure is based on a series of economic relationships. The model consists of the following seven sub-models (DSC & MEP, 1999) p. 122f:

- *Basic industry*: the model takes exogenously given production targets in each zone and then determines endogenously the labour demands, the floor space utilisation and land requirements of the basic industry, the wages of labour and the rent for location in the zone.
- *Non basic industry*: this operates in broadly the same fashion as the basic industry sub-model, except that the pattern of location is endogenously determined.
- *Property*: this represents the residential and the commercial property markets separately. It determines the quantity of construction and demolition of residential units as well as vacancies, rents and market values in each zone. The commercial real estate model operates similarly but estimates zonal floor space areas, rather than numbers of dwelling units.
- *Vacant land*: this determines the amount of and the market value of vacant land available for development in each zone.
- *Households*: this determines the distribution of households residing in each zone by type of residential unit (single or multiple family residential building), by workplace of family head, household income and mode of commuting to work of the family head.

- *Travel*: this consists of two trip purposes: commuting to work and non-work travel. The commuting travel demand matrix is calculated from a unified residential location, job choice and mode choice model. For non-work travel the trip frequencies and patterns of travel by mode to each destination zone are calculated. These destination patterns in turn influence the location patterns of non-basic industry.
- *Traffic assignment*: The car matrices are assigned to the road network and an equilibrium assignment is carried out to update the travel times to take account of congestion.

METROSIM can be used as a static model to produce a long run equilibrium forecast for location and travel patterns. Alternatively it might be operated as a quasi-dynamic model operating in yearly increments producing yearly changes. Table 2.5 shows a comparison of the segmentation of METROSIM and MARS.

Table 2.5: Segmentation available within METROSIM and MARS

Segmentation of activities	METROSIM		MARS	
	No.	Description	No.	Description
Employment types	2	basic, non basic	2	production and service sector
Housing types	2	single and multiple family housing units	1	though the maximum number of floors may differ by zone
Household types	1	though the average income and number of workers may differ by zone	1	though the average income and number of workers may differ by zone
Commercial buildings	2	for basic and non-basic industries	2	for production and service sector businesses
Trip purpose	2	commuting and non-work	2	commuting and non-work
Modes	5	car, bus, rail, rapid transit, other	4	car, bus, metro, slow

Source: (DSC & MEP, 1999) p. 123, MARS added by the author

2.6.8 TRANUS-J

TRANUS[19] is a software package similar to MEPLAN (Hunt, J. D. and Simmonds, D. C., 1993) p. 231. The TRANUS-J model is based on a hierarchical structure (de la Barra, T. et al., 1984). TRANUS-J has a highly integrated architecture and relies on the random utility approach (see section 2.5.3). Figure 2.8 shows the decision tree and the sequence of calculations in TRANUS-J.

[19] The TRANUS software package is the property of Modelistica of Caracas, Venezuela. http://www.modelistica.com

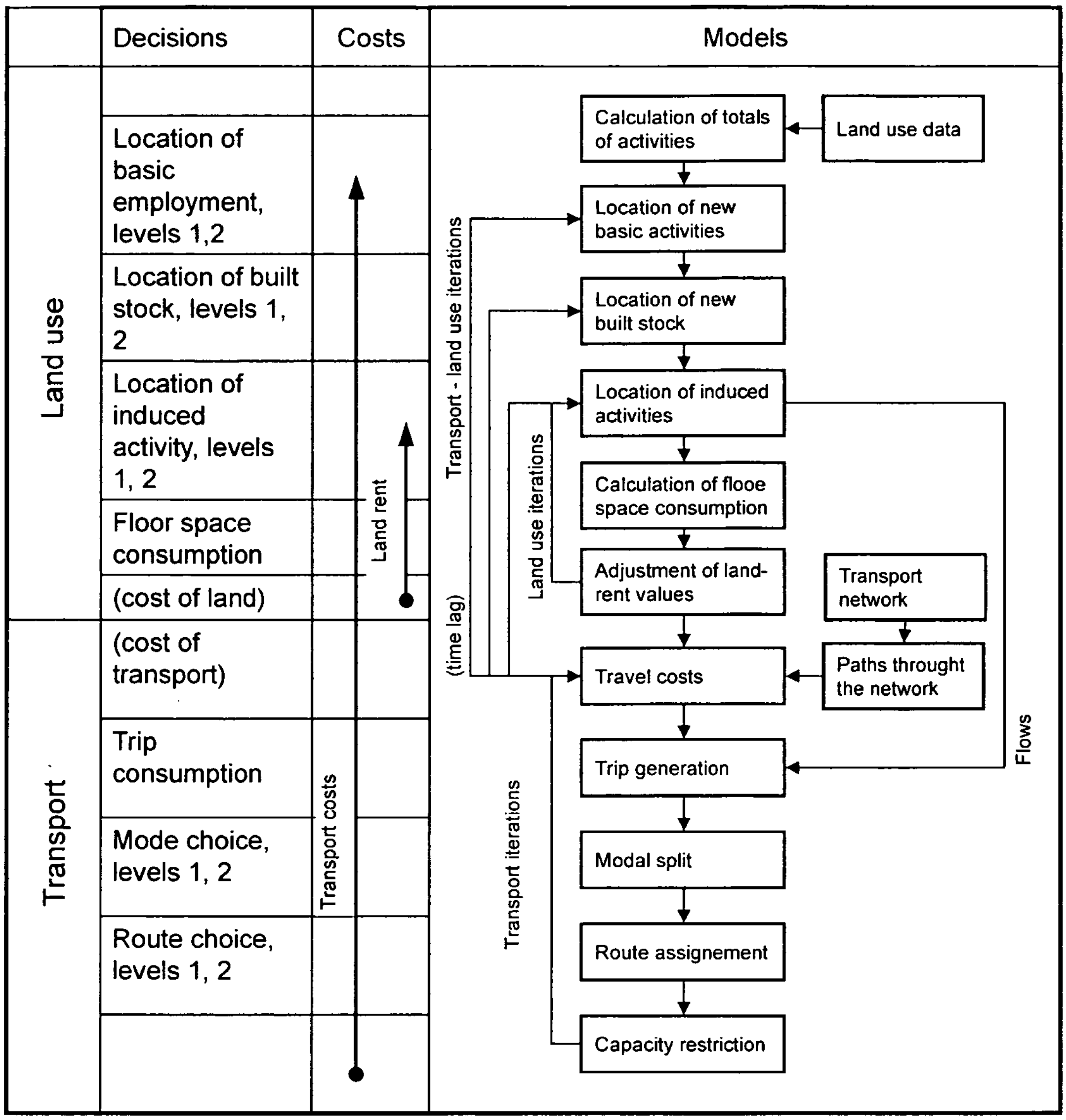

Figure 2.8: Decision tree and sequence of calculations in TRANUS-J (de la Barra, T. et al., 1984)

2.6.9 ITLUP (Integrated Transportation and Land-use Model Package)

The Integrated Transportation and Land-Use model Package (ITLUP) is probably the first deserving to be called a transport and land use integrated model (Berechmann, J. and Small, K. J., 1988). The ITLUP model combines two separate components: a land use model and a transportation network model. In the original version each component was a modification of an existing model. The land-use component was based on a modified Garin-Lowry model. The network model was a conventional capacity-restrained incremental-assignment model. Later the land-use component was again revised and named Disaggregated Residential Allocation Model[20] (DRAM). Figure 2.9 shows the basic structure of the ITLUP model.

[20] http://dolphin.upenn.edu/~yongmin/usl/intro.html

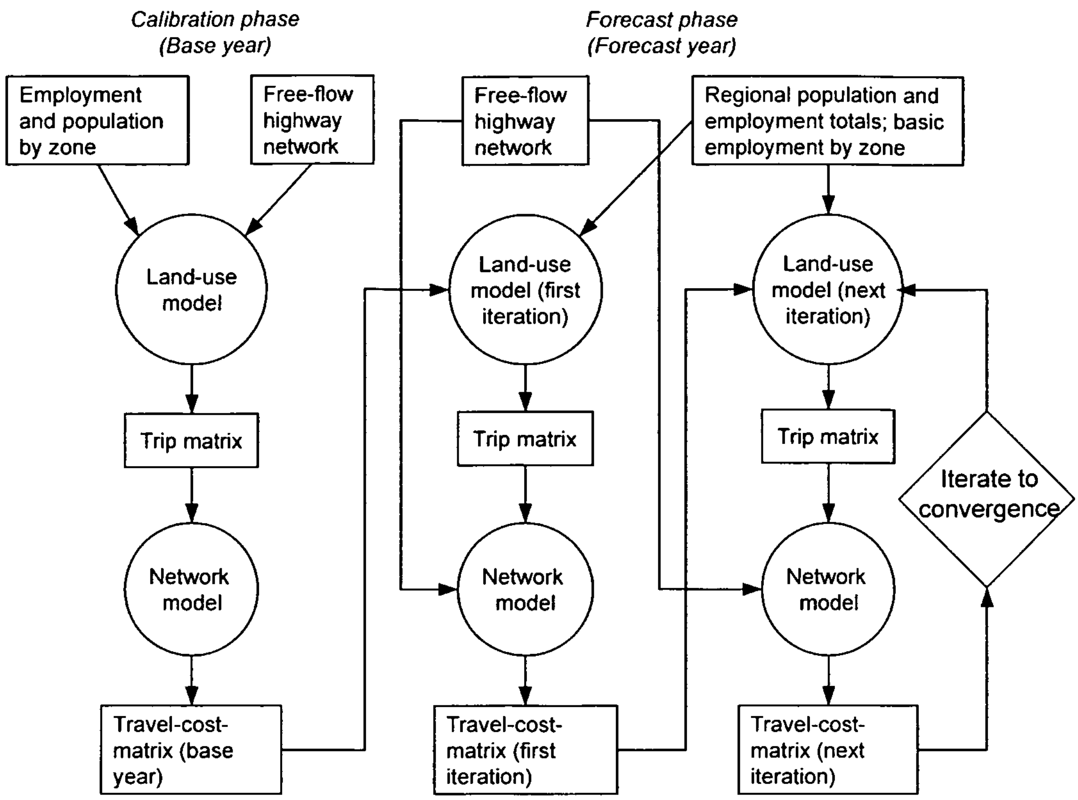

Figure 2.9: The ITLUP model (Berechmann, J. and Small, K. J., 1988)

2.6.10 RETRO/IMREL

The original Integrated Model of Residential and Employment Location (IMREL) is based on random utility theory with fixed travel costs. (Boyce, D. and Mattson, L.-G., 1999) reformulated the IMREL model to include the user-optimal route choice condition. The IMREL model consists of two sub-models: a sub-model for residential location choice (RES) and a sub-model for employment location choice (EMP). IMREL is a static allocation model requiring an external transport model (DSC & MEP, 1999). The IMREL model e.g. was connected to the four stage transport model RETRO[21] (Vold, A., 1999; Vold, A., 2000).

IMREL represents policy by placing limits on the number of workplaces or households that can locate in a zone. IMREL produces a pattern of land use based on one set of accessibilities given by a particular run of the transport model. Therefore it is cross-sectional rather than incremental. The residential and employment sub-models are integrated. The location of households respond to the employment pattern and the employment choice responds to the pattern of households. The model iterates until equilibrium is obtained. IMREL is used to compare strategies. As it is cross-sectional it is only run once for the reference scenario and once for a transport strategy. IMREL has no segmentation of households or employment. Housing stock is not represented in IMREL. It is

[21] **RE**gional **TR**ansport model for the greater **O**slo area

assumed that housing stock matches the number of households (DSC & MEP, 1999).

2.6.11 MUSSA

MUSSA is a static model of Santiago de Chile, developed by Francisco Martinez and colleagues (DSC & MEP, 1999) p. 83. MUSSA has been primarily used as a research tool. (DSC & MEP, 1999) sees the main contribution in providing numerical illustration of Martinez' work on accessibility and benefit measurement[22]. MUSSA is linked to a conventional large scale, four stage transport model. MUSSA predicts the total (cross-sectional) land-use pattern given a particular set of accessibility inputs. MUSSA and the linked transport model are iterated until equilibrium (at least to some equilibrium conditions, if not to complete equilibrium). The accessibility measures are designed to measure consumer surplus of transport users. This allows transport benefits to be measured in the land-use model. The land-use model itself is disaggregated. The probabilities of location of all households and firms in a sample derived from surveys are calculated. As in conventional disaggregate transport modelling future growth is represented by changing the expansion factors attached to each record in the sample. The location process involves a sophisticated representation of households'/firms' willingness to pay for different locations and of landlords' preference for taking the highest bid for each available dwelling/site. MUSSA is based on several equilibrium assumptions. To allow it to be used in dynamic modelling the number of equilibrium assumptions needs to be reduced.

2.6.12 IRPUD-model

The IRPUD-model is designed to simulate intra-regional location and mobility choices for an urban region (Wegener, M., 1998). In each simulation period the location choices of companies and businesses, construction investor and households are calculated. The location choices of the different groups result in migration processes, commuting patterns, housing and commercial development changes and land use changes. Figure 2.10 shows the major sub-systems and their interactions. The four squares at the edges show the four major variable areas: population, employment, residential and non residential buildings. The actors residents (households), employees, construction investors and companies and businesses are associated to these variable areas. The actors interact on five different markets:

- *Labour market:* recruitment, dismissal
- *Non residential housing market:* New and relocation of companies and businesses
- *Residential housing market:* Moving in, moving out, i.e. intra-zonal migration
- *Construction and property market:* Changes in use due to demolition, conversion or new building
- *Transport market:* Trips

[22] E.g.: Martinez, F. J. (1995). "Access: The transport - land use economic link." *Transportation Research B* **29** (6): 457-470.

Figure 2.10 shows the supply and demand side plus the resulting transactions for each of the markets.

The IRPUD-model has a modular structure and consists of six sub-models: transport, ageing, policy measures, building activity, labour market and housing market. Figure 2.11 shows the cyclical sequence in which the sub-models are operated.

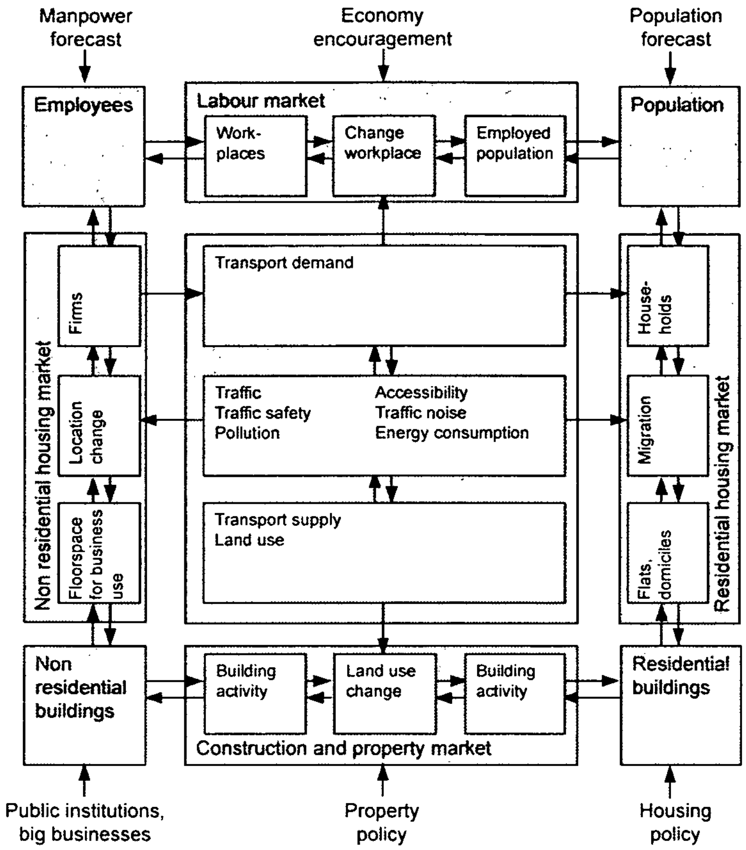

Figure 2.10: Basic structure of the IRPUD model (Wegener, M., 1998)[23]

[23] My paraphrase, original in German.

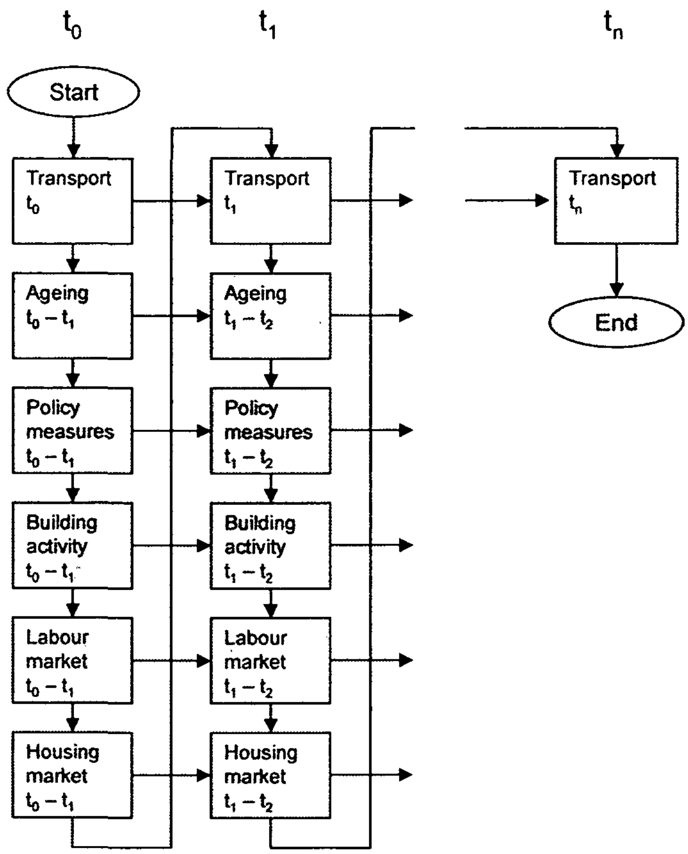

Figure 2.11: Cyclical sequence of the IRPUD sub-models (Wegener, M., 1998)[24]

2.6.13 CUF (California Urban Futures model)

The California Urban Futures model (CUF) was probably the first urban simulation model to make use of the possibilities of GIS (Landis, J. D., 1994). Additionally it was the first operational urban growth model which was truly disaggregate, that is, it did not rely on zones (Landis, J. and Zhang, M., 1998). The first version only dealt with residential development. This and some other shortcomings were remedied in the second version CUF-2. The logic of the CUF-2 model is shown in Figure 2.12. The first stage *activity projection* projects household and commercial and industrial job growth by city and county. The second stage *spatial database* assembles different data layers (for example wetlands, farmlands, slope, city boundaries) with the hectare grid cell lattice. The third stage *land-use change model* estimates a multinominal logit model of historical land use change.

$$P = f(i, j)$$

Equation 2.25: CUF-2 land-use change model

P .... Hectare land-use change

i .... Site characteristics

j .... Area characteristics

[24] My paraphrase, original in German.

The fourth stage *simulation engine* allocates projected households and jobs to highest-rated hectare sites in three cycles: (1) within use; (2) between use; and (3) spillover to other areas.

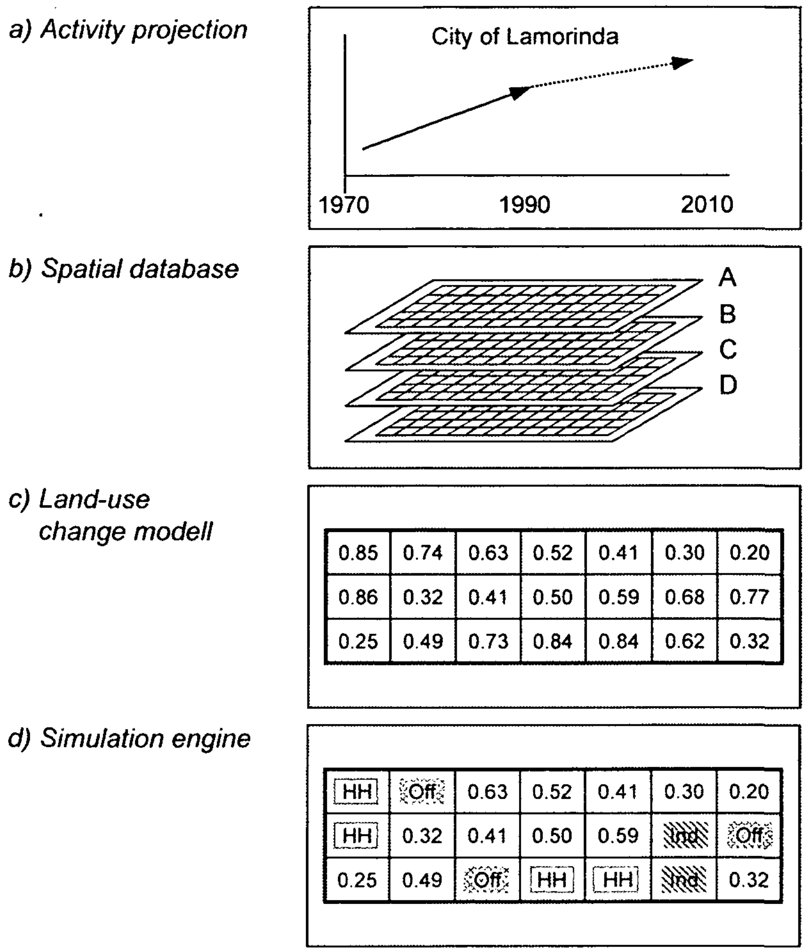

Figure 2.12: The logic of the CUF-2 model (Landis, J. and Zhang, M., 1998) p. 660

2.6.14 LUCI (static Land Use Change Indicator model

The static **L**and **U**se **C**hange **I**ndicator model LUCI was originally developed by David Simmonds in 1991 (Still, B. G. et al., 1999) p. 86. The structure of LUCI is shown in Figure 2.13. The model uses exogenous population and employment forecasts. Spatial-interaction type accessibilities by trip purpose are calculated using the forecasts and the forecast year matrices of generalised costs from a START transport model[25]. Changes in the pattern of forecast year accessibility and a transport policy are used to re-distribute population and employment relative to do-minimum. Time is not represented in LUCI. A LOGIT model was applied as residential choice model (Equation 2.26). Retail and non-retail service employment location choices are treated in a similar way (Equation 2.27). All other variables than accessibility which can influence location choice are assumed as being constant. LUCI does not include feedback loops nor any constraints on land or floor space availability. For this reasons the outputs are termed as *indicators*

[25] See Table 2.3 in section 2.4.2 From the first quantitative models to the state of the practice p. 15.

rather than forecasts (Still, B. G. et al., 1999) p. 87. As the model is not iterative it runs very quickly. LUCI is calibrated using cross-sectional data.

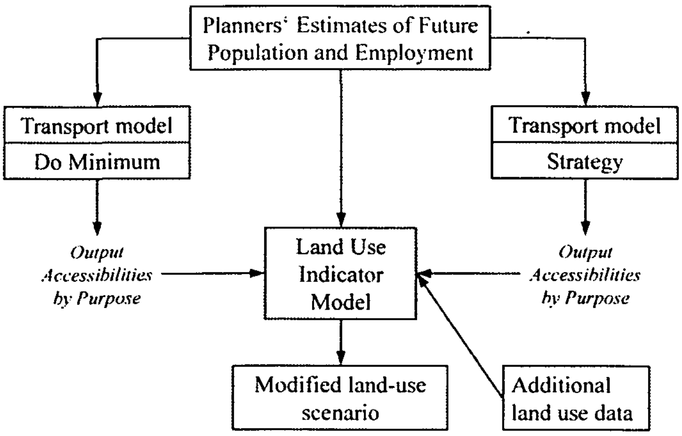

Figure 2.13: Structure of the static land use change indicator model LUCI in combination with a transport model (Still, B. G. et al., 1999)

$$P_i^2 = P^* * \frac{P_i^1 * e^{\alpha*(A_i^2 - A_i^1)}}{\sum_i P_i^1 * e^{\alpha*(A_i^2 - A_i^1)}}$$

Equation 2.26: LUCI model population location (Still, B. G. et al., 1999) p. 86

P_i^2.................New zonal population resulting from an accessibility change

P^*.................Fixed total study area population

P_i^1.................Exogenously forecast do-minimum population of zone i

α.................Calibrated coefficient on accessibility

A_i^2.................Accessibility to work for zone i for the transport strategy 2

A_i^1.................Accessibility to work for zone i for the do-minimum strategy 1

$$E_i^2 = E^* * \frac{E_i^1 * (A_i^2 / A_i^1)^\alpha}{\sum_i E_i^1 * (A_i^2 / A_i^1)^\alpha}$$

Equation 2.27: LUCI model employment location (Still, B. G. et al., 1999) p. 87

E_i^2.................Modified zonal employment in zone i

E^*.................Fixed total study area retail employment

E_i^1.................Exogenously forecast do-minimum retail employment of zone i

A_i^2.................Accessibility to residents for zone i for the transport strategy 2

A_i^1.................Accessibility to residents for zone i for the do-minimum strategy 1

α.................Calibrated coefficient on accessibility

2.6.15 The DELTA land use model

The land use model DELTA was developed by David Simmonds Consultancy (Still, B. G. et al., 1999) p. 87. As with LUCI the START model[25] is used as transport model. DELTA and START run dynamically at intervals of two years. DELTA represents the urban processes of development, demographic and economic (employment) change, location choice, changes in urban area quality and employment market matching. The underlying philosophy is that the sub-models represent familiar urban processes (and associated markets) that are important in urban development. Time is explicitly incorporated. The model is moving forward in steps of two years. This allows to represent time lags, e.g. for construction of floor space. The main sub-models and their linkages are shown in Figure 2.14.

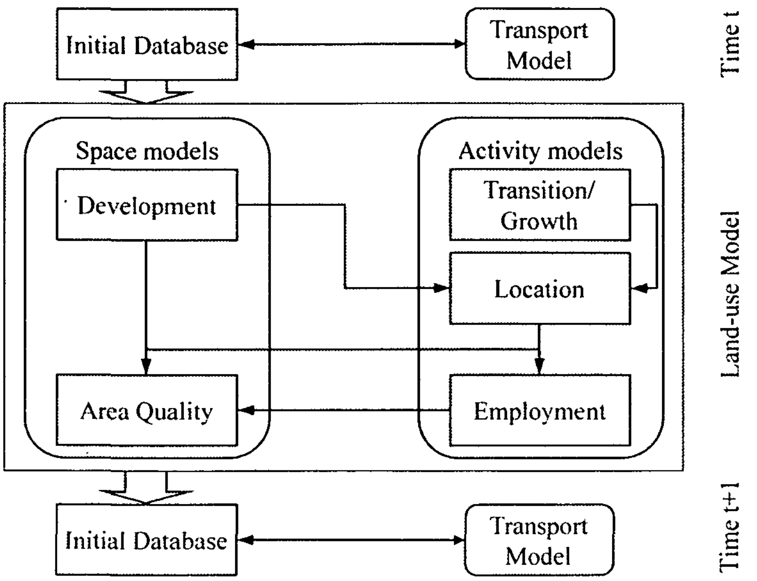

Figure 2.14: DELTA land use model structure (Still, B. G. et al., 1999)

The development model of housing and commercial floor space represents private sector developments for greenfield and brownfield sites. Equation 2.28 shows the initial calculation of the (unconstrained) demand for floor space. The term in the main brackets represents the average profitability of starting to build floor space of type u on greenfield sites. This development is then constrained. Developers will seek to retain a stock of developable land, not using up all of their stock within one period. Development is then allocated to zones on the basis of the expected zonal profitability using a weighted LOGIT formula.

$$F(U,G)_t^u = \alpha_t^u * \sum_i F_{ti}^u * \left\{ \frac{\sum_i \left(r_{ti}^u - c(G)_{ti}^u\right) * F_{ti}^u}{\sum_i F_{ti}^u} \right\}^{\beta_t^u}$$

Equation 2.28: DELTA development model (Still, B. G. et al., 1999) p. 87

$F(U,G)_t^u$........Total unconstrained floor space of type u to be started in time t on Greenfield sites

α_t^u.................Scaling parameter for the entire function

β_t^u.................Parameter expressing the elasticity with respect to average profitability

F_{ti}^u.................Floor space of type u in zone i in time t

$c(G)_{ti}^u$ ....Cost of building floor space type u in zone i in time t

r_{ti}^u................Rent of floor space type u in zone i in time t

Demographic change is represented via a Markov-chain type "transition" model that households of a type transform into another type. The location choice model for employment and households takes into account several factors, namely utility of consumption, accessibility, area quality and transport related environmental quality. The utility of location is calculated as shown in Equation 2.29.

$$\Delta V_{ti}^h = \theta^{hU} * \left(U_{ti}^h - U_{(t-n)i}^h\right) + \theta^{hA} * \left(A_{ti}^h - A_{(t-n)i}^h\right) + \theta^{hQ} * \left(Q_{ti}^h - Q_{(t-n)i}^h\right) + \theta^{hR} * \left(R_{ti}^h - R_{(t-n)i}^h\right)$$

Equation 2.29: DELTA utility location choice model (Still, B. G. et al., 1999) p. 88

ΔV_{ti}^h..............Change in total utility to be gained in a zone for a given household type

U_{ti}^h ....Utility of consumption for households h locating in zone i at time t

A_{ti}^h.................Accessibility of zone i for households h at time t

Q_{ti}^h ....Quality of housing in zone i at time t

R_{ti}^h................Transport related environmental quality as perceived by households h in zone i at time t

Θ.................Parameters on each term which determine the sensitivity of households between accessibility, the environment, quality and utility of consumption

Complex, activity specific accessibility measures are used by DELTA. The change in utility ΔV_{ti}^h is used as an incremental LOGIT model location function.

$$H_{ti}^h = H_{t*}^h * \frac{H_{ti.}^h * \left(F(V)_{ti}^h / F_{ti}^h\right) * e^{\left(\Delta V_{ti}^h\right)}}{\sum_i H_{ti.}^h * \left(F(V)_{ti}^h / F_{ti}^h\right) * e^{\left(\Delta V_{ti}^h\right)}}$$

Equation 2.30: DELTA household location choice model (Still, B. G. et al., 1999) p. 88

H_{ti}^h ....Households of type h choosing zone i in time t

H_{t*}^h...............Total number of households h to be located

$H_{ti.}^h$...............Households of type h living in zone i at current time t

F_{ti}^h................Total residential floor space at time t

$F(V)_{ti}^h$............Available floor space in zone i at time t

ΔV_{ti}^h..............Change in utility of location as in Equation 2.29

The location model iterated, adjusting rents until all "mobile" households are located. The employment activities use a similar but simpler form of Equation 2.28. Utility maximisation is replaced by cost minimisation and the environmental variables are excluded. An employment matching sub-model adjusts the number of workers in households until supply meets demand. The area quality model represents changes in the quality of the urban fabric as a linear lagged function of the average income of residents living there.

2.6.16 The Oregon micro simulation model

(Hunt, J. D., 2002) presents results of a large co-ordinated program exploring techniques for integrated land use transport modelling. The work includes the development of an extensive modelling system for the State of Oregon in the United States. Various elements of agent-based micro-simulation have been included in the development of the practical modelling system. Agents include people, households, business establishments and developers.

The practical model framework is a combination of seven integrated modules:

- Regional economics and demographics
- Production allocations and interactions
- Household allocation
- Land development
- Commercial movements
- Household travel
- Transport supply

Some of them are aggregated representations relying on equilibrium solutions. Others are fully dynamic dis-equilibrium agent based micro-simulations. Household demographics, residential location decisions, employment decisions and daily activity patterns are represented using micro-simulation. Travel tours by household member and commodity movement patterns are also represented by micro-simulation. Trips are loaded on the transport supply networks link-to-link using minimum path assignment. Randomly assigned utility function sensitivities are used to allow dispersion in travel choices. A spatial disaggregated input-output model is used to identify patterns of spatial location and interaction between economic sectors in an aggregated treatment. An aggregate regional economic model is used to identify area-wide production level and population in-migration. Developer actions are simulated in a Monte Carlo treatment in small area grid cells. The whole system evolves through time in discrete year-by-year steps (Figure 2.15).

The model covers the entire State of Oregon plus a ring of about 50 miles around it. The area is divided into a coordinated system of zones, link tributary areas and grid cells. The different divisions of space are used in different parts of the model. 3,200 zones, roughly the size of travel analysis zones, cover the entire study area. Grid cells vary between 30 by 30 meters (within and near to built up areas) and 300 by 300 meters (open space). About 14.5 million grid cells cover the entire model area.

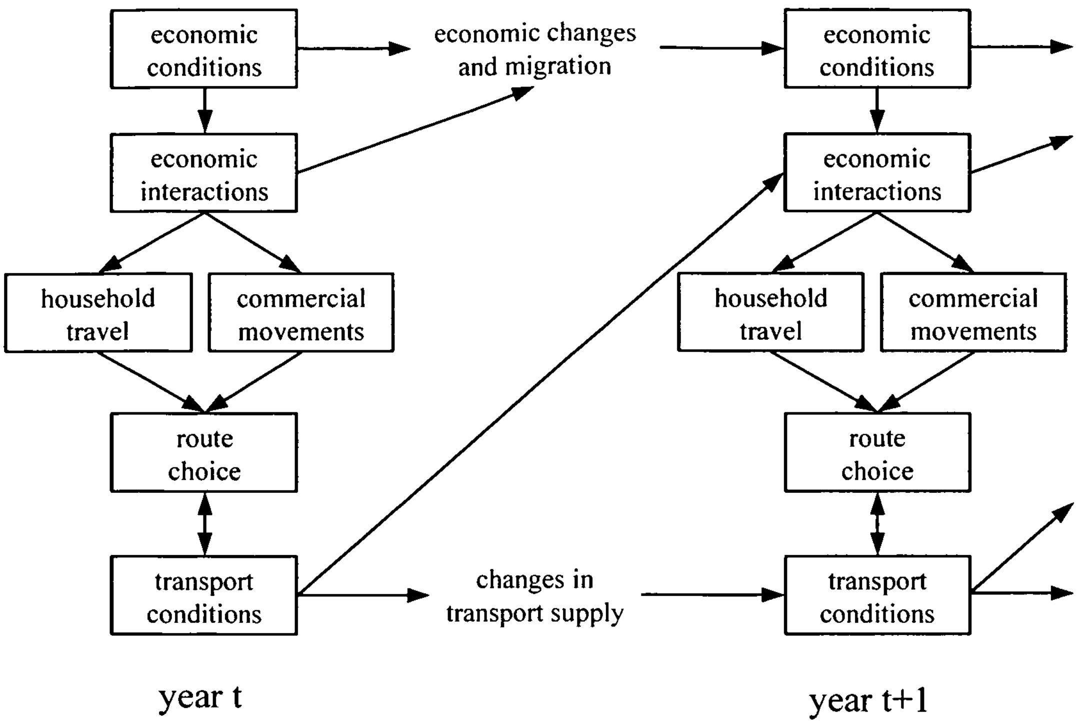

Figure 2.15: Process used to step the Oregon model through time (Hunt, J. D., 2002) p. 71

Table 2.6: Sub-models Oregon integrated land use transport model

Sub-model	Model type
Regional economics and demographics	Combined input-output and econometric model, requires exogenous national forecasts, calculates regional totals of production by sector, imports and exports, employment and payroll by sector, in migration.
Production allocations and interactions	Aggregate treatment, extended version of the spatially-disaggregated input-output approach used in MEPLAN (Hunt, J. D. and Simmonds, D. C., 1993).
Household allocation	Micro-simulation, Monte Carlo simulation is used to assign specific conditions to each to household, with selection probabilities for alternative possible conditions based on either exogenously specified conditional distributions or choice probabilities.
Land development	Behavioural, developers make decisions aiming at improving their properties based on current prices and vacancy rates, Monte Carlo simulation
Commercial movements	Fully disaggregated list of truck movements.
Household travel	Activity pattern assigned to each household member for the day, Monte Carlo process to identify the sequence of activities undertaken and activity duration, home and work based tours are considered separately, primary destination and tour mode are assigned to tours, trip mode is assigned to trips (Monte Carlo process).
Transport supply	Micro-assignment at the level of individual vehicles and travelers.

2.6.17 URBANSIM

The UrbanSim software is distributed as Open Source software under the GNU General Public License, which allows anyone to use, modify and redistribute the source code at no cost (Waddell, P., 2002). It is available at http://www.urbansim.org/. The design of UrbanSim differs significantly from several existing modelling approaches. To show the differences Table 2.7 compares some key features of UrbanSim and other land use and transport models. Figure 2.16 depicts the data integration process for UrbanSim. Data from sources like the census have to be transformed to grid cell data. Synthesized households are probabilistically assigned to parcel data. UrbanSim uses 150 by 150 meter grid cells. Parcel data are collapsed into the cells.

Table 2.7: Comparison of operational model characteristics

Characteristic	DRAM/EMPAL	MEPLAN, TRANUS	CUF2	UrbanSim	MARS
Section	2.6.9	2.6.5, 2.6.7	2.6.13		
Model structure	Spatial interaction	Spatial Input-Output	Discrete choice	Discrete choice	Spatial interaction
Household location choice	Modelled	Modelled	Not modelled	Modelled	Modelled
Household classification	Aggregate, 8 categories	Aggregate, user defined	Not represented	Disaggregate, income, persons, workers, child	Aggregate
Employment location choice	Modelled	Modelled	Not modelled	Modelled	Modelled
Employment classification	Aggregate, 8 categories	Aggregate, user defined	Not modelled	Disaggregate, 10-20 sectors	Aggregate, 2 categories
Real estate development	Not modelled	Modelled	Modelled	Modelled	Modelled
Real estate measure	Acres	Acres Units Floor space	Acres	Acres Units Floor space	Acres Units Floor space
Real estate prices	Not modelled	Modelled	Not modelled	Modelled	Modelled
Geographical basis	Census tracts or aggregates	User defined zones (2-300)	Grid cells	Grid cells	User defined zones (2-34)
Temporal basis	Quasi-dynamic, equilibrium (5-10 years steps)	Cross-sectional, equilibrium	Annual, dynamic	Annual, dynamic	Annual, dynamic
Interaction with travel model	Yes	Yes	No	Yes	Yes
Modular model structure	Partial	No	No	Yes	Yes
Software access	Proprietary	Proprietary	NA	Open source	On request

Source: (Waddell, P., 2002), MARS added by the author

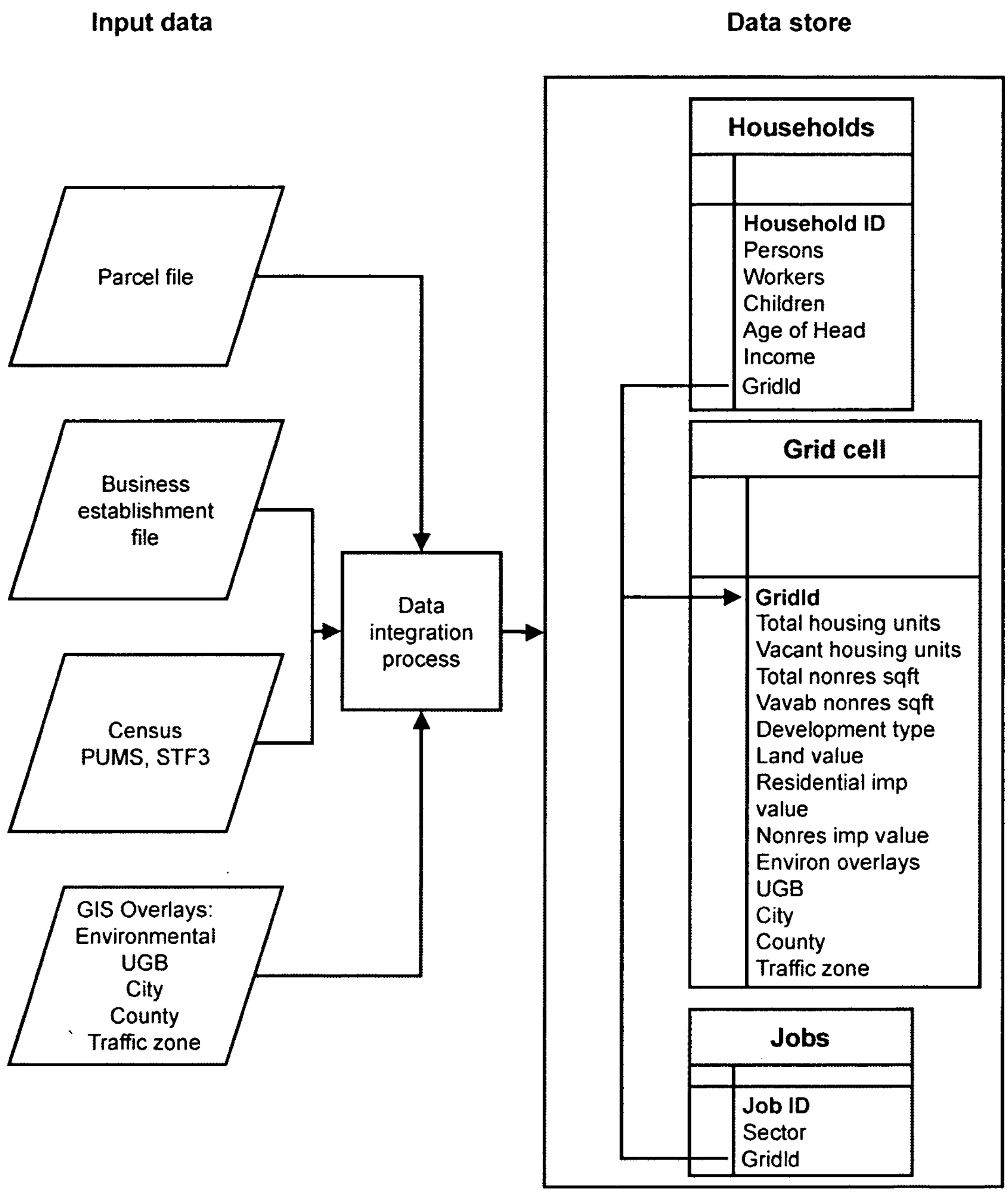

Figure 2.16: UrbanSim data integration process (Waddell, P., 2002)

The structure and processing of UrbanSim is shown in Figure 2.17. The individual model components predict:

- the pattern of accessibility by car ownership level (access model),
- the creation or loss of households and jobs by type (demographic and economic transition),
- the movement of households or jobs within the region (household and employment mobility model),
- the location choices of households and jobs from the available vacant real estate (household and employment location model),

- the location, type and quantity of new construction and redevelopment by developers (development model) and
- the price of land at each location (land price model).

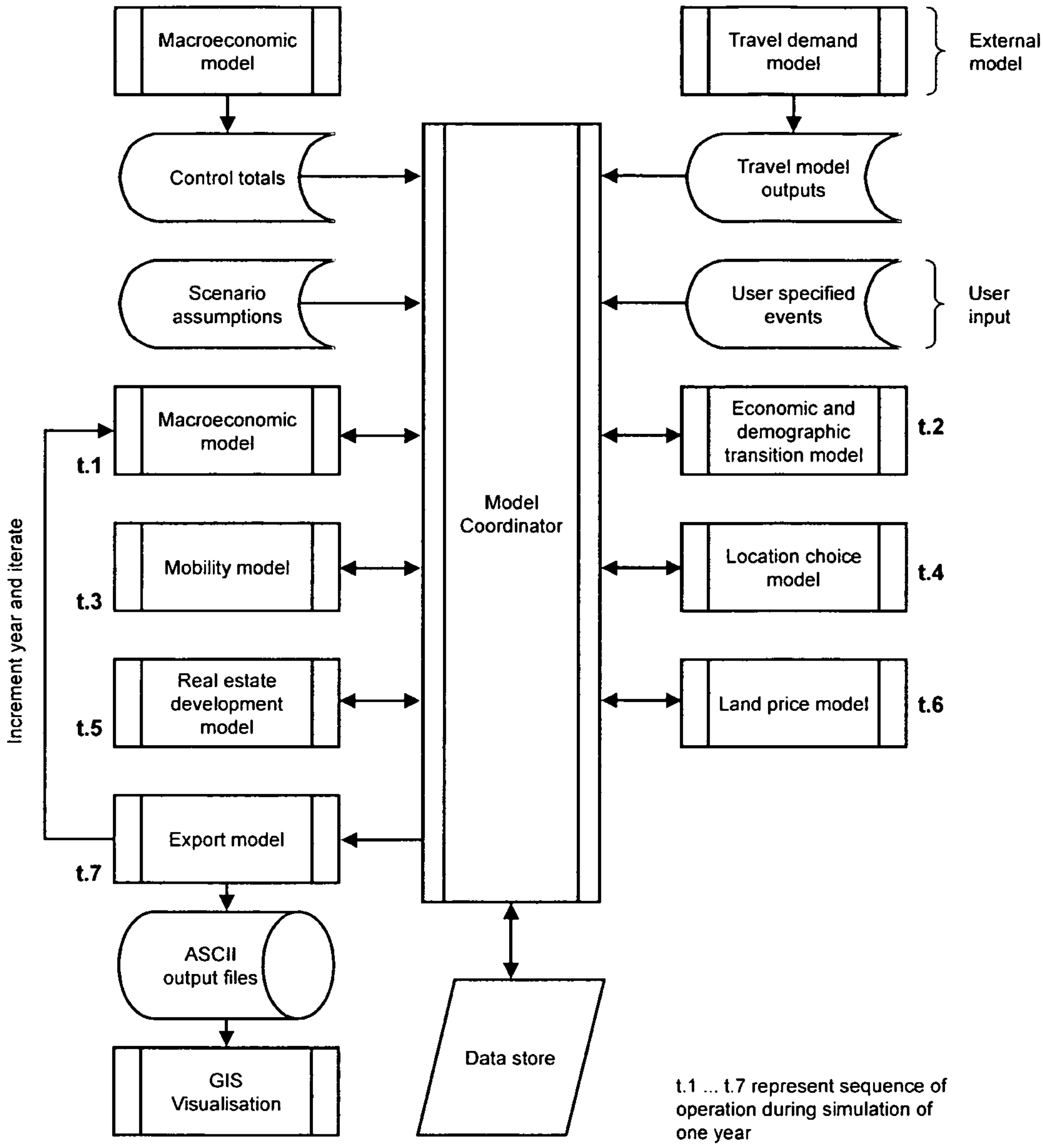

Figure 2.17: UrbanSim model structure and processing (Waddell, P., 2002)

Table 2.8: Description of UrbanSim core models (Waddell, P., 2002)

Demographic and economic transition models
The demographic transition model simulates births and deaths in the population of households. Newly created households are added to the household list without an assignment to a specific location. They are placed in housing later by the household location choice model. The employment transition model is responsible for modelling job creation and loss.
Household and employment mobility models
The household mobility model determines whether a household decides to move. Movement probabilities are based on historical data. The employment mobility model determines which jobs will move from their current location using a similar approach to the household mobility model.
Household and employment location model
The household location model chooses a location for each household without a current location (newly created households and mobile households). For each such household, a sample of locations with vacant housing units is randomly selected from the set of vacant housing. Each alternative is evaluated for its desirability. A multinominal LOGIT model calibrated to observed data is used for this purpose. The household is assigned to its most desired location among those available. The employment location model is responsible for determining a location for each job without a location (newly created jobs, mobile jobs). The same principles as in the household location model are used. The variables used in the household location model include attributes of the housing grid cell (price, density, age), neighbourhood characteristics (land use mix, density, average property values, local accessibility to retail) and regional accessibility to jobs. Variables in the employment location model include real estate characteristics in the grid cell (price, type of space, density, age), neighbourhood characteristics (average land value, land use mix, employment in each other sector) and regional accessibility to population.
Real estate development model
The real estate development model simulates developer choices about what kind of construction to undertake and where, including both development and redevelopment of existing structure. Each year the model creates a list of grid cells on which developments are possible. The probability for each alternative (including not to develop) is calculated in a multinominal LOGIT model. Variables include characteristics of the grid cell (current development, policy constraints, land and improvement value), characteristics of the site location (proximity to highways, arterials, existing development and recent development) and regional accessibility to population.
Land price model
The land price model simulates land prices of each grid cell as the characteristics of locations change over time. It is based on urban economic theory, which states that the value of location is capitalised into the price of land. The model is calibrated from historical data using a hedonic regression to include effect of site, neighbourhood, accessibility and policy effects on land prices. Similar variables are used as in the development model.

2.7 Conclusions

2.7.1 Outlook

(Hensher, D. A. and Button, K. J., 2000) p. 6 present the result of a Delphi survey undertaken to identify the key issues in near future transport modelling. The following twelve top issues in transport modelling ranked by their importance were raised:

1. Activity modelling
2. Stated preference/choice
3. Location-based choice models
4. GIS as spatial database
5. Joint revealed/stated preference modelling
6. Measures of accessibility
7. Dynamic traffic assignment
8. Travel market segmentation
9. Advanced static choice models
10. Equilibrium procedures
11. Survey collection strategy
12. Vehicle ownership

The same survey highlighted a gap between state of the art theory and its application. Most modelling experts see the future in activity-based approaches (McNally, M. G., 2000). *Aggregate travel models are unable to reproduce the complex spatial behaviour of individuals and to respond to sophisticated travel demand management measures. As a reaction, disaggregate travel models aim at a one-to-one reproduction of spatial behaviour by which individuals choose between mobility options in their pursuit of activities during a day. Activity-based travel models start from interdependent "activity programmes" of household members of a "synthetic population" and translate these into home based "tours" consisting of one or more trips.* (Wegener, M., 2003) p. 12. This allows to consider the interdependencies between household members as well as between trips of a tour. Activity based models furthermore allow the modelling of choice of time of day. Also disaggregate traffic assignment models based on queuing etc. exist.

(Wegener, M., 2003) argues that a higher spatial resolution is needed to be able to address environmental and equity issues. *From a technical point of view, the prospects are excellent. More powerful computers will remove former barriers to increasing the spatial, temporal and substantive resolution of models. ... Geographic information systems will become the mainstream data organisation of urban models. ... Aggregate probabilistic approaches (e.g. entropy maximising) will be replaced by disaggregate stochastic (microsimulation) approaches* (Wegener, M., 2003) p. 11. Figure 2.18 shows the past and future evolution of land use and transport models as seen by (Wegener, M., 2003). Two major trends in transport and land use modelling can be derived from the reviewed literature:

- an increasing disaggregation, leading to microsimulation approaches and

- an integration of GIS-systems.

These trends are additionally fuelled by the continuously growing computational power.

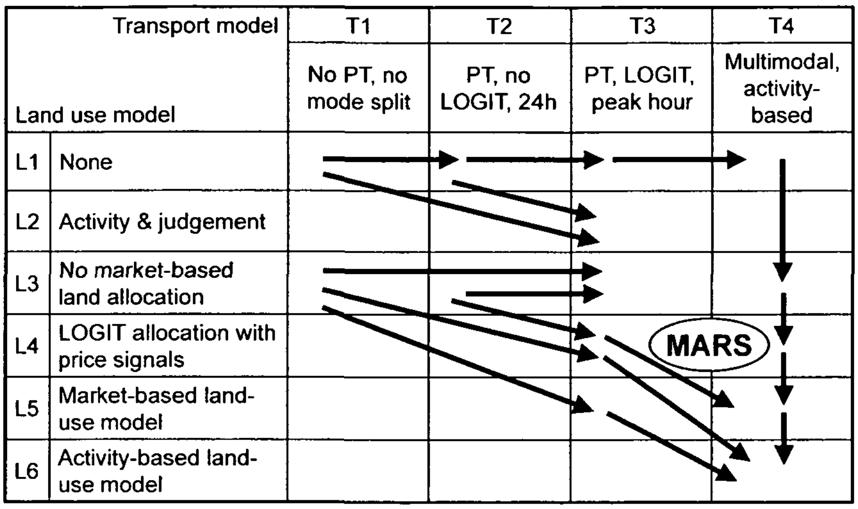

Figure 2.18: Evolution of urban land-use and transport models (Wegener, M., 2003), MARS added by the author

2.7.2 Personal summary and position of MARS within land use and transport modelling

The future looks bright from the modelling experts perspective. E.g. (Wegener, M., 2003) is very enthusiastic about the prospects of urban land use and transport modelling. Nevertheless some doubts have to be raised at this point. Transport models are used to predict the impacts of transport policies since at least 30 years. In parallel the level of detail in transport modelling was rapidly growing. The accuracy of model predictions should have benefited from this progress and therefore lead to the right decisions to remedy problems. The latter has obviously not come true. Transport and land use related problems are still unsolved: urban sprawl, pollution, accidents, consumption of non-renewable resources (just to name some of them). In contrary they even seem to increase. There is not yet empirical evidence that the *sophisticated travel demand management measures* have substantial impact. An ever increasing dis-aggregation therefore cannot be the one and only solution.

For strategic questions like sustainability the macroscopic behaviour of the urban system is essential not the microscopic behaviour. Transport problems are not problems of individual behaviour, they are problems of collective behaviour. Synergetics, the science of collaboration, deals with collective behaviour[26]. Two concepts are central to synergetics, namely the concept of the *order parameter* and that of *slaving* (Haken, H., 1983) p. 35. In self-organising systems the high number of variables, which the system is made up of, is *slaved* by one variable. This variable is the *order parameter.*

[26] Haken, H. (1983). Erfolgsgeheimnisse der Natur - Synergetik: Die Lehre vom Zusammenwirken; Deutsche Verlags-Anstalt, Stuttgart.
Haken, H. (1983). Advanced Synergetics - Instability Hierarchies of Self-Organizing Systems and Devices; *Springer Series in Synergetics*, **20**; Springer-Verlag,

The basic hypothesis underlying the model MARS is that urban systems are self-organising systems. Therefore the principles of synergetics can be applied. In the case of the transport system the order parameter seems to be the physiological energy consumption of the transport user. Other variables are slaved by the body energy consumption[27]. If a strategic objective like sustainability is the matter of concern, it is seen as appropriate to use an aggregated modelling approach. In contrary to the common trend of an ever increasing level of spatial detail, MARS is based on an aggregated approach.

Are the principles of synergetics valid for a system built up of human beings? *Synergetics deals with systems composed of many subsystems, which may be of quite different natures, such as electrons, atoms, molecules, cells, neurons, mechanical elements, photons, organs, animals or even humans* (Haken, H., 1983) p. 1. (Haken, H., 1983) furthermore cites examples of applications to the fields of economy (p. 16) and sociology (p. 17). An application of the principles of synergetics to urban systems is therefore seen as justified.

MARS is an integrated land use and transport model. Unlike many other models MARS fully considers the non motorised modes in its transport sub-model. MARS is comprehensive as it covers seven of the eight sub-systems defined by (Wegener, M., 2003)[28]. Unlike many other models MARS does not rely on cross sectional modelling. On the contrary MARS models changes of land use and transport over time. MARS models the development of stock (floor space, road network) and activities (location choices, transport choices). Due to its aggregated and strategic character MARS takes into account a relative small number of different actors and sectors. But its segmentation is comparable with other models[29]. In general the MARS modelling approach and its different sub-parts are in line with theories and approaches established in international land use and transport modelling research.

The position of MARS in Figure 2.18 was added by the author. MARS is seen as being placed on the border between transport model evolution stage T3 and T4. MARS is multimodal. It is in a certain sense activity based, although only two types of activities are considered. It does not model peak hour, but the time of day choice is currently not endogenously defined. The land use model is not fully market-based but uses at least an allocation with price signals.

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[27] The perception of travel time determines human travel behaviour. Knoflacher has shown that the perception of travel time is based on the physiological energy consumption during travelling.
Knoflacher, H. (1981). Human Energy Expenditure in Different Modes: Implications for Town Planning. International Symposium on Surface Transportation System Performance, US Department of Transportation.
Knoflacher, H. (1987). Verkehrsplanung für den Menschen; Wirtschaftsverlag Dr. Anton Orac, Wien. p. 55ff.
Based on these findings Kölbl advocates in his thesis the hypothesis of constant physiological energy consumption budgets. Kölbl, R. (2000). A bio-physical model of trip generation/trip distribution. Phd-thesis. Department of Civil and Environmental Engineering. University of Southampton.

[28] See Table 2.4 in section 2.6.1 Introduction p. 20.

[29] See e.g. Table 2.5 in section 2.6.7 METROSIM p. 29.

3. QUALITATIVE DESCRIPTION OF THE DYNAMIC TRANSPORT AND LAND USE INTERACTION MODEL MARS

3.1 Introduction

This section aims on the one hand at giving a complete qualitative description of the MARS sub-systems and the links between them. On the other hand the research from which MARS stems will be presented. Additionally the methods used to derive the qualitative model are described briefly.

The first step of the MARS development was a qualitative analysis using causal loop diagramming (CLD)[30] and subsystem diagrams[31]. First of all at the highest level of aggregation MARS can be divided into two main sub-models: the *land-use* and the *transport model*[32] (Figure 3.1). Changes in the transport subsystem cause time lagged changes in the land use system. Changes in the land use system cause as well immediate as time lagged reactions in the transport subsystem.

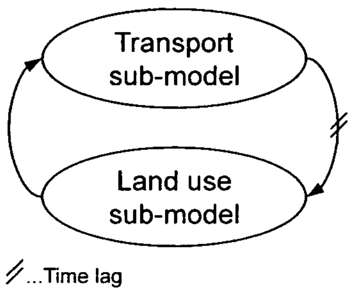


Figure 3.1: MARS subsystem diagram on the highest level of aggregation

The land use sub-model can be further subdivided into a *residential* and a *workplace location sub-model.* The links between the sub-models are shown in Figure 3.2. Accessibility is one of the outputs of the *transport model.* Accessibility in the year n is used as an input into the *location models* in the year n+1. Workplace and residential location is an output of the *land use model.* The number of workplaces and residents in each zone in the year n is used as attraction and potential in the *transport model* in the year n+1. There are also links between the *land use sub-models* as they are competing for land and availability of land

[30] More detailed information about CLD can be found in section 12.1 Causal loop diagramming (CLD) or in the following literature:
Emberger, G. and Fischer, P. (2001). Easy Understanding of Causal Loop Inherent Dynamics - EUCLID Method. Vienna, Institute for Transport Planning and Traffic Engineering, Vienna University of Technology: 4.;
Anderson, V. and Johnson, L. (1997). Systems Thinking Basics - From Concepts to Causal Loops; Pegasus Communications, Inc., Waltham.or
Roberts, N., Andersen, D. F., Deal, R. M., Garet, M. S. and Shaffer, W. A. (1994). Introduction to Computer Simulation - A System Dynamics Approach; Productivity Press., Portland.

[31] Sterman, J. D. (2000). Business Dynamics - Systems Thinking and Modeling for a Complex World; McGraw-Hill Higher Education, p. 99 ff.

[32] Entities from sub-system diagrams mentioned in the text are written in *Italics* to highlight the links between text and figures.

influences its price. MARS iterates in a time lagged manner between the *transport* and the *land use sub-model* over a period of 30 years.

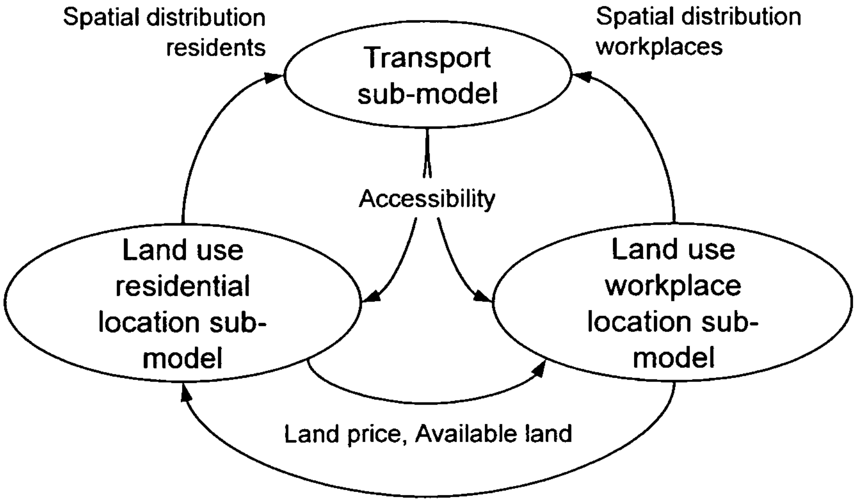


Figure 3.2: Link between the transport and the land use sub-models of MARS

The followings sections describe the qualitative sub-models in detail.

3.2 Transport model part

3.2.1 Introduction

Strategic transport models previously developed at TUW-IVV[33] were used as basis for the development of the MARS transport sub-model. These models use the highest possible level of simplification to represent the road and public transport network. I.e. the network is aggregated to one link per origin-destination (OD) pair. The consequence is that there is no route choice stage in MARS (Figure 3.3)[34]. The non-motorised modes pedestrian and bike are represented as an aggregated mode in MARS. The original plan was to consider them as separate modes, but MARS with four different modes failed to work with more than 25 zones. The

[33] For a fuller description see:
Knoflacher, H., Pfaffenbichler, P. C. and Emberger, G. (2000). A strategic transport model-based tool to support urban decision making processes. 2nd International Conference on Decision Making in Urban and Civil Engineering, Lyon, INSA Lyon (Fr), ESIGC Chambery (Fr), ENTPE Vaulx-en-Velin (Fr), ETS Montreal (Ca). or
Pfaffenbichler, P. C. and Emberger, G. (2001). Ein strategisches Flächennutzungs-/Verkehrsmodell als Werkzeug raumrelevanter Planungen. CORP 2001: Computergestützte Raumplanung, Vienna, Institut für EDV-gestützte Methoden in Architektur und Raumplanung.

[34] For the European Union funded research project SAMI (Strategic Assessment Methodology for the Interaction of CTP-Instruments) a strategic transport model employing a simple all or nothing assignment was developed and used. To either include an assignment in MARS or to link MARS to an external assignment are seen as potential improvements for future developments. See section 9.3 Suggestions for future MARS improvements.
See also: Pfaffenbichler, P. and Emberger, G. (2000). Ein strategisches Verkehrsmodell von Europa (EURO9). CORP 2000, 5. Symposium zur Rolle der Informationstechnologie in der Raumplanung, Wien.

reason was a Microsoft Visual Basic bug[35]. As a straight forward short term solution it was decided to overcome the problem by combining pedestrians and bike to one aggregate mode referred to as "non motorised" or "slow"[36].

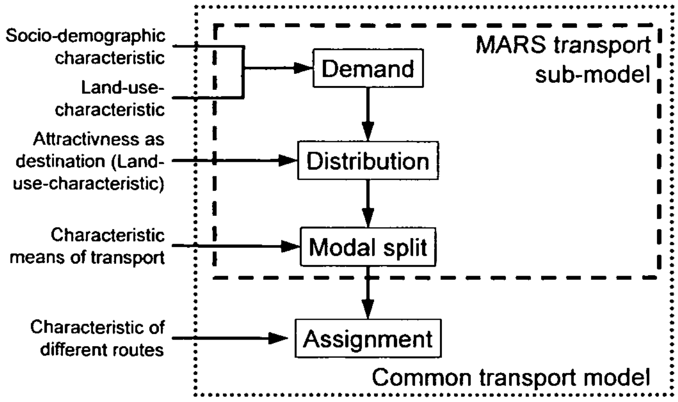


Figure 3.3: MARS transport sub-model and common four stage transport model

3.2.2 Trip generation sub-model

Two types of activities are considered in MARS: work and others. Four origin-destination-groups are considered in the trip generation sub-model of MARS:

- Home – Work (HW),
- Work – Home (WH),
- Home – Others (OH) and
- Others – Home (HO).

MARS uses a tour-based concept similar e.g. to the Orestad traffic model of the city of Copenhagen (Jovicic, G. and Overgaard Hansen, C., 2003). In this concept a tour is defined to be a sequence of a simple trip to destination and a return simple trip from destination to home. Two different types of tours are considered in MARS:

- Home – Work – Home (HWH) and
- Home – Others – Home (HOH).

The two tour types considered cover a high share of daily mobility[37]. Given the strategic nature of MARS they are seen as representing urban mobility precisely enough.

[35] Basically, the error is the result of a bug in the Visual Basic compiler when allocating memory for passing User Defined Types (UDTs) to functions or subroutines in DLLs. The error may occur when this amount exceeds approximately 64KB. You can work around this problem by changing the way that such UDTs are passed to the DLL. When you pass a UDT to a DLL, you are actually passing a pointer to the first memory location of the UDT. Another way to pass this pointer is by copying the UDT to a Byte array and passing the first element of the Byte array by reference (http://support.microsoft.com/default.aspx?scid=kb;en-us;Q179140; accessed 01/08/2003).

[36] For a long term perspective the addition of a fourth distinct mode is seen as a potential improvement. See section 9.3 Suggestions for future MARS improvements. The fourth mode can be used to represent either the mode bicycle or, of special interest for Asian cities, the mode motorcycle.

Trip generation follows the overall principle of constant travel time budgets[38]. Trip rates per capita and day are assumed being constant for the tour HWH[39]. For the sum of the tours HWH and HOH travel time per capita and day is constant.

Figure 3.4 shows the trip generation subsystem diagram of MARS. Hatched entities are global constants, double hatched entities are linked to the land use sub-model, checked entities are linked to the distribution and mode choice sub-model and white entities are endogenous to the trip generation sub-model. The transport model calculations in MARS start at the bottom of Figure 3.4. A multiplication of the constant *trip rate commuting* with the exogenously[40] defined *workforce* in the study area gives the total number of *commuting trips*. Multiplying the total number of *commuting trips* with the *travel time per commuting trip* gives the total *travel time commuting.* The link between the total number of *commuting trips* and *travel time per commuting trip* indicates that MARS considers a speed flow relationship. Actually this link is part of the trip distribution and mode choice sub-model. *Travel time per commuting trip* is also influenced by the destination and mode choices resulting from this sub-model.

The transport model calculations continue at the top part of Figure 3.4. Multiplying the constant travel time budget (*travel time per person and day*) with the *number of residents* in the study area gives the *total travel time* budget. The available *travel time non working* (HOH tours) is calculated by subtracting the total *travel time commuting* (HWH tours) from the *total travel time* budget. Dividing the total *travel time non working* by the *travel time per non working trip* gives the *number of non working trips* (HOH tours) in the study area. Again the total number of trips and the destination and mode choices calculated in the trip distribution and mode

[37] According to data from a 1995 survey in Vienna tours HWH and HOH cover about 71% of the Viennese mobility. Herry, M. and Russ, M. (1999). Mobilität in Wien und im Umland von Wien. Vienna, Stadt Wien Magistratsabteilung 18: 89. p. 80.
According to data from a 1991 survey in Vienna tours home – work - home, home – shopping – home and home –leisure – home cover about 58% of daily mobility. Socialdata (1993). Mobilität in Wien; *Beiträge zur Stadtforschung, Stadtentwicklung und Stadtgestaltung*, **Band 45**, Wien. p. 11.
According to data from a 1991 survey in Dresden tours HWH and HOH cover about 80% of daily mobility. Schnabel, W. and Lohse, D. (1997). Grundlagen der Straßenverkehrstechnik und der Verkehrsplanung, **Band 2: Verkehrsplanung**; Verlag für Bauwesen, Berlin. p. 164.

[38] Numerous studies and household surveys have shown that travel time budgets are stable as well over time as across cites, countries and even continents:
Brög, W. and Erl, E. (1999). Kenngrößen für Fußgänger und Fahrradverkehr; *Berichte der Bundesanstalt für Straßenwesen, Mensch und Sicherheit*, M109; BASt, Bergisch Gladbach.;
Hupkes, G. (1982). "The Law of Constant Travel Time and Trip Rates." *Futures*: 38-46.; Marchetti, C. (1994). "Anthropological Invariants in Travel Behaviour." *Technological Forecasting and Social Change* 47: 75-88.;
Schafer, A. (2000). "Regularities in travel demand: an international perspective." *Journal of Transportation and Statistics* 3 (3): 1-32.
Therefore constant travel time budgets are seen as an appropriate concept to model trip generation in MARS. For more details see section 12.2 Constant travel time budgets.

[39] Despite predicted effects of teleworking etc. observed data still indicate that trip rates home to work are constant. Contrary to this observed trip rates for other purposes do not seem to be constant. Schafer, A. (2000). "Regularities in travel demand: an international perspective." *Journal of Transportation and Statistics* **3** (3): 1-32.

[40] Caution: Exogenous means exogenous to the considered sub-model! From the perspective of the whole MARS model the workforce is endogenous.

choice sub-model have an influence on the specific travel time per trip. A division of the *number of non working trips* by the *number of residents* gives the *trip rate non working* which is not a constant in MARS.

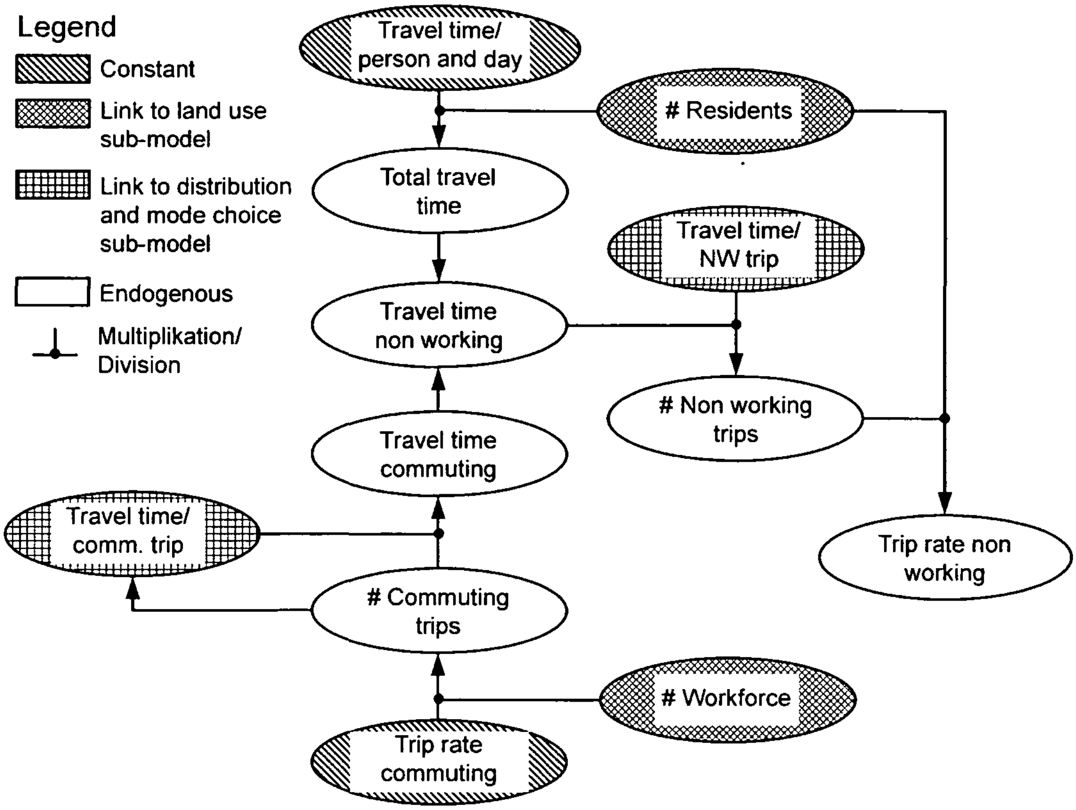


Figure 3.4: Trip generation subsystem diagram

3.2.3 Trip distribution and mode choice

The transport sub-model distributes trips simultaneous to destinations and modes. The trip distribution and mode choice sub-model is further divided into an HWH- and an HOH-sub-model. Two person groups, those with access and those without access to a car, are considered in each of the sub-models.

- **HWH tours**

Figure 3.5 shows the commuting (HWH tour) distribution and mode choice subsystem diagram. The number of commuting trips per origin zone i is defined exogenously by the trip generation sub-system. The trip distribution and mode choice sub-model calculates the probability that a destination and mode combination is chosen for a commuting trip from a given origin.

The *attraction of a zone j to be a destination* for a commuting trip is the number of workplaces within the zone (top right corner in Figure 3.5). Workplace location is given by the land use sub-model. Those with access to a car can choose between slow modes, public transport and car. Those without access to a car can only choose between slow modes and public transport. *Travel times and costs per mode and OD pair* are the link to policy instruments. Policy instruments affect either directly or indirectly the supply side, i.e. travel times, and/or the travel costs. *Travel times and costs per mode and OD pair* are used to calculate *friction factors* *per mode and OD pair*[41]. *Travel time pedestrian (slow)* and *travel costs for public transport* are defined exogenously. Other times and costs are influenced by the outcome of the distribution and mode choice model in the next iteration and therefore endogenous. The *probability that a commuting trip* starting in origin i is distributed to destination j and mode m corresponds to the ratio of *attraction* to *friction factor per mode and destination* to the *sum of all attractions to friction factors from origin i.*

As already mentioned there are several feedback loops within the distribution and mode choice model. First there is a feedback from the probability that PT is used for commuting (*Prob. Comm. trips PT* ij) to the *friction factor PT ij*. This feedback considers overcrowding effects. If a user defined capacity is exceeded, the friction factor increases. This feedback is performed once within an iteration. There is a feedback from the number of commuting trips to the entities travel cost private car and travel times private car and public transport. Travel time private car is influenced due to the speed flow relationship and changes in the parking place searching time. Travel time public transport is influenced by the speed flow relationship and the share of PT operated by busses. Travel costs private car are influenced by the speed flow relationship. There is also a feedback from the number of PT trips to the PT friction factor which takes into account the effects of overcrowding. For more details see chapter 4. Quantitative description of the Dynamic Transport and Land Use Interaction Model MARS.

- **HOH tours**

Figure 3.6 shows the non working trip (HOH tour) distribution and mode choice subsystem diagram. In the destination and mode choice stage of the transport sub model the travel time available for the purpose non working per origin zone i is defined exogenously by the trip generation sub system. This time is then distributed to modes and destinations. The attraction of a zone j as a destination is given by the land use sub-model. Travel times and travel costs per mode and OD pair give the friction factor per mode and OD pair. Travel time pedestrian and public transport and travel costs for public transport are defined exogenously. The travel time of trips starting in origin i is distributed to destinations and modes corresponding to the ratio friction factor per mode and destination to the sum of all attractions to friction factors from origin i. The number of trips is calculated by dividing the total travel time per mode and OD pair by the specific travel time per mode and OD pair. There is a feedback from the number of commuting trips to the entities travel cost private car and travel times private car. Travel time private car is influenced due to changes in the parking place searching time. There is also a feedback from the number of PT trips to the PT friction factor which takes into account the effects of overcrowding. To calculate trips in the HOH tour sub-model, the distributed time has to be divided by the specific times per OD pair. For more

[41] Friction factors measure the subjectively perceived expense for a journey. Travel time and costs are considered in the friction factors. In MARS a definition using generalised costs weighted by exponential functions is used. Source: Walther, K., Oetting, A. and Vallée, D. (1997). Simultane Modellstruktur für die Personenverkehrsplanung auf der Basis eines neuen Verkehrswiderstands; *Veröffentlichungen des Verkehrswissenschaftlichen Instituts der Rheinisch-Westfälischen Technischen Hochschule Aachen*, **52**, Aachen.
For more details about the concept of friction factors see section 12.3 Friction factors.

details see chapter 4. Quantitative description of the Dynamic Transport and Land Use Interaction Model MARS.

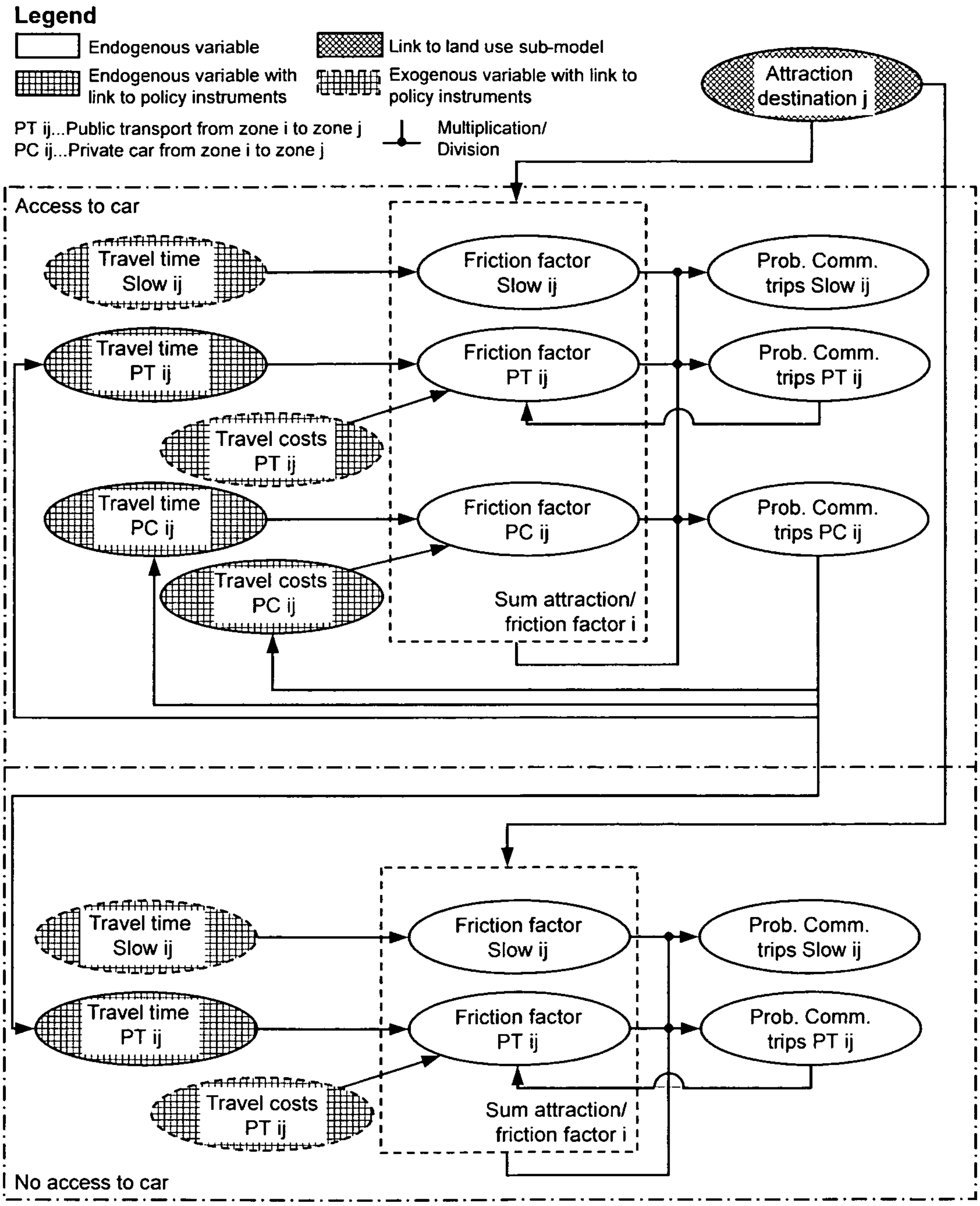


Figure 3.5: Distribution and mode choice subsystem diagram for travel purpose commuting (HWH tours) and person group with and without access to a car

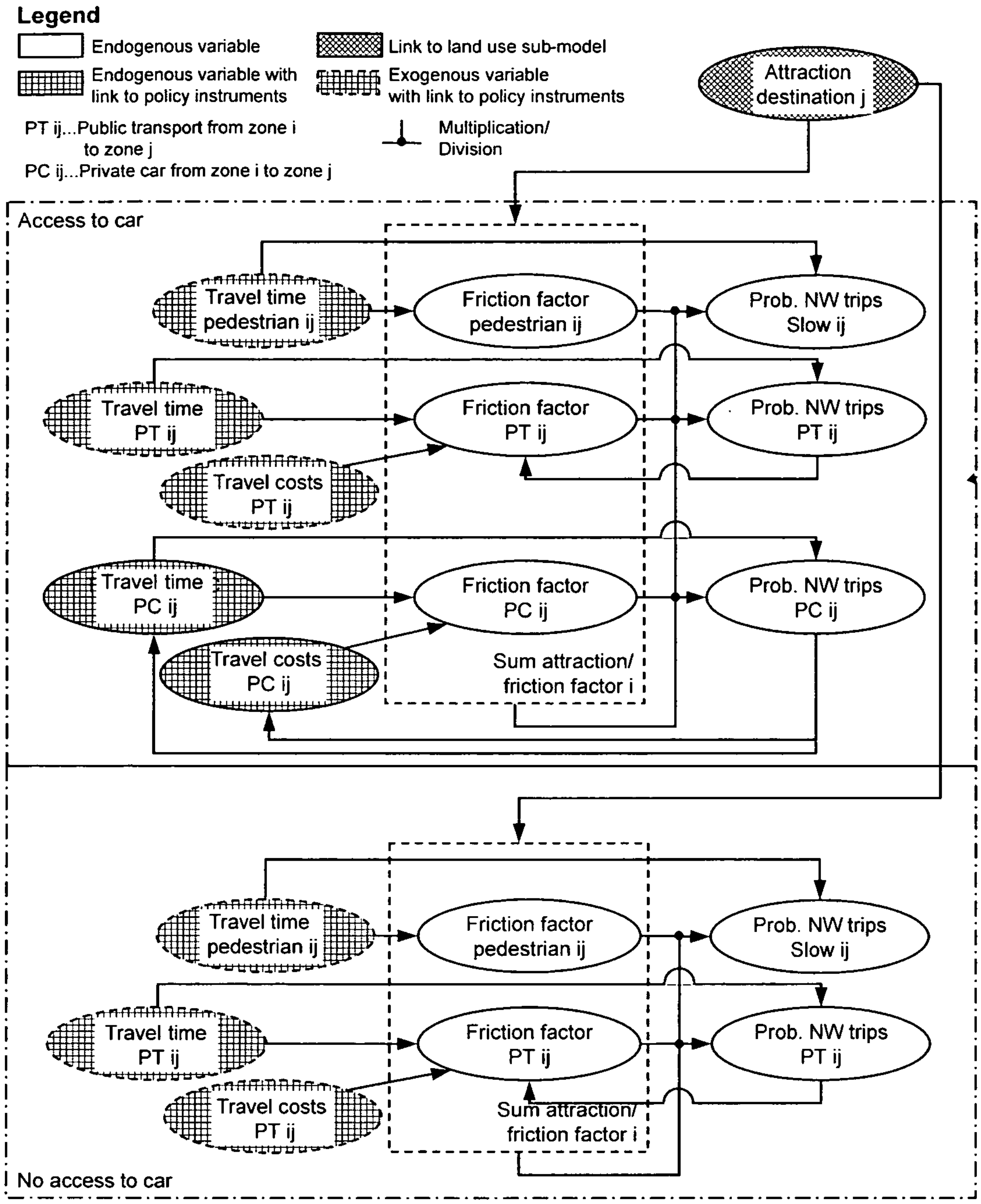


Figure 3.6: Distribution and mode choice subsystem diagram for travel purpose non working (HOH tours) and person group with access to car

3.2.4 Summary transport sub model

Figure 3.7 gives an overview about the whole transport sub-model. For reasons of simplification no distinction between the person groups with and without access to car is made in this figure.

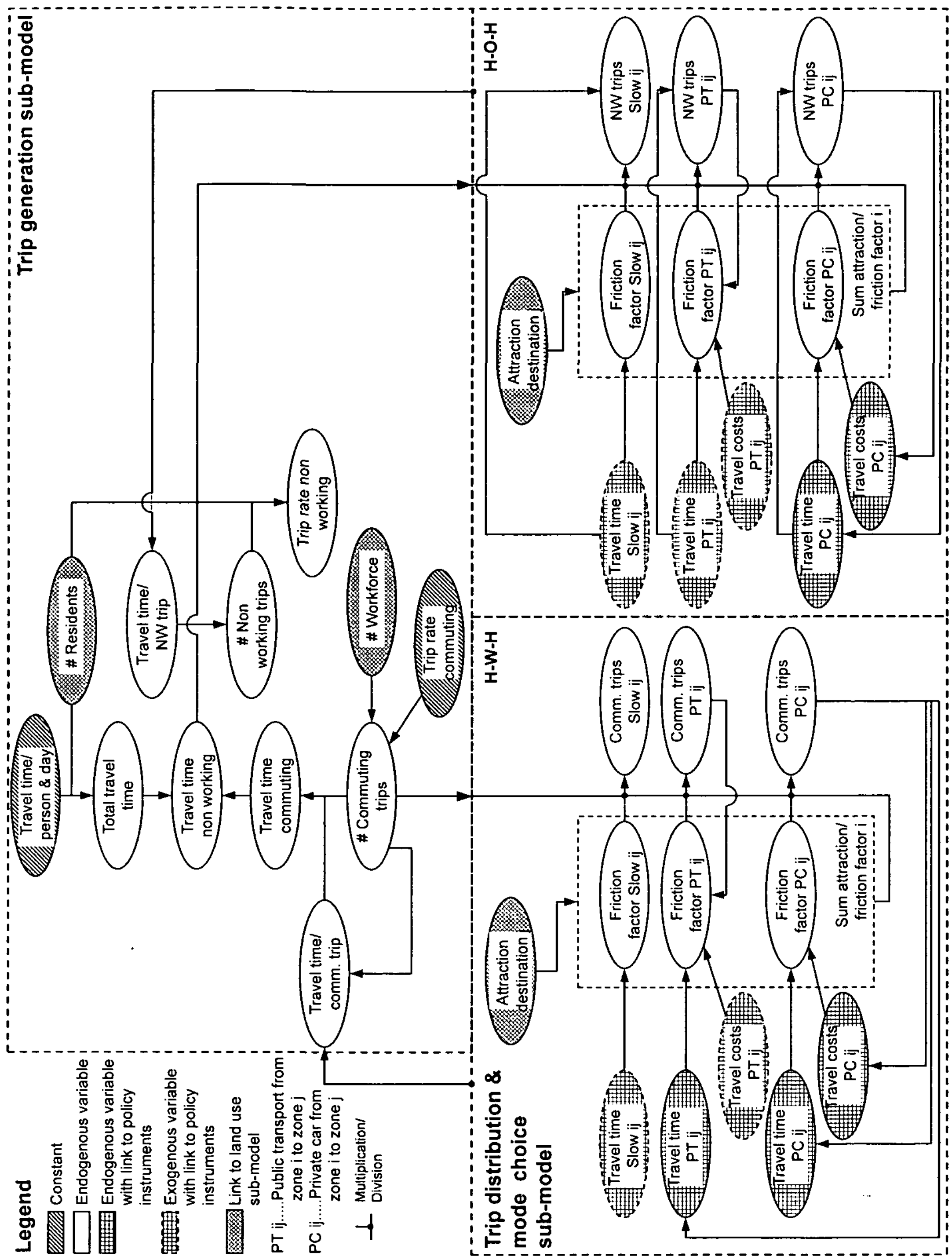


Figure 3.7: Transport model sub-system diagram

3.2.5 Example policy variable reduction of PT fares

For a better understanding of the complex interactions in the MARS transport sub-model the causal effects for varying a policy instrument are shown in Figure 3.8.

Reducing PT fares for commuting trips was chosen for this exercise. The starting point is the Roman numeral I near the left, lower edge of Figure 3.8. If PT fares are decreased, the travel costs for a PT trip will decrease. This is indicated by the downwards pointing arrow. If travel costs decrease, generalised costs and therefore the friction factor for PT trips will decrease. This is indicated by the character "s." which stands for "same" (See section 12.1 Causal loop diagramming (CLD) p. 227). A change in the first entity causes a change in the same direction in the linked entity. If the friction factor for PT trips decreases, the number of PT trips will increase. This is indicated by the character "o.". A change in the first entity causes a change in the opposite direction in the linked entity. As the friction factors for car and slow modes increase relatively to the friction factor of PT, car and slow mode trips will decrease.

If the number of car trips decreases, the travel time for a car trip will decrease (s.). As commuting trips occur mainly in the peak period and peak period speed is low, also travel costs for car trips will decrease (s.). If travel time and costs decrease, the friction factor will decrease (s.). If the friction factor decreases, car trips will increase (o.). Summarising the links of this feedback loop we recognise that it is a balancing feedback loop (s.*s.*o. = b.).

If at least a part of modelled PT system is bus-based, a decrease of car trips will also decrease PT travel times (s.). If travel times PT decrease, the friction factor for PT trips will decrease (s.). If the friction factor for PT trips decreases, the number of PT trips will increase (o.). If the number of PT trips increases, the number of car trips will decrease (o.). This gives in total a reinforcing feedback loop (o.*s.*s.*o. = r.). But this reinforcing feedback loop is controlled by the previously found balancing feedback loop. Therefore PT trips are oscillating around a dynamic equilibrium instead of increasing exponentially.

There are also links from the HWH-distribution and mode choice sub-model to the trip generation sub-model. If travel times for PT and car decrease, the travel time per commuting trip decreases (s.). If travel time per commuting trip decreases, then the total commuting travel time decreases (s.). If the total commuting travel time decreases, the total travel time available for other purposes increases (o.). If the number of non working car trips increases, travel times and costs increase due to higher parking place searching times (s.). In the HOH sub-model no speed flow relationships is applied. The assumption is that non working trips were made mainly during the off-peak period[42]. If travel times and costs increase, the friction factor increases (s.). If the friction factor increases, the number of car trips decreases (o.). Again this results in a balancing feedback loop (s.*s.*o. = b.).

Again there is a link back to the trip generation sub-model. If car travel time increases, then the average travel time per non working trip increases (s.) If the average travel time per non working increases, the number of non working trips decreases (o.). There is another balancing feedback loop formed by the entities travel time per non working trip, non working car trips and car travel time (o.*s.*s. = b.).

[42] Changes in these assumptions are subject to suggestions for further MARS improvements (see section 9.3 Suggestions for future MARS improvements).

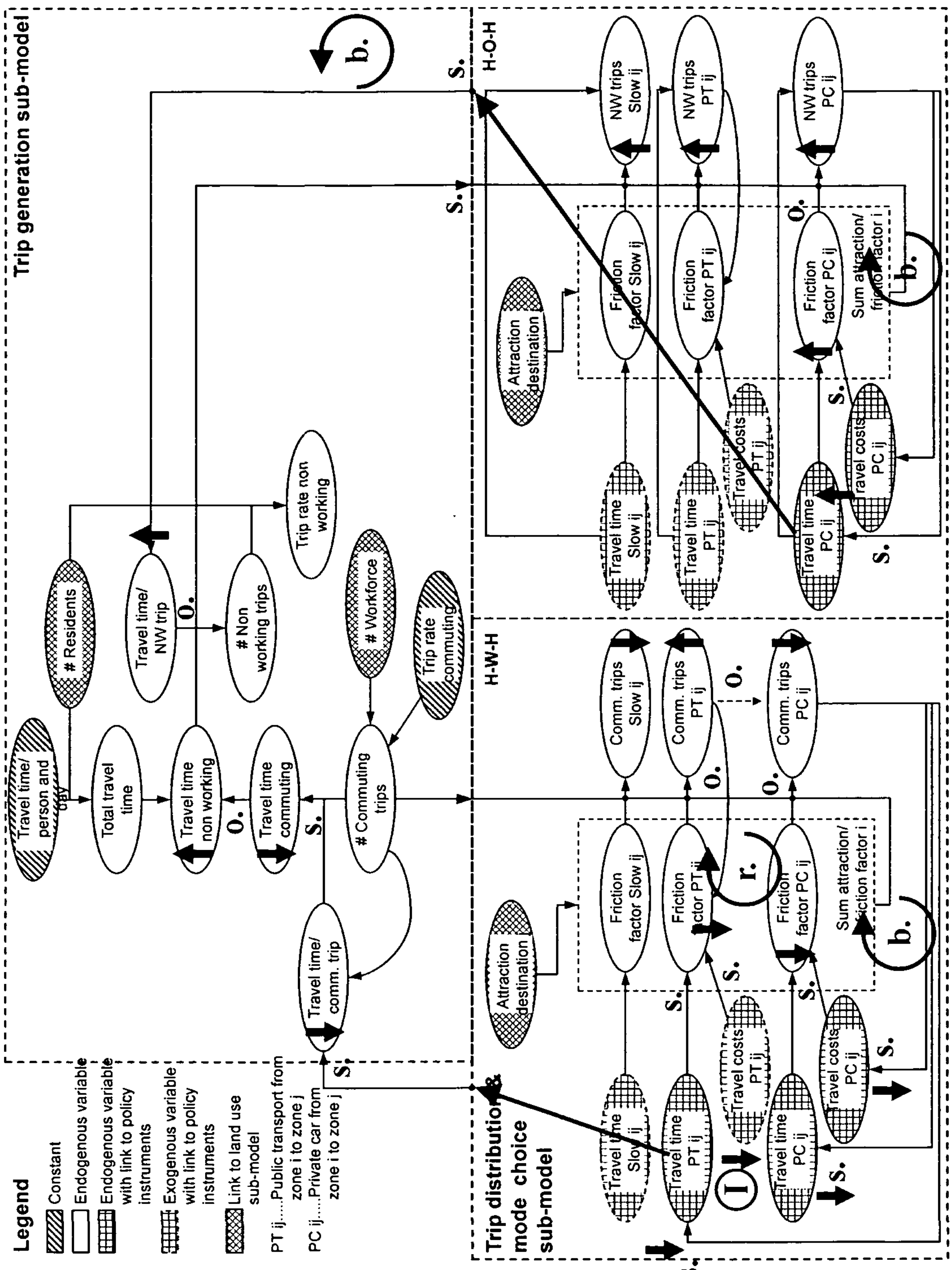


Figure 3.8: Causal effects of the policy instrument "reduce PT fare"

3.3 Land use model

3.3.1 Introduction

The land use sub-model was developed based on research performed for the Viennese Municipal Department 18 "Urban Development and Planning"[43]. The land use sub-models consists of a residential and a workplace location model. The land use sub-models use in general LOGIT or gravity type models. The ratio of the exponential function value of utilities and dis-utilities of an alternative to the sum of all alternatives is used to distribute a potential to different locations. The detailed equations of the land use sub-model are included in the chapter 4. Quantitative description of the Dynamic Transport and Land Use Interaction Model MARS. The location models consist of four further sub-models: a development model, a willingness to move out model, a willingness to move in model and a supply/demand redistribution model. The first one models the development of building stock while the others model the activities of households and businesses.

Two qualitative land use and transport interaction models of Vienna were the starting point of the MARS land use sub-model.

- **Population location**

A first qualitative land use and transport interaction model (Figure 3.9) was designed to explain the mechanisms causing urban sprawl[44]. Urban sprawl is a migration of opportunities from the core area of functional urban regions into their outskirts. If this entity increases, the use of the mode private car increases (Figure 3.9, link "s"). If car use increases, trips made by public transport (PT) or by the non motorised modes pedestrian and bike (slow) will decrease ("o")[45]. Furthermore if car use increases, the demand for car infrastructure increases. This relation is depicted by the arrow from the entity car in the box "Means of Transport" to the entity car in the box "Transport structure". Today's transport planning practice reacts by providing more car infrastructure ("s"). If car infrastructure is extended, quantity and quality of PT and slow mode infrastructure is reduced ("o") in relative and absolute terms. If there is less PT and slow mode infrastructure, there will be

[43] Knoflacher, H. and Pfaffenbichler, P. (2000). Wirtschaftliche Vorteile für österreichische Regionen durch eine institutionelle Koordinierung von Verkehrs- und Raumplanung (Economic Benefits of an Efficient Institutional Co-ordination between Transport and Land Use policy Illustrated on Austrian Level (BENEFICIAL)). Wien, im Auftrag der Magistratsabteilung 18 Stadtentwicklung und Stadtplanung.;

[44] Pfaffenbichler, P. (2001). "Verkehrsmittel und Strukturen." *Wissenschaft & Umwelt Interdisziplinär* (3): 35-42.; Emberger, G. and Pfaffenbichler, P. (2001). Verringerung des Flächenverbrauchs durch verkehrliche Maßnahmen am Beispiel Wien. Versiegelt Österreich? Der Flächenverbrauch und seine Eignung als Indikator für Umweltbeeinträchtigungen. Umweltbundesamt. Wien. Tagungsberichte. **Bd. 30**. and Pfaffenbichler, P. (2001). Promoting cycle use to counteract urban sprawl. Velo-City 2001, Edinburgh, Glasgow.

[45] Empirical observations show that the average travel time per person and day is constant. See e.g.:
Schafer, A. (2000). "Regularities in travel demand: an international perspective." *Journal of Transportation and Statistics* 3 (3): 1-32. or
Brög, W. and Erl, E. (1999). Kenngrößen für Fußgänger und Fahrradverkehr; *Berichte der Bundesanstalt für Straßenwesen, Mensch und Sicherheit*, M109; BASt, Bergisch Gladbach.
More details can be found in section 12.2 Constant travel time budgets.

less trips made by PT and slow modes ("s"). If there are less PT and slow mode trips, there will be more car trips ("o"). This forms a reinforcing feedback loop[46].

Car infrastructure is also in competition with other land use opportunities within the city structure (residing, shopping, working, etc., "o"). On the one hand there is physical competition for space. On the other hand car infrastructure also leads to qualitative degradation for other uses. If the opportunities in the core area decrease, the migration of opportunities into the outskirts increases ("o"). This is on the one hand due to long term physical movement. But on the other hand there is also short term change in destination choice. This forms another reinforcing feedback loop. Reinforcing feedback loops result in exponential growth and are unsustainable. Only balancing feedback loops result in dynamic equilibrium system behaviour. To reach a state of dynamic equilibrium is indispensable to achieve the objective of sustainability. The qualitative analysis proves that the current transport and land-use planning practise is unsustainable. The development of the residential location sub-model of MARS is an attempt to quantify the cause-effect-relations depicted in Figure 3.9.

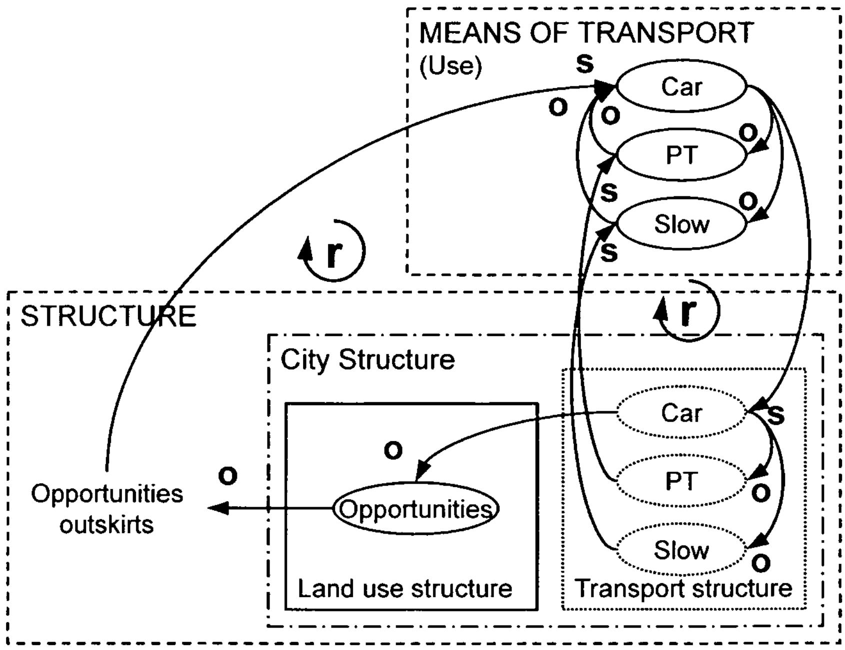
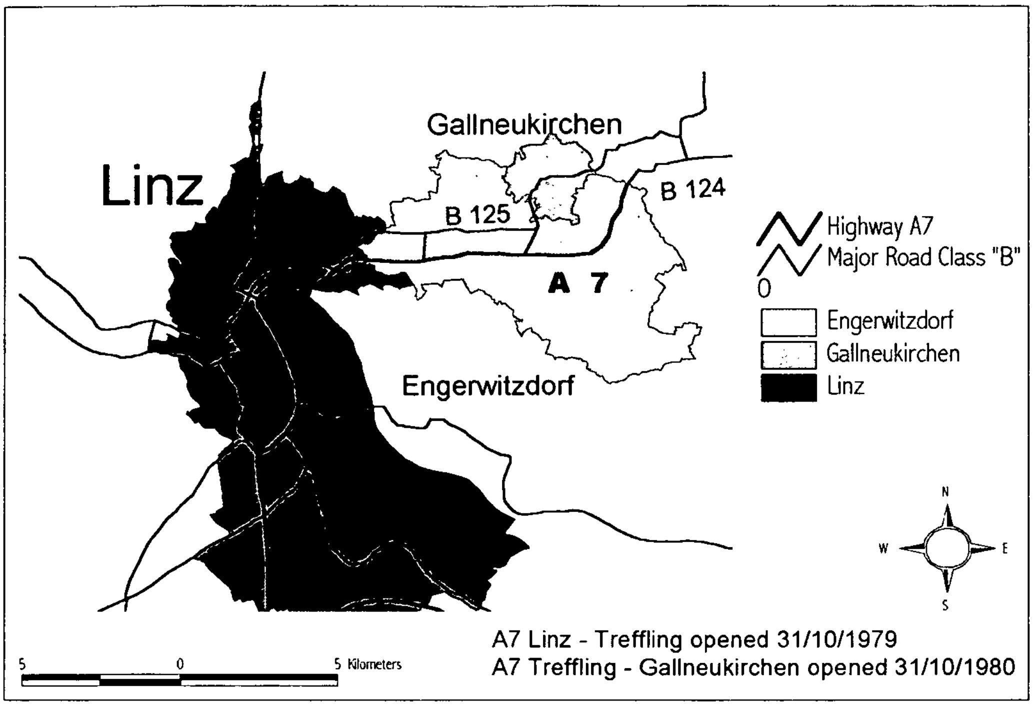


Figure 3.9: Causal loop diagram: transport modes - city structure (Pfaffenbichler, P., 2001)

Figure 3.10 and Figure 3.11 show empirical evidence to back (Magistratsabteilung 66 - Statistisches Amt, 1994)up the qualitative model shown in Figure 3.9. Linz, the capital of the Austrian county "Upper Austria", and its neighbouring municipalities Gallneukirchen and Engerwitzdorf were selected as an example because a highway connecting them was built in the observed period. According to the qualitative model described above, this should lead to growth in the outskirts

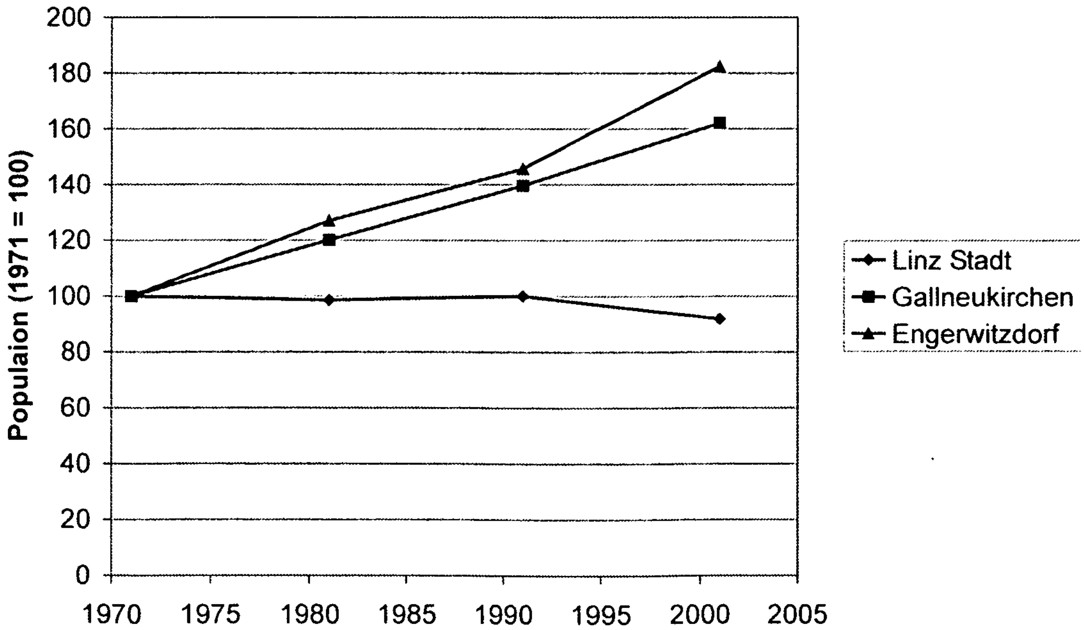
[46] The characteristic of a feedback loop is determined in the following way. "s" is adequate to the sign "+". "o" is adequate to the sign "-". The signs of the links forming a feedback loop have to be multiplied. If the result is "+", the feedback loop is reinforcing ("r"). If the result is "-", the feedback loop is balancing ("b"). Here s*o*s*o = +*-*+*- = + = r.

and decline in the city centre. As it could be seen in Figure 3.11, the observed data correspond with the predicted development over time.



Source: (BMwA, 1998)

Figure 3.10: The upper Austrian capital Linz and its surroundings



Source: (ÖSTZ, 1973), (ÖSTZ, 1984), (ÖSTAT, 1994), (Statistik Austria, 2003)

Figure 3.11: Development of population in the Upper Austrian capital Linz and its surroundings

- **Business and workplace location**

In (Knoflacher, H. and Pfaffenbichler, P., 2000) five hypothesis were proposed and tested for the city of Vienna:

1. There is a correlation between land prices for business sites and for residential sites.
2. The higher the accessibility, the higher the price of the land.
3. Businesses settle where the availability of land is high, the accessibility is high and the land price is low.
4. The development of new building land (for businesses) takes place where accessibility has recently increased.
5. When businesses may choose between equally available sites, differences in land price are more important than differences in accessibility.

Hypotheses 1 and 2 were only supporting theses carried out to test the usefulness of certain data. The main part of the analysis was hypothesis 3.

A qualitative model of consumer oriented businesses location decisions in a functional urban region (FUR) was developed based on this work (Pfaffenbichler, P. C., 2001). The CLD of this model is shown in Figure 3.12. The model describes the migration process between the core area and the outskirts of the FUR[47] for retail trade businesses.

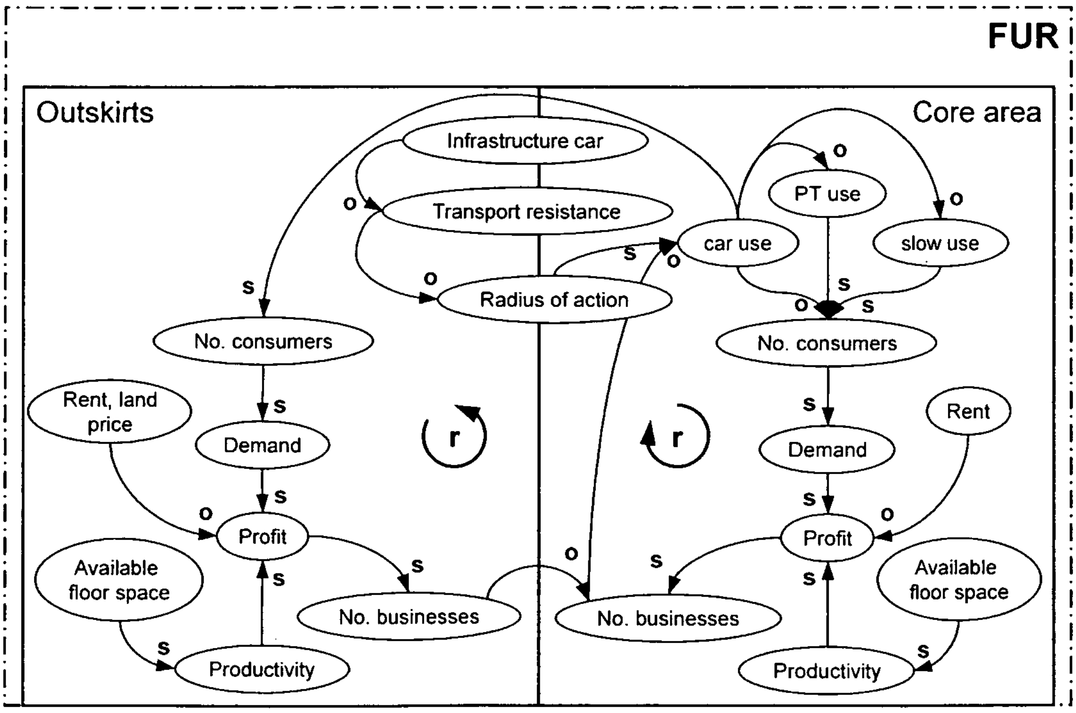


Figure 3.12: Causal-loop diagram: migration of consumer oriented businesses within a FUR (Pfaffenbichler, P. C., 2001)

[47] The core area of a FUR is defined as the densely populated inner area (it covers more than the "central business district"). The outskirts are defined as the residuum. The FUR and its subdivisions do not necessarily correspond with administrative districts. Maier, G. and Tödtling, F. (1992). Regional- und Stadtökonomik - Standorttheorie und Raumstruktur; Springer Verlag, Wein, New York.

A certain *number of consumers* live in the core area and in the outskirts of a FUR. As long as the *resistance to travel*[48] between both parts of the region is rather high, the economic development in both parts will be considerably independent from each other. Therefore the following explanations are valid for both sides of the diagram. If the *number of consumers* increases, the *demand* for goods increases. If *demand* increases, the potential *profit* increases. Higher *rent* or *land price* decreases the *profit*. Increasing the amount of *available floor* space leads to higher productivity and *profits*. This cause-effect-relation can be explained by economics of scale (Gabler, T., 1988), (Knoflacher, H., 1995). If the potential *profit* increases, the *number of businesses* will increase.

Improving *infrastructure for private car* in the region reduces the *transport resistance*. Due to the law of constant travel time[38] the *radius of action* for car users is increased. *Car use* will increase. The *number of consumers* able to go shopping in the outskirts increases, while the number of consumers in the core decreases. *PT use* and *slow mode use* will decrease. Therefore the *number of consumers* shopping in the inner city area is further decreased.

There are two reinforcing feedback loops initialised by the measure car infrastructure improvement. Businesses migrate from the inner city into the outskirts of the city (urban sprawl). This process is further fuelled by the fact that rent and land price are lower and availability of land is higher in the outskirts of the city.

Empirical observations back up the qualitative model shown in Figure 3.12. In the early sixties the highway A2 Südautobahn was opened, connecting Vienna with the southbound district Mödling (BMwA, 1998). A sectional view along the highway A2 and its extension towards the city centre includes the Viennese districts Wieden, Margareten, Favoriten, Liesing and the Lower Austrian district Mödling (Figure 3.13). Wieden and Margeten are situated inside an urban ring road named Gürtel and are densely built-up areas. Favoriten is situated outside the Gürtel and still has potential development areas at its disposal. Liesing is the southernmost Viennese district and has development areas available too. Mödling is a Lower Austrian district, which borders on the south of Vienna and is characterised by high availability of land.

Data about transactions of land for business/industrial use in Vienna are available from a data collection of the "Municipal Department 40 - Real estate evaluation and assessment (MA 40)" for the period of time between 1986 and 1997. No transactions were reported in Wieden and only two in Margareten. The average price per square meter (in 1988 terms) is approximately 1340 Euro in Margareten, 260 Euro in Favoriten and 130 Euro in Liesing. In 1988 more than 95% of Wieden and Margareten were built-up land including transport infrastructure. However only around 45% in Favoriten and 60% in Liesing were already built-up land in 1988 [Source: (Magistratsabteilung 66 - Statistisches Amt, 1994)].

[48] The resistance to travel depends on the generalised costs of a trip (travel time and monetary costs). See friction factors in chapter 4. Quantitative description of the Dynamic Transport and Land Use Interaction Model MARS and section 12.3 Friction factors.

Data about workplaces from the censuses in 1971, 1981 and 1991 show the following trend (Figure 3.14). It can be seen that the inner districts lose workplaces while the outskirts gain workplaces. The empirical analysis depicts a system behaviour as predicted by the qualitative model.

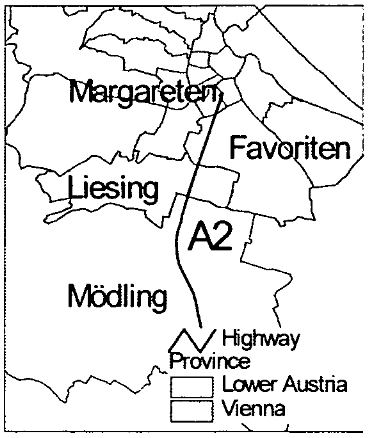
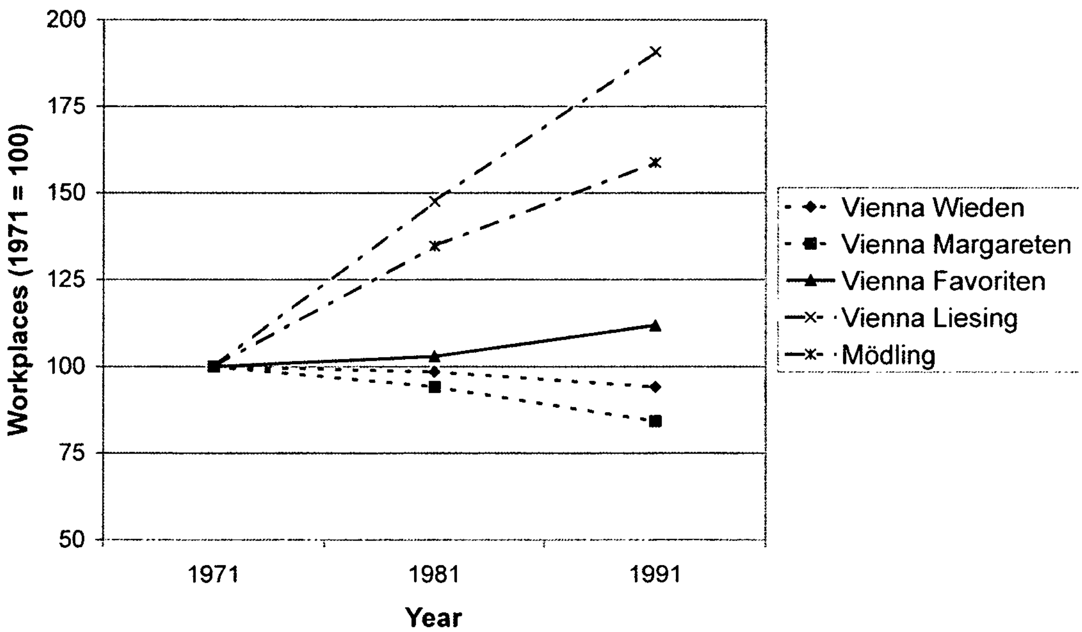


Figure 3.13: Vienna and its neighbouring district Mödling



Source: (ÖSTZ, 1974), (ÖSTZ, 1985), (ÖSTZ, 1985), (ÖSTAT, 1995), (ÖSTAT, 1995)

Figure 3.14: Trend of workplaces sectional view along the highway A2

3.3.2 Residential location model

- **Overview**

Figure 3.15 shows the structure of the residential location MARS sub-model. The residential location sub-model has a sequential structure. Firstly the hypothetical developers decide whether, how much and where to build new housing units. Their decisions depend on three factors:

- The height of the *rent* which they believe that they can achieve after the housing units are ready for occupation. It is assumed that this is the rent which is paid in the year of the development decision.
- The height of the *land price* in the decision year.
- The *availability of land* in the decision year.

The time lagged output of the *development sub-model* is a number of *new built housing units* ready for occupation per zone. Construction of housing units reduces *green land* and *land available* for construction. If *available land* becomes rare, the *land price* will go up.

The next step is the residents *moving out* or household mobility sub-model. The decision to move out from the actual home depends on:

- The *rent* per square meter in the decision year.
- The share of *green land* in the zone. The share of green land is seen as an indicator to represent the quality of living in a zone.
- The *accessibility* of the zone which indicates the number of opportunities of shopping and working.

The result of the *moving out model* is a spatial distribution of *empty housing units* ready for occupation in each year. The sum of new and empty housing units ready for occupation gives the number of *housing units supplied* in each iteration year.

The third step is the *moving in sub-model.* The desire to move into a housing unit in a certain zone depends on:

- The *rent* per square meter in the decision year.
- The share of *green land* in the zone. The share of green land is seen as an indicator to represent the environmental quality of a zone.
- The *accessibility* of the zone which indicates the number of opportunities of shopping and working..

The result of the *moving in sub-model* is the spatial distribution of *demanded housing units.* The total number of housing units is additionally determined by the external defined indicator *potential growth.*

A comparison of the moving in and moving out sub-model results gives a ratio of *demanded to supplied housing units* for each zone. If there are more housing units demanded than supplied in a zone then the over demand is *re-distributed* to second best choices in zones with over supply. This procedure is repeated until each housing demanding a housing unit found one or until all supplied housing units are full. If the second option is the case, unsatisfied demand is stored and added in the next iteration.

The ratio of *demanded to supplied housing units* is affecting the *rents.* In zones with over demand rent goes up while in zones with over supply it goes down.

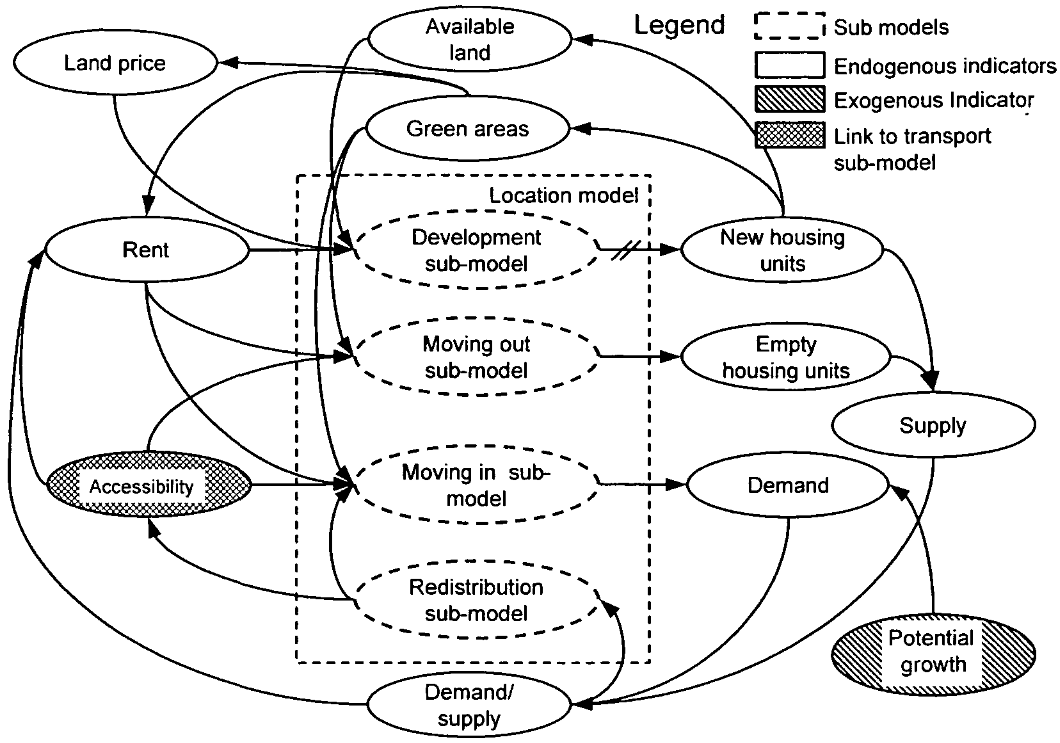


Figure 3.15: Sub-system diagram land use part

- **Development sub-model**

As said above the decision of developers is influenced by the achievable rent, the land price and the amount of available green land in a zone. For the starting iteration *0* a user defined number of new developments is needed to initiate the model (*Potential growth iteration 0*). In the next iterations the number of new planned housing units is calculated internally. In Figure 3.16 this number is called *potential growth iteration n.* "Potential" refers to the fact that this number of housing units only can be realised if enough land is available. The *potential growth in iteration n* is influenced by the ratio of *demanded to supplied housing units* in iteration *n-1.* The potential for new domiciles is distributed to the zones according to the *attraction* to build in a zone. The attraction is defined as the ratio of the *rent* the developer believes to achieve and the *land price.* The outcome is the number of *new housing units* per zone which will be ready to occupy after a external defined time lag. MARS controls whether there is enough land for the proposed developments. If not the number of developments in the zone is cut down. There is no redistribution process to other locations in the development sub-model. The change in the availability of land influences land price and rent.

The number of *demanded new housing units* comes from the moving in sub-model. The *number of empty domiciles* comes from the moving out sub-model. The ratio of *demanded to supplied housing units* has an influence on *land price* and *rent.*

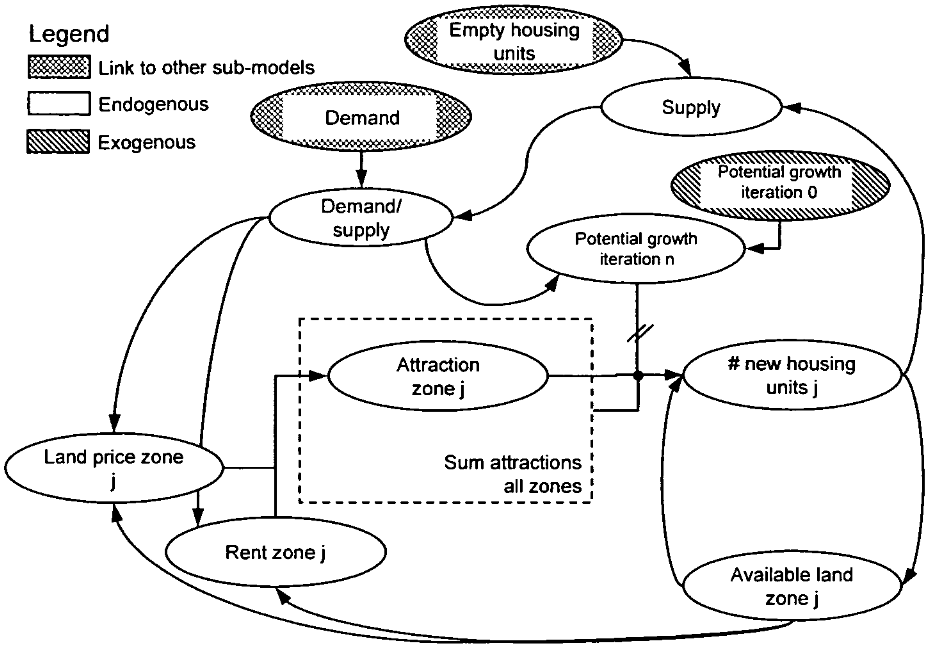


Figure 3.16: Sub-system diagram development sub-model

- **Move out sub-model**

The user of MARS has to define an average period of time between two moves of an average household. This is used to calculate the "*Potential to move*" (Figure 3.17) which is the total number of residents moving within the study area in one iteration. The spatial distribution of moving households per iteration is calculated using a LOGIT model. The utility depends on the share of *green areas*, the *accessibility* and the *rent* in a zone. The *rent* depends on the ratio of *residences demanded and supplied.*

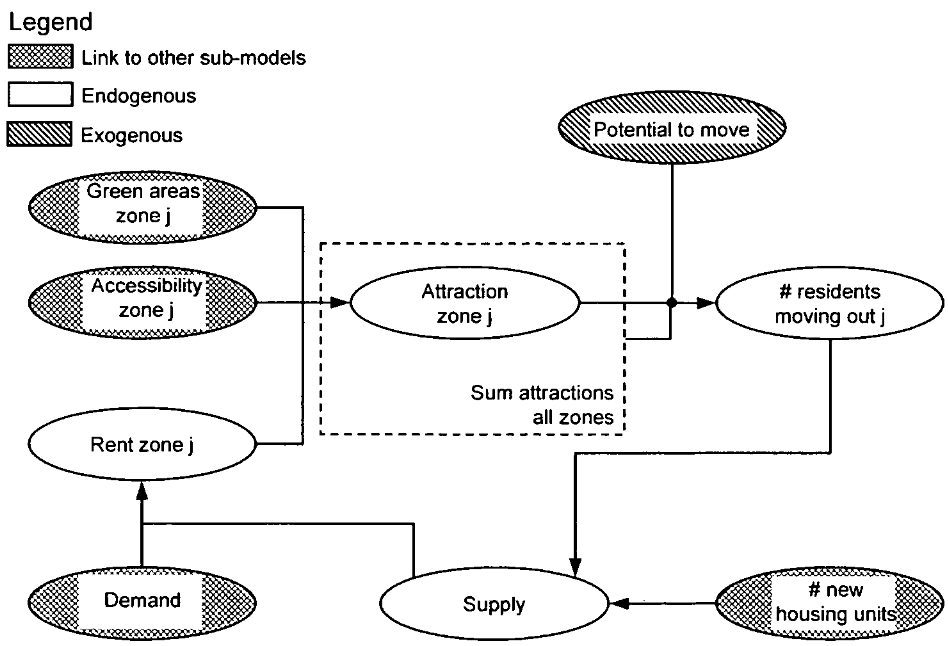


Figure 3.17: Sub-system diagram move out model of the residential location model

- **Move in sub-model**

The decision to move into a zone depends on the share of *green areas*, the *accessibility* and the *rent* in a zone. The spatial distribution of in moving households per iteration is calculated using a LOGIT model. The utility of moving in is calculated from the indicators share of *green areas*, *accessibility* and *rent*.

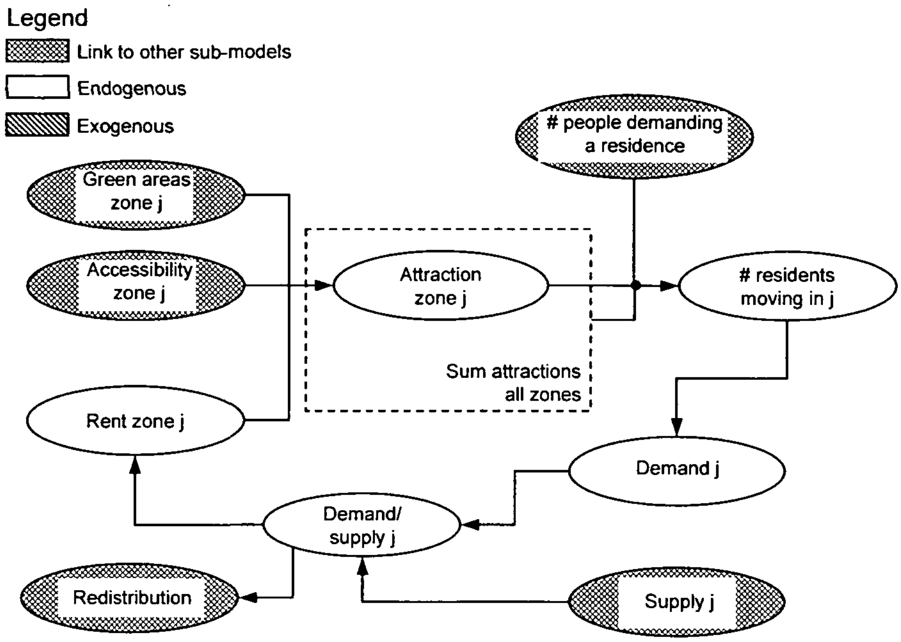


Figure 3.18: Sub-system diagram move in sub-model of the residential location sub-model

- **Redistribution sub-model**

If the demanded number of housing units in a zone is higher than the supplied number of housing units then the resulting over demand is re-distributed to other zones with over supply of housing units. The attractiveness in zones with over demand is set zero. A new number of households requiring housing units is calculated by summarising the unsatisfied demand. This new potential is distributed to zones with free housing units using the moving in sub-model. The procedure is repeated until either all households found new homes or until all available housing units are occupied. In the latter case the remaining demand is stored and added to the external growth rate in the next iteration. An increasing potential of households willing to move into the study area stimulates the development activities in the development sub-model.

3.3.3 Workplace location sub-model

The workplace location sub-model consists of two parts: one for the production sector[49] and one for the service sector[50]. The basic structure of the workplace location models is similar to the residential model (Figure 3.15).

[49] NACE code: C Mining and quarrying; D Manufacture; E Electricity, gas and water supply; F Construction

- **Development sub-model**

The study area wide workplace development has to be defined as an exogenous scenario. The user can define a negative or positive growth rate for each iteration. There is no MARS internal mechanism to adjust development of businesses and workplaces except the limits of land availability.

- **Move out sub-model**

The move out sub-model is exogenous. The user has to define the average number of years until a business moves to another location or goes bankrupt. I.e. a similar ratio of businesses and workplaces moves out in each zone and iteration.

- **Move in sub-model**

MARS calculates the amount of space available for business use and allocates the total potential of re-allocating and newly developed businesses to the different locations using a LOGIT model. The utility to move to a location is determined by the *land price*, the *availability of land* and the *accessibility*.

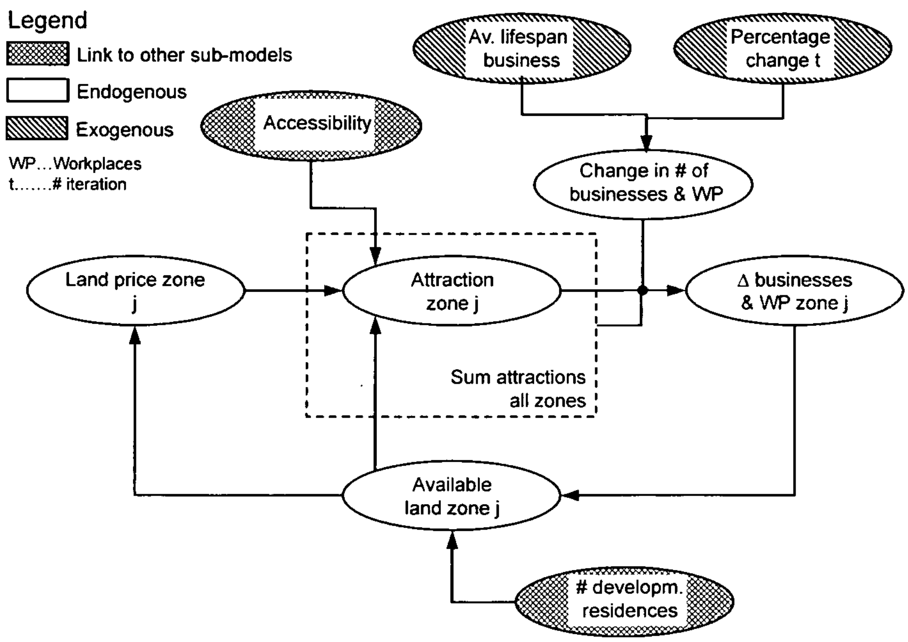


Figure 3.19: Sub-system diagram workplace location sub-model

[50] NACE Code: G Wholesale and retail trade, repair of motor vehicles, motorcycles and personal household goods; H Hotels and restaurants; I Transport, storage and communication; J Financial intermediation; K Real estate, renting and business activities; L Public administration and defence, compulsory social security; M Education; N Health and social work; O Other community, social and personal service activities; P Private households with employed persons; Q Extra territorial organisations and bodies

- **Redistribution sub-model**

The number of businesses and workplaces is limited by the amount of available land. The redistribution model of the workplace subsystem is similar to the one used in the residential subsystem. Over demand is redistributed to locations of second best choice until all businesses and workplaces found a feasible location or all land is consumed.

3.4 Stepping through time

Figure 3.20 shows the connection between the subsystems and iterations. MARS starts with a *transport sub-model* calculation. *Accessibility* indicators are input into the *household location sub-model.* After the household location MARS calculates the *availability of land*, which is input into the *workplace location sub-model.* The *transport sub-model* passes results from the *speed flow* calculation over to the next iteration. The *household location sub-model* passes the *spatial distribution* of households to the *transport sub-model* of the next iteration. Information about *new developed residences* are passed within the *household location sub-model* to a time lagged iteration *t+T.* The *workplace sub-model* passes information about the *spatial distribution* of workplaces and the *availability of land* over to the *transport and household location sub*-model of the next iteration.

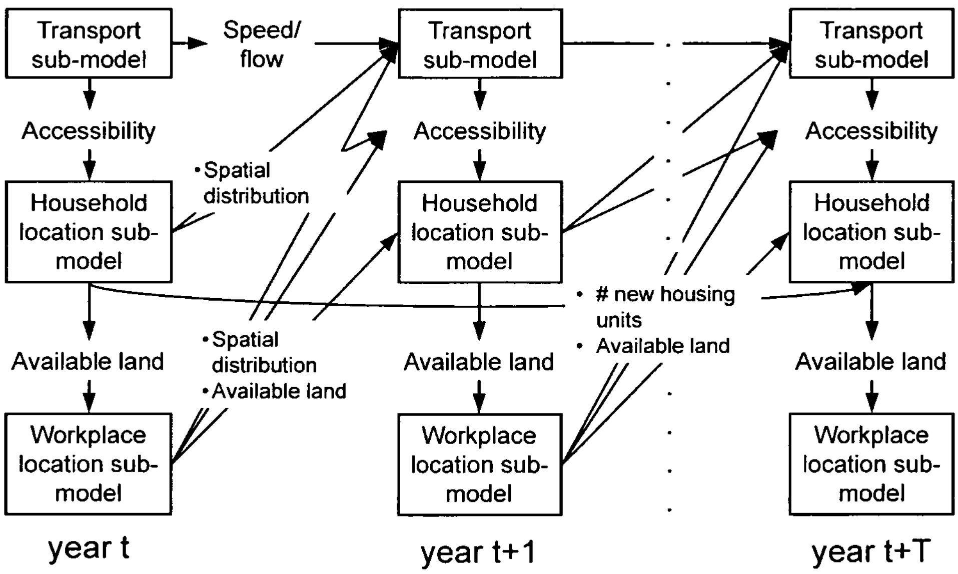


Figure 3.20: Process used to step the MARS sub-models through time

3.5 Summary

Section 3 gives an overview about the qualitative sub-models underlying MARS. The hypotheses and the basic research from which the models stem are presented. The qualitative models are presented and analysed using causal loop diagramming and sub-system diagrams. The transport sub-model behaviour is illustrated for the policy instrument public transport fare changes. The principle land use sub-model behaviour was analysed with the causal loop technique. The resulting model behaviour was compared with observed data. The qualitative land use models are backed up by the empirical observations. The qualitative models form a sound basis for the quantification of MARS.

4. QUANTITATIVE DESCRIPTION OF THE DYNAMIC TRANSPORT AND LAND USE INTERACTION MODEL MARS

4.1 Introduction

The aim of chapter 4 is to give a full mathematical description of the MARS sub-models. The nomenclature used in the equations is defined (section 4.2). Section 4.3 presents the quantitative description of the transport sub-models. Section 4.4 shows the equation system of the land use sub-models. The basic principles underlying the quantitative models are described.

4.2 Nomenclature

The nomenclature shown in Equation 4.1 was used as far as possible in the following sections. The right hand side lower case indices refer to MARS zones. The index i always refers to the source of an activity, the index j always refers to the destination of an activity. The upper case indices on the right hand side refer to modes in the transport sub-model and to sub-models and actions in the land use sub-model (domiciles, residents, workplaces, moving in or out). The uppercase indices on the left hand side refer to additional information like different cost components. The index in brackets refers to iteration numbers ("years") within a single MARS run (0<=t<=30).

$$^{p}X_{ij}^{m}(t) = f(p,m,i,j,t)$$

Equation 4.1: Nomenclature

4.3 Transport sub-model

4.3.1 Trip generation sub-model

The trip rate method[51] is used in the trip generation sub-model for tours home – work – home. The number of employed residents in a zone is multiplied with a constant trip (tour) rate to generate the production of trips (tours) for the purpose work (Equation 4.2).

$$P_i\big|_{HWH} = r\big|_{HWH} * E_i$$

Equation 4.2: Trip generation sub-model for tours home – work – home

$P_i/_{HWH}$ .... Production of trips at source i for tours home – work - home

$r/_{HWH}$ .... Trip rate for tours home – work - home

E_i .... Number of employed residents living in zone i

The distribution and mode choice model for the tours home – work – home has to run before the trip generation sub-model for tours home – others – home can work. The total travel time spent for tours home – work – home is calculated (Equation 4.3). Then a remaining travel time budget per person for tours home –

[51] See section 2.4 A brief review of transport modelling.

other – home is calculated (Equation 4.4). The zone wise production for tours home – other home as time is calculated by multiplying the travel time budget per person with the number of residents per zone (Equation 4.5).

$$t|_{HWH} = \left[\sum_{ijm} T_{ij}^{m} * t_{ij}^{m}\right]_{HWH}$$

Equation 4.3: Total travel time home – work – home

$t/_{HWH}$............Total travel time for tours home – work – home (min)

$T^m{}_{ij}$..............Trips from i to j by mode m for tours home – work - home

$t^m{}_{ij}$...............Travel time for trips from i to j by mode m for tours home – work - home

$$t_B|_{HOH} = \frac{\left(t_B * N - t|_{HWH}\right)}{N}$$

Equation 4.4: Total travel time home - other – home

$t_B/_{HOH}$...........Travel time budget per person for tours home – other – home (min)

t_B.................Travel time budget per person (min)

N.................Number of residents in the study area

$$P_i|_{HOH} = t_B|_{HOH} * N_i$$

Equation 4.5: Travel time production for tours home – other – home

$P_i/_{HOH}$...........Travel time production for tours home – other – home in zone i (min)

N_i................Number of residents in zone i

4.3.2 Trip distribution and mode choice sub-model

Equation 4.6 to Equation 4.28 describe the whole trip distribution and mode choice part of the MARS transport sub-model. The trip distribution and mode choice sub-model uses a combination of the analogy to the law of gravity and Kirchoff's law from electrical engineering (Equation 4.6). The production of trips P_i, given by the trip generation sub-model, is distributed to the available destinations j and modes m according to the ratio of attraction to friction factor of destination j to the sum of attraction to friction factor over all destinations. The attraction A_j depends on the activity for which the destination is chosen. For tours home – work – home the attraction is equal to the number of workplaces in the destination zone. For tours home – other activities – home the attraction is the sum of the population living in the destination zone and the workplaces in retail trade. The first part should represent the attraction for the activity visit, while the second should represent the attraction for the activity shopping. Friction factors[52] are indicators to measure the subjectively perceived effort in terms of time and money which is necessary to travel from origin i to destination j. Trip and tour matrices $T^m{}_{ij}$ are calculated separately for the activities work and other.

[52] For more details about friction factors see section 12.3 Friction factors.

$$T_{ij}^{m} = \left[P_i * \frac{A_j / f(t_{ij}^{m}, c_{ij}^{m})}{\sum_{mj} A_j / f(t_{ij}^{m}, c_{ij}^{m})} \right]_{HWH} + \left[P_i * \frac{A_j / f(t_{ij}^{m}, c_{ij}^{m})}{\sum_{mj} A_j / f(t_{ij}^{m}, c_{ij}^{m})} \right]_{HOH}$$

Equation 4.6: Simultaneous trip distribution and mode choice

T^{m}_{ij} .... Number of trips by mode *m* from source *i* to destination *j*

P_i .... Production of trips at source *i*

A_j .... Attraction of zone *j* as destination

t^{m}_{ij} .... Travel time by mode *m* from *i* to *j* (min)

c^{m}_{ij} .... Travel costs for a trip by mode *m* from *i* to *j* (€)

$f(t^{m}_{ij}, c^{m}_{ij})$ ..... Friction factor for a trip by mode *m* from *i* to *j* (min)

HWH .... Tour home – work - home

HOH .... Tour home – other activities – home

The trip distribution and mode choice sub-model considers two person groups: those with access to a car and those without access to a car. Those with access to a car are free to choose between slow modes, public transport and car. Those without access to a car can only choose between slow modes and public transport. The calculation of car availability considers car ownership rates, car ownership growth rates, occupancy rates and the share of driver license holders (Equation 4.7).

$$Ac^{PC} = \frac{ow^{PC} * o^{PC} * p^{drl}}{1000}$$

Equation 4.7: Car availability

Ac^{PC} .... Share of those with access to a car (%)

ow^{PC} .... Car ownership rate (cars per 1,000 residents)

o^{PC} .... Car occupancy rate (persons per car)

p^{drl} .... Percentage of driver license holders (%)

The friction factors $f(t^{m}_{ij}, c^{m}_{ij})$ (Equation 4.6) are a function of travel time (including subjective valuation of different parts of a journey) and travel costs. The friction factors used in MARS were developed within a long term research programme of the Institute of Transport Science, Aachen University of Technology (Walther, K., 1991). The friction factor parameters used in MARS come from an updated version (Walther, K. et al., 1997). The principle form and the parameters of the friction factors was derived from before and after studies in German cities. Their soundness was verified with several case studies in German cities. For more details see section 12.3 Friction factors p. 229. The basic form of the time dependent component of the friction factors used in MARS is shown in Equation 4.8. The basic form of the cost dependent component is shown in Equation 4.9. The two components are added to give the total friction factor.

$$f(t_{ij}^{m}) = t_{ij}^{m} * e^{t_{ij}^{m}}$$

Equation 4.8: General form friction factor travel time (Walther, K. et al., 1997)

$$f\left(c_{ij}^{m}\right)=\frac{c_{ij}^{m}}{\alpha * Inc_{i}}$$

Equation 4.9: General form friction factor travel costs (Walther, K. et al., 1997)

α................. Factor for value of time

Inc_i.............. Household income in zone i (€/min)

- **Slow modes**

Equation 4.10 shows the friction factor for slow modes (pedestrian, bike) as used in MARS. (Walther, K. et al., 1997) uses discrete, distance dependent friction factors for the mode pedestrians (Table 4.1).

Table 4.1: Friction factor values for the mode pedestrian (Walther, K. et al., 1997) p. 18

Distance (km)	0.5	1.0	2.0	3.0	4.0	5.0	6.0	7.0	8.0	9.0	10.0	11.0	12.0
Friction factor	0.84	6.2	20.5	88.0	272	600	1,200	2,500	5,000	10,000	20,000	40,000	80,000

The data from Table 4.1 were used to derive a slow mode friction factor of the following form:

$$w_{ij} = \alpha * t_{ij} * e^{\beta * t_{ij}}$$

Equation 4.10: Friction factor slow modes

α, β............ Constant factors (Table 4.2)

t_{ij}................. Walking time from i to j (min)

Minimising the distance between the values given by (Walther, K. et al., 1997) and Equation 4.10 using the Excel Solver tool gives the following parameters.

Table 4.2: Parameters friction factor slow modes

Parameter	Value
α	0.206
β	0.0463

- **Public transport**

A trip with the mode public transport consists of four different parts (Figure 4.1):

- Walking from the source to the public transport stop
- Driving from the public transport stop to the destination
- Changing time
- Walking from the public transport stop to the destination

Each of these parts is perceived and valued differently by the public transport users. The different subjective valuation factors in Equation 4.11 reflect this fact.

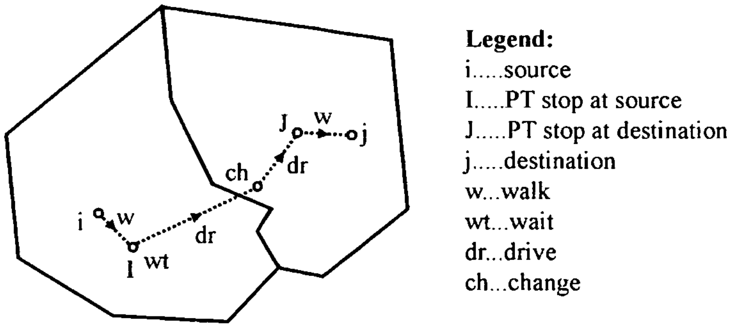


Figure 4.1: Components of a public transport trip from source i to destination j in MARS

Source: (Walther, K. et al., 1997) p. 20 ff

$$f\left(t_{ij}^{PT}, c_{ij}^{PT}\right) = t_{iI}^{PT,w} * SV_{iI}^{PT,w} + t_{I}^{PT,wt} * SV_{I}^{PT,wt} + \sum t_{IJ}^{PT,dr} + \sum t_{IJ}^{PT,ch} * SV_{IJ}^{PT,ch} + t_{Jj}^{PT,w} * SV_{Jj}^{PT,w} + Z_{ij}^{PT}$$

Equation 4.11: Friction factor public transport

$t^{PT,w}_{iI}$............Walking time from source i to public transport stop I (min)

$SV^{PT,w}_{iI}$.........Subjective valuation factor walking time from source to public transport stop

$t^{PT,wt}_{I}$............Waiting time at public transport stop I (min)

$SV^{PT,wt}_{I}$.........Subjective valuation factor waiting time at public transport stop

$t^{PT,dr}_{IJ}$...........Total in-vehicle time from PT stop I to PT stop J (min)

$t^{PT,ch}_{IJ}$...........Total changing time from PT stop I to PT stop J (min)

$SV^{PT,ch}_{IJ}$........Subjective valuation factor changing time

$t^{PT,w}_{Jj}$............Walking time from public transport stop J to destination j (min)

$SV^{PT,w}_{Jj}$.........Subjective valuation factor walking time from public transport stop to destination

Z^{PT}_{ij}.............Impedance from costs travelling from i to j by public transport (min)

(Walther, K. et al., 1997) defines separate friction factors for the public transport modes bus, tramway and underground/light rail. MARS makes a distinction whether public transport is separated from individual road traffic or not. For public transport separated from car traffic (e.g. Underground) the following subjective valuation factors are used in MARS (Walther, K. et al., 1997) p. 21-23:

$$SV_{iI}^{PT,w} = 0.569179 + 0.274495 * e^{0.342636 * t_{iI}^{PT,w}}$$

Equation 4.12: Subjective valuation factor time walking to PT stop for PT separated from individual road traffic

$$SV_{I}^{PT,wt} = 0.787579 + 0.511118 * e^{0.341750 * t_{I}^{PT,wt}}$$

Equation 4.13: Subjective valuation factor waiting time at PT stop for PT separated from individual road traffic

$$SV_{IJ}^{PT,ch} = 0.498569 + 0.557746 * e^{0.317002 * t_{IJ}^{PT,ch}}$$

Equation 4.14: Subjective valuation factor changing time at intermediate PT stop for PT separated from individual road traffic

$$SV_{Jj}^{PT,w} = 0.569179 + 0.274495 * e^{0.342636 * t_{Jj}^{PT,w}}$$

Equation 4.15: Subjective valuation factor time walking from PT stop for PT separated from individual road traffic

Figure 4.2 shows the subjective overestimation of access/egress, waiting and changing time in relation to physical time for public transport separated from road (metro, light rail).

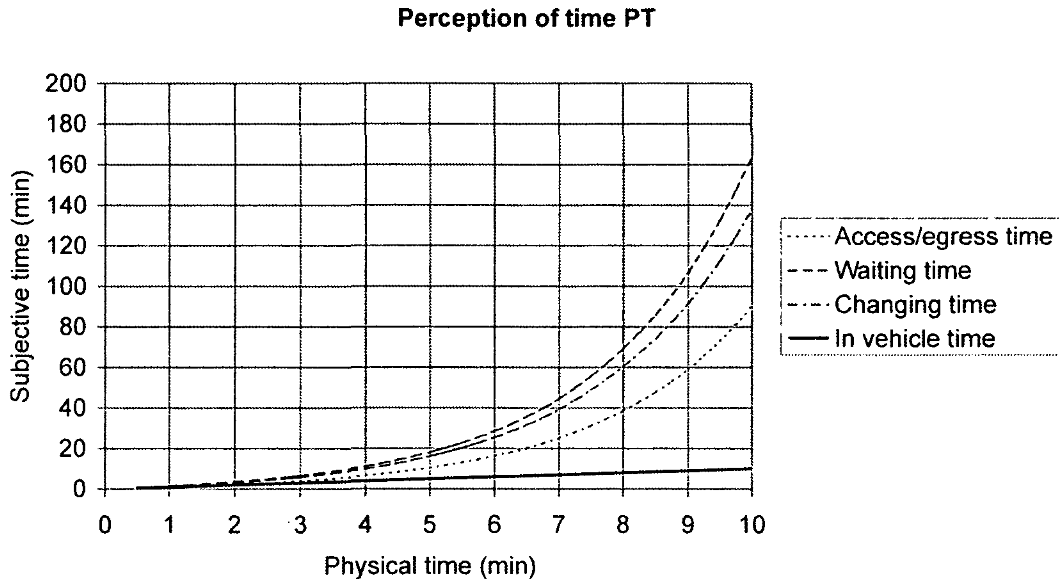


Figure 4.2: Perception of time for public transport separated from individual road traffic (Walther, K. et al., 1997)

For public transport not separated from car traffic (e.g. bus, tramway) the following subjective valuation factors are used in MARS (Walther, K. et al., 1997) p. 21-23:

$$SV_{iI}^{PT,w} = 0.506502 + 0.268792 * e^{0.396047 * t_{iI}^{PT,w}}$$

Equation 4.16: Subjective valuation factor time walking to PT stop for PT not separated from individual road traffic

$$SV_{I}^{PT,wt} = 1.632673 + 0.256768 * e^{0.459240 * t_{I}^{PT,wt}}$$

Equation 4.17: Subjective valuation factor waiting time at PT stop for PT not separated from individual road traffic

$$SV_{IJ}^{PT,ch} = 0.744725 + 0.284470 * e^{0.437923 * t_{IJ}^{PT,ch}}$$

Equation 4.18: Subjective valuation factor changing time at intermediate PT stop for PT not separated from individual road traffic

$$SV_{Jj}^{PT,w} = 0.506502 + 0.268792 * e^{0.396047 * t_{Jj}^{PT,w}}$$

Equation 4.19: Subjective valuation factor time walking from PT stop for PT not separated from individual road traffic

Figure 4.3 shows the subjective overestimation of access/egress, waiting and changing time in relation to physical time for public transport combined with individual road traffic (bus, tramway). The overestimation of access/egress, waiting and changing time is higher for the slower public transport modes bus and tramway than for the faster ones metro and light rail.

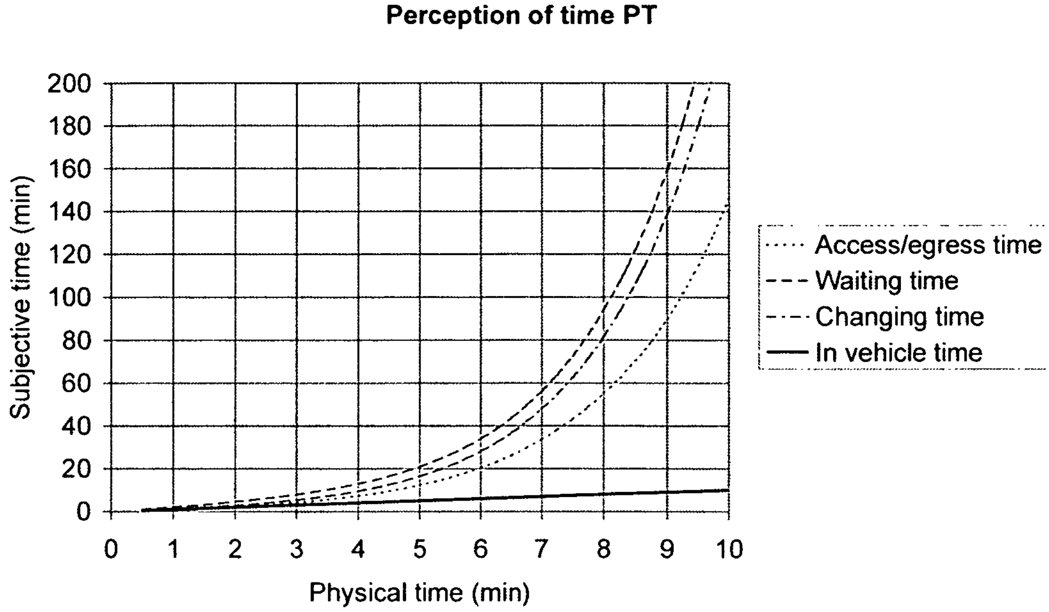


Figure 4.3: Perception of time for public transport combined with individual road traffic (Walther, K. et al., 1997)

The following friction factor for public transport costs is used in MARS (Walther, K. et al., 1997) p. 19:

$$Z_{ij}^{PT} = \frac{c_{ij}^{PT}}{\alpha * Inc_i}$$

Equation 4.20: Friction factor from public transport costs

c^{PT}_{ij} .... Costs for a public transport trip from i to j (€/trip)

α .... Factor for value of time; 0.17 Source: (Walther, K. et al., 1997) p. 19

Inc_i .... Household income in zone i (€/min)

Overcrowding of public transport is considered as follows. The MARS user has to specify the occupancy rate for the base which is used to calculate the public transport seat capacity (Equation 4.21). The seat capacity is constant until policy instruments (frequency increase or new lines) are introduced. If the ratio trips to capacity is greater than 1 in iteration t then the friction factor for public transport is recalculated (Equation 4.22) and the transport sub-model re-run is made within iteration t.

$$S_{ij}^{PT}(0) = \frac{T_{ij}^{PT}(0)}{o^{PT}}$$

Equation 4.21: Seat capacity public transport

$S^{PT}_{ij}(0)$ ....Seat capacity public transport from i to j in the base year 0

$T^{PT}_{ij}(0)$ ....Public transport trips from i to j in the base year 0

o^{PT}...............Occupancy rate public transport (persons per seat)

$$If\ \frac{T_{ij}^{PT}(t)}{S_{ij}^{PT}(t)} > 1\ then\ f\left(t_{ij}^{PT}(t), c_{ij}^{PT}(t)\right) = f\left(t_{ij}^{PT}(t), c_{ij}^{PT}(t)\right) * \left(\frac{T_{ij}^{PT}(t)}{S_{ij}^{PT}(t)}\right)^2$$

Equation 4.22: Public transport overcrowding

- **Private car**

A trip with the mode private car consists of four different parts (Figure 4.4).

- Walking from the source to the parking place
- Driving from the parking place to the destination
- Searching a free parking space
- Walking from the parking place to the destination

Again the subjective perception of the different parts of a trip is different (Equation 4.23).

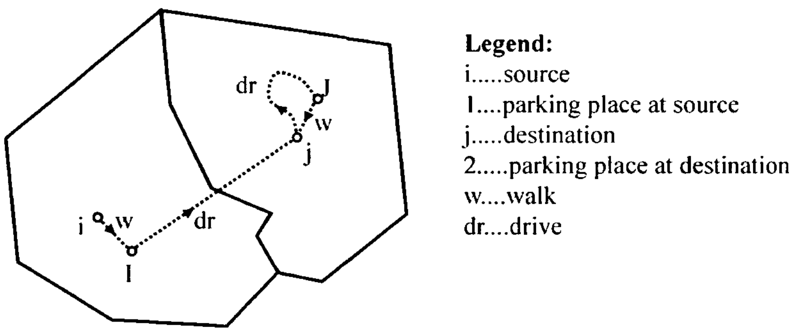


Figure 4.4: Components of a car trip from source i to destination j in MARS

Equation 4.23 to Equation 4.28 show the detailed calculation of the friction factor for the mode private car (Walther, K. et al., 1997) p. 23 ff.

$$f\left(t_{ij}^{PC},c_{ij}^{PC}\right)=(t_{il}^{PC,w}*SV_{il}^{PC,w}+t_{lj}^{PC,dr}+t_{jJ}^{PC,ps}*SV_{jJ}^{PC,ps}+t_{Jj}^{PC,w}*SV_{Jj}^{PC,w})*SV_{ij}^{PC}+{}^{k}Z_{ij}^{PC}$$

Equation 4.23: Friction factor private car

$t^{PC,w}{}_{il}$............Walking time from source i to parking place l (min)

$SV^{PC,w}{}_{il}$.........Subjective valuation factor walking time from source i to parking place l

$t^{PC,dr}{}_{lj}$...........In-vehicle time from parking place l to destination j (min)

$t^{PC,ps}{}_{jJ}$...........Parking place searching time at destination j to find parking place J (min)

$SV^{PC,ps}{}_{jJ}$........Subjective valuation factor parking place searching time at destination j to find parking place J

$t^{PC,w}{}_{Jj}$............Walking time from parking place J to destination j (min)

$SV^{PC,w}{}_{Jj}$.........Subjective valuation factor walking time from parking place J to destination j

$SV^{PC}{}_{ij}$...........Aggregated subjective valuation factor private car for origin-destination pair ij

${}^{k}Z^{PC}{}_{ij}$............Impedance to travel by car from i to j caused by cost component k (cost components are fuel costs, other operating costs, parking charges and road charges) (min)

For the mode car the following subjective valuation factors are given by (Walther, K. et al., 1997) p. 25:

$$SV_{il}^{PC,w}=1.0$$

Equation 4.24: Subjective valuation factor walking time from source i to parking place I

$$SV_{jJ}^{PC,ps}=2.0+10^{-4}*e^{0.8*t_{jJ}^{PC,ps}}$$

Equation 4.25: Subjective valuation factor parking place searching time at destination j to find parking place J

$$SV_{Jj}^{PC,w}=2.0+10^{-4}*e^{0.8*t_{Jj}^{PC,w}}$$

Equation 4.26: Subjective valuation factor walking time from parking place J to destination j

Unlike (Walther, K. et al., 1997) MARS uses the same subjective valuation factor (Equation 4.26) for access to the parking place as for parking place searching and egress time.

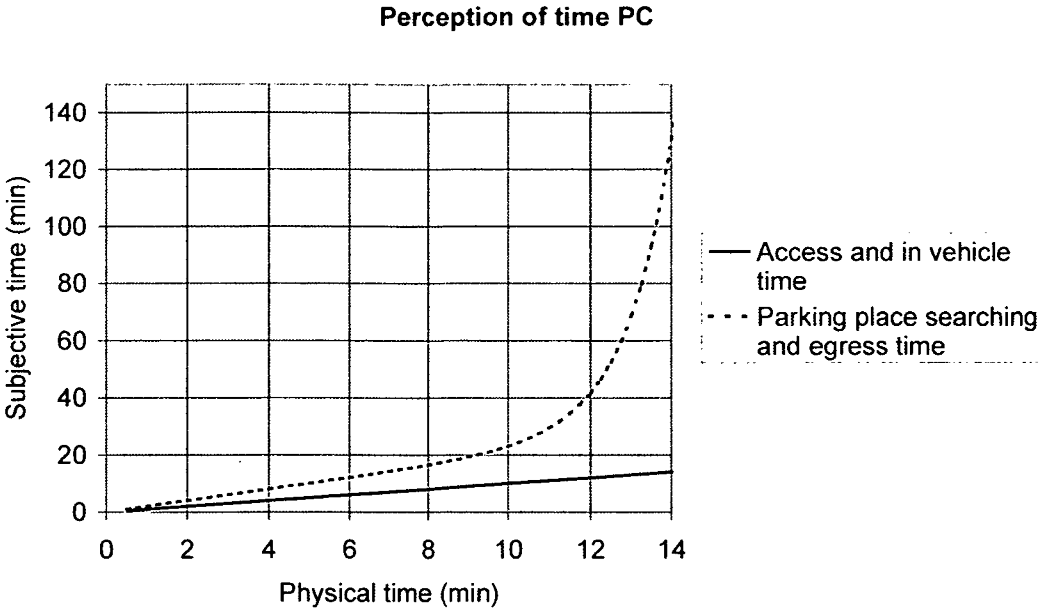


Figure 4.5: Perception of time private car (Walther, K. et al., 1997)

$$SV_{ij}^{PC} = 0.8507 * (1 - 0.7318 * e^{-0.1879 * D_{ij}^{PC}})$$

Equation 4.27: Aggregated subjective valuation factor private car for origin-destination pair ij

D^{PC}_{ij}............Travel distance from i to j by car (km)

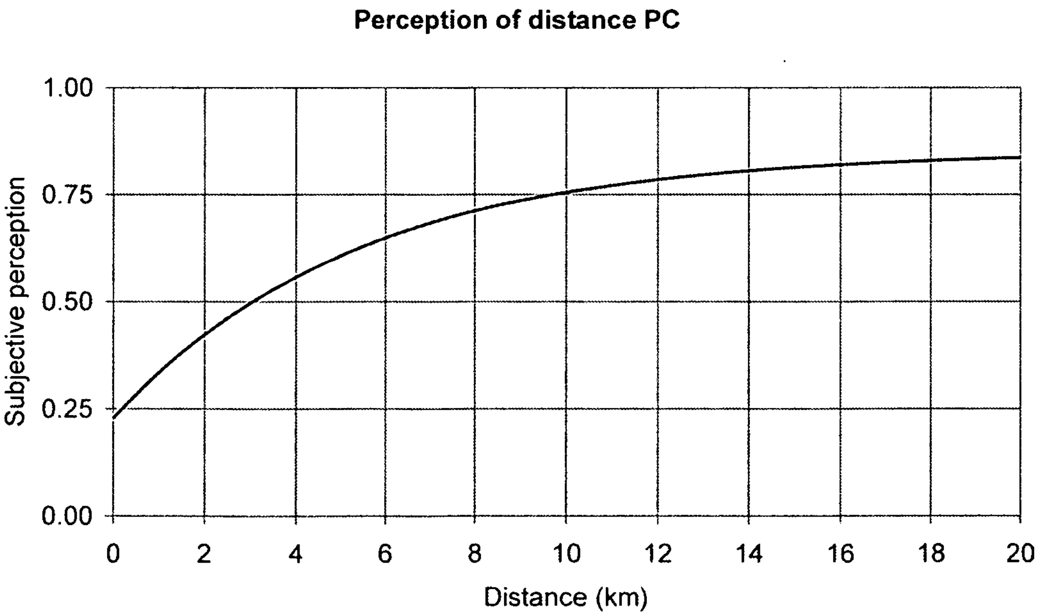


Figure 4.6: Aggregated perception of a private car trip depending on trip distance (Walther, K. et al., 1997)

The validation of MARS has shown that the share of the mode private car is overestimated using this aggregated subjective valuation factor. Therefore and for reasons of consistency MARS does not make use of this factor.

The following friction factor for private car costs is used with MARS (Walther, K. et al., 1997) p. 24:

$$^{k}Z_{ij}^{PC} = \frac{^{k}c_{ij}^{PC}}{^{k}\alpha * Inc_i * o^{PC}}$$

Equation 4.28: Friction factor from costs for car use

$^{k}c^{PC}_{ij}$ .... Costs of costs component *k* for a car trip from *i* to *j* (€/trip)

$^{k}\alpha$ .... Factor willingness to pay for cost component *k*; 0.43 for fuel and other running costs, 0.769 for parking and road charging costs; Source: (Walther, K. et al., 1997) p. 24

Inc_i .... Household income in zone *i* (€/min)

o^{PC} .... Car occupancy rate

- **Area speed flow relationship**

MARS uses an area speed flow relationship in the peak period. The speed flow relationship is described in Equation 4.29 and Equation 4.31. It uses the following principle form (Singh, R., 1999):

$$V_{ij}^{PC,pk} = \frac{V_{ij}^{PC,fr}}{1 + \beta * \left(DF_{ij}^{PC,pk}\right)^{\alpha}}$$

Equation 4.29: Speed flow relationship

$V^{PC,pk}_{ij}$ .... Speed by car from *i* to *j* during the peak period [km/h]

$V^{PC,fr}_{ij}$ .... Free flow speed by car from *i* to *j* [km/h]

$DF^{PC,pk}_{ij}$ .... Demand factor road from *i* to *j* during the peak period

α, β .... Constant factors

Figure 4.7 shows two speed flow curves as given by (Singh, R., 1999). The steeper one, marked with crosses, is based on data fro the 1965 Highway Capacity Manual. The smoother one, marked with diamonds, is based on data from the 1994 Highway Capacity Manual. The latter is used in MARS.

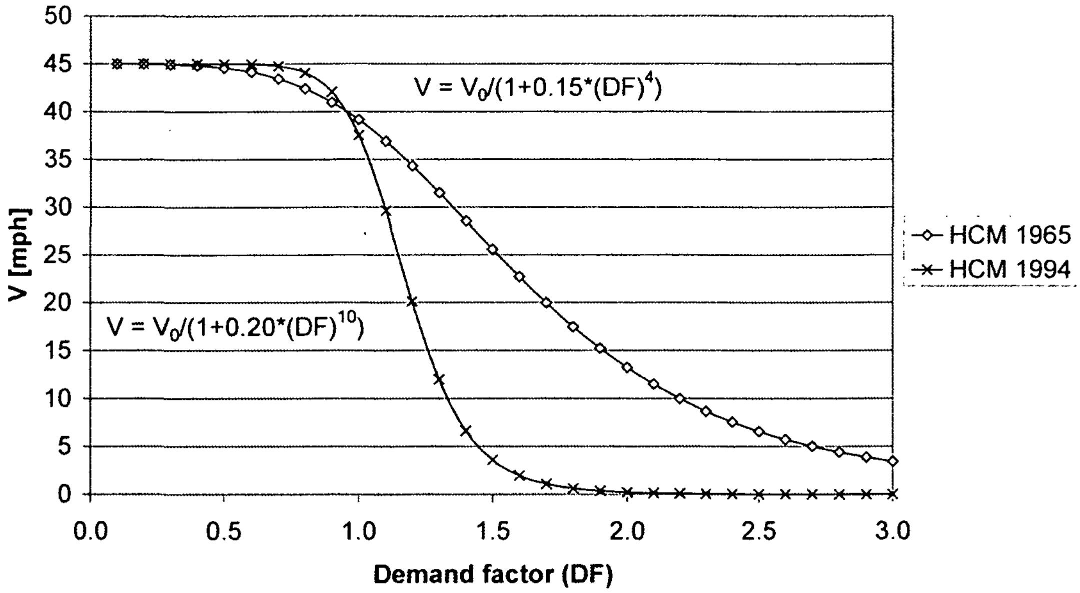


Figure 4.7: Speed flow relationship (Singh, R., 1999)

Equation 4.29 is applied in MARS to calculate the speed flow relationship as follows. Two speed matrices are needed as MARS input: average speed in the base year and free flow speed in the base year. These matrices are required to calculate initial demand factors (Equation 4.30).

$$DF_{ij}^{PC,pk}(0) = \sqrt[\alpha]{\frac{V_{ij}^{PC,fr}(0) - V_{ij}^{PC,pk}(0)}{\beta * V_{ij}^{PC,pk}(0)}}$$

Equation 4.30: Calculation initial demand factor

$DF^{PC,pk}_{ij}(0)$ ... Demand factor road from *i* to *j* during the peak period in iteration 0

$V^{PC,fr}_{ij}(0)$ .... Free flow speed by car from *i* to *j* in iteration 0 [km/h]

$V^{PC,pk}_{ij}(0)$ ...... Speed by car from *i* to *j* during the peak period in iteration 0 [km/h]

In the next iterations *t* the demand factors are recalculated as follows.

$$DF_{ij}^{PC,pk}(t) = \frac{DF_{ij}^{PC}(0)}{1 + \Delta C_j^{PC}(t-1) * \frac{D_{ii}^{PC}}{D_{ij}^{PC}}} * \frac{\sum_i T_{ij}^{PC,pk}(t-1) + \sum_j T_{ij}^{PC,pk}(t-1)}{\sum_i T_{ij}^{PC,pk}(0) + \sum_j T_{ij}^{PC,pk}(0)}$$

Equation 4.31: Recalculation of demand factors

$T^{PC,pk}_{ij}(t)$ .... Number of peak period trips by car from source *i* to destination *j* in iteration *t*

$\Delta C^{PC}_{j}(t)$ .... Additional road capacity in zone *j* in iteration *t* (%) (see Equation 4.32)

D^{PC}_{ij}............. Distance for a trip by car from source *i* to destination *j*

D^{PC}_{ii}............. Distance for an intra-zonal trip by car in zone *i*

The demand factors from Equation 4.31 are used in Equation 4.29 to re-calculate the values $V^{PC,pk}_{ij}(t)$ in the speed matrices. MARS summarises over all sources and destinations. I.e. *DF* changes with the number of all incoming and outgoing trips.

If there are zones with a low share of developed areas in the base year, then the land use sub-model will develop a quite significant amount of new domiciles and workplaces in these zones. Especially if there are high growth rates assumed. If this is the case, the number of trips will rise significantly. If the basic assumptions for speed flow are kept constant, an unrealistic drop in average car speed will occur. If growth in the number of workplaces and/or residents in a zone is higher than a user defined threshold and car speed drops below a user defined threshold, then MARS calculates endogenously road infrastructure improvements (Equation 4.32). $\Delta C^{PC}_j(t)$ is used to lower the basic demand factor in Equation 4.31. To reflect that changes in capacity in zone j affect only a part of a trip from i to j, the capacity changes are weighted by the ratio of intra-zonal to inter-zonal trip distance (Equation 4.31). Lowering the demand factor is equivalent to additional road infrastructure capacity. The basic demand factor also changes if the policy instruments "road capacity changes" or "road infrastructure investments" are applied:

$$If\ \frac{N_j^{HH}(t)+N_j^{WP}(t)}{N_j^{HH}(0)+N_j^{WP}(0)} \geq 1+C\ and\ V_{ij}^{PC}(t) \leq V_{ij}^{PC,\min}\ then\ \Delta C_j^{PC}(t)=\frac{D_j(t)+N_j^{WP}(t)}{D_j(0)+N_j^{WP}(0)}-1$$

Equation 4.32: Road capacity adaptation

$N^{HH}_j(t)$.......... Number of households in zone j in iteration t

$N^{WP}_j(t)$......... Number of workplaces in zone j in iteration t

C................. Threshold value

$V^{PC}_{ij}(t)$......... Car driving speed from zone i zone j in iteration t

$V^{PC,min}_{ij}$........ Threshold car speed from zone i zone j

- **Accessibility**

Accessibility as output of the transport sub-model and input in the land use sub-model is calculated as follows.

$$^{WP}Acc_i^m(t)=\sum_j N_j^{WP}(t)*\left|10^{-4}*\left(t_{ij}^m(t)\right)^2-0.0183*t_{ij}^m(t)+0.75\right|$$

Equation 4.33: Accessibility workplaces

$$^{C}Acc_i^m(t)=\sum_j N_j^{R}(t)*\left|10^{-4}*\left(t_{ij}^m(t)\right)^2-0.0183*t_{ij}^m(t)+0.75\right|$$

Equation 4.34: Accessibility of shops by potential customers

$Acc^C_{m,i,t}$........ Accessibility of costumers by mode m from TAZ i in the year t

$t_{op,m,i,j,t}$.......... Travel time in the off peak period by mode m from TAZ i to TAZ j in the year t

$N_{j,t}^{Res}$........... Number of residents in TAZ j in the year t

The weighting factors in Equation 4.33 and Equation 4.34 are derived from a study made by the Institute for Transport Planning and Traffic Engineering, Vienna University of Technology on behalf of the Viennese Municipal Department 18 "Urban Development and Planning" (Knoflacher, H., 1997).

4.4 Land use sub-models

4.4.1 Residential location sub-model

- **Domicile development sub-model**

The development of new domiciles (single family dwelling or flat, housing units) is described by Equation 4.35. The basic assumption is that there is an overall potential will to develop a certain number of new housing units $P^D(t-T)$ within the study area in each iteration t. This quantity has to be externally defined for the starting year 0. In the following iterations it is endogenously calculated (Equation 4.46). The spatial distribution depends on one side on the rent, which the developer believes is achievable. It is assumed that this is the actual rent which has to be paid in the year of the decision to develop t-T. As rent changes endogenously (Equation 4.47), this will be different from the rent in the year t in which the housing unit will be ready for occupation. Secondly the decision depends the land price in the decision year t-T. The land price also changes endogenously (Equation 4.48). It is assumed that construction and maintenance costs are homogenous in the study area. The number of developed domiciles is controlled by land availability. If not enough land is available the decision not build is made. There is no re-distribution of intended construction activities to other zones with enough land. The basic form of Equation 4.35 was derived from an analysis of data observed in Vienna.

$$\Delta D_j(t) = P^D(t-T) * \frac{a^D * \dfrac{R_j^D(t-T)}{LP_j(t-T)} + b^D}{\sum_j a^D * \dfrac{R_j^D(t-T)}{LP_j(t-T)} + b^D}$$

Equation 4.35: Domicile development sub-model

$\Delta D_j(t)$ .... Number of new built domiciles available on the market in zone j in the year t

$P^D(t-T)$ .... Quantity of new built domiciles demanded in the year t as perceived by the developer in the year t-T

T .... Time lag to plan and build domiciles

$R^D_j(t-T)$ .... Monthly rent or mortgage for a domicile in zone j in the year t-T (€)

$LP_j(t-T)$ .... Price for land in zone j in the year t-T (k€/m²)

a^D, b^D .... Parameter (derived from a regression analysis using observed data)

- **Residential supply sub-model**

The number of residents (households) moving out per zone j and iteration t is calculated as given in Equation 4.36. The total number of people leaving their residential location (either moving out or dying) in an iteration t is calculated by dividing the total population by an average stay time (Equation 4.37). The spatial distribution of movers depends on the accessibility by car, the share of green land and the rent in zone j. Accessibility by car is intended to reflect the disutility of living near to major road infrastructure. Share of green land is used as indicator to measure the quality of living in zone j. Rent obviously measures the costs of living in zone j[53]. The basic form of Equation 4.36 was derived from an analysis of data observed in the city of Vienna.

$$N_j^{mv}(t) = P^{mv}(t) * \frac{a^{mv} * e^{b^{mv} * {}^{WP}Acc_j^{PC}(t) + c^{mv} * ShGr_j(t) + d^{mv} * R_j^D(t)}}{\sum_j a^{mv} * e^{b^{mv} * {}^{WP}Acc_j^{PC}(t) + c^{mv} * ShGr_j(t) + d^{mv} * R_j^D(t)}}$$

Equation 4.36: Residential moving out sub-model

$N^{mv}_j(t)$ ....Number of residents moving from zone j in the year t

$P^{mv}(t)$ ....Potential of moving residents in the year t

${}^{WP}Acc^{PC}_j(t)$....Accessibility of working places by private car from zone j in the year t

$ShGr_j(t)$........Share of green land in zone j in the year t

$R^D_j(t)$............Monthly rent or mortgage for a domicile in zone j in the year t (€)

$a^{mv}, b^{mv}, c^{mv}, d^{mv}$ Parameter (derived from a regression analysis using observed data and the calibration)

$$P^{mv}(t) = \frac{N^R(t)}{\Delta T^{mv}}$$

Equation 4.37: Potential number of residents moving out

$N^R(t)$ ....Total number of residents in the study area in the year t

T^{mv}...............Average time living at the same residence

The number of movers plus the number of living places in new built housing units plus unoccupied stock from the previous iteration[54] t-1 gives the total supply of living places per zone in iteration t[55].

$$S_j^D(t) = \Delta D_j(t) * n_j^{HH}(t) + N_j^{mv}(t) + S_j^D(t-1) - N_j^{in}(t-1)$$

Equation 4.38: Supply with living places in domiciles per zone

$S^D_j(t)$ ....Supply with living places in domiciles in zone j in the year t

$n^{HH}_j(t)$ ....Number of residents per household in zone j in the year t

$N^{in}_j(t\text{-}1)$ ....Number of people moving into new living places in zone j in the year t

$$S^D(t) = \sum_j S_j^D(t)$$

[53] MARS basically assumes that people are looking for cheap living space. One difficulty is that the other indicators are at least reflected in rent to a certain extent. People try to maximise the utility from the other indicators while minimising their costs. To remedy these difficulties the use of at least two distinct income groups is suggested for further improvements of MARS. See section 9.3 Suggestions for future MARS improvements.

[54] The redistribution process (Equation 4.45) guarantees that the stock of unoccupied housing units $S^D_j(t\text{-}1)$- $N^{in}_j(t\text{-}1)$ is never negative.

[55] The underlying assumption has a substantial weak point. In MARS each person leaving a location gives room for another person to move in. In reality, e.g. if children grow up and move out or one partner of an elderly coupe dies, the domicile might still be occupied. This lead to difficulties in some zones in the calibration and model testing (see section 6 and 7). Therefore a suggestion for future MARS developments is to include an ageing sub-model. See section 9.3 Suggestions for future MARS improvements.

Equation 4.39: Total supply with living places in domiciles

$S^D(t)$............Total supply with living places in domiciles in the year t

- **Residential demand model**

Initially the overall number of people requiring a domicile in year t is the total number of movers (Equation 4.37) plus the in study area population due to migration and natural growth (Equation 4.40). The growth rates for population change have to be defined exogenously (Equation 4.41). If the supply with living places is not sufficient to satisfy the external growth rates, then growth is limited (Equation 4.42 and Equation 4.43). The over demand in an iteration t is stored and cumulated to the external growth in iteration $t+1$ (Equation 4.49). An increasing potential of people to move into the study area stimulates new development activities in following iterations (Equation 4.46).

$$P^{in,d}(t) = P^{mv}(t) + N^{gr}(t) = \sum_j N_j^{mv}(t) + N^{gr}(t)$$

Equation 4.40: Quantity of living places demanded

$P^{in,d}(t)$ ....Total quantity of living places demanded in the year t

$N^{gr}(t)$............Change in population in year t (natural growth & migration, can be positive or negative)

$$N^{gr}(0) = p^{gr}(0) * N^R(0)$$

Equation 4.41: Change in population (natural growth & migration) in year 0

$p^{gr}(0)$ ....Percentage change in population in year 0 (natural growth & migration, can be positive or negative)

$$DF^D(t) = \frac{P^{in,d}(t)}{S^D(t)}$$

Equation 4.42: Demand factor for domiciles

$DF^D(t)$..........Demand factor for domiciles in the year t

$$If\ DF^D(t) > 1\ then\ P^{in}(t) = \sum_j S_j^D(t)\ else\ P^{in}(t) = P^{in,d}(t)$$

Equation 4.43: Constraint on demand

$P^{in}(t)$ ....Total demand for living places which can be satisfied in the year t

The spatial distribution of people moving into new residential locations depends on the aggregated accessibility by public transport and car, the share of green land and rent (Equation 4.44). The accessibility by public transport and car reflects the utility from being able to reach employment opportunities. The share of green land is used as an indicator to measure the quality of living in a zone. A quadratic share of green land term was added to reflect the fact that high density, inner city locations are highly attractive to certain person groups. Rent again measures the cost of living in a zone[53]. The basic form of Equation 4.44 was derived from an analysis of data observed in the city of Vienna.

$$N_j^{in}(t) = P^{in}(t) * \frac{A_j^{in}(t) / f\left(Z_j^{in}(t)\right)}{\sum_j A_j^{in}(t) / f\left(Z_j^{in}(t)\right)} = P^{in}(t) * \frac{a^{in} * e^{b^{in} * {}^{WP}Acc_j^{PC,PT}(t) + ShGr_j(t) * \left(c^{in} * ShGr_j(t) + d^{in}\right) + e^{in} * R_j^D(t)}}{\sum_j a^{in} * e^{b^{in} * {}^{WP}Acc_j^{PC,PT}(t) + ShGr_j(t) * \left(c^{in} * ShGr_j(t) + d^{in}\right) + e^{in} * R_j^D(t)}}$$

Equation 4.44: Distribution of residents demanding a living place

$N^{in}_j(t)$ .... Number of residents demanding a living place in zone j in the year t

$A^{in}_j(t)$ .... Attraction to move into zone j in year t

$f(Z^{in}_j(t))$ .... Friction factor to move into zone j in year t caused by impedance Z

${}^{WP}Acc^{PC,PT}_j(t)$ .... Aggregated accessibility of working places from zone j in the year t

$ShGr_j(t)$ .... Share of green land in zone j in the year t

$R^D_j(t)$........................ Monthly rent or mortgage for a domicile in zone j in the year t (€)

a^{in}, b^{in}, c^{in}, d^{in}, e^{in} .... Parameter (derived from a regression analysis using observed data and calibration)

- **Redistribution model**

A redistribution of movers is needed in the case that more people want to move into a zone than there are living places supplied. Figure 4.8 and Equation 4.45 show the iterative process of the redistribution of over demand to zones with sufficient supply.

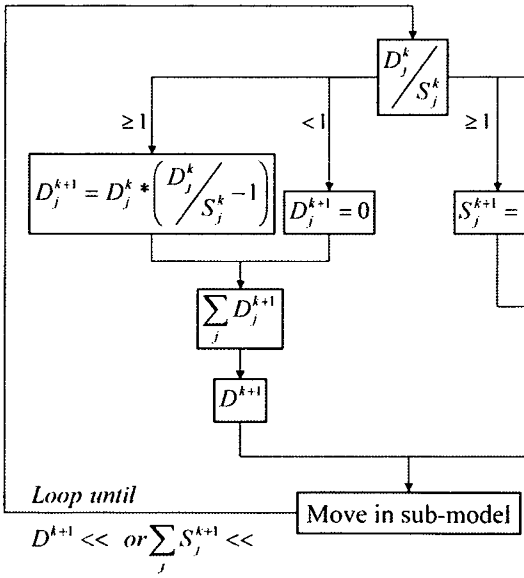


Figure 4.8: Sub-system diagram redistribution sub-model of the residential location sub-model

Legend:

k................. Number of iteration in the re-distribution process

j.................. Index of zone

D................. Quantity of residences demanded

S.................. Quantity of residences supplied

$$\textit{Do until } \forall \; N_j^{in}(t)\big|_k \leq S_j^D(t)\big|_k$$
$$\textit{If } N_j^{in}(t)\big|_k > S_j^D(t)\big|_k \textit{ then}$$
$$P_j^{in}(t)\big|_{k+1} = N_j^{in}(t)\big|_k - S_j^D(t)\big|_k \textit{ and } \left.\frac{A_j^{in}(t)}{f\left(Z_j^{in}(t)\right)}\right|_{k+1} = 0 \textit{ else}$$
$$P_j^{in}(t)\big|_{k+1} = 0 \textit{ and } \left.\frac{A_j^{in}(t)}{f\left(Z_j^{in}(t)\right)}\right|_{k+1} = \left.\frac{A_j^{in}(t)}{f\left(Z_j^{in}(t)\right)}\right|_k$$
$$\textit{Next } k$$

Equation 4.45: Re-distribution of over-demand to second choice zones

k..................Number of iteration in the redistribution process

After each iteration t the demanded quantity of domiciles and the rent and mortgage for domiciles are adapted according to the demand/supply situation (Equation 4.46 and Equation 4.47). Developers adopt their willingness to construct residential housing in line the ratio of demand to supply on the housing market (Equation 4.46).

$$P^D(t+1) = \left(P^D(t) + a\right) * \left(DF^D(t)\right)^2$$

Equation 4.46: Relationship potential to build domiciles and demand factor

$DF^D(t)$..........Aggregated demand factor for domiciles in year t

a..................Small constant number to allow a recovery of demand in year $t+1$ if demand was 0 in year t

The development of rents depends on the ratio of demand to supply on the residential housing market and changes in car traffic volumes (Equation 4.47). The latter is intended to reflect that residential property values decrease with increasing exposure to noise and pollution from car traffic.

$$R_j^D(t+1) = R_j^D(t) * \frac{\alpha}{\beta + \gamma * e^{-\delta * DF_j^D(t) * \frac{\sum_i T_{ij}^{PC}(t-1) + \sum_j T_{ij}^{PC}(t-1)}{\sum_i T_{ij}^{PC}(t) + \sum_j T_{ij}^{PC}(t)}}}$$

Equation 4.47: Relationship rent to demand factor and road traffic

$\alpha, \beta, \gamma, \delta$ ...Constant factors

If the study area begins to run short of land, land prices are increasing (Equation 4.48).

$$LP_j(t+1) = LP_j(t) * e^{\left(\frac{ShGr_j(t-1)}{ShGr_j(t)} - 1\right)}$$

Equation 4.48: Relationship land price and green land per zone

Unsatisfied external demand is cumulated (Equation 4.49) and stimulates building activities via the demand factor for domiciles.

$$N^{gr}(t+1) = p^{gr}(t+1) * N^{Res}(t) + \left(P^{in}(t) - S^{D}(t)\right)$$

Equation 4.49: External demand for next iteration

4.4.2 Workplace location sub-model

The basic structure of the workplace location sub- models is similar to that of the residential location sub-model except that there is no explicit development model. Businesses and companies are seen as their own developers. Therefore MARS does not use a separate actor "developer". The sub-models for the service and production sector are identical except from the parameters in the distribution equations. Service sector businesses are located before production sector businesses are located.

- **Floor space supply model**

MARS uses a very simple workplace move out sub-model[56]. The average lifetime of a business at a location within the study area is used to calculate a percentage of businesses moving in each iteration (Equation 4.50). This percentage is used to calculate the number of businesses and workplaces moving in each zone (Equation 4.51). The multiplication with average floor space per workplace gives the unoccupied floor space per economic sector (Equation 4.52).

$$p^{s}_{mv} = \frac{1}{T^{s}_{mv}}$$

Equation 4.50: Percentage of workplaces moving out

p^{s}_{mv} .... Percentage workplaces economic sector s (service, production) moving out every year

T^{s}_{mv} .... Average number of years until a business in economic sector s (service, production) either relocates or goes bankrupt

$$\Delta N^{s,mv}_{j}(t) = N^{s}_{j}(t-1) * p^{s}_{mv}$$

Equation 4.51: Moving out sub-model workplace location model

$\Delta N^{s,mv}_{j}(t)$ .... Number of workplaces in sector s moving out of zone j in year t

$N^{s}_{j}(t-1)$ .... Workplaces in sector s in zone j in year $t-1$

$$F^{s,u}_{j}(t) = \Delta N^{s,mv}_{j}(t) * F^{s}_{j} + F^{s,u}_{j}(t-1)$$

Equation 4.52: Unoccupied floor space for workplaces

$F^{s,u}_{j}(t)$ .... Unoccupied floor space for workplaces in sector s in TAZ j in the iteration t

F^{s}_{j} .... Floor space per workplace in sector s in TAZ j

- **Floor space demand and development model**

The workplace moving in sub-model is similar to the residential moving in model. The potential number of new businesses and workplaces has to be defined exogenously for each year. The exogenous growth rates are cut down if there is not enough space to be developed (see section Redistribution model below). The

[56] Employing a move-out model with a similar structure as the residential move out model is one of the suggestions for future MARS improvements. See section 9.3 Suggestions for future MARS improvements.

spatial distribution of the new workplace locations depends on land availability, accessibility by car and land price (Equation 4.53). The floor space which has to be new developed is calculated for each zone (Equation 4.56). The redistribution models control if these requirements can be met by the available land.

$$\Delta N_j^{s,in}(t) = P^s(t) * \frac{A_j^{s,in}(t)/f(Z_j^{s,in}(t))}{\sum_j A_j^{s,in}(t)/f(Z_j^{s,in}(t))} = P^s(t) * \frac{e^{(a^s + b^s * AvLd_j(t) + c^s * {}^{WP}Acc_j^{PC}(t) + d^s * LP_j(t))} - 1}{\sum_j e^{(a^s + b^s * AvLd_j(t) + c^s * {}^{WP}Acc_j^{PC}(t) + d^s * LP_j(t))} - 1}$$

Equation 4.53: Workplace location sub-model

$\Delta N^{s,in}_j(t)$........Number of workplaces sector s moving into zone j in the year t

$A^{s,in}_j(t)$..........Attraction for a sector s business to move into zone j in year t

$f(Z^{s,in}_j(t))$.......Friction factor sector s business to move into zone j in year t caused by impedance Z

$AvLd_j(t)$........Available land in zone j in the year t (1 = average)

${}^{WP}Acc^{PC}_j(t)$....Accessibility of workplaces by car in zone j in the year t (1 = average)

$LP_j(t)$...........Price for land in zone j in the year t (1 = average)

a^s, b^s, c^s, d^s ...Parameter (derived from a regression analysis using observed data and calibration)

$$P^s(t+1) = N^s(t) * (p^s(t) - p^s_{mv})$$

Equation 4.54: Potential number of workplaces to locate

$P^s(t+1)$.........Potential workplaces to locate in sector s in year $t+1$

$p^s(t)$.............Percentage external change of workplaces sector s in year t

$$\Delta N_j^s(t) = \Delta N_j^{s,in}(t) - \Delta N_j^{s,mv}(t)$$

Equation 4.55: Change in workplaces per zone

$\Delta N^s_j(t)$..........Change in workplaces in sector s in zone j in year t

$$F_j^{s,dv}(t) = \Delta N_j^{s,mv}(t) * F_j^s - F_j^{s,u}(t)$$

Equation 4.56: Floor space to be developed for workplaces

$F^{s,dv}_j(t)$..........Floor space to be developed for workplaces in sector s in TAZ j in the iteration t

- **Redistribution model**

MARS controls if the demanded amount of new businesses and workplaces for both the service and the production sector can be met in a zone, i.e. if enough developable land is available (Equation 4.57). The over demand is redistributed to other zones if this it is possible (Equation 4.58). Otherwise the potential external growth is cut down.

$$\text{If } F_j^{s,av}(t) < \Delta N_j^s(t) * F_j^s \text{ then}$$

$$\Delta N_j^{s,in}(t) = \frac{F_j^{s,dv}(t)}{F_j^s} \text{ and } F_j^{s,dv}\Big|_k = 0 \text{ and } \left(A_j^{s,in}(t) \Big/ f(Z_j^{s,in}(t)) \right)\Bigg|_k = 0 \text{ else}$$

$$F_j^{s,av}(t)\Big|_k = F_j^{s,av}(t)\Big|_{k-1} - \Delta N_j^{s,in}(t) * F_j^s$$

Equation 4.57: Constraining workplace development by the developable floor space

k .... Iteration index redistribution

$F^{s,av}_j(t)$ .... Floor space available to be developed for workplace in sector s in TAZ j in the iteration t

F^s_j .... Floor space per workplace in sector s in TAZ j

MARS redistributes the unsatisfied demand for floor space in an iterative way (Equation 4.58). First the potential number of workplaces which has to be redistributed to second best choice zones is calculated. Than the workplace location procedure is rerun using the updated values from Equation 4.57. The iterations stop if the number the number of unallocated workplaces is smaller than a threshold value which is 100 in the current version or all available land is used up.

$$\textit{Do Until } P^s(t)-\sum_j \Delta N_j^{s,in}(t)\Big|_k < 100 \textit{ or } \sum_j F_j^{s,dv}(t)\Big|_k = 0$$

$$P^{s,re}(t)\Big|_{k+1} = P^s(t)-\sum_j \Delta N_j^{s,in}(t)\Big|_k \textit{ and}$$

$$\textit{Do Equation 4.53 and Equation 4.57}$$

$$\Delta N_j^{s,in}(t) = \Delta N_j^{s,in}(t)\Big|_k + \Delta N_j^{s,in}(t)\Big|_{k-1}$$

$$\textit{Loop}$$

Equation 4.58: Re-distribution of over-demand for workplace floor space

$P^{s,re}(t)/_k$ .... Number of workplaces to redistribute in sector s in iteration k

4.5 Summary

Chapter 4 presents the quantitative description of the MARS sub-models. Section 4.3 describes the transport sub-models. The trip generation model is based on a constant trip rate for tours home – work – home and on a constant travel time budget for total travel. The trip distribution and mode choice is treated simultaneously. A combination of the analogy to the law of gravity and Kirchoff's law from electrical engineering is used in this stage. Currently no assignment stage is used in MARS[57]. For road traffic an area speed flow relationship takes supply side effects into account. Accessibility is measured in terms of time[58].

The land use sub-model consists of two main parts: a residential and a workplace model. Both parts use the same basic structure. The workplace sub-models are partially simpler than the residential sub-model. The basic structure consists of a stock development model, an activity model and a relocation model. The activity model consists of a moving out (household or workplace mobility) model and a moving in (household and workplace location) model. In general the land use sub-models are based on LOGIT models. A relocation to sites of second best choice is performed if there is not sufficient floor space available.

[57] To include an assignment stage is a suggestion for future MARS improvements. See chapter 9.3 Suggestions for future MARS improvements.

[58] To consider accessibility in terms of generalised costs is a suggestion for future MARS developments. See chapter 9.3 Suggestions for future MARS improvements.

5. CALIBRATION OF THE VIENNESE MARS MODEL

5.1 Introduction

The minimisation algorithm AMOEBA, which is described in chapter 7. A framework for finding optimal policy packages, was used to calibrate the transport and land use sub-models. The distance measure which was minimised is shown in Equation 5.1.

$$D = \sum_i \sum_j \left| v_{ij}^e - v_{ij}^m \right|$$

Equation 5.1: Distance measure (Schnabel, W. and Lohse, D., 1997) p. 228

D .... Distance measure

v^e_{ij} .... Empirical value

v^m_{ij} .... Value resulting from model calculations

The calibration of MARS was performed in the following sequence. A MARS model based on data from the year 1981 was set up. This model is referred to as MARS81. A cross-sectional calibration of the transport sub-model to the modal split observed in the year 1981 was made (section 5.2). This was followed by a calibration of the land-use sub-models to the changes in housing units, population and workplaces in the service and production sector (section 5.3). MARS81 then was used to validate whether the model is able to predict changes in the transport system from 1981 to 1991, changes in the number of housing units from 1991 to 1998 and changes in population from 1991 to 2001 (see chapter 6. Model Testing)[59].

Next a model based on data from the year 1991 was set up. Logically this model is referred to as MARS91. The transport sub-model was slightly re-calibrated (section 5.4). The land use model was re-calibrated to housing unit developed between 1991 and 1998 and population developed between 1991 and 2001[59] (section 5.5).

A regression analysis is an appropriate method to examine the conformity between observed and calculated values (Schnabel, W. and Lohse, D., 1997) p. 229.

$$\sum_i \sum_j \left[v_{ij}^e - v_{ij}^{\bullet} \right]^2 = \sum_i \sum_j \left[v_{ij}^e - \left(a + b * v_{ij}^m \right) \right]^2 \Rightarrow Minimum$$

Equation 5.2: Regression analysis (Schnabel, W. and Lohse, D., 1997) p. 229

A good fit between observations and model results is characterised by:

- a around 0,
- b around 1 and
- R^2 near 1.

[59] Employment and commuting data from the 2001 census are not available yet.

In (Balz, W. and Frik, H., 1996) p. 123 the following parameters are used to asses the performance of model predictions:

- Sum of deviations between observed and predicted values (Equation 5.3)
- Sum of absolute deviations between observed and predicted values (Equation 5.4)
- Sum of relative deviations between observed and predicted values (Equation 5.5)
- Standard deviation of the above mentioned parameters
- Histograms of the deviations
- Maximum deviation

$$\sum_i (O_i - P_i)$$

Equation 5.3: Sum of deviations

O_i .... Observed values

P_i .... Predicted values

$$\sum_i |O_i - P_i|$$

Equation 5.4: Sum of absolute deviations

$$\sum_i \left(1 - \frac{P_i}{O_i}\right)$$

Equation 5.5: Sum of relative deviations

The literature was searched for calibration and validation exercises with other models. The aim was to benchmark the performance of MARS. Only a few relevant references were found. The MARS results are compared to these results.

Exceptional events in the development of housing units and population happened between 1991 and 2001. The implications for the MARS model and its fit to observed reality are discussed in the conclusions.

5.2 Transport sub-model 1981

5.2.1 Data

Table 5.1 shows the modal split data to which MARS81 is calibrated. The mode split for trips home – work is calculated using the 1981 census data (ÖSTZ, 1985). Household survey data from 1986 and 1991 were used to estimate the overall mode split and the mode split for trips home – other (Herry, M. and Snizek, S., 1993).

Table 5.1: Mode split calibration data 1981

Mode	Home - Work	Home - Other	Total
Slow	14.7%	28.0%	26.2%
PT	44.9%	36.5%	37.7%
Car	40.4%	35.5%	36.1%

Source: (ÖSTZ, 1985), (Herry, M. and Snizek, S., 1993), own calculations

5.2.2 Calibration parameters

Table 5.2 shows the mode and purpose specific parameters derived from the initial calibration of the MARS base year result to the mode split data shown in Table 5.1.

Table 5.2: Mode and trip purpose specific calibration parameters β_m of the final calibration

	Slow	PT	Car
Home - Work	0.77	1.06	1.59
Home - Other	0.69	1.16	1.43

5.2.3 Conformity between observed and calculated data

The following sections compare home – work trips by OD-pair and intra- and inter-zonal home - work trips by mode as calculated by calibrated versions of MARS and census 1981 data. No similar observed data were available for trips home – other.

- **Initial calibration results**

Figure 5.1 shows results of an initial calibration. The number of trips home – work per OD-pair as calculated by MARS81 is compared with census data. The gradient of the regression is with about 0.6 not very satisfying. The coefficient of determination R^2 of about 0.81 is acceptable. MARS81 is underestimating the number of trips for OD pairs with higher numbers of trips. A more detailed analysis shows that these are the intra-zonal OD pairs in the bigger zones. Excluding intra-zonal trips results in a better fit (see Figure 5.2). It was therefore tried to improve the model fit by changing the definition for the intra-zonal distances[60].

[60] The new definition of intra zonal trip distances is described in the 12.6.1 Transport related data p. 246.

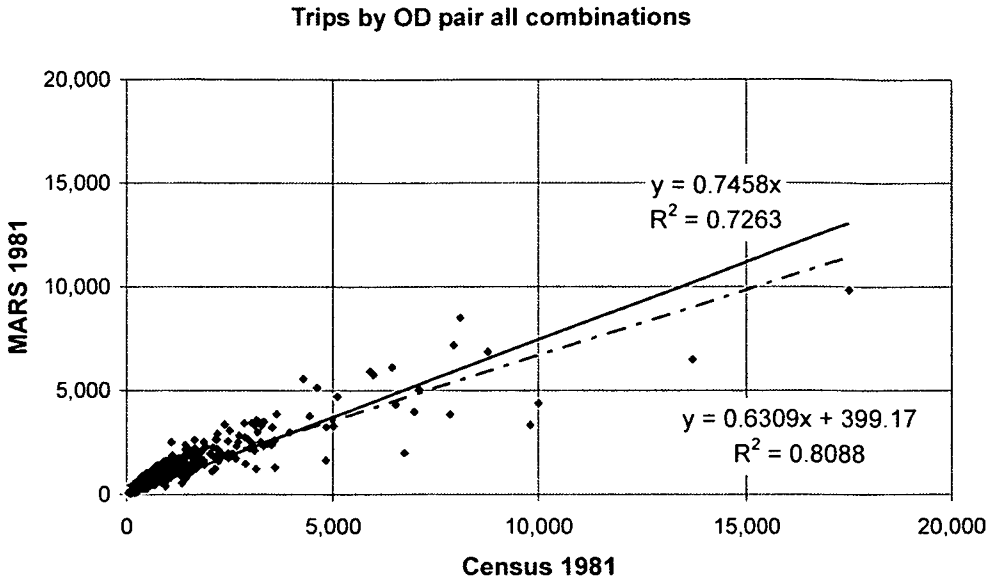


Figure 5.1: Comparison census data[61] – MARS81 results OD matrix home – work for the year 1981 initial calibration

Table 5.3: Performance indicators comparison census data – MARS81 results OD matrix home – work for the year 1981 initial calibration

Indicator	Deviation	Absolute deviation	Relative deviation
Sum	-9,715	171,562	103.60
Standard deviation	782	711	0.38
Median	77	159	0.16
Maximum	1,439	7,680	2.04

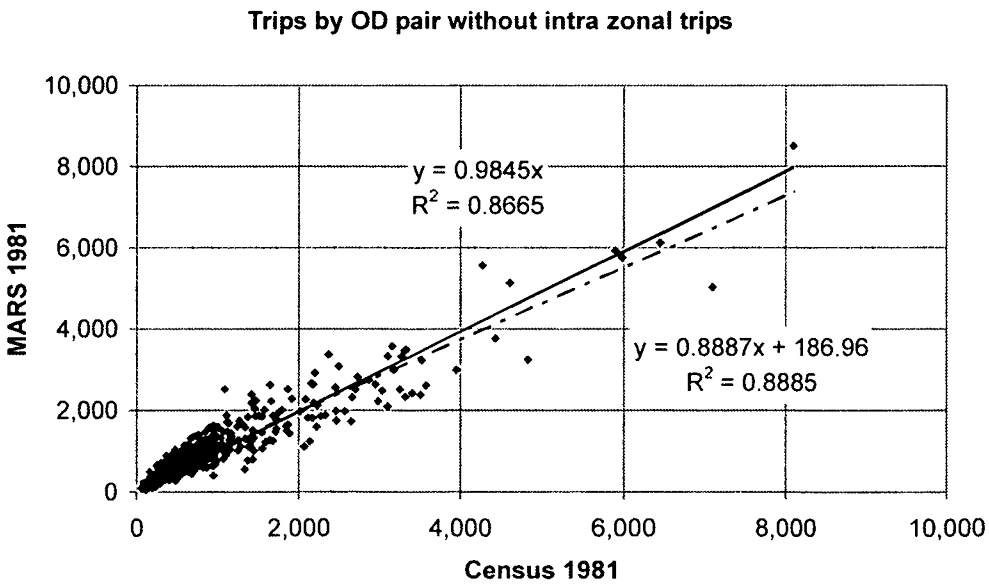


Figure 5.2: Comparison census data[61] – MARS results OD matrix home – work without intra-zonal trips for the year 1981 initial calibration

[61] Source: ÖSTZ (1985). Volkszählung 1981 - Hauptergebnisse II Wien; *Beiträge zur Österreichischen Statistik*, **Heft 630.20**; Österreichisches Statistisches Zentralamt, Wien.

Table 5.4: Performance indicators comparison census data – MARS81 results OD matrix home – work without intra-zonal trips for the year 1981 initial calibration

Indicator	Deviation	Absolute deviation	Relative deviation
Sum	43,210	115,247	110.27
Standard deviation	326	248	0.37
Median	82	153	0.18
Maximum	1,439	2,057	2.04

- **Re-calibration using a different definition of intra-zonal trip length**

Indeed the conformity between observation and model results could be improved (see Figure 5.3). The gradient of the regression was improved to about 0.7 and the coefficient of determination was improved to nearly 0.9.

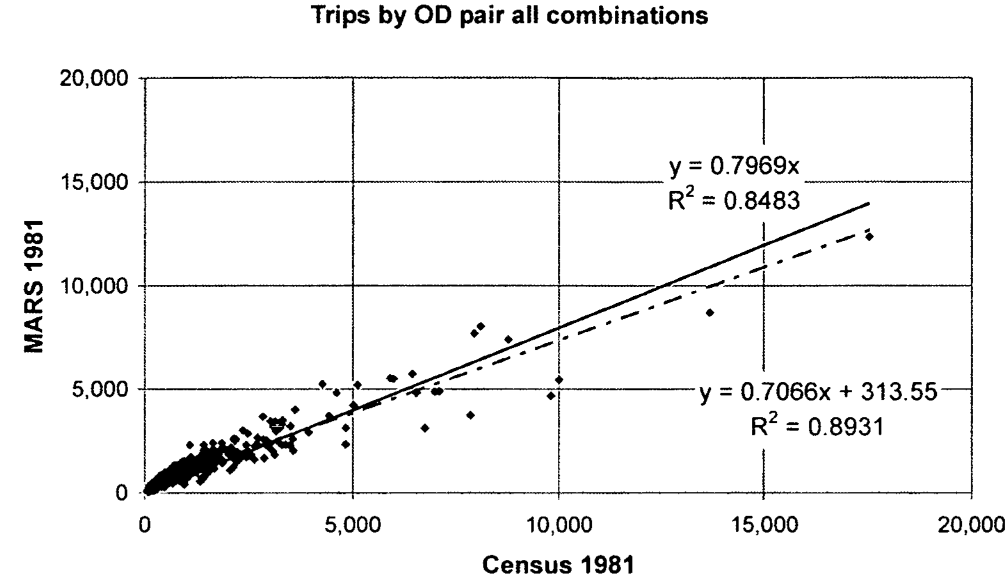


Figure 5.3: Comparison census data[61] – MARS results OD matrix home – work for the year 1981 new definition of intra-zonal distance

Table 5.5: Performance indicators comparison census data – MARS81 results OD matrix home – work for the year 1981 new definition of intra-zonal distance

Indicator	Deviation	Absolute deviation	Relative deviation
Sum	-9,715	153,611	95.00
Standard deviation	622	550	0.37
Median	69	151	0.14
Maximum	1,222	5,167	1.91

Figure 5.4 shows the relation between observed data and model results without considering intra-zonal trips.

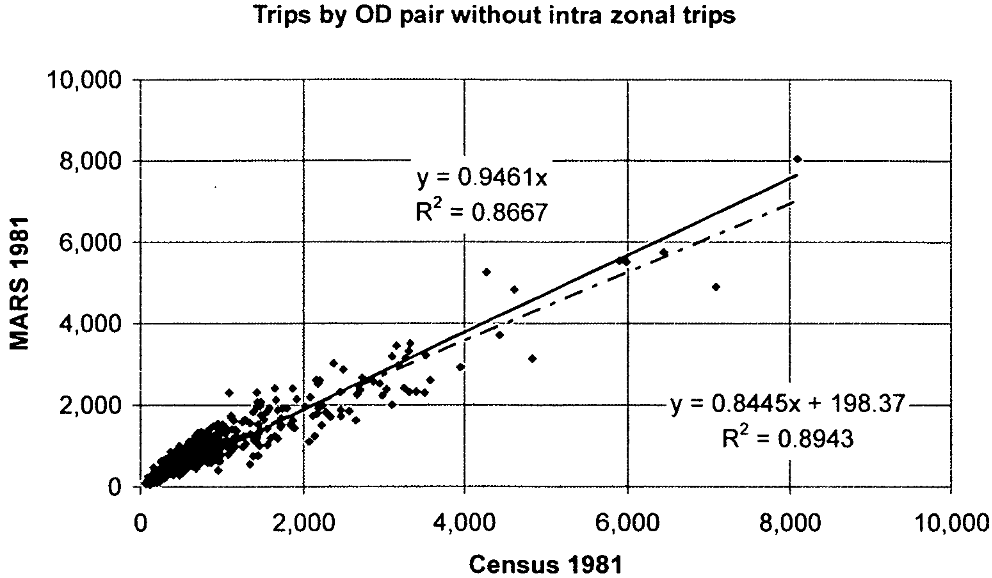


Figure 5.4: Comparison census data[61] – MARS results OD matrix without home – work intra-zonal trips for the year 1981 new definition of intra-zonal distance

Table 5.6: Performance indicators comparison census data – MARS81 results OD matrix home – work without intra-zonal trips for the year 1981 new definition of intra-zonal distance

Indicator	Deviation	Absolute deviation	Relative deviation
Sum	28,588	111,054	99.68
Standard deviation	321	241	0.36
Median	77	144	0.16
Maximum	1,222	2,185	1.91

It can be argued that the few points with high values drive the regression. To show that this is not the case a regression analysis for OD pairs with less than 5,000 and less than 1,000 trips was performed (Figure 5.5 and Figure 5.6) There is still a reasonable correlation in the cloud of points with lower values. It could be seen that MARS tends to overestimate OD pairs with low numbers of trips (i.e. with high distances) and to underestimate OD pairs with high numbers of trips (i.e. with short distances)[62].

[62] Currently distances to and from PT stops and parking places as well as parking place searching times are only reasonable guesses. A more detailed survey of these data is assumed to have a high potential to improve the conformity between observed and calculated data. See chapter 9.3 Suggestions for future MARS improvements.

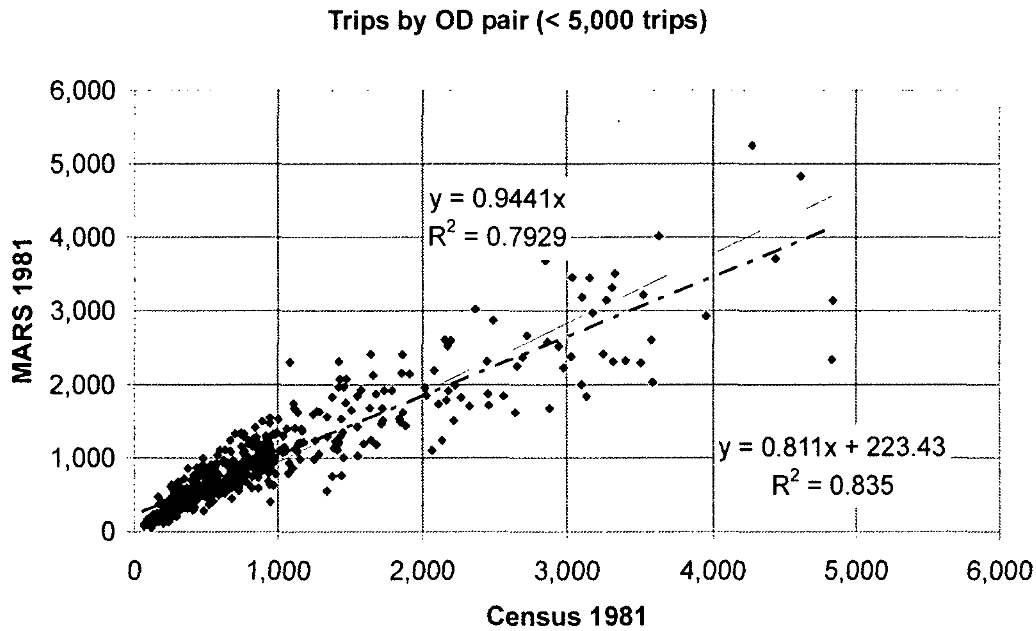


Figure 5.5: Comparison census data[61] – MARS results OD matrix for OD pairs with less than 5,000 trips home – work for the year 1981 new definition of intra-zonal distance

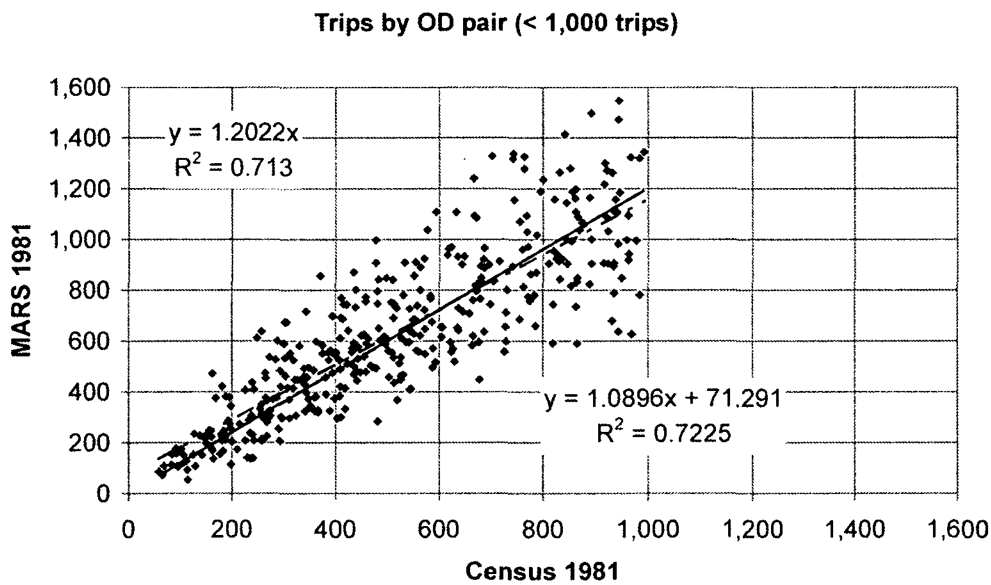


Figure 5.6: Comparison census data[61] – MARS results OD matrix for OD pairs with less than 1,000 trips home – work for the year 1981 new definition of intra-zonal distance

Data about commuting trips by OD pair and mode were not available from the 1981 census. Only a distinction between intra- and inter-zonal trips by mode was possible. MARS is underestimating intra-zonal trips. The slope is below 1 for all modes as well as for the total number of intra-zonal trips (Figure 5.7 to Figure 5.10). The coefficient of determination R^2 is sufficiently high. Especially intra-zonal PT trips are underestimated (Figure 5.8)[62].

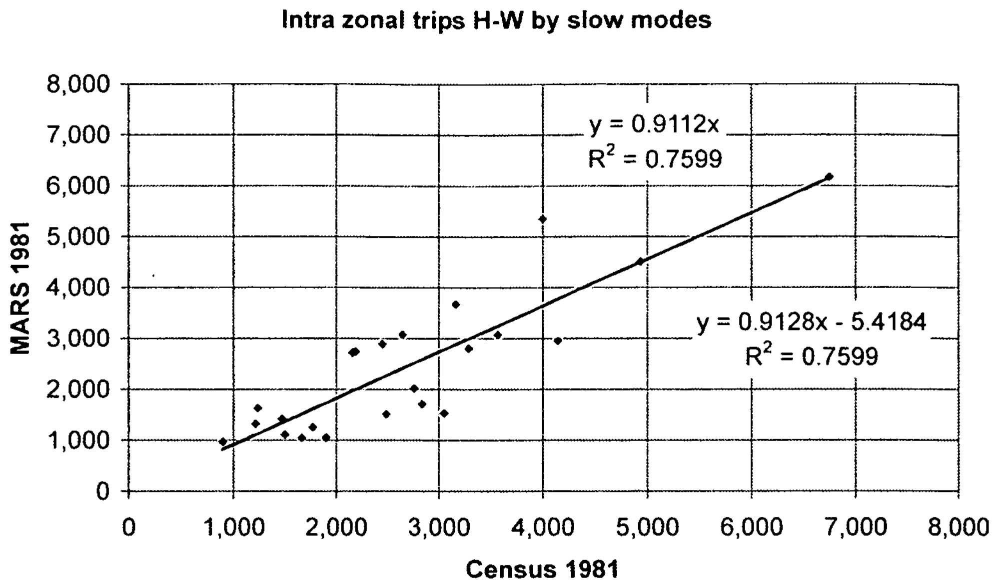


Figure 5.7: Comparison census data[61] – MARS results for intra-zonal trips slow modes home – work in the year 1981

Table 5.7: Performance indicators comparison census data – MARS results for intra-zonal trips slow modes home – work in the year 1981

Indicator	Deviation	Absolute deviation	Relative deviation
Sum	-5,538	14,382	-1.86
Standard deviation	705	387	0.27
Median	-430	516	-0.09
Maximum	1,355	1,517	0.34

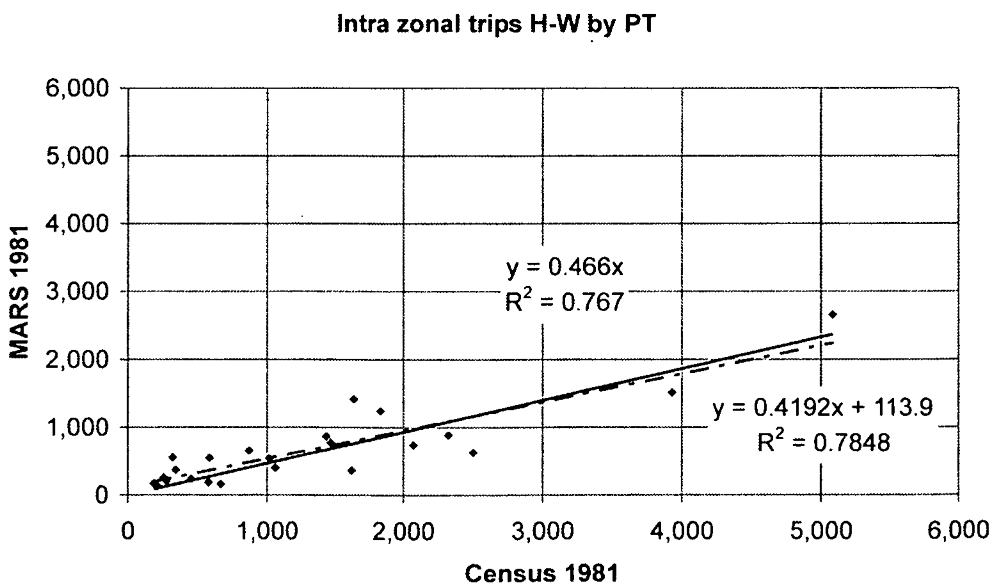


Figure 5.8: Comparison census data[61] – MARS results for intra-zonal trips PT home – work in the year 1981

Table 5.8: Performance indicators comparison census data – MARS results for intra-zonal trips PT home – work in the year 1981

Indicator	Deviation	Absolute deviation	Relative deviation
Sum	-14,486	14,985	-8.45
Standard deviation	613	589	0.35
Median	-603	603	-0.47
Maximum	234	1,964	0.73

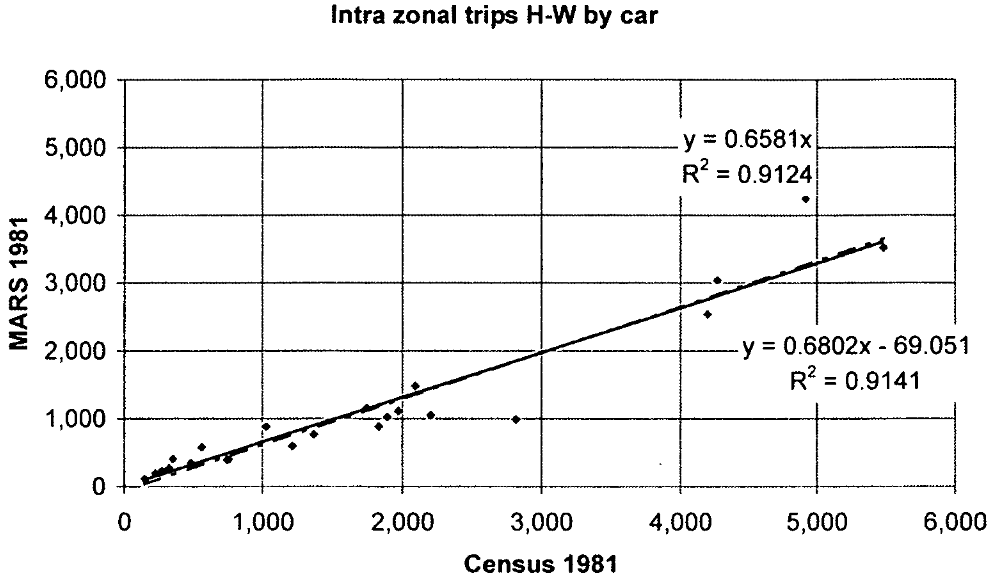


Figure 5.9: Comparison census data[61] – MARS results for intra-zonal trips car home – work in the year 1981

Table 5.9: Performance indicators comparison census data – MARS results for intra-zonal trips car home – work in the year 1981

Indicator	Deviation	Absolute deviation	Relative deviation
Sum	-14,666	14,805	-7.25
Standard deviation	603	596	0.19
Median	-603	603	-0.33
Maximum	55	1,964	0.16

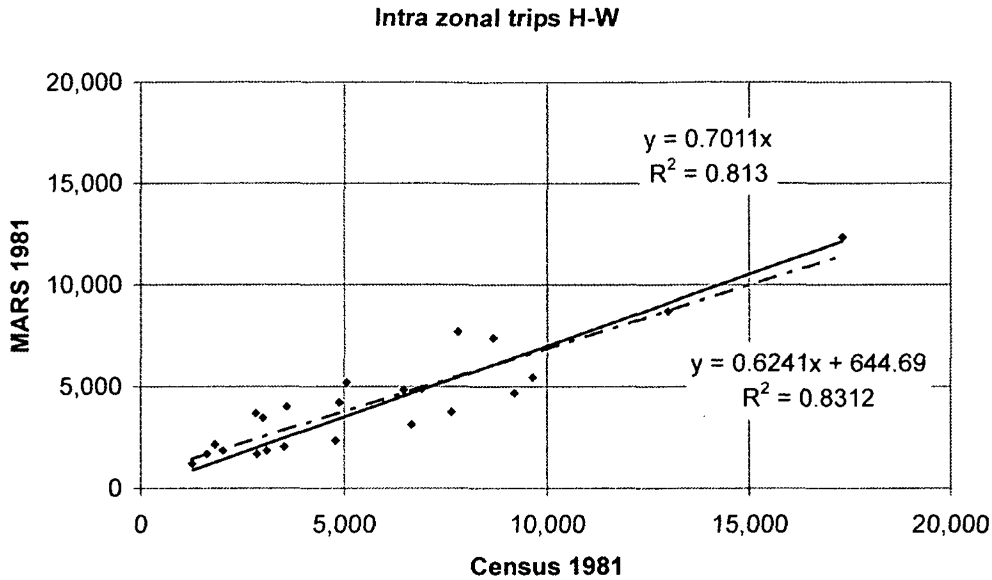


Figure 5.10: Comparison census data[61] – MARS results for intra-zonal trips all modes home – work in the year 1981

Table 5.10: Performance indicators comparison census data – MARS results for intra-zonal trips all modes home – work in the year 1981

Indicator	Deviation	Absolute deviation	Relative deviation
Sum	-93,729	95,429	-4.49
Standard deviation	2,901	2,789	0.25
Median	-3,749	3,749	-0.25
Maximum	850	12,347	0.30

MARS is overestimating inter-zonal trips. The slope is over 1 for all modes as well as for the total number of inter-zonal trips (Figure 5.11 to Figure 5.14). The coefficient of determination is sufficiently high except for slow modes (Figure 5.11).

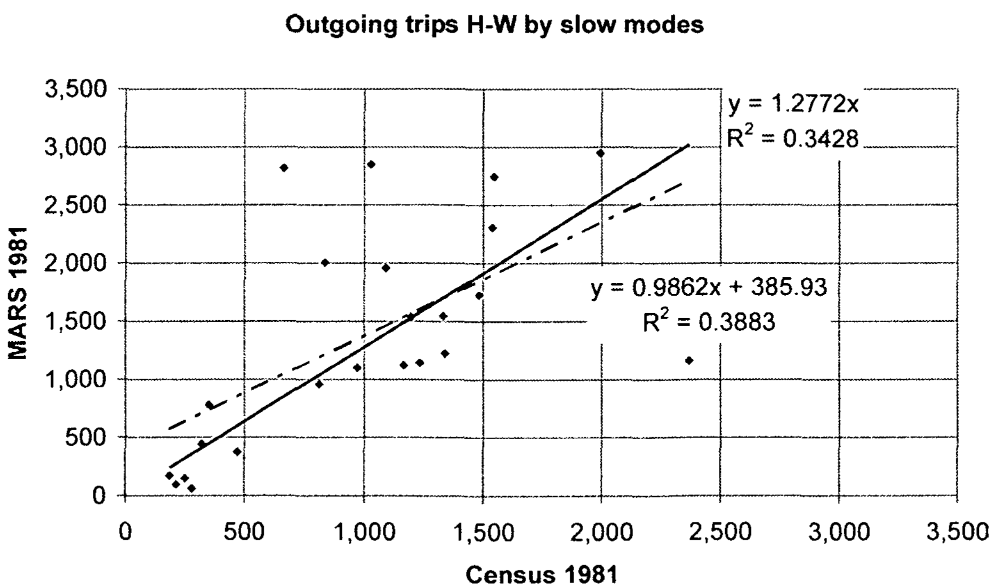


Figure 5.11: Comparison census data[61] – MARS results for out of zone trips slow modes home – work in the year 1981

Table 5.11: Performance indicators comparison census data – MARS results for out of zone trips slow modes home – work in the year 1981

Indicator	Deviation	Absolute deviation	Relative deviation
Sum	8,563	12,566	8.77
Standard deviation	733	609	0.88
Median	146	219	0.17
Maximum	2,152	2,152	3.23

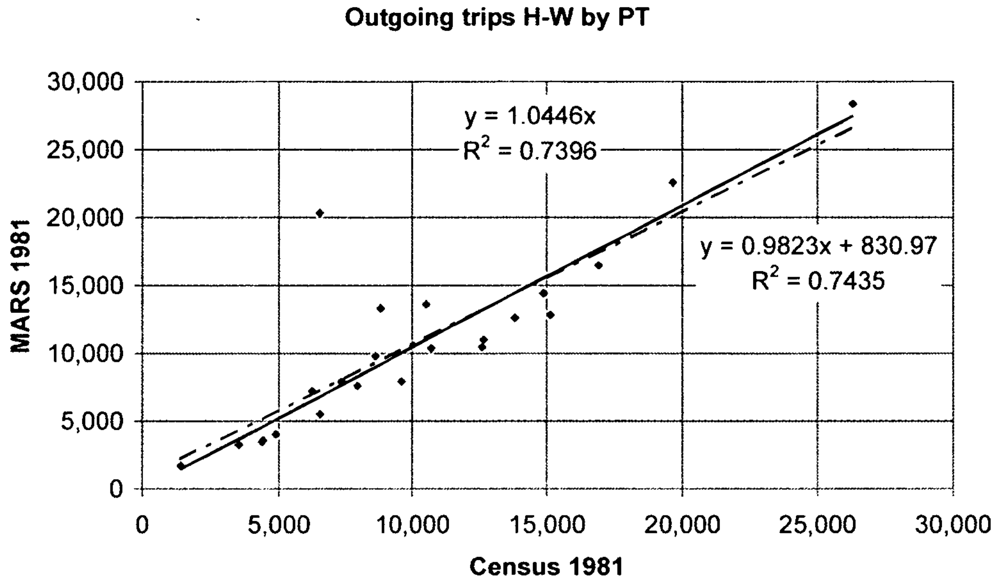


Figure 5.12: Comparison census data[61] – MARS results for out of zone trips PT home – work in the year 1981

Table 5.12: Performance indicators comparison census data – MARS results for out of zone trips PT home – work in the year 1981

Indicator	Deviation	Absolute deviation	Relative deviation
Sum	6,488	14,586	2.09
Standard deviation	710	408	0.48
Median	389	511	-0.03
Maximum	1,751	1,751	2.12

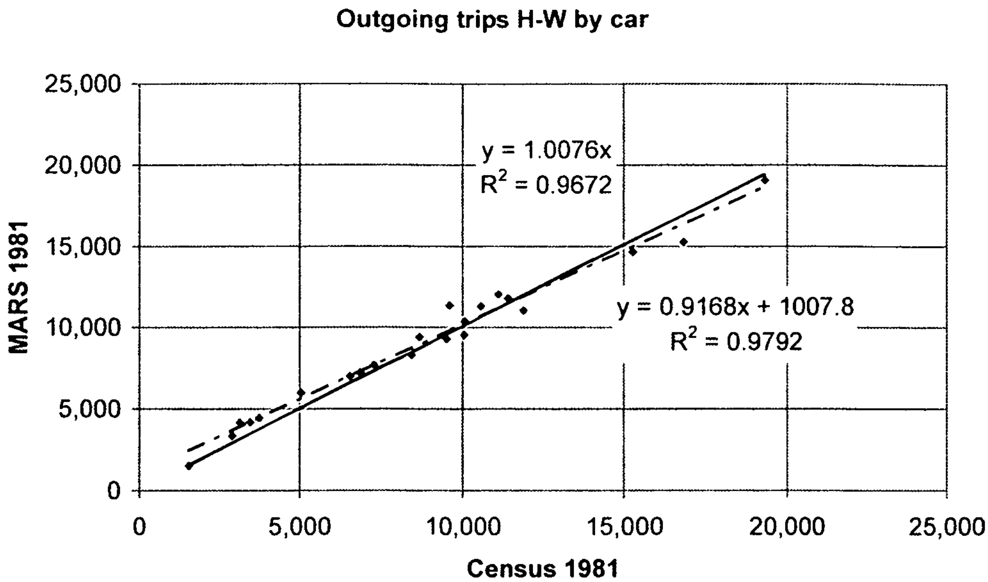


Figure 5.13: Comparison census data[61] – MARS results for out of zone trips car home – work in the year 1981

Table 5.13: Performance indicators comparison census data – MARS results for out of zone trips car home – work in the year 1981

Indicator	Deviation	Absolute deviation	Relative deviation
Sum	6,164	14,338	1.44
Standard deviation	713	420	0.10
Median	389	511	0.05
Maximum	1,751	1,751	0.33

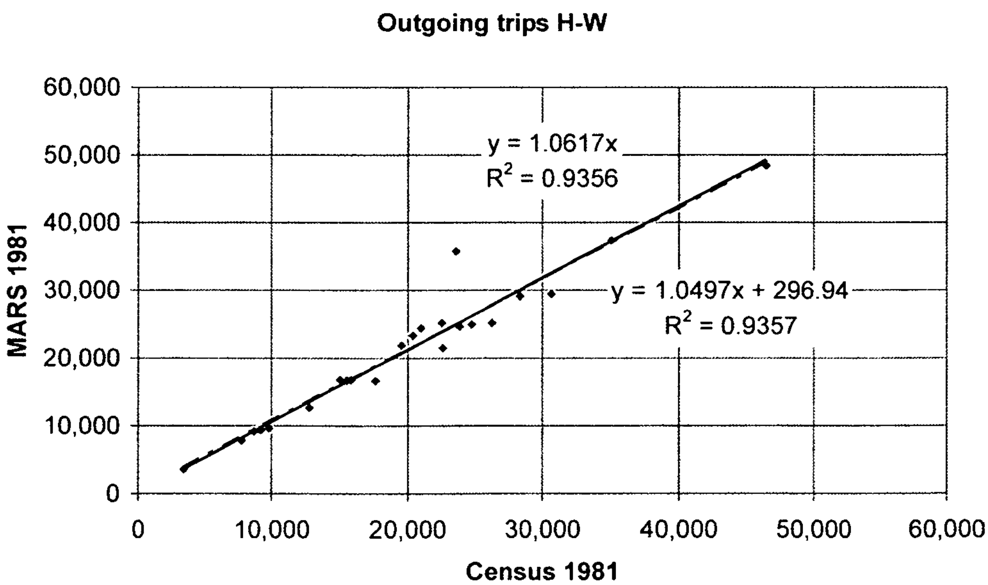


Figure 5.14: Comparison census data[61] – MARS results for out of zone trips all modes home – work in the year 1981

Table 5.14: Performance indicators comparison census data – MARS results for out of zone trips all modes home – work in the year 1981

Indicator	Deviation	Absolute deviation	Relative deviation
Sum	-486,647	486,953	1.40
Standard deviation	10,916	10,889	0.12
Median	-21,867	21,867	0.04
Maximum	153	48,386	0.52

5.2.4 Conclusions

The MARS transport sub-model was calibrated to observed mode split data using mode and trip purpose specific calibration parameters. The resulting parameters are within a reasonable range. OD-pair wise results of the calibrated model were compared with observed data. The resulting regression coefficients are in general reasonably high. The only exception is the fit for inter-zonal slow mode trips (R^2 about 0.4). It could be seen that the MARS model is systematically underestimating short, intra-zonal trips and overestimating long, inter-zonal trips. The intra-zonal trip length was redefined to improve the fit. MARS still underestimates the short, intra-zonal trips, but the slope of the regression has moved nearer to 1. A more detailed survey of access and egress times to parking places and PT stops and parking place searching times is seen as an appropriate future development to further improve the conformity between observed and calculated values (see also chapter 9.3 Suggestions for future MARS improvements).

5.3 Land use sub-model 1981 to 1991

5.3.1 Data

The land use sub-model was calibrated towards changes in number of housing units, population and workplaces in the service and production sector observed in census 1981 and census 1991 (Table 5.16).

5.3.2 Calibration parameters

In a first stage the parameters in the utility functions (see section 4.4 Land use sub-models) were calibrated. Zone specific calibration parameters were estimated in a second round of calibration (Table 5.17).

Table 5.15: Calibration parameters land use sub-model utility functions

Sub-model		*a*	*b*	*c*	*d*	*e*
Residential	Development	2,405.8	-2,902	-	-	-
	Move out	1	-0.186	-1.111	2.796	-
	Move in	1	0.617	0.686	2.275	1.524
Workplace	Service	8.388	0	-0.644	0.957	-
	Production	7.523	0.205	-0.873	0.774	-

Table 5.16: Calibration data land use part Vienna MARS

Housing units

Zone	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23
1981	11,562	48,399	49,330	18,862	31,738	16,763	17,603	14,522	25,882	78,820	30,118	44,841	27,118	43,954	42,091	52,686	29,484	30,507	35,619	40,003	54,400	44,224	32,649
1991	11,259	48,593	48,507	18,620	30,507	17,264	17,859	14,316	25,394	82,589	33,518	44,295	29,240	46,560	39,179	53,216	30,865	29,188	38,873	39,540	61,535	53,029	39,145
Delta	-303	194	-823	-242	-1,231	501	256	-206	-488	3,769	3,400	-546	2,122	2,606	-2,912	530	1,381	-1,319	3,254	-463	7,135	8,805	6,496

Residents

Zone	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23
1981	19,537	95,892	86,054	31,800	52,436	28,771	29,490	24,769	45,314	147,101	65,859	79,408	55,331	78,996	70,066	88,587	49,337	52,548	67,522	73,696	116,033	99,801	72,998
1991	18,002	93,542	84,500	31,410	51,521	30,298	30,396	23,850	40,416	147,636	66,881	79,592	54,909	80,822	69,309	88,931	50,944	49,761	67,377	71,876	119,415	106,589	81,871
Delta	-1,535	-2,350	-1,554	-390	-915	1,527	906	-919	-4,898	535	1,022	184	-422	1,826	-757	344	1,607	-2,787	-145	-1,820	3,382	6,788	8,873

Workplaces

Zone	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23
1981	121,368	41,254	64,157	29,954	22,804	22,822	28,096	17,222	45,091	52,912	28,523	35,273	22,184	32,227	31,486	27,295	17,890	15,645	25,958	21,917	41,418	30,167	40,390
1991	101,863	36,252	61,686	25,396	17,069	19,799	21,648	14,464	47,964	49,991	26,689	29,263	21,319	26,417	30,586	25,548	14,906	13,495	22,190	17,775	41,511	28,653	50,032
Delta	-19,505	-5,002	-2,471	-4,558	-5,735	-3,023	-6,448	-2,758	2,873	-2,921	-1,834	-6,010	-865	-5,810	-900	-1,747	-2,984	-2,150	-3,768	-4,142	93	-1,514	9,642

Workplaces Production Sector

Zone	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23
1981	10,096	8,129	14,991	5,178	6,626	5,290	7,932	2,759	3,745	18,582	14,299	15,788	1,991	13,462	7,708	8,499	6,385	3,635	8,211	7,219	20,311	12,422	22,104
1991	3,792	4,100	8,656	1,768	3,021	2,939	3,014	1,131	1,896	9,476	7,390	9,374	1,062	4,219	3,791	4,922	2,833	1,618	2,988	2,734	16,466	8,332	18,174
Delta	-6,304	-4,029	-6,335	-3,410	-3,605	-2,352	-4,918	-1,628	-1,849	-9,106	-6,909	-6,414	-929	-9,243	-3,917	-3,577	-3,553	-2,018	-5,223	-4,485	-3,845	-4,090	-3,930

Workplaces Service Sector

Zone	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23
1981	111,272	33,125	49,166	24,776	16,178	17,532	20,164	14,463	41,346	34,330	14,224	19,485	20,193	18,765	23,778	18,796	11,505	12,010	17,747	14,698	21,107	17,745	18,286
1991	98,071	32,152	53,030	23,628	14,048	16,860	18,634	13,333	46,068	40,515	19,299	19,889	20,257	22,198	26,795	20,626	12,073	11,877	19,202	15,041	25,045	20,321	31,858
Delta	-13,201	-973	3,864	-1,148	-2,130	-671	-1,530	-1,130	4,722	6,185	5,075	404	64	3,433	3,017	1,830	569	-132	1,455	343	3,938	2,576	13,572

Source: (Magistratsabteilung 66 - Statistisches Amt, 1990), (Magistratsabteilung 66 - Statistisches Amt, 1999), (ÖSTZ, 1984), (ÖSTAT, 1993)

Table 5.17: Land use sub-model calibration parameters

Housing Unit Development																						
1	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**	**13**	**14**	**15**	**16**	**17**	**18**	**19**	**20**	**21**	**22**	**23**
3.19	0.09	0.60	0.99	0.95	2.34	0.16	0.34	2.39	2.13	1.56	0.14	3.10	2.02	0.21	0.13	1.52	0.06	3.28	0.14	2.03	1.93	2.44
Residents																						
1	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**	**13**	**14**	**15**	**16**	**17**	**18**	**19**	**20**	**21**	**22**	**23**
0.94	0.65	0.42	1.19	1.21	1.45	1.44	1.61	0.46	0.42	0.85	1.83	0.28	0.44	0.86	2.03	1.95	1.33	0.92	1.05	1.06	1.11	2.12
Workplaces Service Sector																						
1	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**	**13**	**14**	**15**	**16**	**17**	**18**	**19**	**20**	**21**	**22**	**23**
1.12	0.70	0.68	2.03	0.49	1.42	0.84	1.66	2.94	0.78	0.78	0.59	1.53	0.73	1.06	0.71	0.64	0.80	1.05	0.57	0.61	0.91	1.04
Workplaces Production Sector																						
1	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**	**13**	**14**	**15**	**16**	**17**	**18**	**19**	**20**	**21**	**22**	**23**
5.35	0.62	1.13	2.65	2.19	0.87	4.56	0.66	1.63	1.18	1.53	0.20	0.37	4.80	1.29	0.84	1.06	0.33	4:10	2.38	0.22	0.21	0.25

5.3.3 Conformity between observed and calculated absolute values in 1991

- **Housing units**

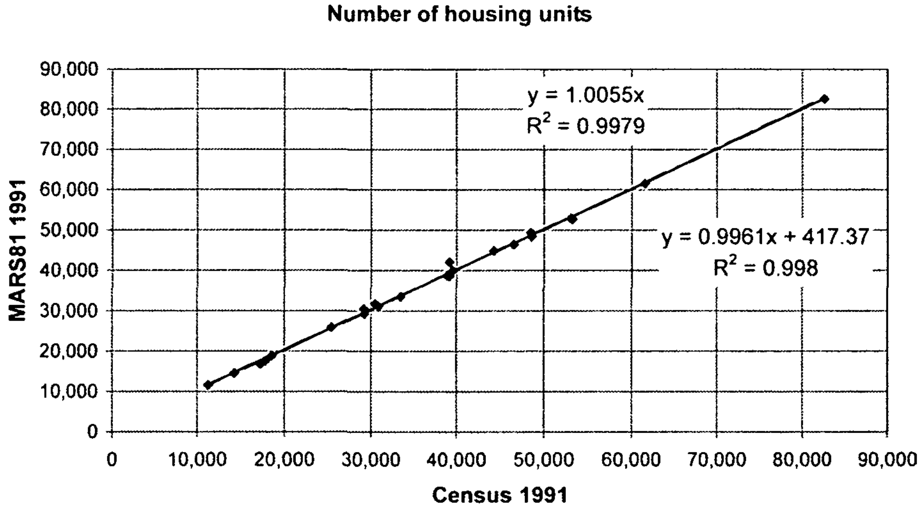


Figure 5.15: Comparison statistical data[63] – MARS81 number of housing units in 1991

Table 5.18: Performance indicators comparison census data – MARS81 results number of housing units by zone in 1991

Indicator	Deviation	Absolute deviation	Relative deviation
Sum	6,266	11,238	0.20
Standard deviation	759	636	0.02
Median	5	256	0.00
Maximum	2,912	2,912	0.07

- **Population**

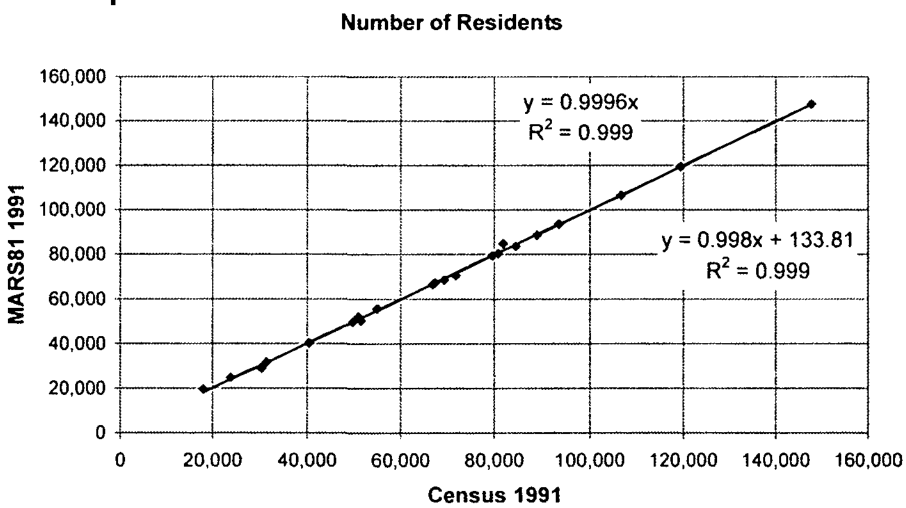


Figure 5.16: Comparison statistical data[64] – MARS81 number of residents in 1991

[63] Magistratsabteilung 66 - Statistisches Amt (1994). Statistisches Jahrbuch der Stadt Wien 1993; Magistrat der Stadt Wien, Wien.

Table 5.19: Performance indicators comparison census data – MARS81 results number of residents by zone in 1991

Indicator	Deviation	Absolute deviation	Relative deviation
Sum	-4	15,918	0.05
Standard deviation	994	699	0.03
Median	-120	395	0.00
Maximum	2,901	2,901	0.09

- **Workplaces**

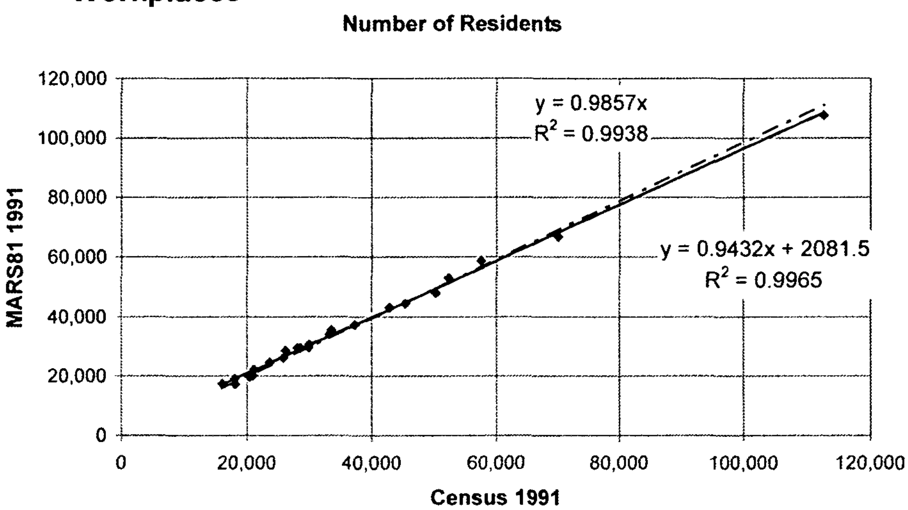


Figure 5.17: Comparison statistical data[65] – MARS development workplaces service sector between 1981 and 1991

Table 5.20: Performance indicators comparison census data – MARS81 results number of workplaces by zone in 1991

Indicator	Deviation	Absolute deviation	Relative deviation
Sum	7	29,523	0.24
Standard deviation	1,735	1,135	0.04
Median	616	982	0.02
Maximum	2,258	5,162	0.09

[64] ÖSTAT (1993). Volkszählung 1991 - Hauptergebnisse I Wien; *Beiträge zur Österreichischen Statistik*, **Heft 1.030/9**; Österreichisches Statistisches Zentralamt, Wien.

65 ÖSTAT (1995). Volkszählung 1991 - Hauptergebnisse II Wien; *Beiträge zur Österreichischen Statistik*, **Heft 1.030/19**; Österreichisches Statistisches Zentralamt, Wien.

5.3.4 Conformity between observed and calculated changes between 1981 and 1991

- ***Housing units***

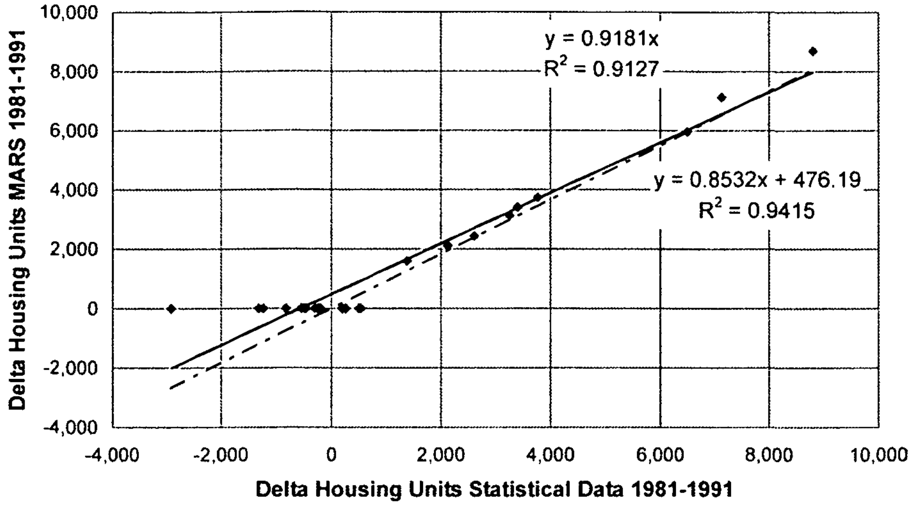


Figure 5.18: Comparison statistical data[66] – MARS development of housing units between 1981 and 1991

Table 5.21: Performance indicators comparison census data – MARS81 results change in number of housing units by zone between 1981 and 1991

Indicator	Deviation	Absolute deviation	Relative deviation
Sum	6,266	11,238	-14.06
Standard deviation	759	636	0.50
Median	5	256	-1.00
Maximum	2,912	2,912	0.15

[66] Magistratsabteilung 66 - Statistisches Amt (1990). Statistisches Jahrbuch der Stadt Wien 1989, Magistrat der Stadt Wien. and Magistratsabteilung 66 - Statistisches Amt (1992). Statistisches Jahrbuch der Stadt Wien 1991; Magistrat der Stadt Wien, Wien.

- **Population**

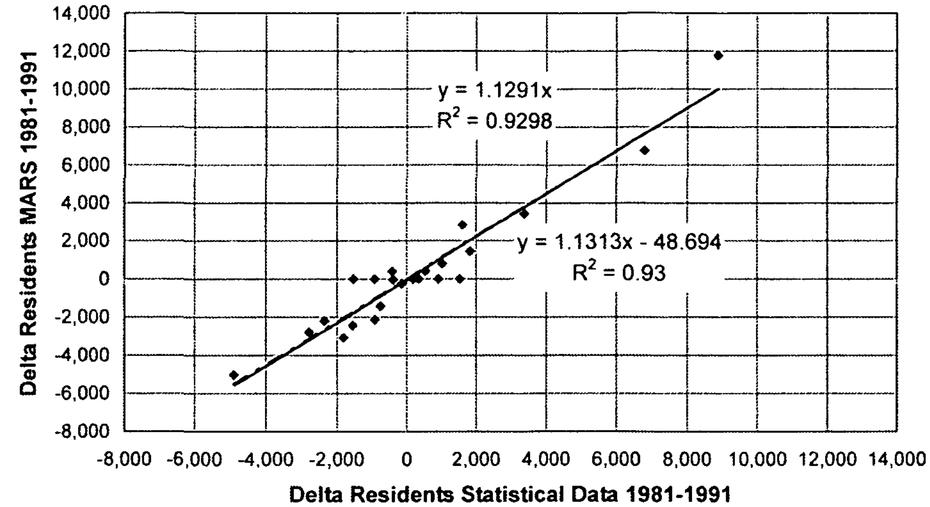


Figure 5.19: Comparison statistical data[67] – MARS development residents between 1981 and 1991

Table 5.22: Performance indicators comparison census data – MARS81 results change in number of residents by zone between 1981 and 1991

Indicator	Deviation	Absolute deviation	Relative deviation
Sum	-4	15,918	-4.37
Standard deviation	994	699	0.81
Median	-120	395	-0.06
Maximum	2,901	2,901	1.33

[67] ÖSTZ (1984). Volkszählung 1981 - Hauptergebnisse I Wien; *Beiträge zur Österreichischen Statistik*, **Heft 630/10**; Österreichisches Statistisches Zentralamt, Wien. and ÖSTAT (1993). Volkszählung 1991 - Hauptergebnisse I Wien; *Beiträge zur Österreichischen Statistik*, **Heft 1.030/9**; Österreichisches Statistisches Zentralamt, Wien.

- **Service sector workplaces**

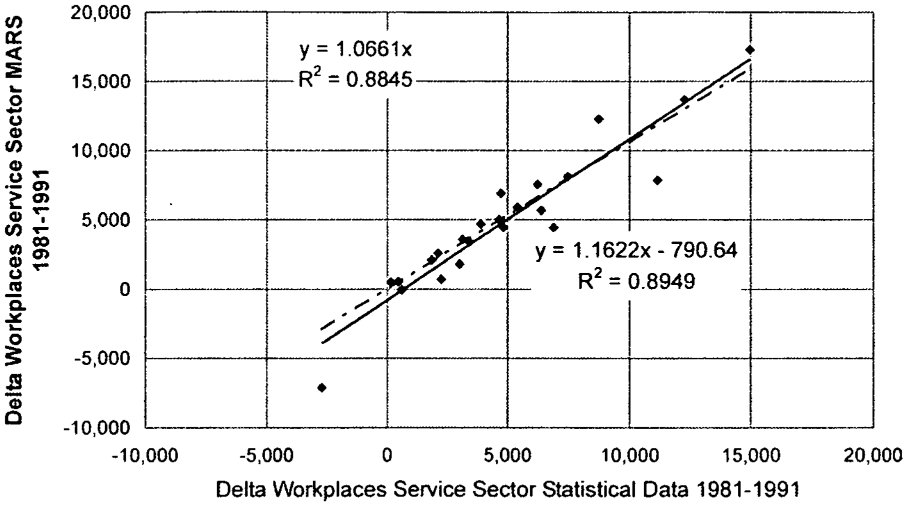


Figure 5.20: Comparison statistical data[68] – MARS development workplaces service sector between 1981 and 1991

Table 5.23: Performance indicators comparison census data – MARS81 results change in number of service sector workplaces by zone between 1981 and 1991

Indicator	Deviation	Absolute deviation	Relative deviation
Sum	-34	29,301	3.36
Standard deviation	1,780	1,213	0.67
Median	346	719	0.12
Maximum	3,539	4,417	2.23

[68] ÖSTZ (1985). Volkszählung 1981 - Hauptergebnisse II Wien; *Beiträge zur Österreichischen Statistik*, **Heft 630.20**; Österreichisches Statistisches Zentralamt, Wien.,
ÖSTAT (1995). Volkszählung 1991 - Hauptergebnisse II Wien; *Beiträge zur Österreichischen Statistik*, **Heft 1.030/19**; Österreichisches Statistisches Zentralamt, Wien.,
Magistratsabteilung 66 - Statistisches Amt (1990). Statistisches Jahrbuch der Stadt Wien 1989, Magistrat der Stadt Wien. and
Magistratsabteilung 66 - Statistisches Amt (1999). Statistisches Jahrbuch der Stadt Wien 1998; Magistrat der Stadt Wien, Wien.

- **Production sector workplaces**

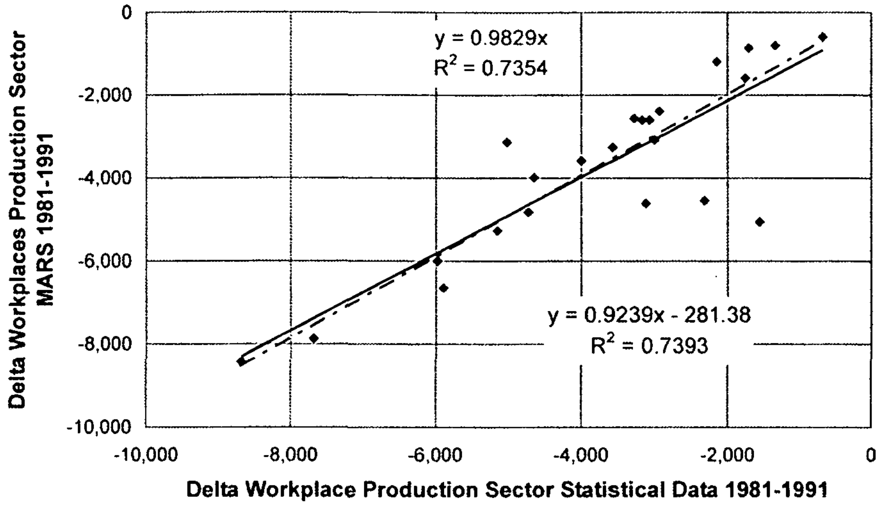


Figure 5.21: Comparison statistical data[68] – MARS development workplaces service sector between 1981 and 1991

Table 5.24: Performance indicators comparison census data – MARS81 results change in number of production sector workplaces by zone between 1981 and 1991

Indicator	Deviation	Absolute deviation	Relative deviation
Sum	41	16,887	0.83
Standard deviation	1,120	832	0.57
Median	260	535	-0.09
Maximum	1,875	3,498	2.24

5.3.5 Conclusions

The MARS land use sub-model was calibrated to census data changes between 1981 and 1991 using utility function internal and zone specific calibration parameters. The fit between the predicted and observed values of the year 1991 is extremely well. The conformity between observed and predicted changes is not as good as for the absolute values but still quite satisfying. The slope is around 1 and the coefficients of determination R^2 are above 0.7. Some suggestions for potential MARS modifications to improve the fit are given in chapter 9.3 Suggestions for future MARS improvements.

5.4 Transport sub-model 1991

5.4.1 Data

The mode split for trips home – work is calculated using the 1991 census data[69] (ÖSTAT, 1995). Household survey data from 1991 (Herry, M. and Snizek, S., 1993) were used to estimate the overall mode split and the mode split for trips home – other (Table 5.25).

Table 5.25: Mode split calibration data

Mode	Home - Work	Home - Other	Total
Slow	12.0%	28.1%	25.9%
PT	43.8%	35.7%	37.3%
Car	44.1%	36.2%	36.8%

Source:(ÖSTAT, 1995), (Herry, M. and Snizek, S., 1993), own calculations

5.4.2 Conformity between observed data and MARS model results using 1981 calibration parameters

Using all calibration parameters as in the MARS81 (see section 5.2 and 5.3) results in the following mode split (Figure 5.22) and OD matrices (Figure 5.23 to Figure 5.26).

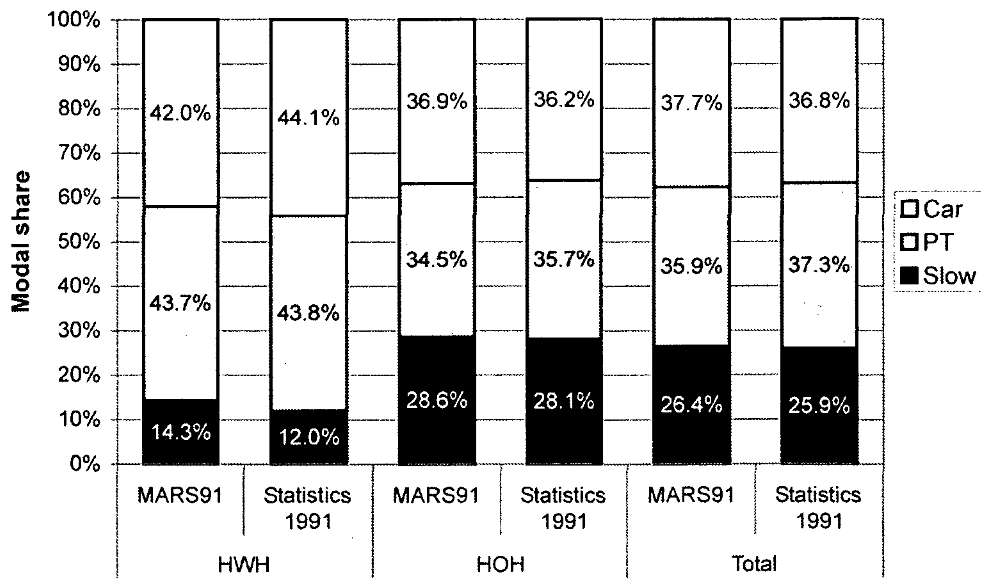


Figure 5.22: Comparison of modal share statistics 1991 and MARS base year 1991 with 1981 calibration parameters

[69] ÖSTAT (1995). Volkszählung 1991 - Hauptergebnisse II Niederösterreich; *Beiträge zur Österreichischen Statistik*, **Heft 1030.13**; Österreichisches Statistisches Zentralamt, Wien. and ÖSTAT (1995). Volkszählung 1991 - Hauptergebnisse II Wien; *Beiträge zur Österreichischen Statistik*, **Heft 1.030/19**; Österreichisches Statistisches Zentralamt, Wien.
Data were made available in electronic form by "Amt der NÖ Landesregeriung". Data are therefore available by OD pair while in the printed version only data for intra-zonal and in and outgoing trips are available.

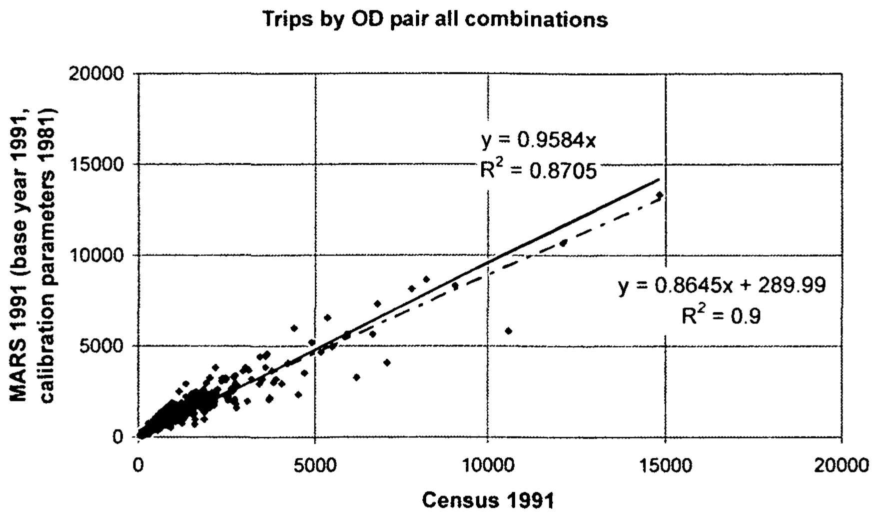


Figure 5.23: Comparison of trips by OD pair census 1991[69] and MARS base year 1991 with 1981 calibration parameters

Table 5.26: Performance indicators comparison census data – MARS base year 1991, calibration parameters 1981 results OD matrix home – work for the year 1991

Indicator	Deviation	Absolute deviation	Relative deviation
Sum	73,814	158,443	155.83
Standard deviation	472	391	0.36
Median	151	194	0.26
Maximum	1,664	4,773	1.69

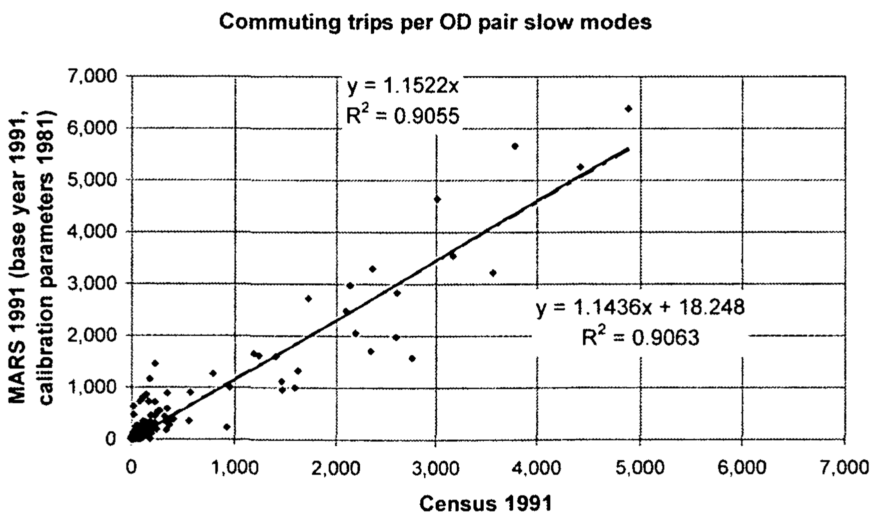


Figure 5.24: Comparison of slow trips by OD pair census 1991[69] and MARS base year 1991 with 1981 calibration parameters

Table 5.27: Performance indicators comparison census data – MARS base year 1991, calibration parameters 1981 results OD matrix slow modes home – work for the year 1991

Indicator	Deviation	Absolute deviation	Relative deviation
Sum	20,308	37,185	318.48
Standard deviation	209	200	2.97
Median	-1	8	-0.20
Maximum	1,884	1,884	41.52

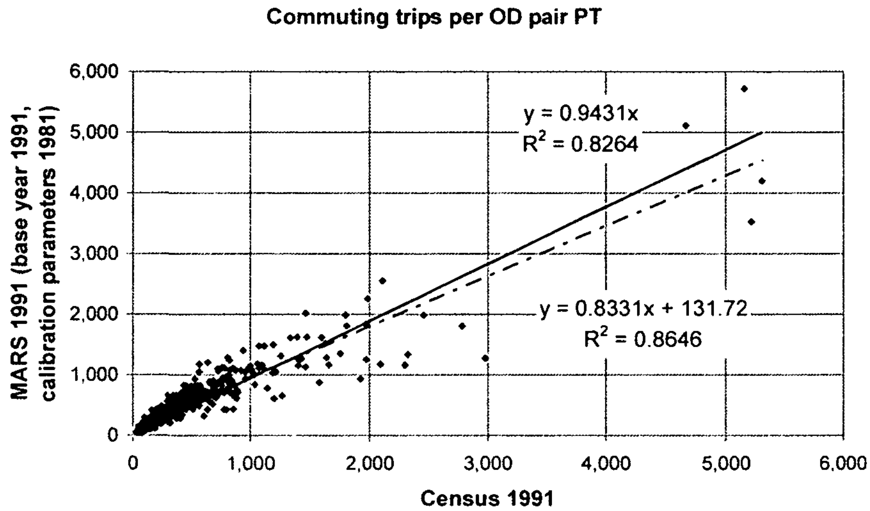


Figure 5.25: Comparison of PT trips by OD pair census 1991[69] and MARS base year 1991 with 1981 calibration parameters

Table 5.28: Performance indicators comparison census data – MARS base year 1991, calibration parameters 1981 results OD matrix PT home – work for the year 1991

Indicator	Deviation	Absolute deviation	Relative deviation
Sum	25,537	85,661	162.95
Standard deviation	259	208	0.55
Median	50	91	0.18
Maximum	939	1,909	2.89

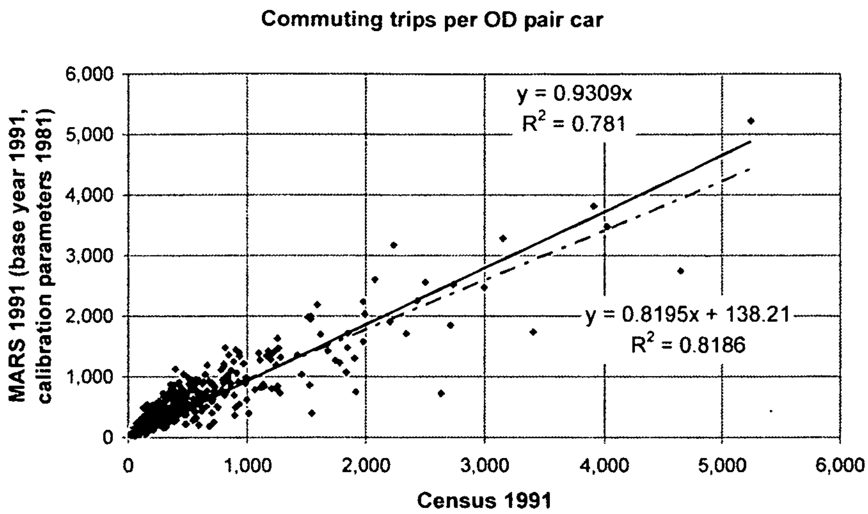


Figure 5.26: Comparison of car trips by OD pair census 1991[69] and MARS base year 1991 with 1981 calibration parameters

Table 5.29: Performance indicators comparison census data – MARS base year 1991, calibration parameters 1981 results OD matrix home – work for the year 1991

Indicator	Deviation	Absolute deviation	Relative deviation
Sum	27,969	70,889	153.37
Standard deviation	216	178	0.36
Median	65	80	0.27
Maximum	608	1,705	1.99

5.4.3 Calibration parameters

The base year 1991 MARS transport sub-model was re-calibrated. Table 5.30 shows the mode and purpose specific parameters derived from the calibration of the MARS base year 1991 to the mode split data shown in Table 5.25.

Table 5.30: Mode and trip purpose specific calibration factors

	Slow	PT	Car
Home - Work	0.71	1.18	2.01
Home - Other	0.67	1.18	1.28

5.4.4 Conformity between observed data and the base year 1991 MARS model results

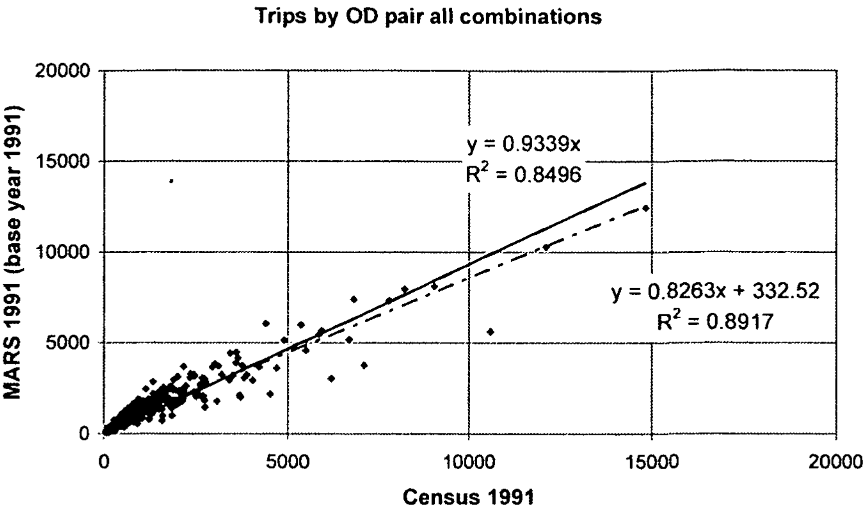


Figure 5.27: Comparison of trips by OD pair census 1991[69] and MARS base year 1991 with 1991 calibration parameters

Table 5.31: Performance indicators comparison census data – MARS base year 1991, calibration parameters 1991 results OD matrix home – work for the year 1991

Indicator	Deviation	Absolute deviation	Relative deviation
Sum	73,814	165,512	168.60
Standard deviation	499	413	0.37
Median	159	208	0.28
Maximum	1,661	4,971	1.72

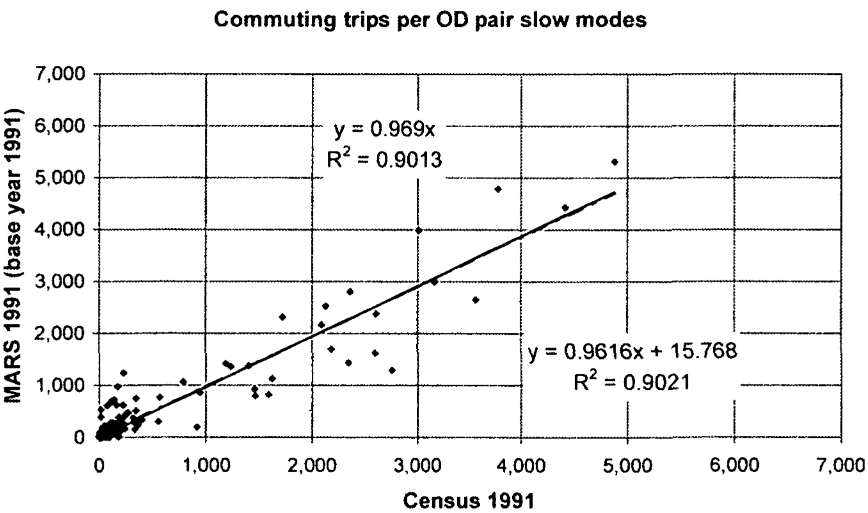


Figure 5.28: Comparison of slow trips by OD pair census 1991[69] and MARS base year 1991 with 1991 calibration parameters

Table 5.32: Performance indicators comparison census data – MARS base year 1991, calibration parameters 1991 results OD matrix slow modes home – work for the year 1991

Indicator	Deviation	Absolute deviation	Relative deviation
Sum	5,489	30,249	187.52
Standard deviation	169	159	2.50
Median	-2	8	-0.34
Maximum	1,015	1,461	34.75

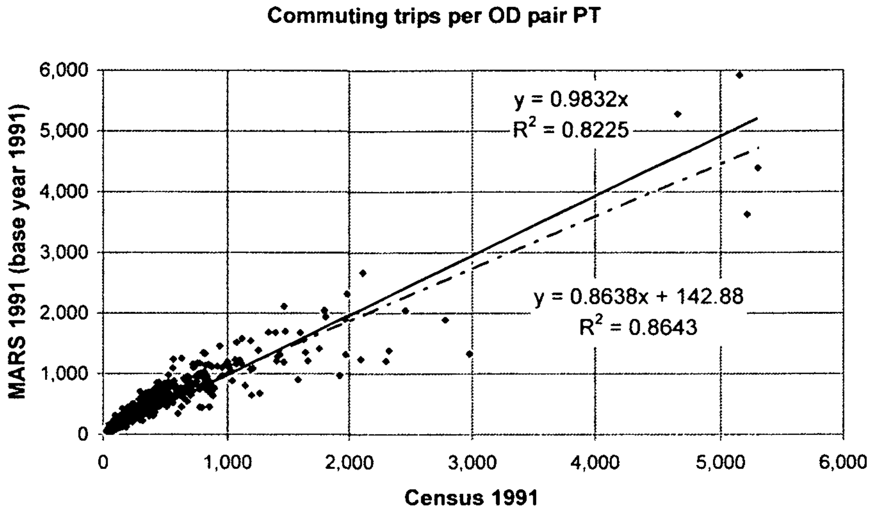


Figure 5.29: Comparison of PT trips by OD pair census 1991[69] and MARS base year 1991 with 1991 calibration parameters

Table 5.33: Performance indicators comparison census data – MARS base year 1991, calibration parameters 1991 results OD matrix home – work for the year 1991

Indicator	Deviation	Absolute deviation	Relative deviation
Sum	26,765	85,640	167.54
Standard deviation	258	207	0.55
Median	55	94	0.19
Maximum	940	1,921	2.82

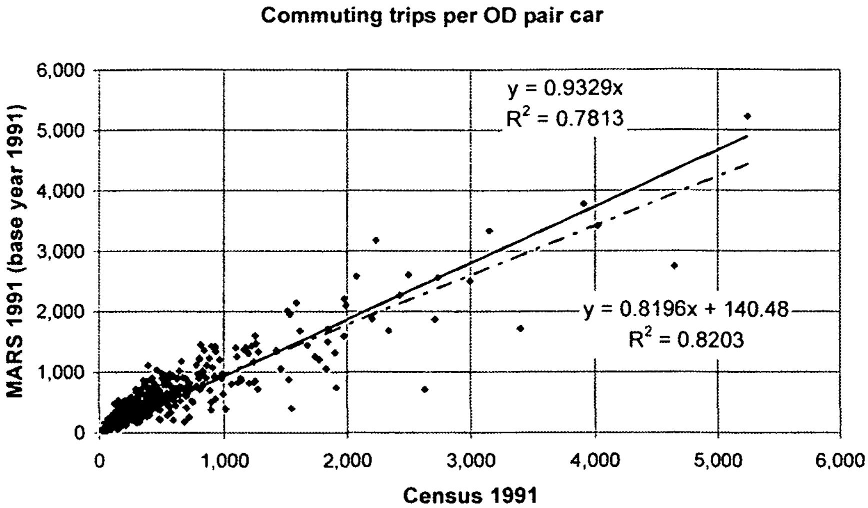


Figure 5.30: Comparison of car trips by OD pair census 1991[69] and MARS base year 1991 with 1991 calibration parameters

Table 5.34: Performance indicators comparison census data – MARS base year 1991, calibration parameters 1991 results OD matrix home – work for the year 1991

Indicator	Deviation	Absolute deviation	Relative deviation
Sum	41,560	78,834	192.79
Standard deviation	216	175	0.38
Median	86	96	0.34
Maximum	763	1,648	2.21

5.4.5 Conclusions

First the base year 1991 MARS model was run with the calibration parameters derived from the 1981 model. The results of this model run were compared with observed data. In this set up the MARS overestimates the share of slow modes and PT. The OD-pair wise fit between observation and prediction is reasonable good. The model then was re-calibrated to fit the mode split observed in the year 1991. The short, intra-zonal trips are still underestimated, but the slope is nearer to 1 than it was the case with base year 1981 model.

5.5 Land use sub-model 1991 to 2001

5.5.1 Data

Workplace data are not yet available from the 2001 census. The MARS land use sub-model is calibrated to fit the observed changes in housing unit and population data (Table 5.35). The workplace location models are kept the same as calibrated for the period 1981 to 1991.

Table 5.35: Calibration data land use part Vienna MARS

Housing units																							
Zone	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**	**13**	**14**	**15**	**16**	**17**	**18**	**19**	**20**	**21**	**22**	**23**
1991	11,259	48,593	48,507	18,620	30,507	17,264	17,859	14,316	25,394	82,589	33,518	44,295	29,240	46,560	39,179	53,216	30,865	29,188	38,873	39,540	61,535	53,029	39,145
1998	12,028	49,796	49,518	18,698	30,586	17,946	17,938	14,562	25,546	86,463	39,448	45,873	30,413	48,266	38,554	53,138	30,701	29,001	41,137	41,190	68,237	65,900	42,929
Delta	769	1,203	1,011	78	79	682	79	246	152	3,874	5,930	1,578	1,173	1,706	-625	-78	-164	-187	2,264	1,650	6,702	12,871	3,784
Residents																							
Zone	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**	**13**	**14**	**15**	**16**	**17**	**18**	**19**	**20**	**21**	**22**	**23**
1991	18,002	93,542	84,500	31,410	51,521	30,298	30,396	23,850	40,416	147,636	66,881	79,592	54,909	80,822	69,309	88,931	50,944	49,761	67,377	71,876	119,415	106,589	81,871
2001	17,056	90,914	81,281	28,354	49,111	27,867	28,292	22,572	37,816	150,636	76,899	78,268	49,574	78,169	64,895	86,129	47,610	44,992	64,030	76,268	128,228	136,444	84,718
Delta	-946	-2,628	-3,219	-3,056	-2,410	-2,431	-2,104	-1,278	-2,600	3,000	10,018	-1,324	-5,335	-2,653	-4,414	-2,802	-3,334	-4,769	-3,347	4,392	8,813	29,855	2,847

Source: (Magistratsabteilung 66 - Statistisches Amt, 1994), (Magistratsabteilung 66 - Statistisches Amt, 1999), (ÖSTZ, 1984), (ÖSTAT, 1993), (Statistisches Amt der Stadt Wien, 2003)

Table 5.36: Land use sub-model calibration parameters

Housing Unit Development																						
1	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**	**13**	**14**	**15**	**16**	**17**	**18**	**19**	**20**	**21**	**22**	**23**
1.87	0.79	0.77	0.81	0.81	0.76	1.08	0.99	0.86	1.08	1.04	1.34	0.65	1.00	1.70	0.68	0.65	0.76	1.64	1.17	0.82	1.03	0.94
Residents																						
1	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**	**13**	**14**	**15**	**16**	**17**	**18**	**19**	**20**	**21**	**22**	**23**
0.84	0.61	1.02	0.85	1.30	1.24	1.26	1.89	0.65	0.50	1.71	0.77	0.92	0.76	0.62	0.69	0.48	0.66	0.70	1.24	1.46	3.82	1.13

5.5.2 Conformity between observed absolute values and MARS model results using 1981 calibration parameters

- **Housing units**

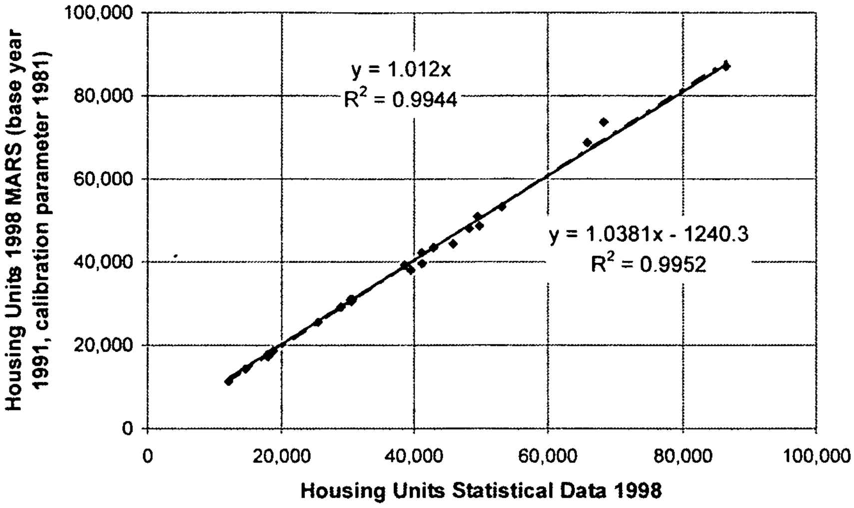


Figure 5.31: Comparison number of housing units in 1998 statistical data[70] – base year 1991 MARS with 1981 calibration parameters

Table 5.37: Performance indicators comparison statistical data – MARS base year 1991, calibration parameters 1981 results number of housing units in the year 1998

Indicator	Deviation	Absolute deviation	Relative deviation
Sum	-240	108,214	0.54
Standard deviation	7,074	5,187	0.08
Median	2,104	2,889	0.06
Maximum	8,358	25,053	0.17

[70] Magistratsabteilung 66 - Statistisches Amt (1999). Statistisches Jahrbuch der Stadt Wien 1998; Magistrat der Stadt Wien, Wien.

- **Population**

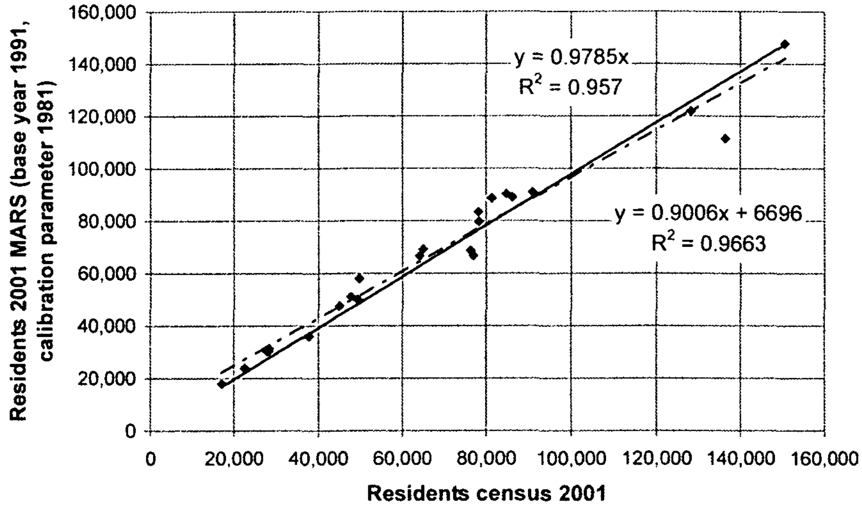


Figure 5.32: Comparison number of residents in 2001 statistical data[71] – base year 1991 MARS with 1981 calibration parameters

Table 5.38: Performance indicators comparison statistical data – MARS base year 1991, calibration parameters 1981 results number of residents in the year 2001

Indicator	Deviation	Absolute deviation	Relative deviation
Sum	5,694	21,606	-0.02
Standard deviation	1,510	1,193	0.03
Median	-32	580	0.00
Maximum	5,444	5,444	0.08

[71] Statistisches Amt der Stadt Wien (2003). Ergebnisse der Volkszählung 2001 für Wien. Last Update: NA. Access: 01/09/2003. http://www.magwien.gv.at/ma66/pdf/grosszaehlung2001.pdf

5.5.3 Conformity between observed changes and MARS model results using 1981 calibration parameters

- **Housing units**

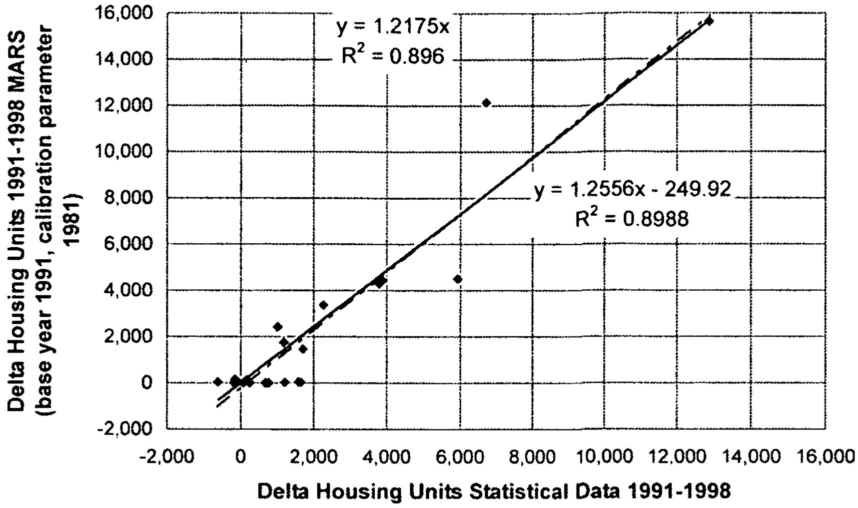


Figure 5.33: Comparison development of housing units between 1991 and 1998 statistical data[72] – base year 1991 MARS with 1981 calibration parameters

Table 5.39: Performance indicators comparison statistical data – MARS base year 1991, calibration parameters 1981 results development of housing units between 1991 and 1998

Indicator	Deviation	Absolute deviation	Relative deviation
Sum	-240	108,214	-19.11
Standard deviation	7,074	5,187	0.86
Median	2,104	2,889	-1.00
Maximum	8,358	25,053	1.93

[72] Magistratsabteilung 66 - Statistisches Amt (1992). Statistisches Jahrbuch der Stadt Wien 1991; Magistrat der Stadt Wien, Wien. and Magistratsabteilung 66 - Statistisches Amt (1999). Statistisches Jahrbuch der Stadt Wien 1998; Magistrat der Stadt Wien, Wien.

- **Population**

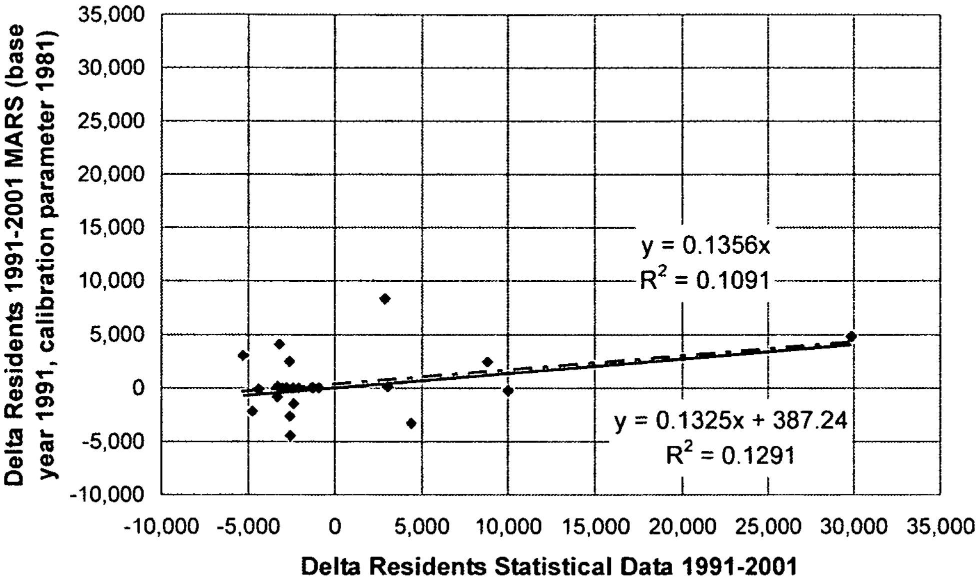


Figure 5.34: Comparison development residents between 1991 and 2001 statistical data[73] – base year 1991 MARS with 1981 calibration parameters

Table 5.40: Performance indicators comparison statistical data – MARS base year 1991, calibration parameters 1981 results development residents between 1991 and 2001

Indicator	Deviation	Absolute deviation	Relative deviation
Sum	5,694	21,606	-11.25
Standard deviation	1,510	1,193	0.81
Median	-32	580	-0.98
Maximum	5,444	5,444	1.39

The correlation between the MARS91 results using the 1981 calibration parameters and the observed data is rather poor. A spatial analysis of the results (Figure 5.35) shows that the districts 13, 14, 17 and 22 are mainly responsible for the weak fit.

[73] ÖSTAT (1993). Volkszählung 1991 - Hauptergebnisse I Wien; *Beiträge zur Österreichischen Statistik*, **Heft 1.030/9**; Österreichisches Statistisches Zentralamt, Wien. and
Statistisches Amt der Stadt Wien (2003). Ergebnisse der Volkszählung 2001 für Wien. Last Update: NA. Access: 01/09/2003. http://www.magwien.gv.at/ma66/pdf/grosszaehlung2001.pdf

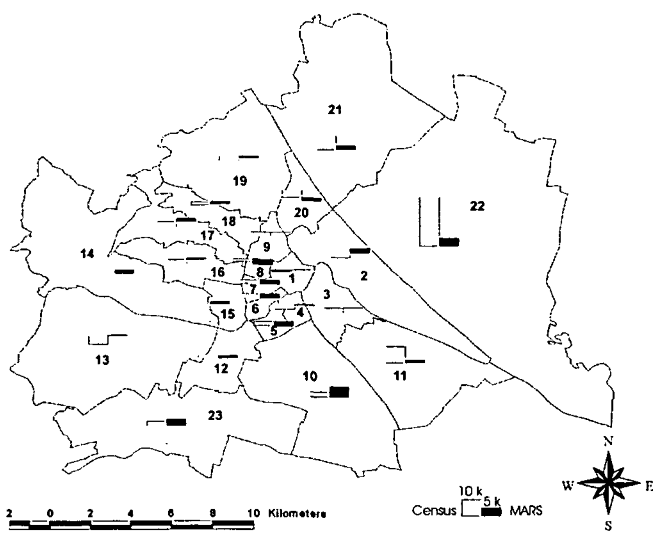


Figure 5.35: Comparison development residents between 1991 and 2001 statistical data[73] – base year 1991 MARS with 1981 calibration parameters

5.5.4 Calibration parameters

For the MARS91 new zone specific calibration parameters for housing unit development and the residential location sub-model were estimated (Table 5.17).

5.5.5 Conformity between observed absolute values and base year 1991 MARS model results

- **Housing units**

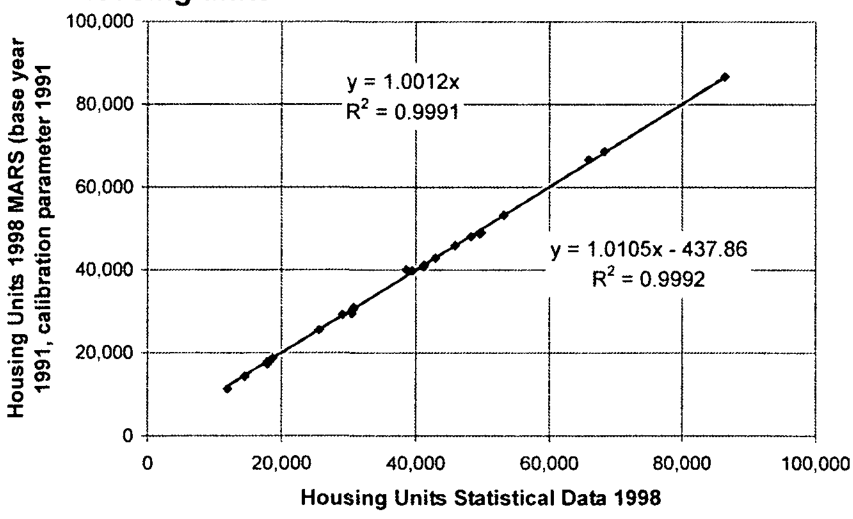


Figure 5.36: Comparison number of housing units in 1998 statistical data[74] – base year 1991 MARS

[74] Magistratsabteilung 66 - Statistisches Amt (1992). Statistisches Jahrbuch der Stadt Wien 1991; Magistrat der Stadt Wien, Wien. and Magistratsabteilung 66 - Statistisches Amt (1999). Statistisches Jahrbuch der Stadt Wien 1998; Magistrat der Stadt Wien, Wien.

Table 5.41: Performance indicators comparison statistical data – MARS base year 1991 results number of housing units in the year 1998

Indicator	Deviation	Absolute deviation	Relative deviation
Sum	-665	8,979	-0.11
Standard deviation	554	385	0.02
Median	-32	246	0.00
Maximum	1,540	1,540	0.04

- **Population**

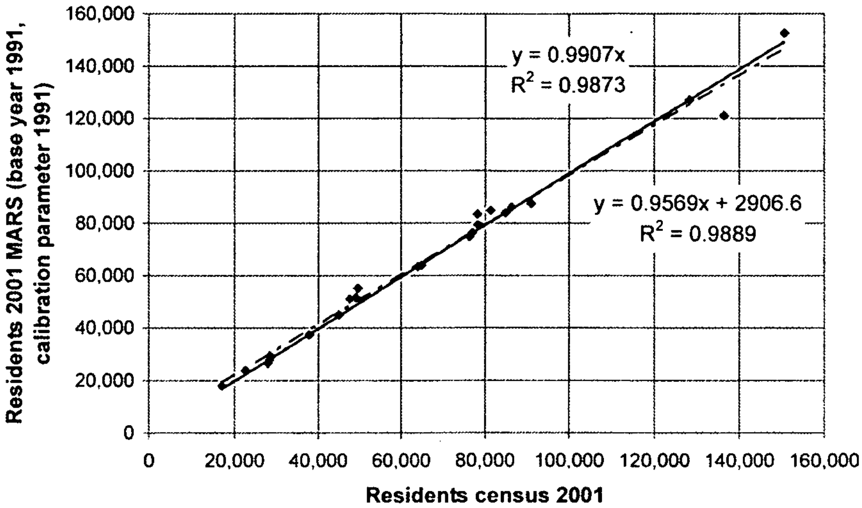


Figure 5.37: Comparison number of residents in 2001 statistical data[75] – base year 1991 MARSTable 5.42: Performance indicators comparison statistical data – MARS base year 1991 results number of residents in the year 2001

Indicator	Deviation	Absolute deviation	Relative deviation
Sum	-15	52,811	0.23
Standard deviation	3,992	3,228	0.05
Median	-81	1,172	0.00
Maximum	5,572	15,323	0.11

[75] Statistisches Amt der Stadt Wien (2003). Ergebnisse der Volkszählung 2001 für Wien. Last Update: NA. Access: 01/09/2003. http://www.magwien.gv.at/ma66/pdf/grosszaehlung2001.pdf

5.5.6 Conformity between observed changes and base year 1991 MARS model results

- **Housing units**

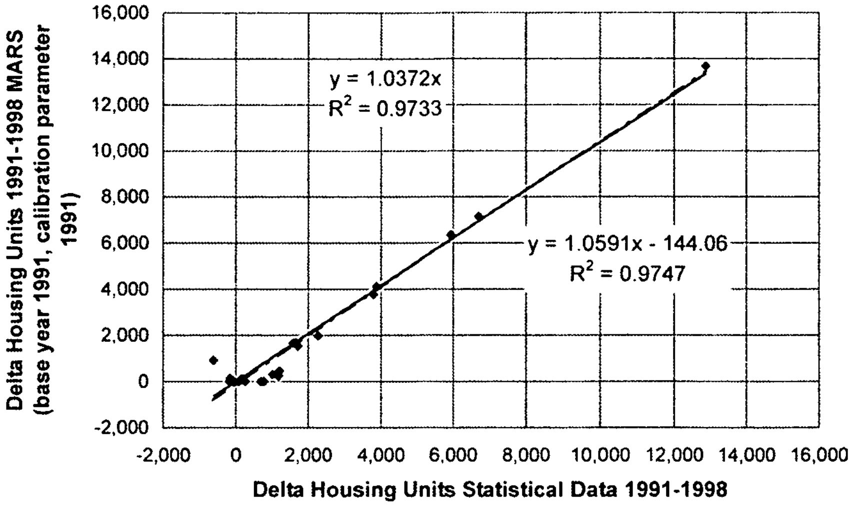


Figure 5.38: Comparison development of housing units between 1991 and 1998 statistical data[76] – base year 1991 MARS

Table 5.43: Performance indicators comparison statistical data – MARS base year 1991 results development of housing units between 1991 and 1998

Indicator	Deviation	Absolute deviation	Relative deviation
Sum	-665	8,979	-15.04
Standard deviation	554	385	0.69
Median	-32	246	-0.69
Maximum	1,540	1,540	0.07

[76] Magistratsabteilung 66 - Statistisches Amt (1992). Statistisches Jahrbuch der Stadt Wien 1991; Magistrat der Stadt Wien, Wien. and Magistratsabteilung 66 - Statistisches Amt (1999). Statistisches Jahrbuch der Stadt Wien 1998; Magistrat der Stadt Wien, Wien.

- **Population**

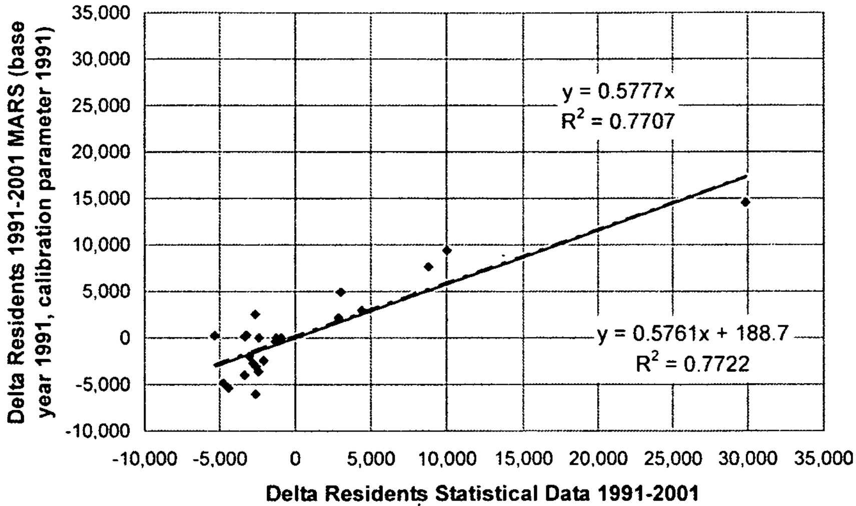


Figure 5.39: Comparison development residents between 1991 and 2001 statistical data[77] – base year 1991 MARS

Table 5.44: Performance indicators comparison statistical data – MARS base year 1991 results development residents between 1991 and 2001

Indicator	Deviation	Absolute deviation	Relative deviation
Sum	-15	52,811	-7.27
Standard deviation	3,992	3,228	0.72
Median	-81	1,172	-0.24
Maximum	5,572	15,323	1.31

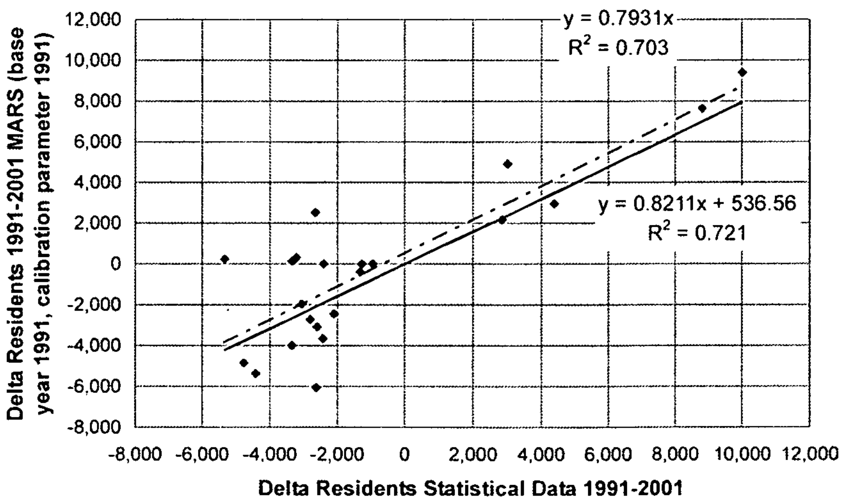


Figure 5.40: Comparison development residents between 1991 and 2001 statistical data[78] – base year 1991 MARS with 1991 equation parameters, using zone specific parameters without zone 22

[77] ÖSTAT (1993). Volkszählung 1991 - Hauptergebnisse I Wien; *Beiträge zur Österreichischen Statistik*, **Heft 1.030/9**; Österreichisches Statistisches Zentralamt, Wien. and Statistisches Amt der Stadt Wien (2003). Ergebnisse der Volkszählung 2001 für Wien. Last Update: NA. Access: 01/09/2003. http://www.magwien.gv.at/ma66/pdf/grosszaehlung2001.pdf

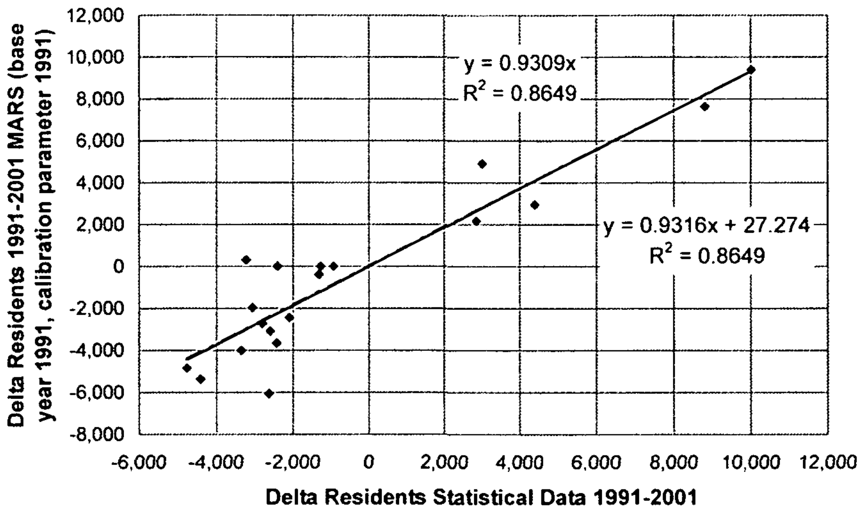


Figure 5.41: Comparison development residents between 1991 and 2001 statistical data[79] – base year 1991 MARS with 1991 equation parameters, using zone specific parameters without the zones 13, 14, 17 and 22

5.5.7 Conclusions

The conformity between observed data and base year 1991 MARS with 1981 calibration parameters is sufficient for the housing unit development model. It is not sufficient for the changes in population. Two reasons have been identified for this. The first is that the ageing process of the population is not included in MARS. There are some districts with a high quality of living and a high share of elderly people (13, 14, 17). During the period 1991 to 2001 a loss of population was observed in these districts. In contrary to this MARS calculates increases in population. Due to the high share of green land districts 13, 14 and 17 are highly attractive to live there. In MARS each resident moving out gives room to another person moving into a housing unit. In reality if one partner of an elderly couple dies, the housing unit will be still occupied. There is a significant correlation between the share of elderly people in a zone and the overestimation of people location in this zone. The inclusion of an ageing model is seen as the most important future MARS adaptation to improve the land use model fit made in chapter 9.3 Suggestions for future MARS improvements. The base year 1991 model was re-calibrated and a reasonable fit between observation and prediction was achieved.

[78] ÖSTAT (1993). Volkszählung 1991 - Hauptergebnisse I Wien; *Beiträge zur Österreichischen Statistik*, **Heft 1.030/9**; Österreichisches Statistisches Zentralamt, Wien. and
Statistisches Amt der Stadt Wien (2003). Ergebnisse der Volkszählung 2001 für Wien. Last Update: NA. Access: 01/09/2003. http://www.magwien.gv.at/ma66/pdf/grosszaehlung2001.pdf

[79] ÖSTAT (1993). Volkszählung 1991 - Hauptergebnisse I Wien; *Beiträge zur Österreichischen Statistik*, **Heft 1.030/9**; Österreichisches Statistisches Zentralamt, Wien. and
Statistisches Amt der Stadt Wien (2003). Ergebnisse der Volkszählung 2001 für Wien. Last Update: NA. Access: 01/09/2003. http://www.magwien.gv.at/ma66/pdf/grosszaehlung2001.pdf

5.6 Comparison of the MARS results with references from other models

Two sources were found giving results for the goodness of fit. The first (Lowry, I. S., 1964) presents a comparison of model results with the 1958 inventory of the Pittsburgh area (Table 5.45).

Table 5.45: Regression statistics – comparison of Lowry model results with 1958 inventory

Sector	Solution	Regression parameters		Goodness of fit R^2
		a (Intercept)	b (slope)	
Number of households by tract	Iterative solution and 1958 inventory	81.8	0.913	0.621
	Partial equilibrium and 1958 inventory	109.7	0.885	0.676
Number of retail workplaces by tract	Iterative solution and 1958 inventory	-80.8	1.277	0.482
	Partial equilibrium and 1958 inventory	-88.2	1.312	0.577

Source: (Lowry, I. S., 1964) p. 92, 100

(Echenique, M. et al., 1969) shows the goodness of fit for a model of calibrated and tested using data of the town of Reading (Table 5.46). Reading was selected because data were available for the year 1962 and had been already transformed into appropriate grid squares.

Table 5.46: Goodness of fit model of Reading 1962

Model	Item	Goodness of fit R^2
Stock model	Floor space	0.96
Activity model	Residential location	0.87
	Services location	0.96

Both sources compare the model results with the observed data in a single year. No changes over a period of time as in the sections 5.3 and 5.5 are considered. Table 5.47 shows the MARS81 prediction for the number residents per zone in the years 1991 and 2001 and the predicted number of workplaces per zone for the year 1991. R^2 is in all three cases very to near to1.

Table 5.47: Goodness of fit land use predictions MARS81

Sector	Year	Regression parameters		Goodness of fit R^2
		a (Intercept)	b (slope)	
Number of residents	1991	-261.47	1.0039	0.9993
	2001	-4,563.5	1.0675	0.9782
Number of workplaces	1991	-2,164.9	1.0591	0.9966

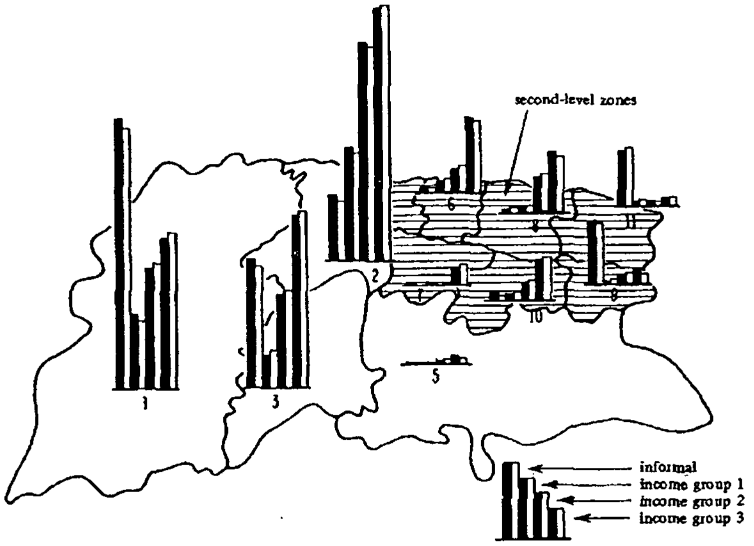


Figure 5.42: Some results obtained with TRANUS-J for the city of Caracas: land use model, where the boxes represent real (black) and simulated (white) populations for three income groups and one "informal" squatter group (de la Barra, T. et al., 1984) p. 99

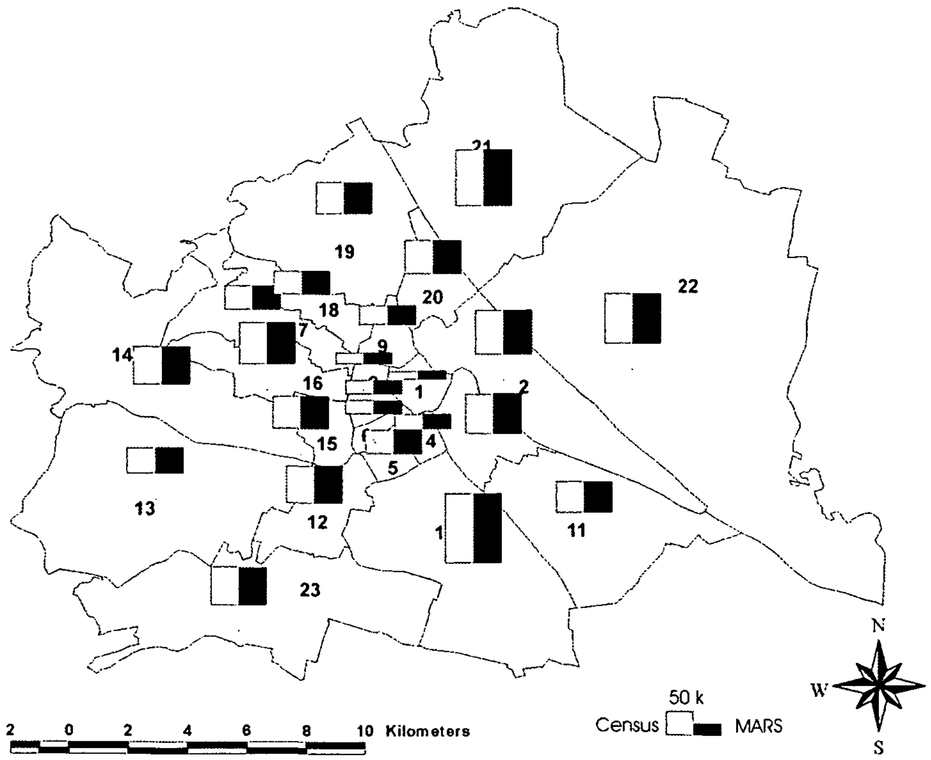


Figure 5.43: Comparison statistical data – MARS81 spatial distribution of residents in 1991

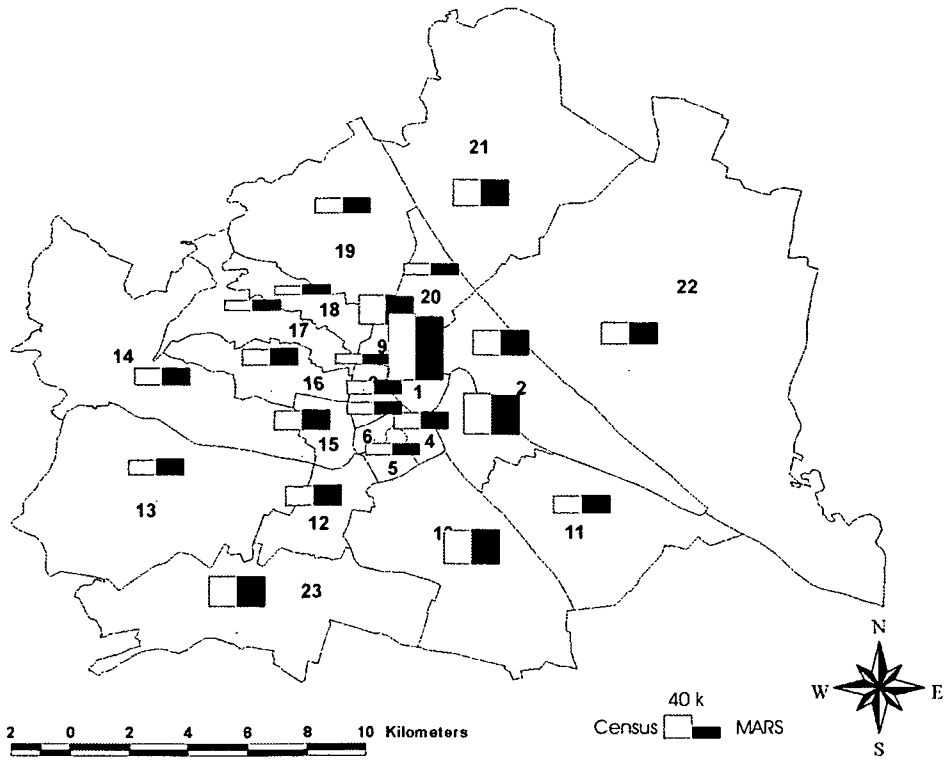


Figure 5.44: Comparison statistical data – MARS81 spatial distribution number of workplaces in 1991

5.7 Conclusions

The MARS model was calibrated in sequential way over the period 1981 to 2001. The transport sub-model was calibrated using cross-sectional data while the land use sub-model was calibrated using longitudinal data. In general the fit of the transport model is satisfying. Nevertheless MARS underestimates short, intra-zonal trips and overestimates long, inter-zonal trips. Potential modifications were suggested to improve the conformity between observed and calculated transport data.

The results of land use model calibration are reasonable. Zone specific calibration parameters were needed to get a satisfying fit for the land use sub-model. MARS overestimated the number of people locating in zones with a high share of green land and a high share of elderly people. Therefore the inclusion of an ageing model was suggested as a future MARS modification.

Finally the calibration results were compared with examples from the literature. Despite the widely mentioned importance of detailed and transparent model calibration and validation examples are very rare in the reviewed literature. In comparison with the few quantified references found the fit gained with the MARS model seems reasonable.

6. MODEL TESTING

6.1 Introduction

The understanding of the terms "calibration" and "validation" in land use and transport modelling is as follows. Calibration is the estimation of certain model parameters to fit the model results to a set of observed data[80]. Validation is the process to assess the conformity between simulation results using the calibrated model and observed data. The data sets used in calibration and validation have to be different.

Numerous references highlight the importance of model validation[81]. Nevertheless published results of model validation exercises are rare. In (Waddell, P., 2002) the results of a back casting exercise with UrbanSim model of Eugene-Springfield are shown. (Hunt, J. D., 1994) shows some comparisons between observed and simulated values for a MEPLAN model of Naples. The MARS results are compared with the results shown in these references.

(Sterman, J. D., 2000) argues that models neither can be verified nor validated. The word "verify" derives from the Latin *verus* – truth. Verify can be defined as establishing the truth, accuracy or reality of something. Valid can be defined as having a conclusion correctly derived from premises. It implies being supported by objective truth. *By these definitions, no model can ever be verified or validated. Why? Because all models are wrong. ..., all models, mental or formal, are limited, simplified representations of the real world.* (Sterman, J. D., 2000) p. 846.

The task of modelling is to build shared understanding and to help solve problems. Modelling is therefore very much a process of communication among modellers, clients and other affected parties. The goal of modelling is to help make better decisions, decisions informed by the best model available for the task in question. "Validation" should not be seen as a testing step after a model is completed. Model building and testing should rather form an iterative loop. Empirical testing plays a prominent role in this feedback loop.

The following questions aim at assessing the overall suitability of the MARS model.

- What is the purpose of the model?
  The purpose of MARS is to assess urban policy strategies towards the objective of sustainability. MARS is part of a framework to detect "second best" policy instrument combinations. The purpose of MARS is strategic in nature. The model is intended to be set up relatively easy. To allow the assessment of land use and transport strategies without excessive need for data was one of the goals of the MARS development.

[80] See chapter 5. Calibration of the Viennese MARS model.

[81] Wegener, M. (2003). Overview of land-use and transport models. CUPUM03 - The 8 th International Conference on Computers in Urban Planning and Urban Management, Sendai, Japan, Center for Northeast Asian Studies, Tohoku University.

- What is the boundary of the model? Are the issues important to the purpose treated endogenously? What important variables and issues are exogenous, or excluded? Are important variables excluded because there are no numerical data to quantify them?
  See Table 6.1: Model boundary chart MARS. Freight transport, route choice, the general economic development and ageing processes of the population are not included in MARS. During the model calibration exercise and the empirical model tests it came quite clear that the MARS land use part would substantially benefit from the inclusion of an ageing sub-model[82].
- What is the time horizon relevant to the problem? Does the model include the factors that may change significantly over the time horizon as endogenous elements?
  The time horizon to assess strategies towards sustainability is at least 20 to 30 years. MARS currently iterates over a period of 30 years. Two factors that might change significantly over the considered time horizon are car ownership and technological improvements in fuel consumption. Nevertheless growth rates for this to variables can be defined.
- Is the level of aggregation consistent with the purpose?
  Sustainability is an aggregated task. The underlying hypothesis of MARS is that urban land use and transport systems are self organising systems. It is not necessary to know the exact behaviour of the single elements to predict the overall behaviour of a self organising system. Therefore it seems appropriate to use a rather high level of spatial and person group aggregation. Especially as the aggregated objective sustainability is the subject of concern.

According to (Sterman, J. D., 2000) one important task in model testing is to show the limits of the model. A model boundary charts is a useful tool for this task. Model boundary charts summarise the scope of the model by listing which key variables are included endogenously, which are exogenously and which are excluded from the model. Table 6.1 shows the model boundary chart of MARS in its current version.

The following sections show the results of empirical model testing. MARS simulations are compared with different observed cross-sectional and longitudinal data. Published results (Hunt, J. D., 1994; Waddell, P., 2002) are used to benchmark the performance of MARS. Conclusions about the performance and potential future improvements of MARS close this chapter.

[82] Suggestions for further model improvements made in chapter 9.3 Suggestions for future MARS improvements, include and endogenous ageing model, and endogenous car ownership model and either the inclusion or a link to an assignment model.

Table 6.1: Model boundary chart MARS

Endogenous	Exogenous	Excluded
Development housing units	Potential growth rate residents	Freight transport
Available green land	Growth rate workplaces (production, services)	Private car route choice
Rent	Car ownership growth rates	GDP
Land price	Household income	Ageing
Distribution households moving out	Household size	
Distribution households moving in	Potential households moving	
Demand factor housing units	Technological improvements fuel consumptions	
Distribution workplaces production	Policy instruments	
Distribution workplaces services		
Number of trips		
Distribution of trips		
Mode share		
Speed private car		
Accessibility		
Fossil fuel consumption		

6.2 Empirical tests

In the following sections results from simulations with the Vienna MARS model are compared with observed data from different sources.

6.2.1 Average trip length by mode

The following data are from a household survey in Vienna (Socialdata, 1993)[83].

Table 6.2: Average trip length internal traffic Vienna

Mode	Observed data (km)	MARS81 in 1993 (km)	Difference
Non motorised	1.2	1.1	-8.3%
Car	7.6	5.1	-32.9%
Public transport	6.3	5.6	-11.1%
All	5.0	4.5	-10.0%

Source for observed data: (Socialdata, 1993) p. 15

According to another source (Herry, M. and Russ, M., 1999) p. 89 the average intra-Viennese trip length was about 4.4 km in the year 1995. The MARS results fit well with these observed data.

[83] 2,079 persons, reply rate 81%. Period of time February-March 1993.

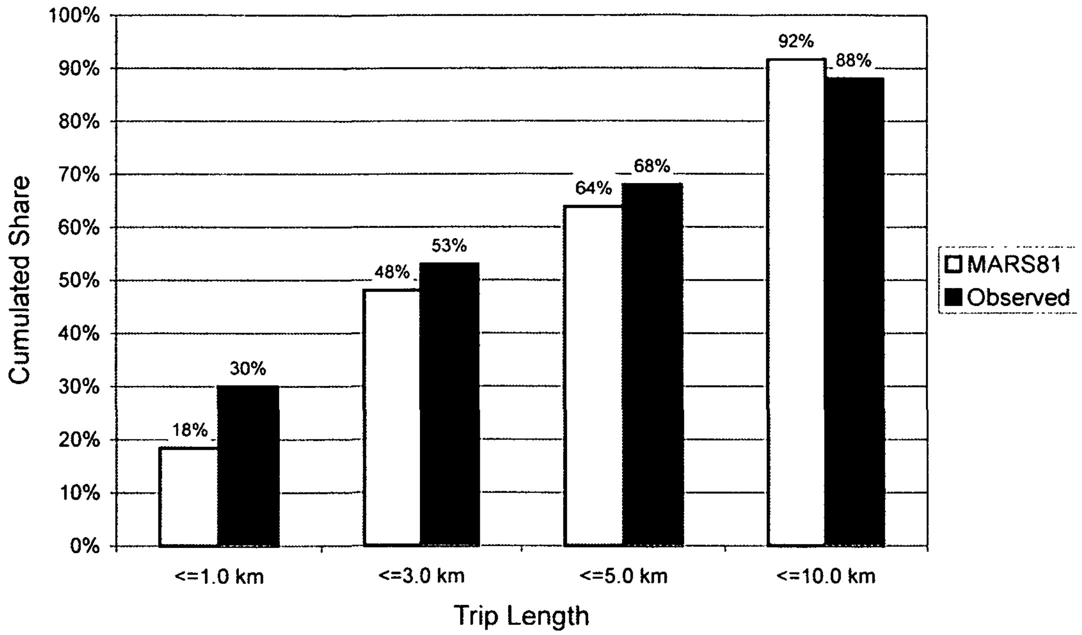


Figure 6.1: Comparison of the cumulated share of trip length MARS – Observed data (Socialdata, 1993)

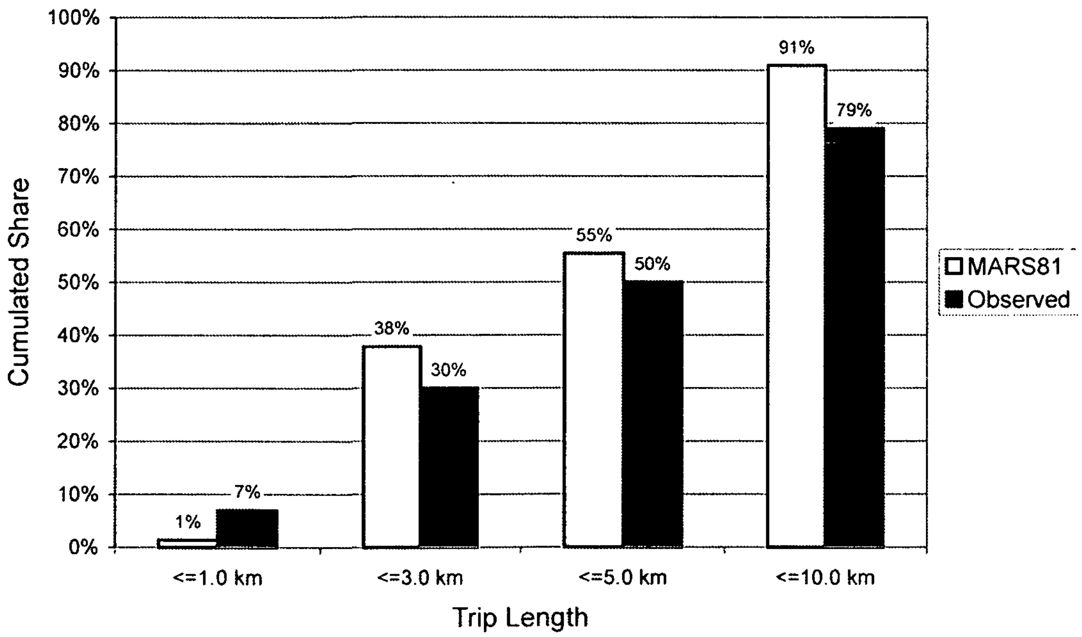


Figure 6.2: Comparison of the cumulated share of car trip length MARS – Observed data (Socialdata, 1993)

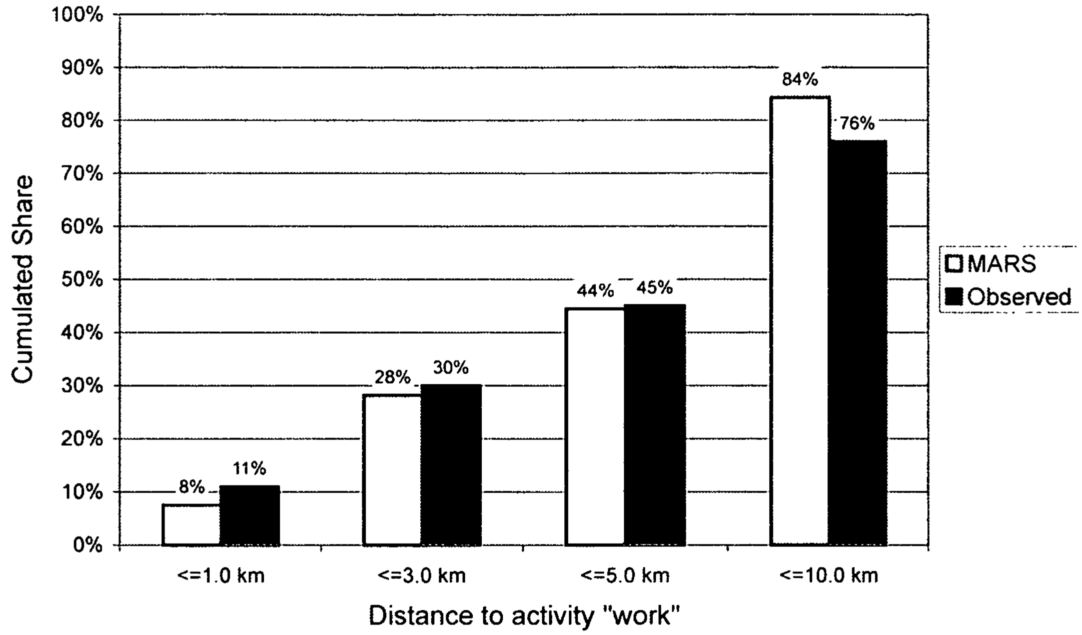


Figure 6.3: Comparison of the cumulated share of distance to the activity "work" MARS – Observed data (Socialdata, 1993)

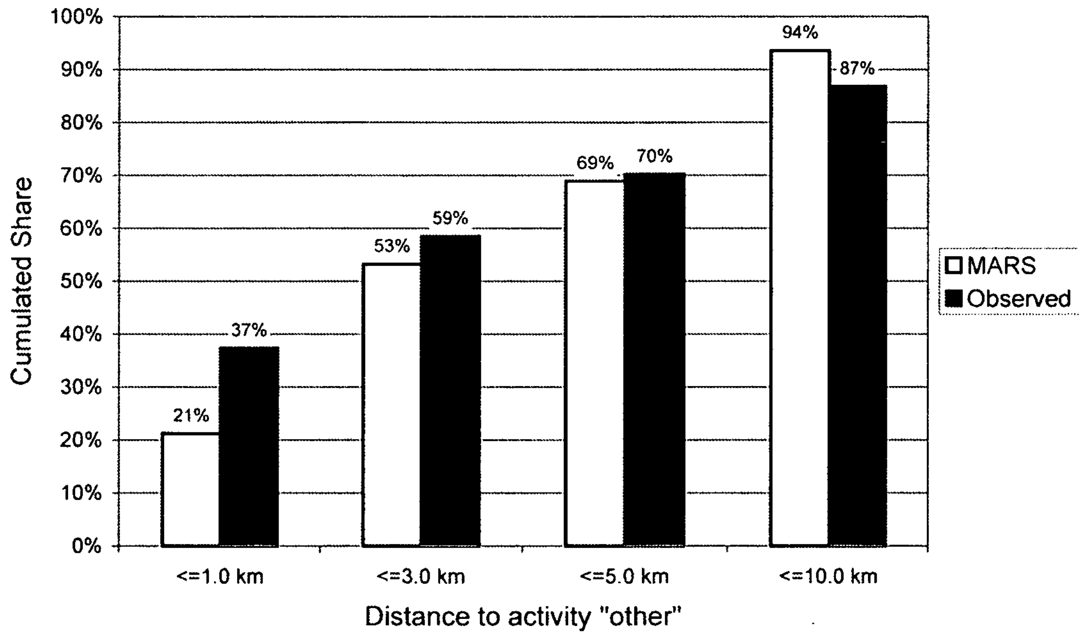


Figure 6.4: Comparison of the cumulated share of distance to the activity "other" MARS – Observed data (Socialdata, 1993)

6.2.2 Trip generation

Figure 6.5 and Figure 6.6 show the conformity between the MARS81 simulation and the census data for the number of originating and ending home – work trips by zone in the year 1991.

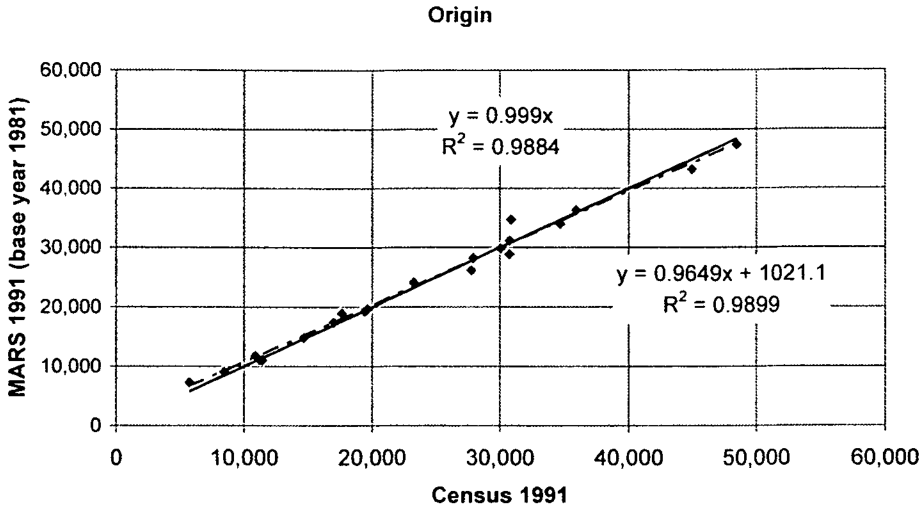


Figure 6.5: Comparison commuter statistics census 1991[84] – base year 1981 MARS results for 1991 originating traffic

Table 6.3: Performance indicators comparison census data – MARS81 results originating trips by zone in 1991

Indicator	Deviation	Absolute deviation	Relative deviation
Sum	3,517	19,326	0.47
Standard deviation	1,202	856	0.07
Median	271	434	0.01
Maximum	3,838	3,838	0.26

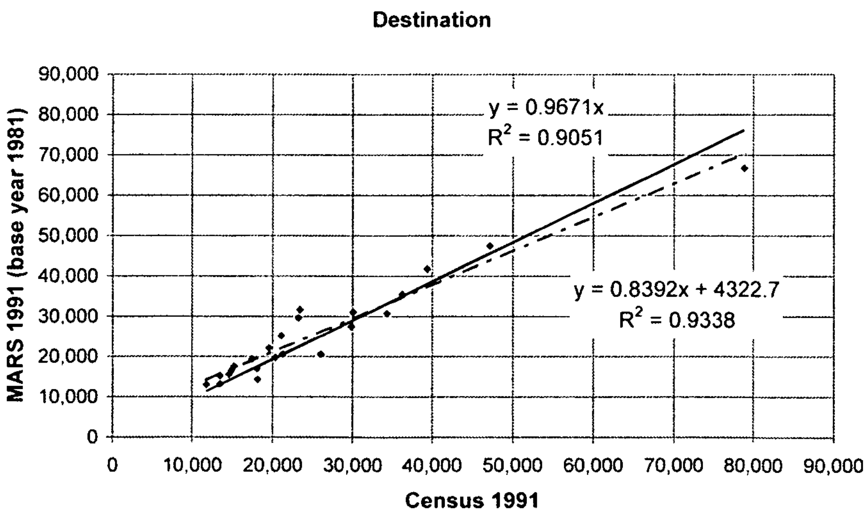


Figure 6.6: Comparison commuter statistics census 1991[84] – base year 1981 MARS results for 1991 destination traffic

[84] ÖSTAT (1995). Volkszählung 1991 - Hauptergebnisse II Wien; *Beiträge zur Österreichischen Statistik*, **Heft 1.030/19**; Österreichisches Statistisches Zentralamt, Wien.
Data were made available in electronic form by "Amt der NÖ Landesregierung". Data are therefore available by OD pair while in the printed version only data for intra-zonal and in and outgoing trips are available.

Table 6.4: Performance indicators comparison census data – MARS81 results destination trips by zone in 1991

Indicator	Deviation	Absolute deviation	Relative deviation
Sum	4,922	65,479	0.84
Standard deviation	4,083	2,871	0.14
Median	1,014	1,971	0.03
Maximum	8,286	12,050	0.35

6.2.3 Distribution

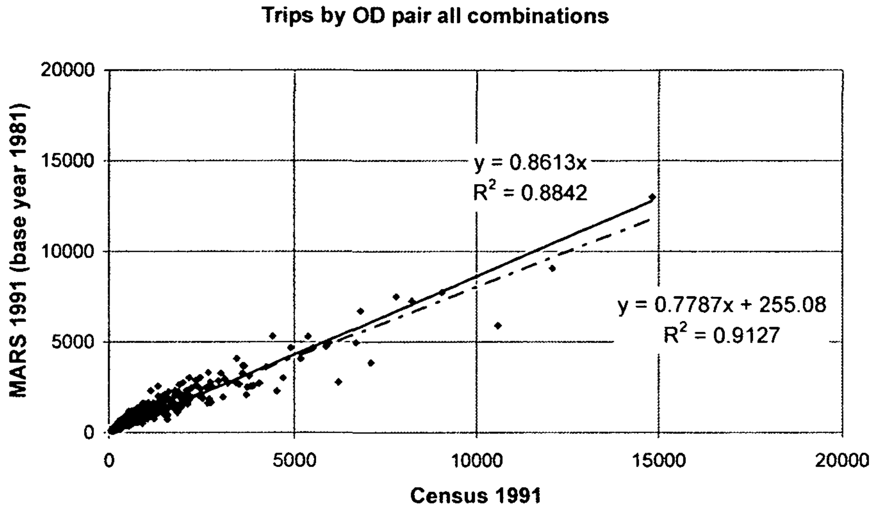


Figure 6.7: Comparison commuter statistics census 1991[84] – 1981 base year MARS results for OD-matrix home – work in 1991

Table 6.5: Performance indicators comparison census data – MARS81 results for OD-matrix home – work in 1991

Indicator	Deviation	Absolute deviation	Relative deviation
Sum	4,922	135,400	96.13
Standard deviation	485	412	0.35
Median	63	138	0.12
Maximum	1,227	4,699	1.40

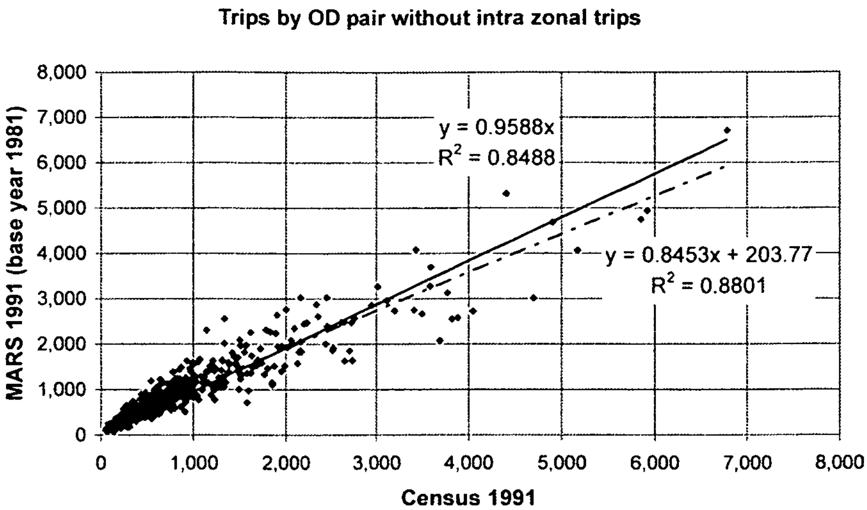


Figure 6.8: Comparison commuter statistics census 1991[84] – 1981 base year MARS results for OD-matrix home – work without intra zonal trips in 1991

Table 6.6: Performance indicators comparison census data – MARS81 results for OD-matrix home – work without intra zonal trips in 1991

Indicator	Deviation	Absolute deviation	Relative deviation
Sum	31,944	106,251	100.22
Standard deviation	313	240	0.35
Median	70	132	0.14
Maximum	1,227	1,683	1.40

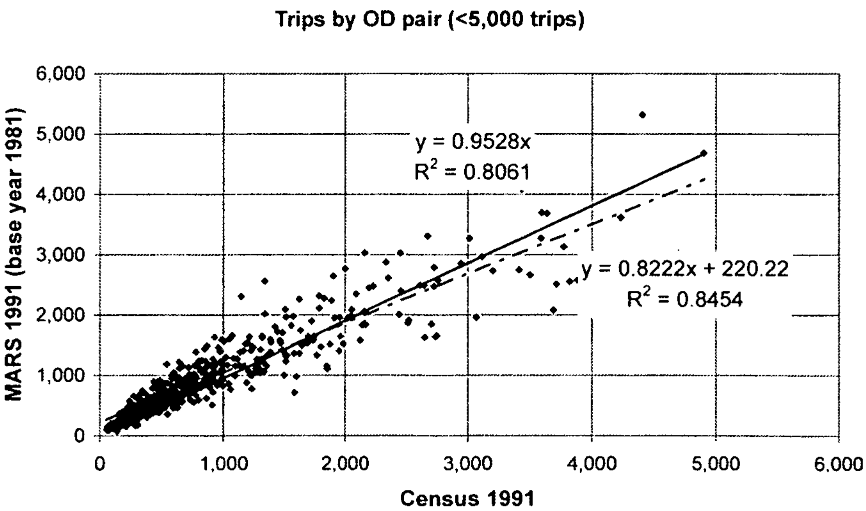


Figure 6.9: Comparison commuter statistics census 1991[84] – 1981 base year MARS results OD-matrix for OD pairs with less than 5,000 trips home – work in 1991

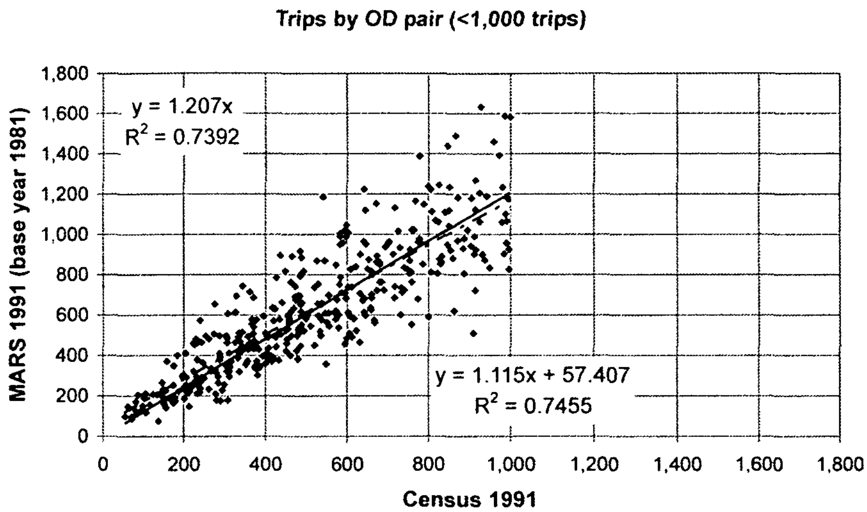


Figure 6.10: Comparison commuter statistics census 1991[84] – 1981 base year MARS results OD-matrix for OD pairs with less than 1,000 trips home – work in 1991

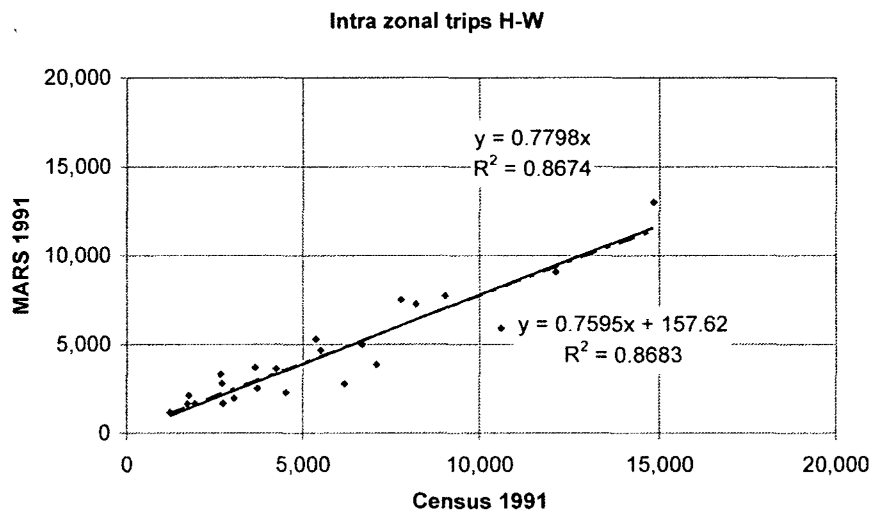


Figure 6.11: Comparison commuter statistics census 1991[84] – 1981 base year MARS results intra-zonal trips home – work in 1991

Table 6.7: Performance indicators comparison census data – MARS81 results intra zonal trips home – work in 1991

Indicator	Deviation	Absolute deviation	Relative deviation
Sum	-27,021	29,150	-4.09
Standard deviation	1,368	1,278	0.21
Median	-941	941	-0.14
Maximum	632	4,699	0.24

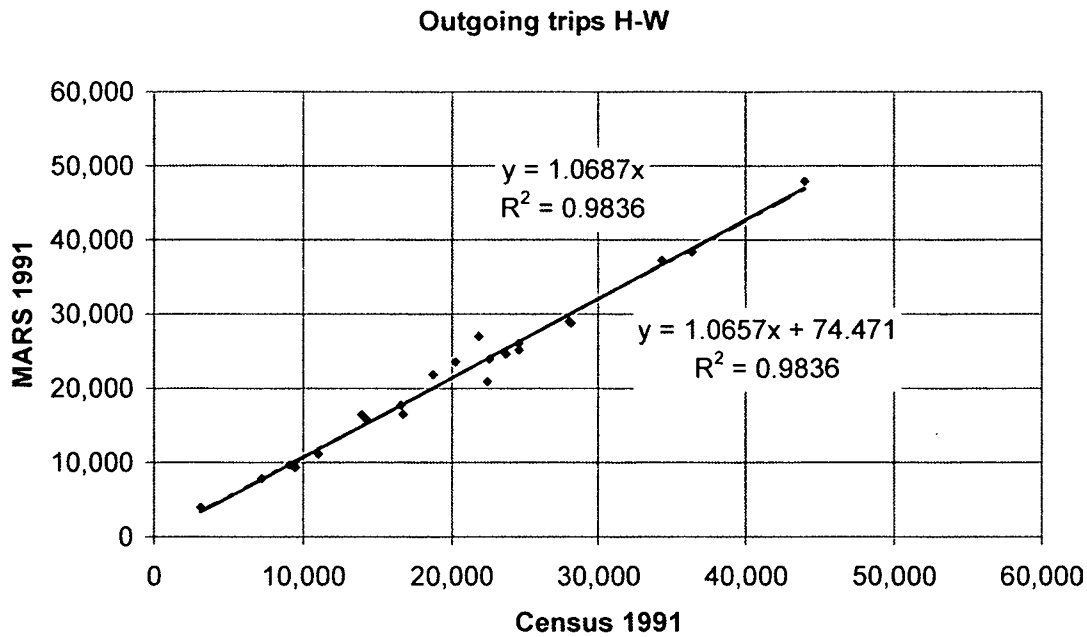


Figure 6.12: Comparison commuter statistics census 1991[84] – 1981 base year MARS results outgoing trips home – work in 1991

Table 6.8: Performance indicators comparison census data – MARS81 results outgoing zonal trips home – work in 1991

Indicator	Deviation	Absolute deviation	Relative deviation
Sum	31,944	35,706	1.73
Standard deviation	1,531	1,356	0.08
Median	975	1,184	0.06
Maximum	5,143	5,143	0.27

6.2.4 Mode choice

- **Development 1981 to 1991**

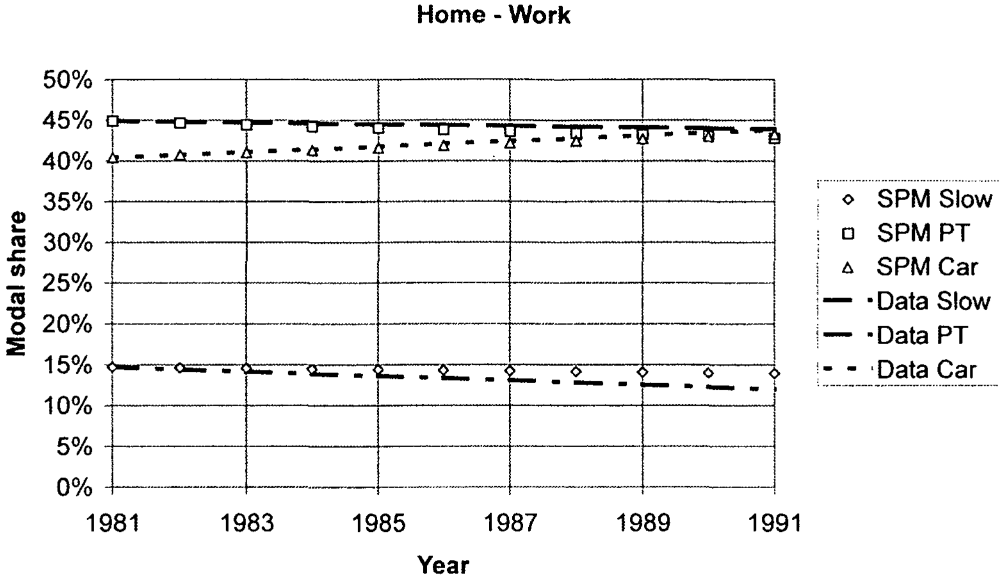


Figure 6.13: Development of mode split home – work between 1981 and 1991 – comparison observed data[85] – MARS results

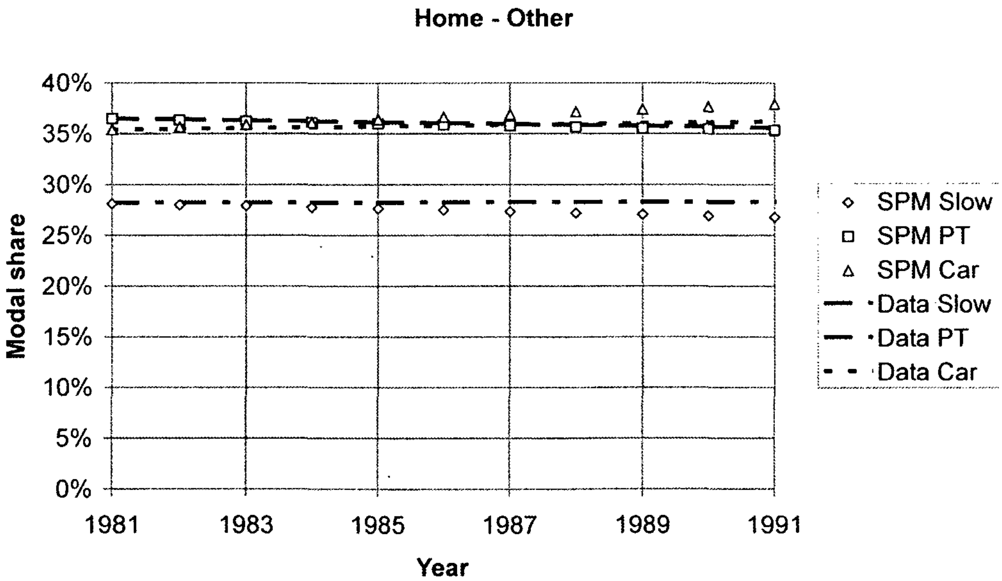


Figure 6.14: Development of mode split home – other between 1981 and 1991 – comparison observed data[86] – MARS results

[85] Data source: ÖSTZ (1985). Volkszählung 1981 - Hauptergebnisse II Wien; Ibid., **Heft 630.20**, and ÖSTAT (1995). Volkszählung 1991 - Hauptergebnisse II Wien; *Beiträge zur Österreichischen Statistik*, **Heft 1.030/19**; Österreichisches Statistisches Zentralamt, Wien.

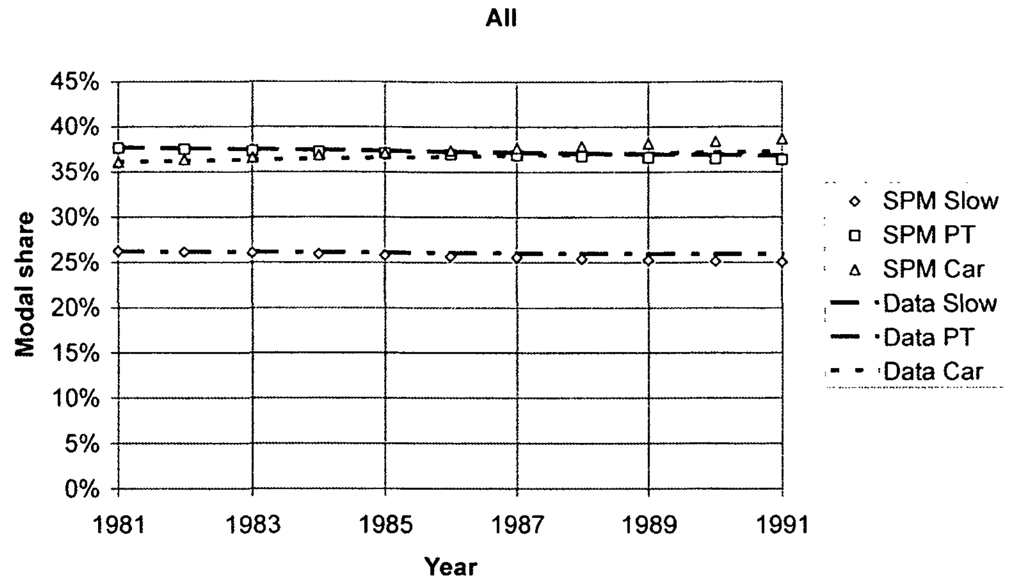


Figure 6.15: Development of mode split all between 1981 and 1991 – comparison observed data[87] – MARS results

- **Comparison census 1991 – MARS base year 1981 results for 1991**

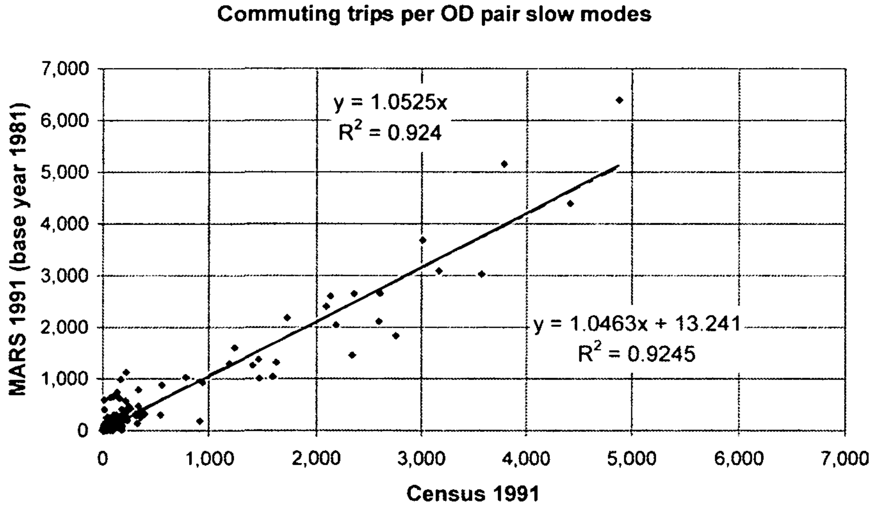


Figure 6.16: Comparison commuter statistics census 1991 – base year 1981 MARS results OD-matrix for slow mode trips home – work in 1991

[86] Data source: ÖSTZ (1985). Volkszählung 1981 - Hauptergebnisse II Wien; *Beiträge zur Österreichischen Statistik*, **Heft 630.20**; Österreichisches Statistisches Zentralamt, Wien.; ÖSTAT (1995). Volkszählung 1991 - Hauptergebnisse II Wien; *Beiträge zur Österreichischen Statistik*, **Heft 1.030/19**; Österreichisches Statistisches Zentralamt, Wien.; Stadtplanung Wien (1994). step 1994 - Stadtentwicklungsplan für Wien; *Beiträge zur Stadtforschung, Stadtentwicklung, Stadtgestaltung*, **Band 53**, and Knoflacher, H., Schopf, M., Grubits, C., Emberger, G., Parkesit, D. and Ripka, I. (1995). Mobilitätsverhalten der Wiener Bevölkerung 1986 und 1991. WIZK - Wiener Internationale Zukunftskonferenz, Wien.

[87] Data source: Stadtplanung Wien (1994). step 1994 - Stadtentwicklungsplan für Wien; *Beiträge zur Stadtforschung, Stadtentwicklung, Stadtgestaltung*, **Band 53**, and Knoflacher, H., Schopf, M., Grubits, C., Emberger, G., Parkesit, D. and Ripka, I. (1995). Mobilitätsverhalten der Wiener Bevölkerung 1986 und 1991. WIZK - Wiener Internationale Zukunftskonferenz, Wien.

Table 6.9: Performance indicators comparison census data – MARS81 results OD-matrix for slow mode home – work in 1991

Indicator	Deviation	Absolute deviation	Relative deviation
Sum	10,437	28,609	236.09
Standard deviation	160	152	2.69
Median	-2	8	-0.26
Maximum	1,512	1,512	38.42

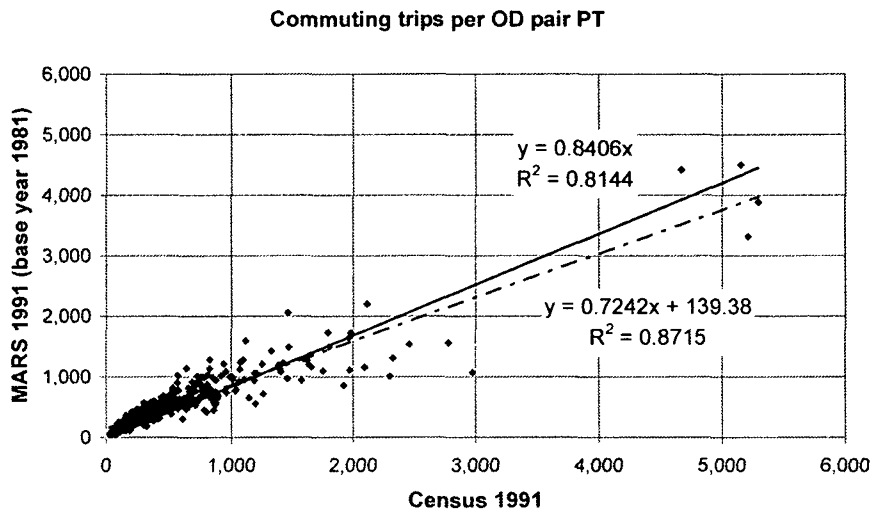


Figure 6.17: Comparison commuter statistics census 1991 – base year 1981 MARS results OD-matrix for PT trips home – work in 1991

Table 6.10: Performance indicators comparison census data – MARS81 results OD-matrix for PT trips home – work in 1991

Indicator	Deviation	Absolute deviation	Relative deviation
Sum	-10,339	84,900	90.91
Standard deviation	276	226	0.54
Median	5	91	0.03
Maximum	637	1,933	2.65

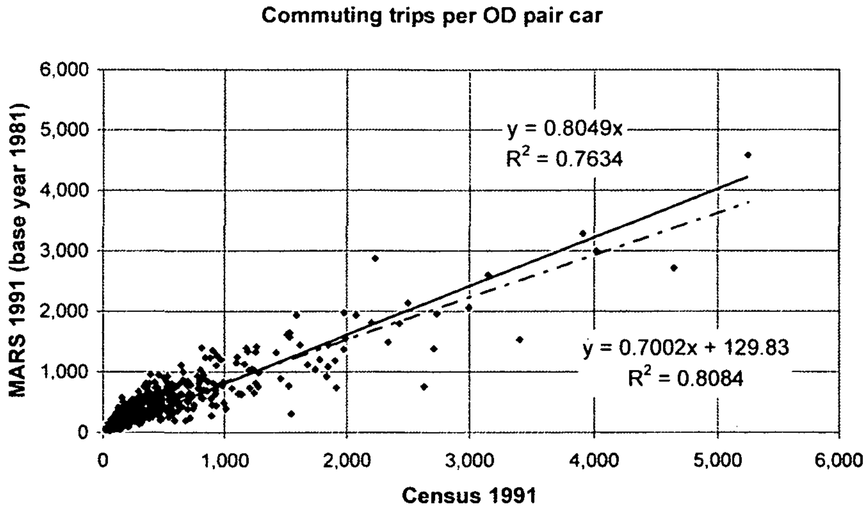


Figure 6.18: Comparison commuter statistics census 1991 – base year 1981 MARS results OD-matrix for car trips home – work in 1991

Table 6.11: Performance indicators comparison census data – MARS81 results OD-matrix for car trips home – work in 1991

Indicator	Deviation	Absolute deviation	Relative deviation
Sum	4,824	63,732	113.59
Standard deviation	229	195	0.35
Median	43	66	0.18
Maximum	594	1,906	1.58

6.2.5 Areas constructed for traffic

There are two limitations in the comparison made in this section. First the observed data of traffic infrastructure (Table 6.12) include all types of transport infrastructure. The loss of transport infrastructure in the 2nd district is e.g. caused by a conversion of a part of a goods station into a residential area. These data do not exactly fit to what the MARS calculates as additional road capacity, but no other data were available. Secondly the road construction model is not calibrated. At the beginning of the model development it was not intended to employ such a model. Problems with underdeveloped, fast growing zones were the reason for its inclusion. Car speed dropped near to zero in such zones if the original road capacity was kept constant. In the next iteration people changed mode and/or destination and the speed went up again. The result was an oscillating, building up model behaviour. To avoid this behaviour it was decided to add road capacity if the development in number of housing units and/or working places exceeds a user defined threshold and if the speed drops below a certain user defined limit. Improvements and calibration of this sub-model should be part of future MARS developments[88].

The fit between endogenously developed road capacity and observed changes in infrastructure is rather bad (Figure 6.19 and Figure 6.20). Nevertheless there is a significant correlation between observation and simulation (Table 6.13 and Table 6.14).

[88] See chapter 9.3 Suggestions for future MARS improvements.

Table 6.12: Development of the Viennese area constructed for traffic

(ha)	1	2	3	4	5	6	7	8	9	10	11	12
1985	125.88	443.03	201.17	47.05	64.48	46.55	40.18	29.87	105.76	574.40	417.11	223.56
1988	125.77	401.99	213.39	46.97	64.52	46.36	39.63	29.87	102.58	590.11	409.99	223.00
1994	125.78	389.60	213.61	46.87	64.70	45.99	39.94	30.01	102.60	601.87	425.15	225.81
1997	125.84	388.76	214.86	46.73	64.22	46.01	40.75	30.01	103.51	597.16	414.43	224.39
(ha)	13	14	15	16	17	18	19	20	21	22	23	
1985	223.88	324.75	128.62	152.66	117.69	102.64	272.31	187.97	599.14	745.22	429.92	
1988	224.57	323.88	128.61	153.92	116.58	102.65	272.34	187.10	599.83	764.00	435.27	
1994	226.30	323.13	130.59	155.54	118.04	102.66	274.13	189.44	625.40	813.31	444.49	
1997	227.32	323.19	129.71	155.57	117.38	101.57	275.42	186.79	630.03	805.67	441.70	

Source: (Magistratsabteilung 66 - Statistisches Amt, 1990) p. 27, (Magistratsabteilung 66 - Statistisches Amt, 1994) p. 25, (Magistratsabteilung 66 - Statistisches Amt, 1999) p. 35, (MA 66 Wien Statistik, 2001) p. 36

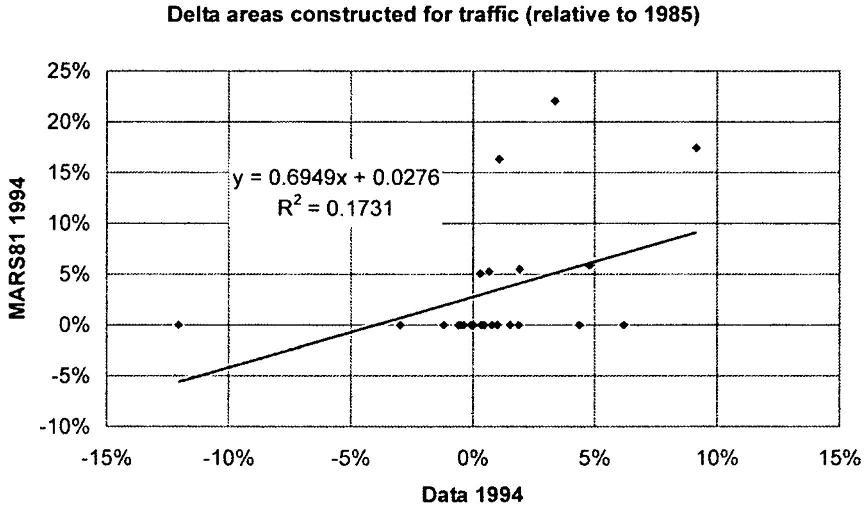


Figure 6.19: Comparison development area constructed for traffic MARS81 – data in 1994 relative to 1985

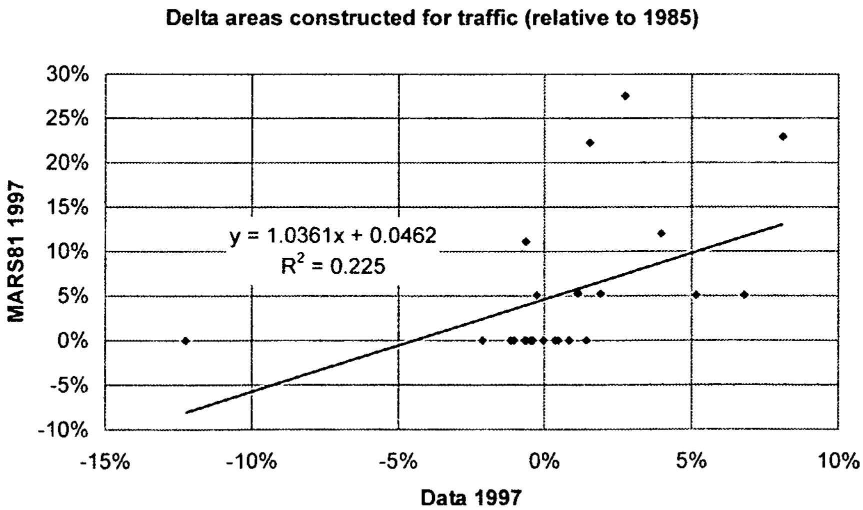


Figure 6.20: Comparison development area constructed for traffic MARS81 – data in 1997 relative to 1985

Table 6.13: Correlation between simulation and observation transport infrastructure development between 1985 and 1994

		DATA_1994	MARS__1994
DATA_1994	Pearson Correlation	1.000	.416(*)
	Sig. (2-tailed)	.	.048
	N	23	23
MARS__1994	Pearson Correlation	.416(*)	1.000
	Sig. (2-tailed)	.048	.
	N	23	23

* Correlation is significant at the 0.05 level (2-tailed).

Table 6.14: Correlation between simulation and observation transport infrastructure development between 1985 and 1997

		DATA_1994	MARS__1994
DATA_1994	Pearson Correlation	1.000	.474(*)
	Sig. (2-tailed)	.	.022
	N	23	23
MARS__1994	Pearson Correlation	.474(*)	1.000
	Sig. (2-tailed)	.022	.
	N	23	23

* Correlation is significant at the 0.05 level (2-tailed).

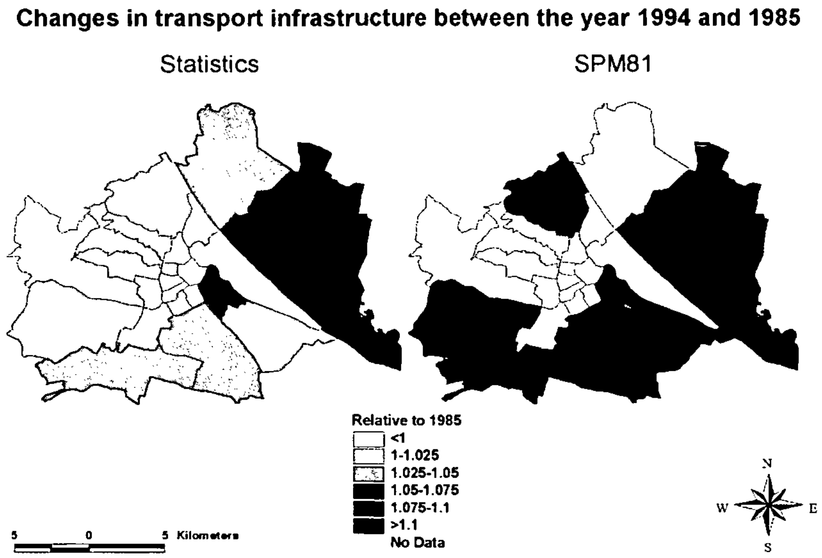


Figure 6.21: Comparison development area constructed for traffic MARS81 – data in 1994 relative to 1985

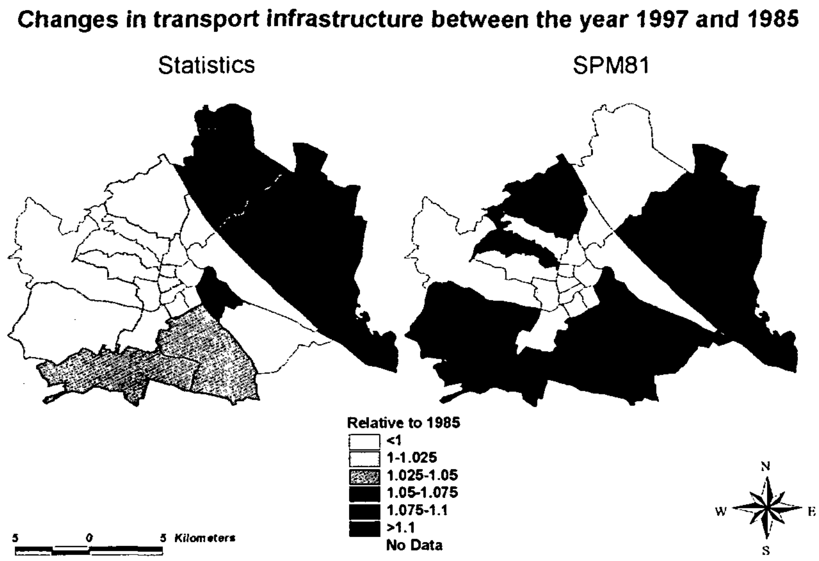


Figure 6.22: Comparison development area constructed for traffic MARS81 – data in 1997 relative to 1985

6.2.6 Development new housing units

The comparison of the MARS81 simulated and observed development of housing units by zone between 1991 and 1998 shows a significant correlation (see Figure 6.24). But the MARS81 systematically underestimates the development of housing units. In the simulation about 15,000 new housing units were built, while the development of about 45,000 new housing units was observed during the same period. Housing development in Vienna is to a high extent influenced by political decisions rather than market economy oriented decisions. It is therefore difficult to model this part of the land use system. Several factors external to a land use transport model influence decisions. E.g. the underestimation of the MARS81 is highest in zone 22 (Figure 6.25). An area near the river Danube should host a world exposition EXPO in 1995 (Strasser, G., 2001). In the year 1991 a referendum stopped these plans. To save the investments into the infrastructure which were already made, the city authorities decided to develop this area with housing and office buildings.

Comparing the observed development of housing units and population (Table 6.15) shows that as well in the Eighties as in the Nineties supply was increasing much faster than demand. If the household size is assumed with 2 persons per household then the increase in supply is about six to nine times higher than the increase in demand. Any model would hardly be able to predict such a production of over supply. One reason might be that the housing market was characterised by a shortage in affordable flats in the early Eighties. There was political will and effort to relax the market. Another reason might be that the census data only count people having their main residence in Vienna. Probably a high share of housing units is occupied by weekly commuters or students. A more detailed analysis of the availability of the housing stock for new occupation could help improve the model prediction.

The only zones in which the MARS81 overestimates housing development are the districts 9 and 15 to 18. In these districts it is difficult to assess the amount of land which is available for development. The districts 16 to 18 have a high share of protected woodland. It was difficult to estimate the amount of protected land from the available data. More detailed data about the availability of land for different the uses is seen to have a high potential to improve the MARS model predictions.

Table 6.15: Observed changes in number of housing units and residents

Period	Number of housing units	Number of residents
1981 – 1991	31,916	10,275
1991 – 2001 (1998)	44,777	10,576

Source: (ÖSTZ, 1984; Magistratsabteilung 66 - Statistisches Amt, 1990; ÖSTAT, 1993; Magistratsabteilung 66 - Statistisches Amt, 1999; Statistisches Amt der Stadt Wien, 2003)

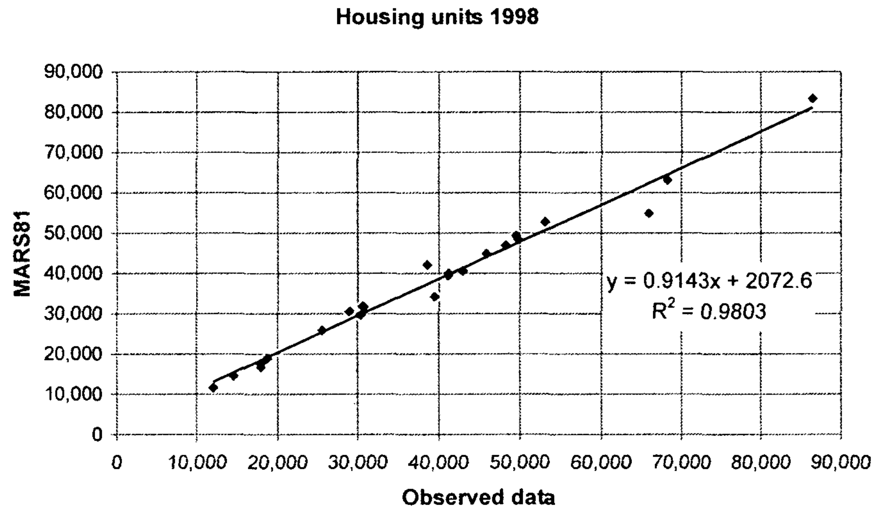


Figure 6.23: Comparison statistical data – MARS81 number of housing units 1998

Table 6.16: Performance indicators comparison census data – MARS81 results number of housing units in 1998

Indicator	Deviation	Absolute deviation	Relative deviation
Sum	-28,847	44,183	-0.50
Standard deviation	2,939	2,493	0.06
Median	-886	1,185	-0.02
Maximum	3,537	11,010	0.09

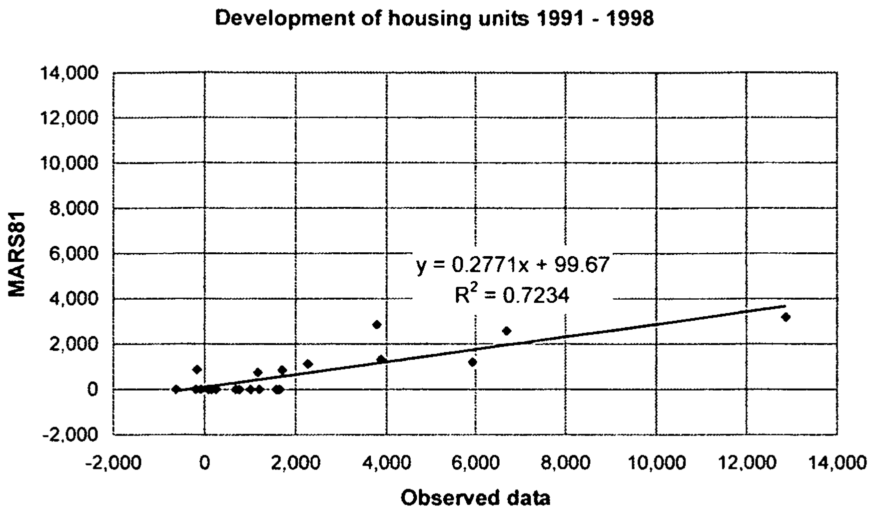


Figure 6.24: Comparison statistical data – MARS81 housing unit development between 1991 and 1998

Table 6.17: Performance indicators comparison census data – MARS81 results number of housing unit development between 1991 and 1998

Indicator	Deviation	Absolute deviation	Relative deviation
Sum	-29,306	33,146	-23.73
Standard deviation	2,327	2,213	1.19
Median	-767	891	-1.00
Maximum	1,030	9,693	-0.25

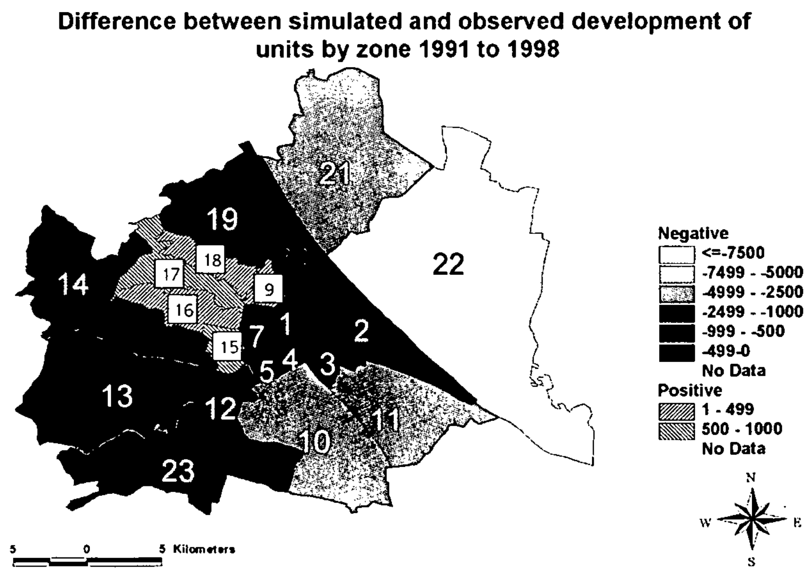


Figure 6.25: Spatial distribution of the difference between simulated and observed development of housing units by zone between 1991 and 1998

6.2.7 Development residential distribution

The comparison between the observed changes in population by zone and the results from the 1981 base year MARS shows a significant correlation (see Figure 6.27). Nevertheless it is obvious that the correlation is driven by a single point to a quite high extent. Additionally the gradient is far below the target of being about 1. A more detailed spatial analysis of the results gives two explanations. On the one hand there is a highly significant correlation between the differences in the observed and simulated development of housing units and the population development. As explained in the previous section a single event which hardly ever can be predicted by a simulation model lead to a severe underestimation of housing unit development in zone 22. This error was passed from the housing unit development model to the residential location model. Another explanation could be found in the different age pyramid in the different zones. The MARS currently does not model household ageing. There is a significant correlation between the share of elderly people in a zone and the overestimation of population development by the MARS (see Figure 6.28).

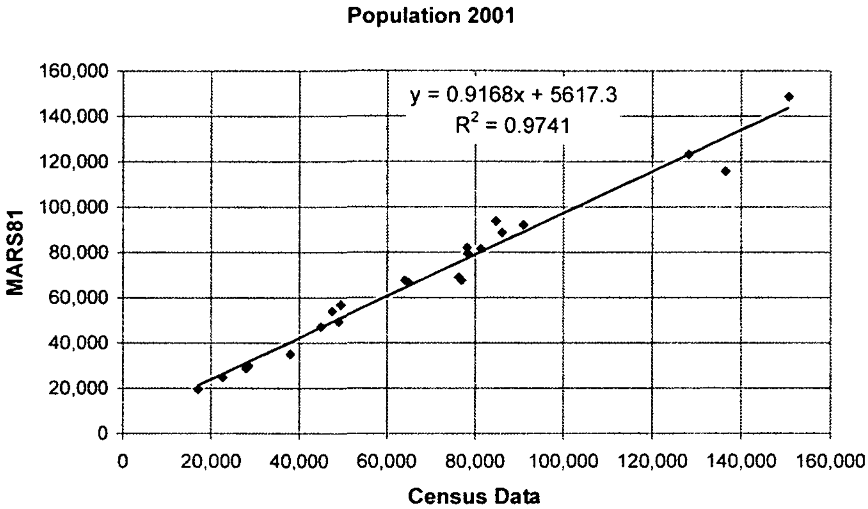


Figure 6.26: Comparison statistical data – MARS81 results population distribution in 2001

Table 6.18: Performance indicators comparison census data – MARS81 results population distribution in 2001

Indicator	Deviation	Absolute deviation	Relative deviation
Sum	-2,189	92,527	0.37
Standard deviation	6,315	4,622	0.08
Median	1,186	2,328	0.03
Maximum	9,003	20,721	0.15

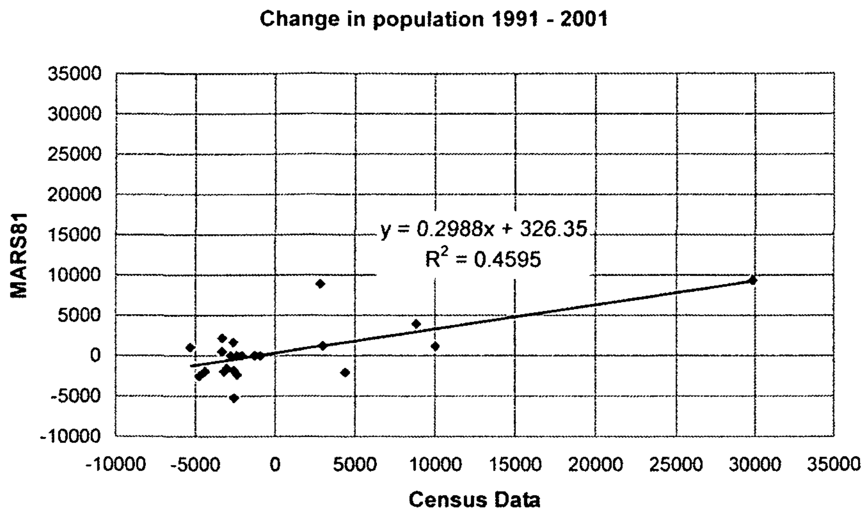


Figure 6.27: Comparison statistical data – MARS81 results change in population distribution between 1991 and 2001

Table 6.19: Performance indicators comparison census data – MARS81 results change in population distribution between 1991 and 2001

Indicator	Deviation	Absolute deviation	Relative deviation
Sum	-645	89,487	-13.93
Standard deviation	5,987	4,302	0.84
Median	1,410	2,558	-0.79
Maximum	6,372	20,516	2.12

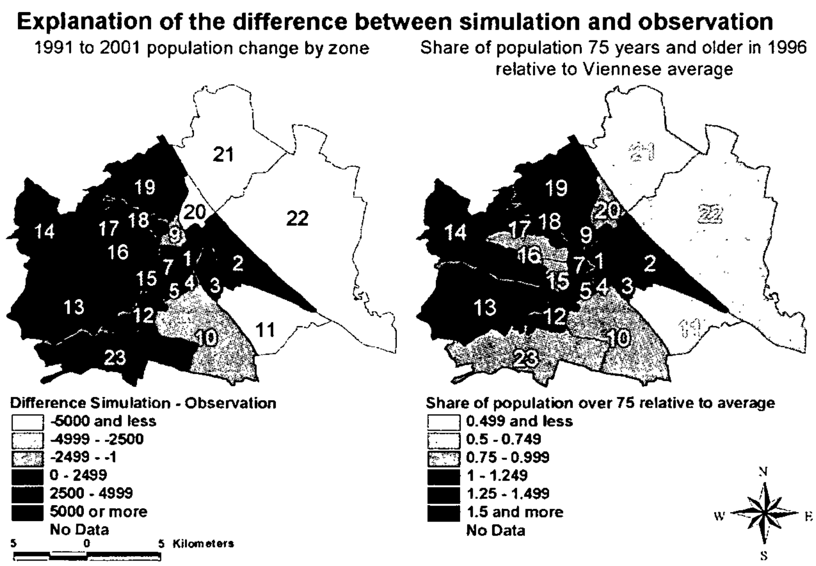


Figure 6.28: Explanation of differences in MARS81 simulation and observation of population changes between 1991 and 2001[89]

[89] Source for share of population 75 or older: MA 66 Wien Statistik (2001). Statistisches Jahrbuch der Stadt Wien. City of Vienna Statistical Yearbook. Ausgabe 2001 Issue.; Magistrat der Stadt Wien, Wien. p. 51.

Table 6.20: Correlation between difference in population development observed and simulated between 1991 and 2001 and share of population 75 or older per zone

		POPROB9101	POR>75
POPROB9101	Pearson Correlation	1.000	.630(**)
	Sig. (2-tailed)	.	.001
	N	23	23
POR>75	Pearson Correlation	.630(**)	1.000
	Sig. (2-tailed)	.001	.
	N	23	23

** Correlation is significant at the 0.01 level (2-tailed).

POPROB9101 ...... **PO**pulation **PR**ediction **OB**servation between 19**91** and 20**01**

POR>75 .... Share of **PO**pulation **R**elative to Viennese average with age **>75** in the year 1996

6.2.8 Policy instruments

The policy instrument "area wide parking charges" is the only one for which observed data from a before and after study exist for Vienna. MARS simulation results are compared with these observations.

- **Parking charges**

Before and after surveys were performed when the parking charging regime was installed in the CBD in 1993 (Herry, M. et al., 1994) and in the districts 6 to 9 in 1995 (Herry, M. et al., 1996), (Dorner A. et al., 1997).

Central business district

Between 6 am and 10 pm a 7% reduction of the car traffic into the CBD was observed due to the parking charging regime (Herry, M. et al., 1994) p. 66. The reduction of incoming car traffic between 6 and 10 am was 15%. The 1981 base year MARS calculates an incoming car traffic reduction of about 11%.

Districts 6 to 9

Traffic counts indicate that the car traffic volumes decreased by 26% due to the parking charging regime installed in the districts 6 to 9 in 1995 (Herry, M. et al., 1996) p. 31. The 1981 base year MARS calculates a reduction of the incoming car traffic of about 24% (18% for trips home – work and 26% for trips home – other).

6.3 Analysis of the sensitivity to changes in transport supply and costs

Policy instruments either affect transport supply or transport costs. In the following sections the response of MARS to the application of different policy instruments is tested. A detailed description of the policy instruments is given in section 8.3.2 Specific policy instruments considered in MARS.

Economists measure price[90] sensitivity using elasticities, defined as the percentage change in consumption of a good caused by a one-percent change in its price or other characteristics, such as traffic speed or road capacity. For example, an elasticity of -0.5 for vehicle use with respect to vehicle operating expenses means that each 1% increase in these expenses results in a 0.5% reduction in vehicle mileage or trips (Victoria Transport Policy Institute, 2003). Values for elasticities for different types of changes in transport supply and costs are summarised e.g. in (Victoria Transport Policy Institute, 2003) or (KonSult, 2002). In the following sections results from MARS calculations are compared to the range of elasticity values[91] given by (Victoria Transport Policy Institute, 2003).

Elasticity values are not available for all modelled policy instruments from the reviewed literature. Therefore the plausibility of mode split changes for the different policy instruments is tested additionally to the elasticities. Finally the plausibility of the effects on land use is tested.

6.3.1 Fuel price

The elasticities shown in Table 6.21 are calculated by increasing and decreasing fuel price by 10% and analysing the OD-pair wise changes in the number of trips as calculated by MARS. As expected a fuel price increase increases the number of slow mode and PT trips. For car trips an unexpected effect occurs. On some OD-pairs the number of car trips increases with increasing fuel price. This effect occurs in the inner city, mainly in the CBD. Destination changes and the speed flow relationship are responsible for this effect. The average elasticity and the minimum elasticity are in line with references found in the literature. MARS elasticities are in average slightly lower than the range given in (Victoria Transport Policy Institute, 2003). The elasticity is within this range for about 40% of the possible OD-pairs.

Table 6.21: Comparison of MARS91 elasticities for fuel price changes with values from literature

Mode	Fuel price	MARS91			Literature	
		Average	MAX	MIN	MAX	MIN
Slow	Increase	0.017	0.046	0.000		
	Decrease	0.019	0.050	0.000		
PT	Increase	0.023	0.051	0.015		
	Decrease	0.026	0.057	0.016		
Car	Increase	-0.052	0.096	-0.160	-0.06	-0.22
	Decrease	-0.054	0.113	-0.211		

Source: (Victoria Transport Policy Institute, 2003)

[90] Prices are the direct, internal, variable, perceived costs involved in consuming a good, that is, the factors that individual consumers must trade off when making purchase decisions. The term is sometimes limited to monetary costs, but it can include non-monetary costs such as time, discomfort and risk.

[91] It is not clear whether these elasticity values are based on stated or revealed preference surveys.

Mode split in MARS reacts as expected. A decrease in fuel price increases the car share and decreases the share of slow modes and PT and vice versa (Figure 6.29 and Figure 6.30). The changes are rather small and the do-minimum trend continues after the implementation of fuel price changes.

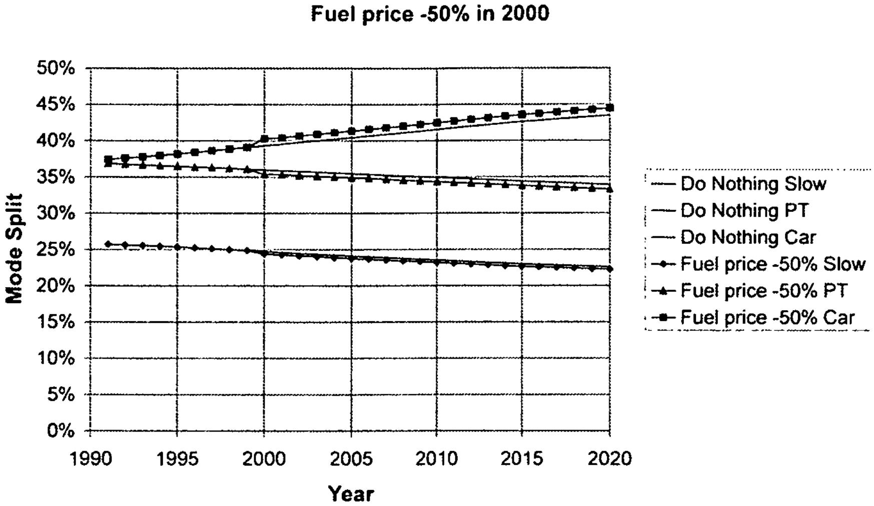


Figure 6.29: Mode split effects 50% reduction of fuel price

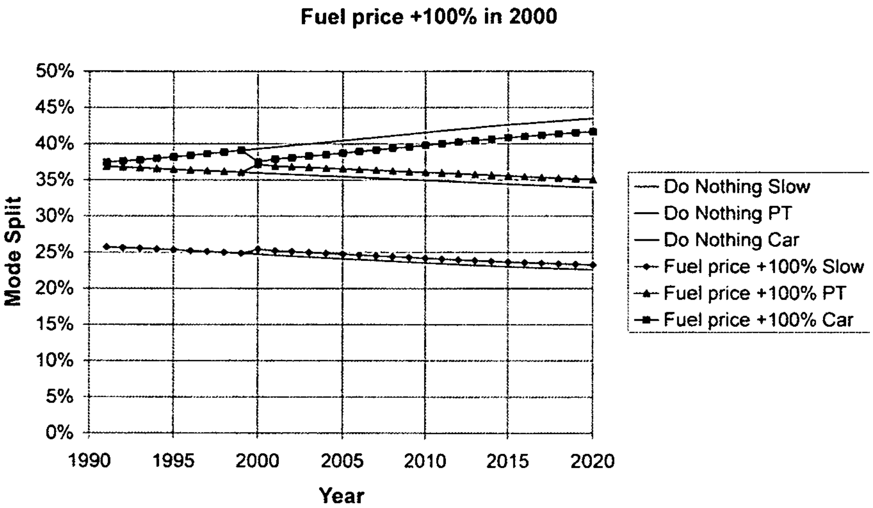


Figure 6.30: Mode split effects 100% increase of fuel price

Effects of the policy instrument fuel price on land use can be neglected. As changes in fuel price affect the study area homogenously, this model behaviour was expected.

6.3.2 Parking charge

The effect of parking charges in MARS is tested against observed data in section 6.2.8. Mode split in MARS reacts as expected. The implementation of a 2 Euro parking charge in the inner city districts 1 to 9 and 20 decreases car share and increases the share of slow modes and PT (Figure 6.31). The changes are small and the do-minimum trend continues after the implementation of the parking charges. Effects on land use are small[92].

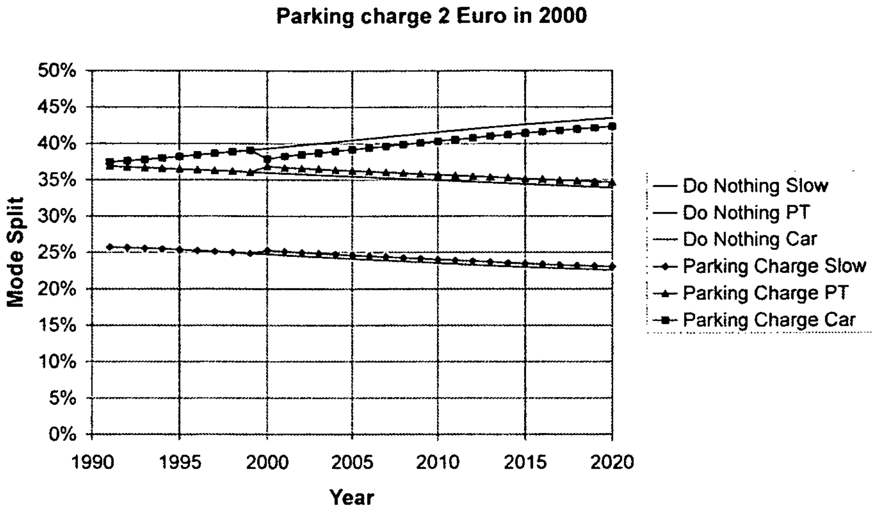


Figure 6.31: Mode spit effects of 2 Euro parking charge

6.3.3 Road charging

Mode split in MARS reacts as expected. The implementation of a 2 Euro road charge for trips into the inner city districts 1 to 9 and 20 decreases car share and increases the share of slow modes and PT (Figure 6.32). The changes are very small and the do-minimum trend continues after the implementation of the road charge. Figure 6.33 shows the results for a 4 Euro road charge. Again the effects are small. The reason is that the number of trips into the charged area is rather small compared to the number of trips within the charged area and within the uncharged area. Effects on land use are small[92].

[92] An accessibility definition using generalised costs instead of time as basis would lead to a more distinct land use reaction. The use of a generalised cost based accessibility definition is suggested for future MARS improvements. See chapter 9.3 Suggestions for future MARS improvements.

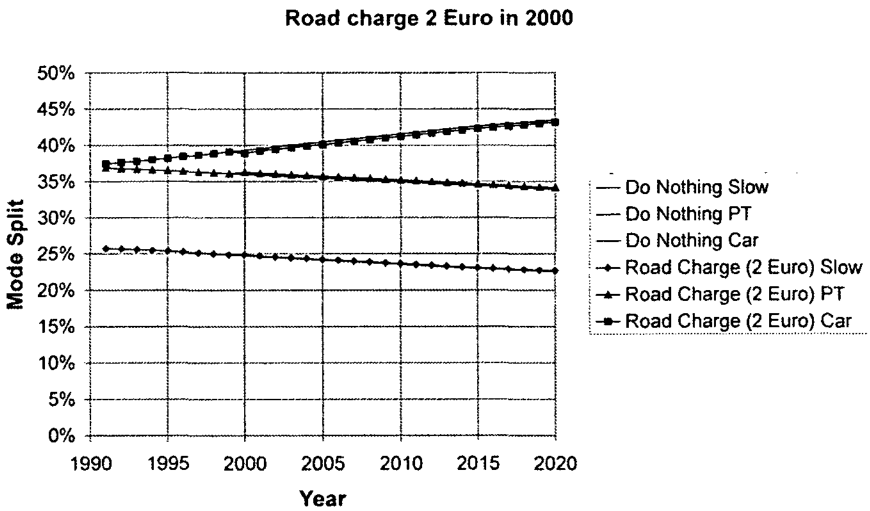


Figure 6.32: Mode split effects of 2 Euro road charge

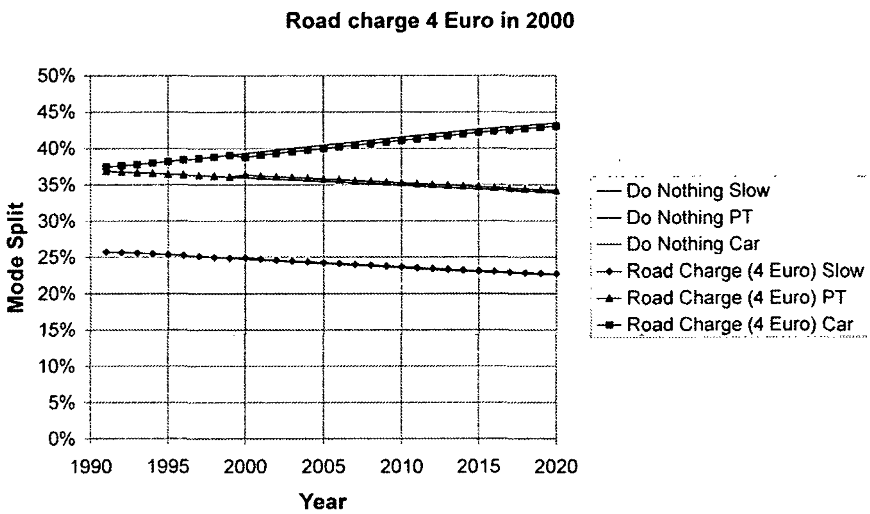


Figure 6.33: Mode split effects of 4 Euro road charge

6.3.4 Road capacity

Mode split reacts as expected. Capacity increases increase the share of car trips and decreases the share of slow mode and PT trips. Nevertheless the overall effect is quite small (Figure 6.34). Decreases in road capacity decrease the share of car trips and increase the share of slow mode and PT trips (Figure 6.35).

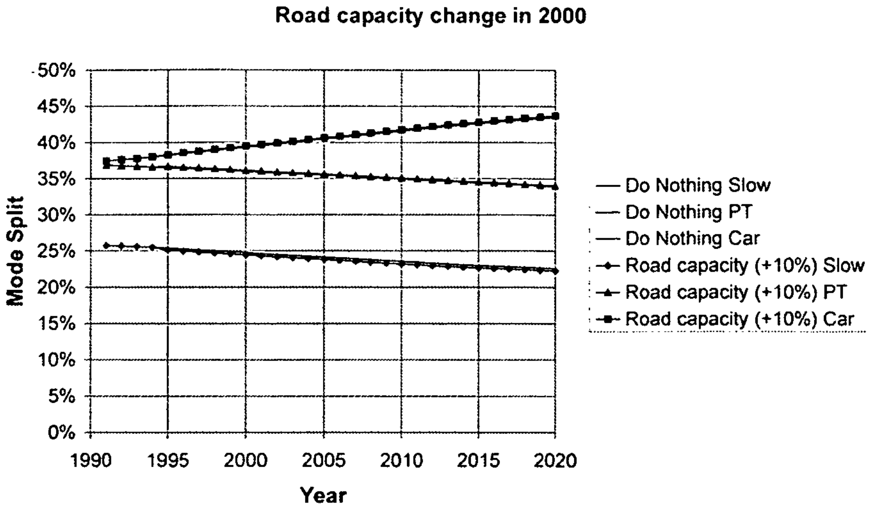


Figure 6.34: Mode split effects of road capacity increase by 10%

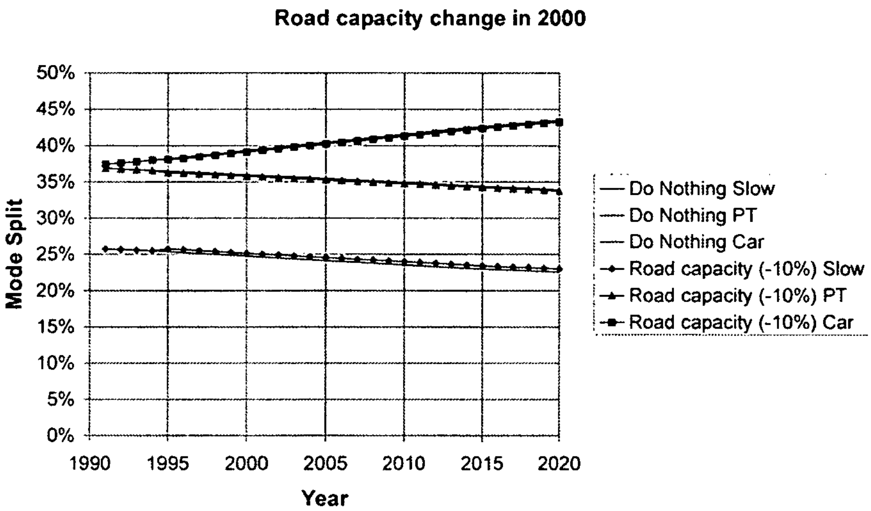


Figure 6.35: Mode split effects of road capacity decrease by 10%

Effects of road capacity changes on land use are as expected. An increase in road capacity causes a migration of households and workplaces into the outskirts (Figure 6.36 and Figure 6.38). A decrease of road capacity causes a migration of households and workplaces into the inner city (Figure 6.37 and Figure 6.39)

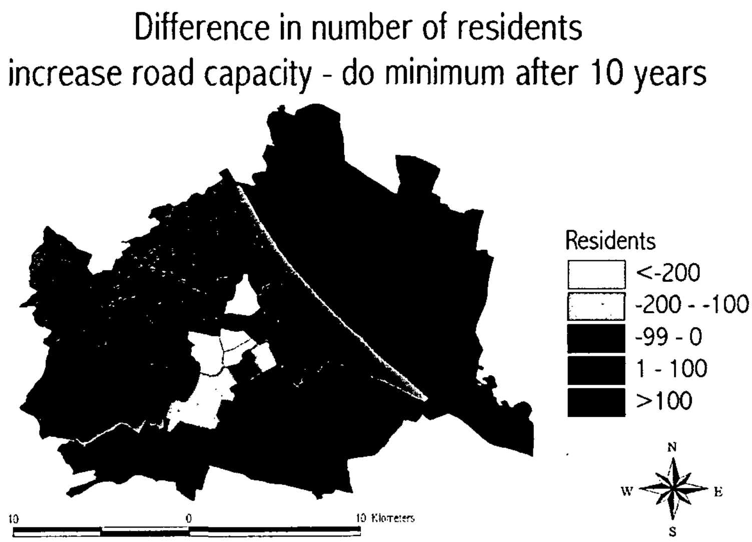


Figure 6.36: Difference in the number of residents between increase in road capacity by traffic management measures and the do minimum scenario (10 years after introduction)

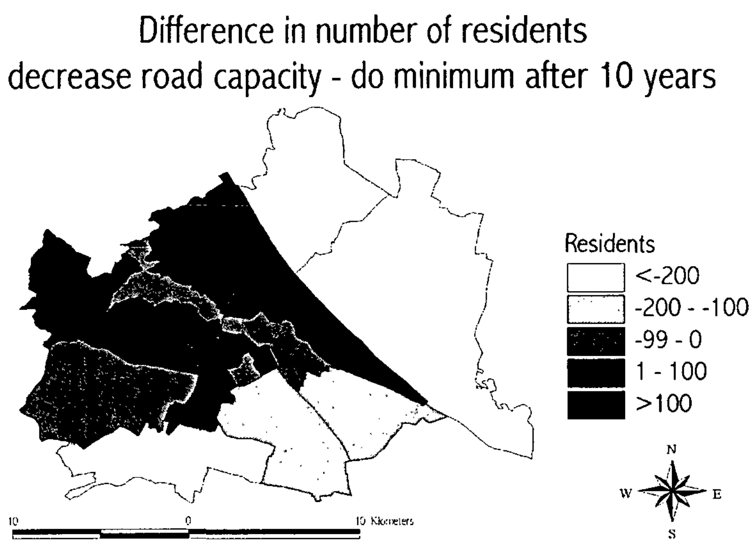


Figure 6.37: Difference in the number of residents between decrease in road capacity by traffic calming measures and the do minimum scenario (10 years after introduction)

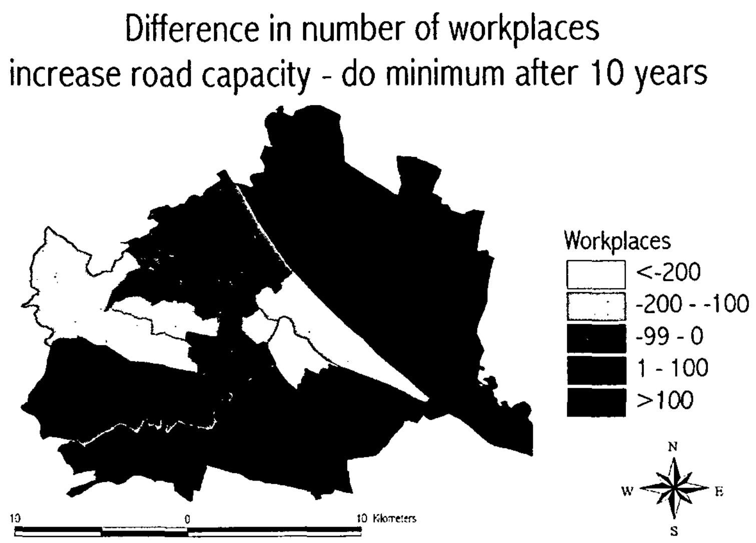


Figure 6.38: Difference in the number of workplaces between increase in road capacity by traffic management measures and the do minimum scenario (10 years after introduction)

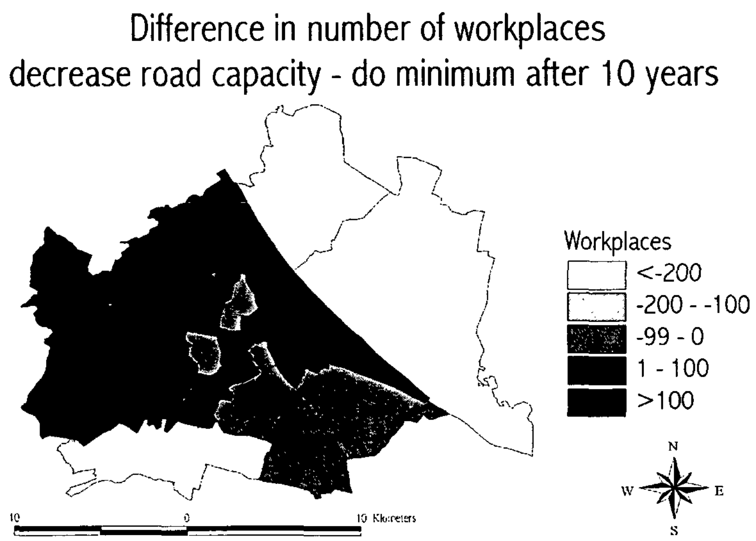


Figure 6.39: Difference in the number of workplaces between decrease in road capacity by traffic calming measures and the do minimum scenario (10 years after introduction)

6.3.5 Road infrastructure

Mode split in MARS reacts as expected. The implementation of additional road infrastructure in the form of a highway type ring road increases car share and decreases the share of slow modes and PT (Figure 6.40). The do-minimum trend continues after the opening of the ring road.

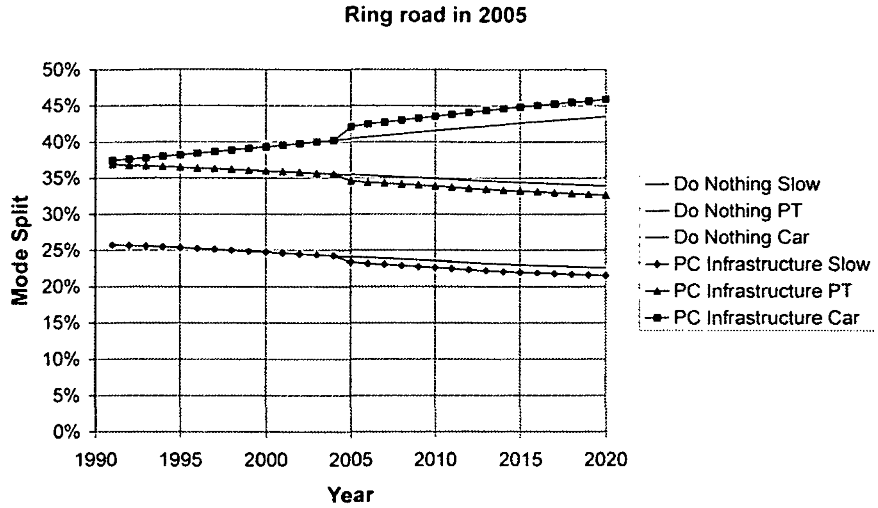


Figure 6.40: Mode split effects of new car infrastructure (ring road)

Effects on land use are as expected (Figure 6.41 and Figure 6.42). Workplaces and households move to the districts 10, 11, 22 and 23 which are connected by the ring road. The effects are not very high but seem to be reasonable.

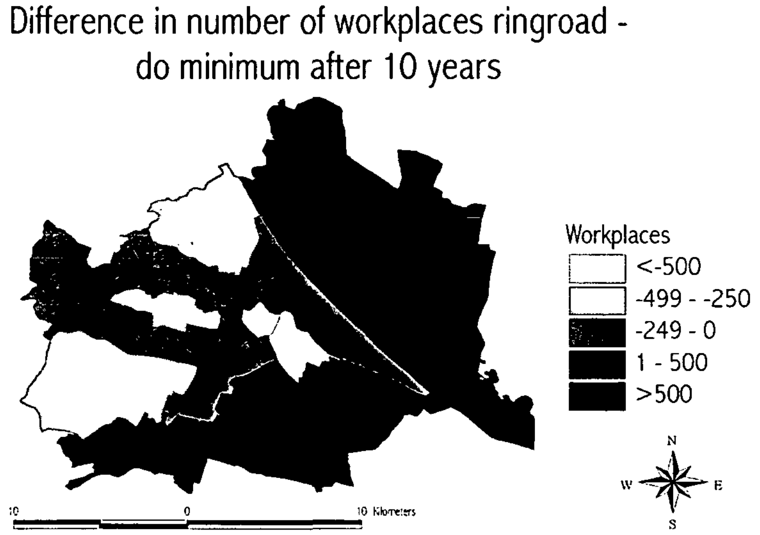


Figure 6.41: Difference in the number of workplaces between development of a ring road and the do minimum scenario (10 years after the ring road was opened)

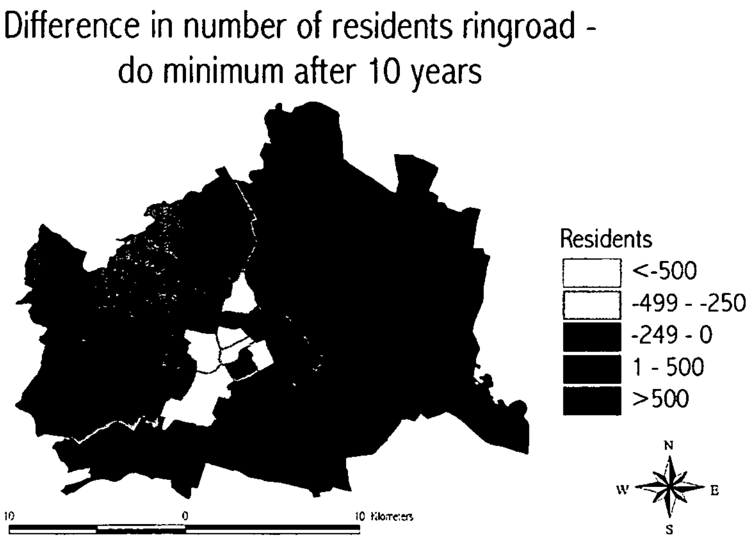


Figure 6.42: Difference in the number of residents between development of a ring road and the do minimum scenario (10 years after the ring road was opened)

6.3.6 PT fares

The elasticities shown in Table 6.22 are calculated by increasing and decreasing PT fares by 10% and analysing the OD-pair wise changes in the number of trips as calculated by MARS. The expected result is that PT trips will go down with increasing PT fares, i.e. the elasticity is negative. Slow mode and car trips are expected to increase with increasing PT fares, i.e. the cross-elasticities are positive. The cross-elasticities for slow mode fulfil the expectations. On some of the OD-pairs PT elasticities and car cross-elasticities have unexpected signs. Again the unexpected results can be explained by the effects of destination change and speed flow relationship. About 20% of the PT elasticities lay within the range given by (Victoria Transport Policy Institute, 2003). About 90% of the car cross-elasticities lay with the given range. Again the effect calculated by MARS is slightly lower than in the references.

Table 6.22: Comparison of MARS91 elasticities for PT fares with values from literature

Mode	PT Fare	MARS91			Literature	
		Average	MAX	MIN	MAX	MIN
Slow	Increase	0.188	0.257	0.000		
	Decrease	0.194	0.269	0.000		
PT	Increase	-0.136	0.044	-0.402	-0.2	-0.5
	Decrease	-0.143	0.032	-0.464		
Car	Increase	0.046	0.088	-0.004	0.1	0.03
	Decrease	0.048	0.095	-0.005		

Source: (Victoria Transport Policy Institute, 2003)

Mode split in MARS reacts as expected. A decrease in PT fares increases the PT share and decreases the share of slow modes and car and vice versa (Figure 6.43 and Figure 6.44). The do-minimum trend continues after the implementation of PT fare changes. The effects on land use can be neglected. As the study area is affected homogenously by fare changes, this behaviour was expected.

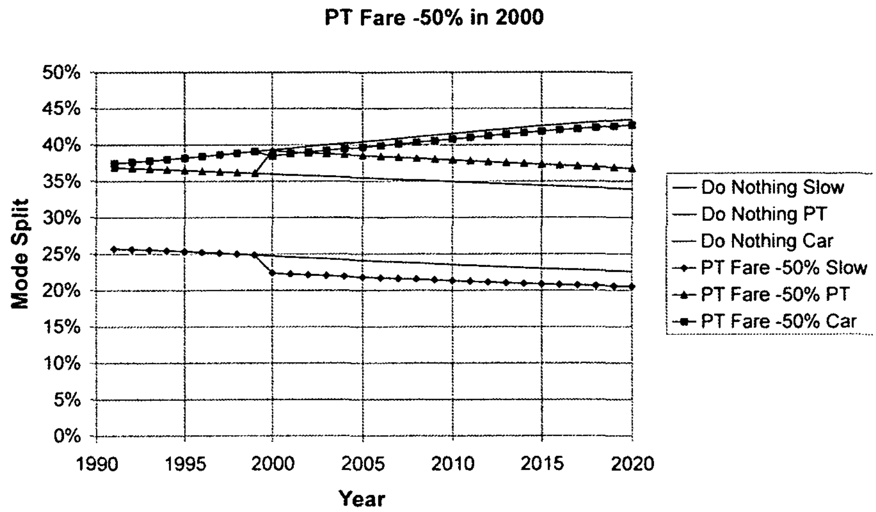


Figure 6.43: Mode split effects of a 50% PT fare reduction

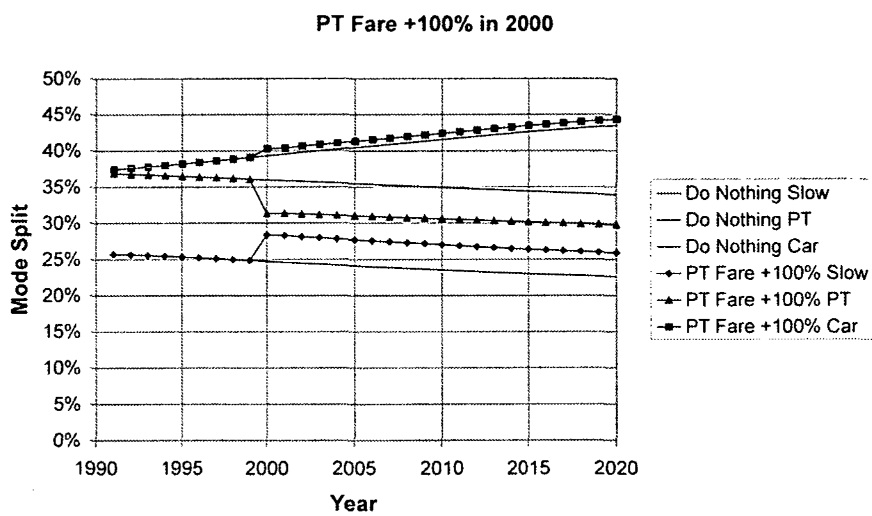


Figure 6.44: Mode split effects of a 100% PT fare increase

6.3.7 PT frequency

The elasticities shown in Table 6.23 are calculated by increasing and decreasing PT frequency by 10% and analysing the OD-pair wise changes in the number of trips as calculated by MARS. The expected result is that PT trips will go up with increasing PT frequency, i.e. the elasticity is positive. Slow mode and car trips are expected to decrease with increasing PT frequency, i.e. the cross-elasticities are negative. All elasticities and cross-elasticities fulfil the expectations. About 10% of the PT elasticities lay within the range given by (Victoria Transport Policy Institute, 2003). Again the effect calculated by MARS is slightly lower than in the references.

Table 6.23: Comparison of MARS91 elasticities for PT frequency with values from literature

Mode	PT Frequency	MARS91			Literature	
		Average	MAX	MIN	MAX	MIN
Slow	Increase	-0.205	0.000	-0.290		
	Decrease	-0.257	0.000	-0.366		
PT	Increase	0.296	0.798	0.062	0.5	0.7
	Decrease	0.336	0.864	0.088		
Car	Increase	-0.041	-0.008	-0.068		
	Decrease	-0.050	-0.011	-0.082		

Source: (Victoria Transport Policy Institute, 2003)

Mode split in MARS reacts as expected. A decrease in PT frequency decreases the PT share and increases the share of slow modes and car and vice versa (Figure 6.45 and Figure 6.46). The do-minimum trend continues after the implementation of PT fare changes. The effects on land use can be neglected. As a change in PT frequency as modelled in MARS affects the whole study homogenously, this behaviour was expected.

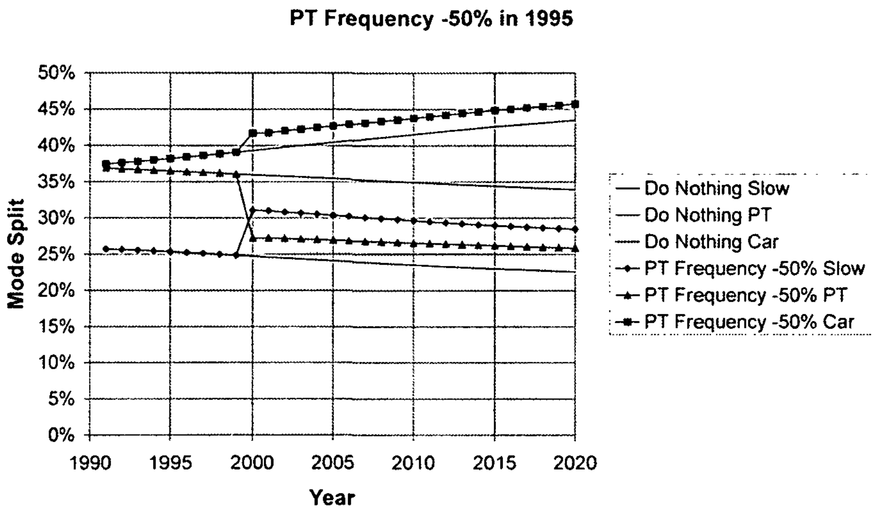


Figure 6.45: Mode split effects of 50% PT frequency reduction

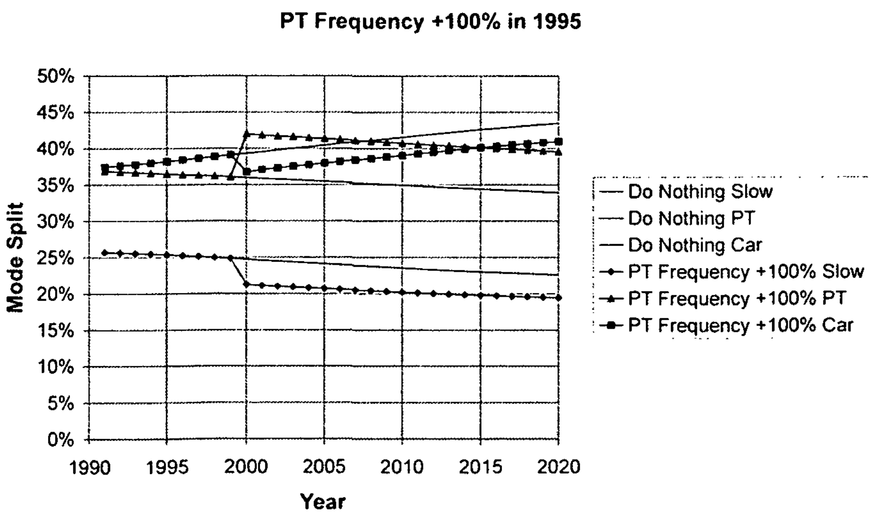


Figure 6.46: Mode split effects of a 100% PT frequency increase

6.3.8 PT infrastructure investments

Mode split in MARS reacts as expected. The implementation of additional PT infrastructure in the form of metro extensions increases PT share and decreases the share of slow modes and car (Figure 6.47). The overall effect for the whole study area is quite small and the do-minimum trend continues after the opening of the metro extensions.

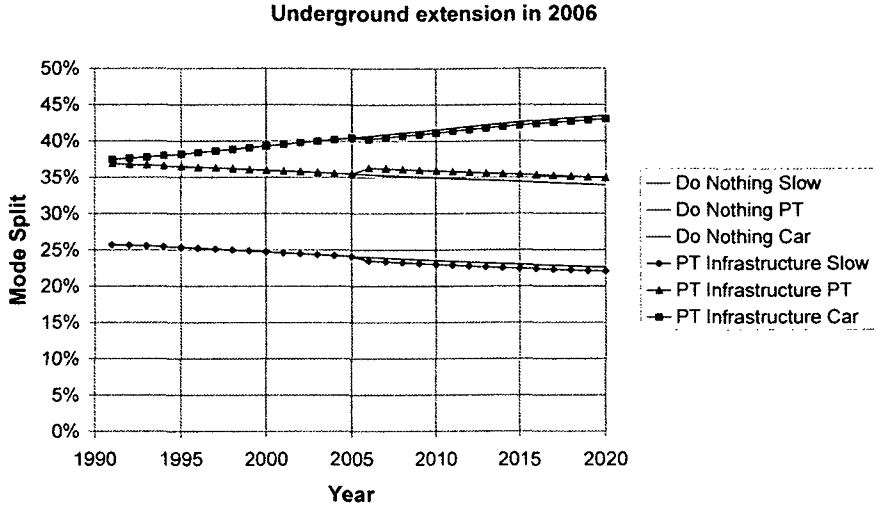


Figure 6.47: Mode split effects of new PT infrastructure (metro line extension)

Effects on land use are as expected (Figure 6.48 and Figure 6.49). Households move to the districts 21 and 22 in which all extensions except on are ending. The effects are not very high but seem to be reasonable. The effects on the workplace location can be neglected.

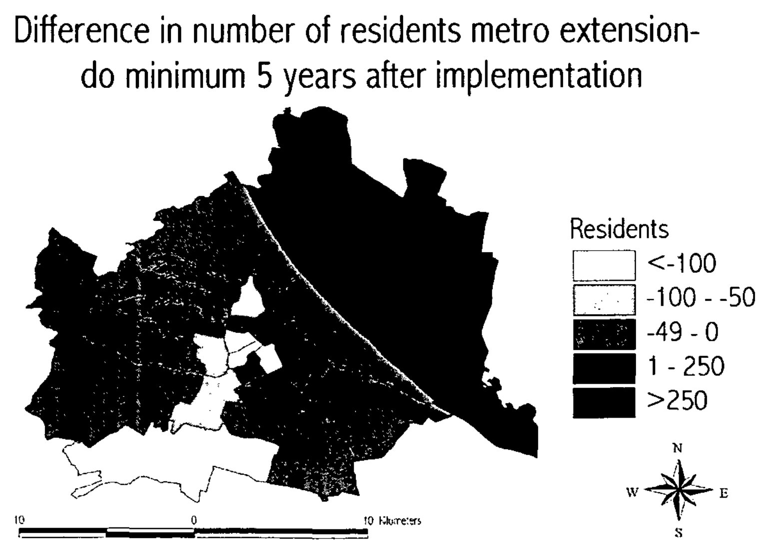


Figure 6.48: Difference in number of residents PT infrastructure investment (metro line extension) and do-minimum scenario 5 years after implementation

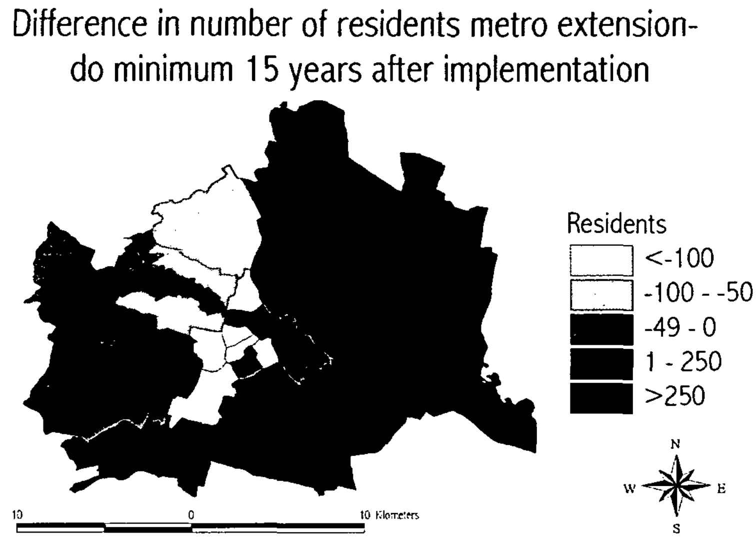


Figure 6.49: Difference in number of residents PT infrastructure investment (metro line extension) and do-minimum scenario 15 years after implementation

6.4 Comparison of the MARS results with references from other models

6.4.1 UrbanSim for Eugene-Springfield, Oregon

The UrbanSim model[93] was tested over a historical period in Eugene-Springfield, Oregon (Waddell, P., 2002). The model was calibrated with a 1994 database. A 1980 database was developed and the 1994 database became the observed target for comparison of simulation results (Table 6.24). The simulation results are compared to observed data at three units of geography. The unit used in the model is the 150 meter grid cell. The model simulation results correlate well after 15 years of simulation to the observed data. Aggregation to traffic analysis zones used in transportation modelling produced higher correlations. Another spatial comparison was made on the grid cells averaged over the cells within one cell radius.

Table 6.24: Correlation of simulated to observed 1994 values UrbanSim (Waddell, P., 2002)

	Cell	Zone	Average over one-cell radius
Employment	0.805	0.865	0.917
Population	0.811	0.929	0.919
Nonresidential square footage	0.799	0.916	0.927
Housing units	0.828	0.927	0.918
Land value	0.830	0.925	0.908

[93] A brief description of the UrbanSim model is given in chapter 2. Review of land use and transport modelling.

A more stringent benchmark than the preceding comparison, is the comparison of observed and simulated changes from 1980 to 1994. Figure 6.20 portrays this comparison for households and employment. The 271 traffic analysis zones are the basis for this comparison. The graph shows the percentage of zones classified according to the size of the differences between the observed and simulated changes in households and employment between 1980 and 1994.

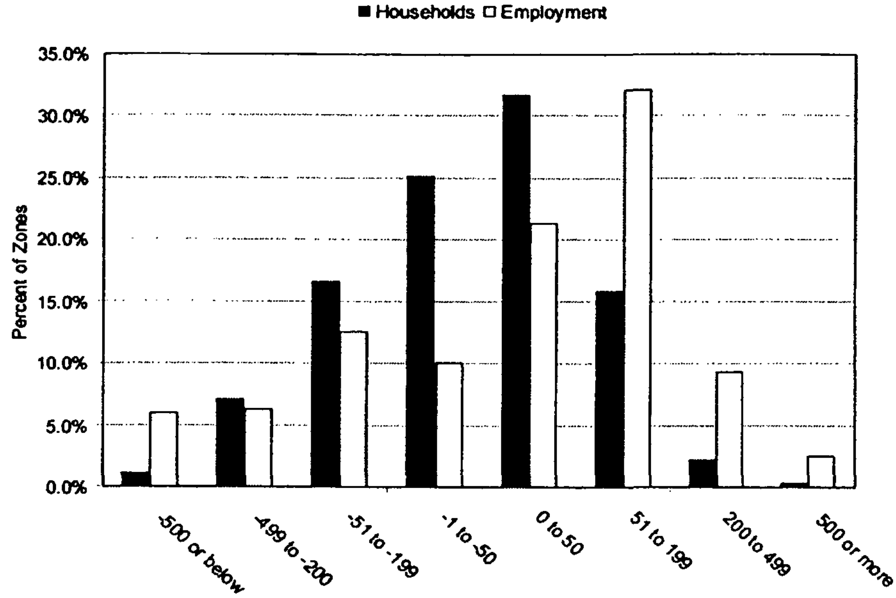


Table 6.25: Difference between simulated and observed 1980 to 1994 change by zone (Waddell, P., 2002)

Table 6.26 shows the correlation between observed data and MARS81 simulation results for the number of residents in 2001 and the number of housing units in the year 1998. The model results and the observations correlate very well. Figure 6.50 and Figure 6.51 show the comparison of the changes observed and simulated with MARS81.

Table 6.26: Correlation of simulated to observed values MARS81

	Year	Correlation coefficient
Population	2001	0.983
Housing units	1998	0.995

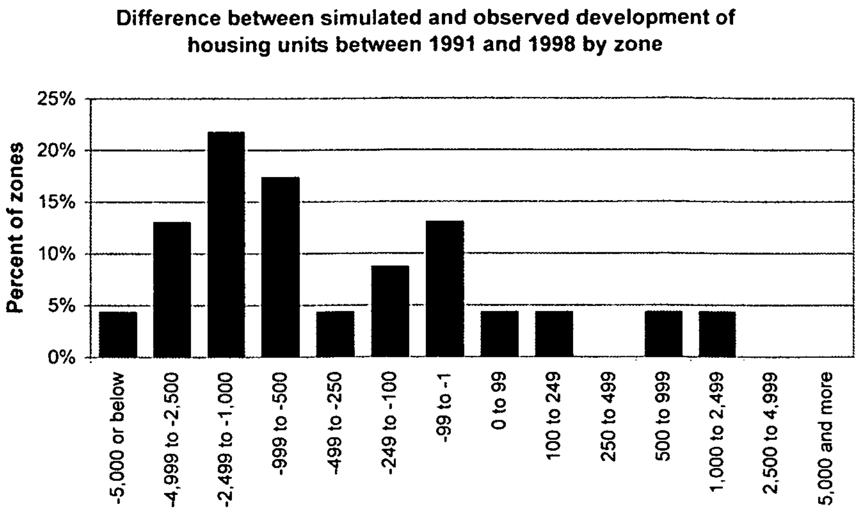


Figure 6.50: Difference in housing unit development from 1991 to 1998 between observation and simulation by MARS81

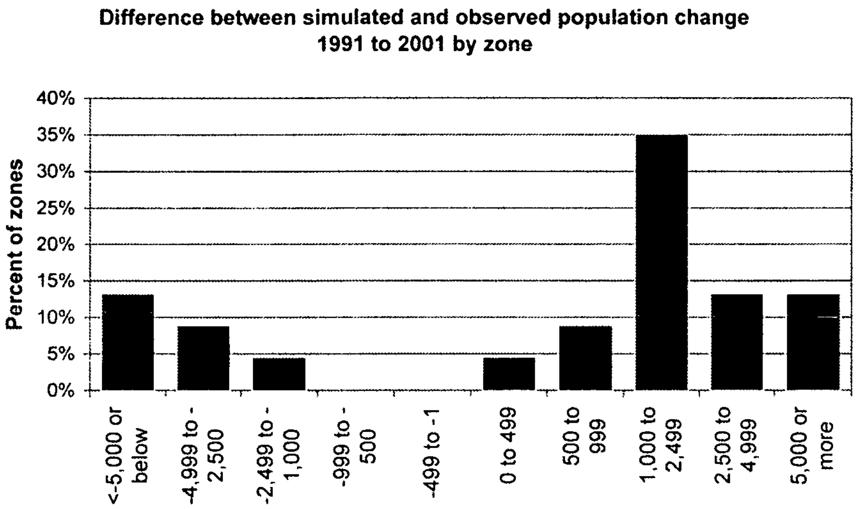


Figure 6.51: Difference in population changes 1991 to 2001 by zone between observation and simulation by MARS81

6.4.2 Naples model (Hunt, J. D., 1994)

The Naples model presented in (Hunt, J. D., 1994) is based on the MEPLAN general spatial interaction modelling framework. The model calibrated for 1981 values was used to predict household locations in the year 1989. Figure 6.52 shows the observed and modelled number of households in each zone inside Naples for 1989. (Hunt, J. D., 1994) gives no quantitative indication of the goodness of fit between the observed and simulated values. Figure 6.53 shows a similar comparison of observed and simulated (MARS81) population location for Vienna.

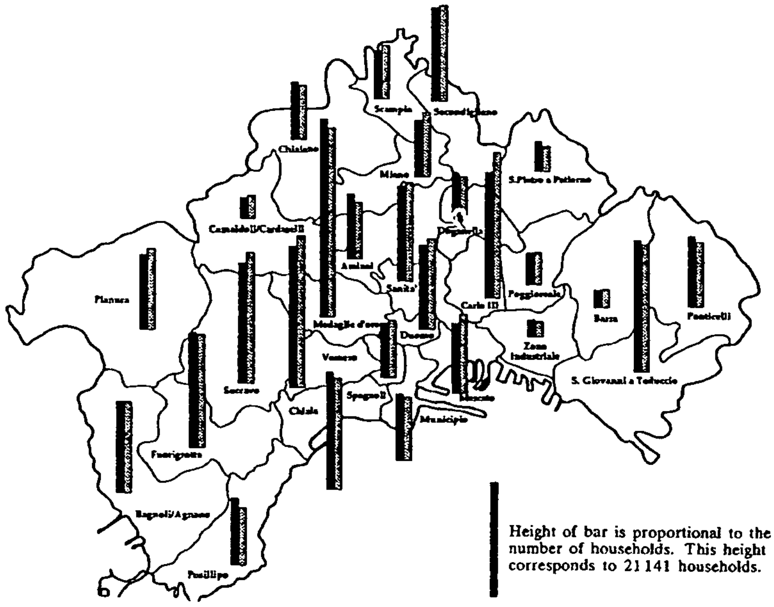


Figure 6.52: Number of households by zone within Naples in 1989, comparing values from model (black bar) and from independent estimates (dotted bars) (Hunt, J. D., 1994) p. 582

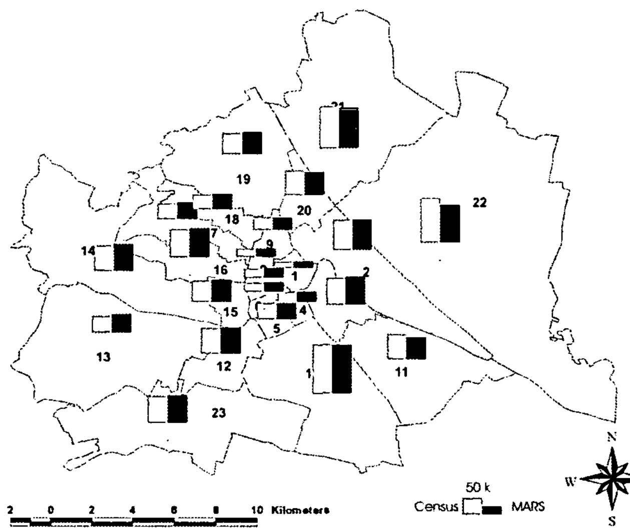


Figure 6.53: Number of residents by zone Vienna 2001, comparing values from the base year 1981 MARS model (black bars) and census data (grey bars)

6.4.3 LILT model (DSC & MEP, 1999)

(DSC & MEP, 1999) p. 86 reports two validation tests performed with LILT in the early years of its development. The first involves a calibration year of 1966 and a forecast to 1971. This produced a good fit for the distribution of population by group and jobs by sector (R^2 of 0.98), although some of the minor sectors and groups had a less good fit. The second calibration was for 1971 and a forecast for 1981. This produced a good match of residential change over time and car ownership forecasts.

6.5 Summary and conclusions

As recommended by (Sterman, J. D., 2000) a wide variety of model tests was performed. The results are presented in this chapter. The purpose and scope of MARS is described. A boundary chart lists the endogenous, exogenous and excluded variables. Extensive empirical testing was performed. MARS simulations were compared with observed data from different sources. The results of the back casting simulations are in general satisfactory. Nevertheless some areas, where the conformity between observed and simulated data was not that convincing, were identified. Explanations for the lower fit were found for all of them. Additionally it was possible to find promising ways for future improvements which are summarised in chapter 9.3 Suggestions for future MARS improvements. Plausibility of effects caused by the implementation of policy instruments was tested. All instruments used in the case study produce plausible results. The MARS performance was benchmarked with examples from the reviewed literature.

7. A FRAMEWORK FOR FINDING OPTIMAL POLICY PACKAGES

7.1 Finding optimal strategies

A framework for strategic policy appraisal with respect to sustainable urban planning was developed and applied in a series of research projects (Emberger, G., 1998), (May, A. D. et al., 2000). This appraisal framework work has been extended to cover sustainability and land use interactions (Minken, H. et al., 2003). Figure 7.1 gives an overview about decision making processes in reality and how the strategic policy appraisal framework simulates these processes. In real life, it is the stakeholder who defines targets. The decision maker weights the targets and compares the weighted result with the reality. Based on this comparison, decisions how to act are made. The whole process is built on personal assumptions of how policy measures affect reality.

The proposed assessment framework simulates system behaviour over time and is designed in a modular way. It consists of four modules:

1. policy instruments,
2. MARS,
3. objective functions and
4. an optimisation method.

Module 1 describes which policy instruments can be applied and/or changed in their values and how this affects the urban land use and transport system. A set of n different policy instruments and their associated values form the input into module 2, the land use and transport model MARS. MARS simulates the urban land use and transport system. Output indicators such as generalised costs, distance travelled by mode, local atmospheric emissions, CO_2 tonnes emitted and accidents are computed by MARS. Module 3, objective functions, transforms real life targets into mathematical functions based on MARS output. I.e. an objective function value is calculated from the relative changes of the indicators mentioned above in comparison to a do nothing scenario. This procedure is repeated n+1 times to produce an objective function vector for a given policy instrument matrix. The matrix and the vector are used to start module 4, the formal optimisation routine. Module 4 identifies the policy instrument combination, which gives the maximum value for the objective function considered. The output of the optimisation routine is a suggestion for a new set of policy instrument levels which is again input to the land use/transport model. This procedure is repeated until a convergence criterion is fulfilled. The policy instrument combination which gives the highest objective function value so far, can be seen as the "optimal strategy", i.e. a solution which is near to an at least local optimum. Sensitivity tests and a re-start of the optimisation with a tighter convergence criterion might be used to check and refine the strategy. A fuller description of the framework and its different parts is given in (May, A. D. et al., 2003) and (Minken, H. et al., 2003).

This framework is able to substitute the subjective assumptions made by the decision maker to a certain extent. As in general, the decision maker is not a transport and/or land use planning expert – the application of the framework is likely to result in a more objective and rational decision making process.

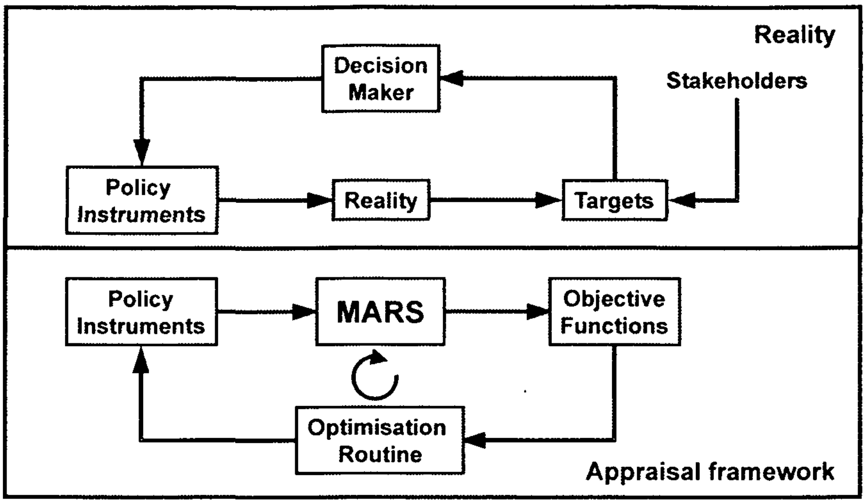


Figure 7.1: Decision making process in reality and its transformation into an assessment framework (Emberger, G., 1998)

The following sections give a brief overview about the modules 1, 3 and 4 of the appraisal framework.

7.2 Objective functions

A possible definition of the overall objective of sustainability is given in (May, A. D. et al., 2003) p. 12:

A sustainable urban transport and land use system

- *provides access to goods and services in an efficient way for all inhabitants of the urban area,*
- *protects the environment, cultural heritage and ecosystems for the present generation, and*
- *does not endanger the opportunities of future generations to reach at least the same welfare level as those living now, including the welfare they derive from their natural environment and cultural heritage.*

Seven relevant sub-objectives to achieve sustainability can be defined as follows (May, A. D. et al., 2003) p. 13:

1. economic efficiency,
2. liveable streets and neighbourhoods,
3. protection of the environment,
4. equity and social inclusion,
5. safety,
6. contribution to economic growth and
7. intergenerational equity.

Optimisation requires a quantifiable objective function to be maximised (or minimised). The objective function used in the appraisal framework presented here is an attempt to take into account these seven sub-objectives of sustainability. The basic idea behind the objective function was developed by (Minken, H., 1999). Further developments were made in different research projects and case studies (May, A. D. et al., 2000), (Knoflacher, H. et al., 2000), (Minken, H. et al., 2003). The core of the definition of sustainability applied here is sub-objective number seven "intergenerational equity". The objective function is a linear combination of the net present value over a period of 30 years and the annual net benefit of the last year of this period. This approach is seen as an approximation for the sub-objective of intergenerational equity. The last year is constrained to satisfy certain environmental and financial requirements so as to represent as far as possible the welfare of future generations.

The first sub-objective is dealt with by discounted net present value. For the sub-objectives two to six, indicators have been defined. For some of the years, there may be targets on some of the indicators, or there may be other constraints on their levels. It is not assumed that the indicators that go into the constraints cannot be used in the objective function, neither is it assumed that all indicators need to be included in the objective function. Some may be used only as constraints or be kept out from the optimisation altogether[94]. The evaluation period is taken to be 30 years though the sustainability issues relate to an even longer term.

For the mathematical description and more details see in the annex section 12.5 Objective function p. 234 and (Minken, H. et al., 2003).

7.3 Policy instruments

7.3.1 General issues

Policy and/or planning decisions can be classified as matters of investment, regulation, or pricing. A policy may involve (a) changing the supply of transport or other factors by investment or disinvestment; (b) controlling demand by enforcing regulations that do not allow people to do something they would prefer to do; or (c) modifying prices (and hence indirectly modifying supply and/or demand) by imposing taxes or granting subsidies. A most important case is the regulation of land supply by zoning controls (Hunt, J. D. and Simmonds, D. C., 1993) p. 223.

Potential instruments cover a wide range of possibilities (May, A. D. et al., 2001). The formal optimisation process will lend itself well to optimisation of strategic instruments which form the basis of an overall package or plan. Strategic instruments can be considered as those instruments which are expected to have a significant impact upon indicators and objectives, or which impact upon a significant area of the urban region. Furthermore most strategic instruments have some level which may be varied e.g. a price which can be optimised.

The policy instruments may consist of differing types of instruments as suggested below :

[94] E. g.: No appropriate indicator for the objective liveable street was found at the MARS spatial aggregation level.

- Continuous overall policy variables are policy variables that are used to change the relative overall level of an instrument applied to the whole of the study area or a significant part thereof. Examples would include changes in the relative level of the fuel tax, parking charges in different zones by the same percentage, changes in uniform tolls around a cordon, uniform changes in public transport fares and frequencies.
- Discrete policy variables are binary variables which describe an instrument as either used or not used (on/off). Whether to implement a large road investment project is one example of a discrete instrument, i.e. the investment project is either implemented or not implemented. Some discrete instruments introduce an associated continuous variable and the dimension of the problem increases, e.g. different cordon locations may be considered as discrete options within the optimisation process with the charge as an associated variable.
- Other dimensions. These basic variables can be given other dimensions in space, by time of day and by other instrument specific attributes. For example pricing instruments can be given different levels in the peak and off-peak as suggested by marginal cost pricing. Parking charges can vary by time of day, duration of stay and by zone within a city. Property taxes may vary according to zone and use of floor-space.

Continuous policy instruments can in the most general case be applied at any level in any one year ($t = 0,\dots,30$). Thus, for a single instrument there could be 30 different levels in a single MARS run. As an example: For finding the optimal public transport fare and frequency levels in the peak and off peak period an optimisation problem in 120 dimensions would have to be solved. To optimise these two types of instruments is already a challenging and time consuming task. As the goal was to formulate strategies consisting of more different types of instruments, it was decided to cut the dimensions of the optimisation problem down. Therefore the variability of instruments over the evaluation period of a MARS run was limited. The concept of "policy profiles" was introduced. Policy instrument levels were allowed to be specified (and later optimised) for two points in time, t_A the implementation year and t_L the long run year (Figure 7.2). Thus we need to specify the year of implementation t_A and the number of years until a long run value is to be expected.

The vector of levels on instruments in the short-term year are denoted X_A and levels on instruments in the long-term year are denoted X_L. The levels on instruments in intermediate years can be determined by interpolating between the instrument levels in year t_A and t_L while the level is then assumed constant for any year after the long run year as depicted in Figure 7.2. The long run year is chosen such that any time-lagged responses in the model have taken full effect by the year t_H which is taken to be the final horizon year of the evaluation period.

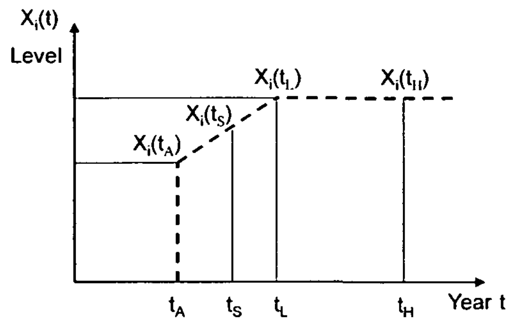


Figure 7.2: Instrument profile for the continuous instruments $X_i(t)$

One may wish to consider the implementation year of certain instruments as a variable to be optimised. This would be feasible but it adds another dimension to the problem and the merits of such an investigation should be viewed in light of the whole set of instruments to be evaluated (i.e. some judgement is needed to decide if the implementation year would affect the objective function significantly).

Policy measures are influencing generalised costs either by changes in travel time or costs or both. The interaction of some policy instruments with travel time and costs is shown in Figure 7.3.

Policy instruments are written white on black ground in Figure 7.3. Time and costs for the different modes and protagonists are written black on white ground. As an example how to read Figure 7.3: If road capacity CAP is increased (indicated by "+"), investment costs INV_{PC} for operators will increase ("+"), travel time private car TT_{PC} will decrease ("-"), while travel time non motorised $TT_{P\&B}$ will increase ("+"). The latter is due to increased separation effects of the road network. The consideration of this relation is one of the unique features of MARS.

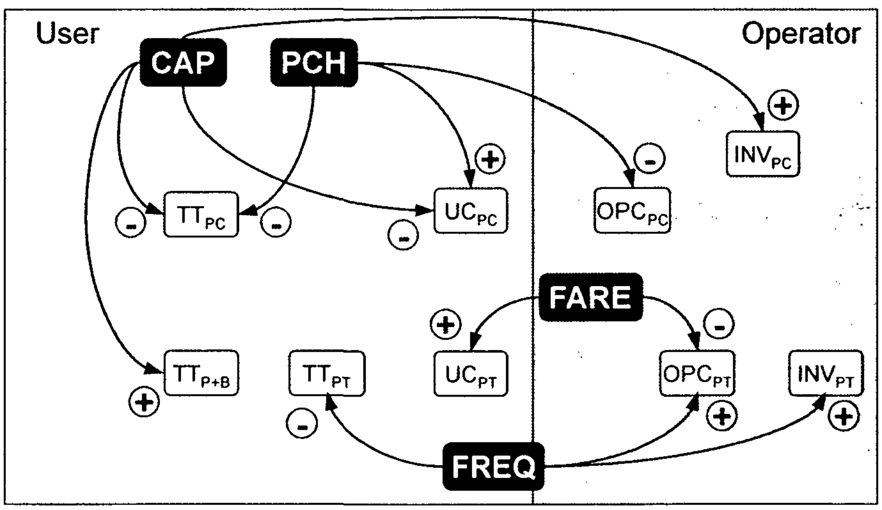


Figure 7.3: Effects of policy instruments on travel time and costs for users and operators

Legend:

Modes:	Time & costs:	Policy measures:
PC .... Private car	TT .... Travel time	CAP .... Road capacity
PT ..... Public transport	UC ... User costs	PCH .... Parking charges
P+B... Pedestrian & bike	OPC Operating costs	FREQ..... Public transport frequency
	INV .. Investment costs	FARE ..... Public transport fare

7.3.2 Specific policy instruments considered in MARS

Table 7.1 shows the full range of policy instruments intended to be used with MARS. Some of the instruments are not yet fully applied and tested (indicated by the term "Intended" in column status). Nevertheless MARS is prepared to take these instruments into account. The term "Manual" indicates that the instrument currently cannot be used in the automated optimisation procedure. Manual changes by the model user are necessary. The instrument can be used in scenario testing.

Table 7.1: Policy instruments modelled in MARS

Policies	Dis-aggregation				Suggested range	Status
	spatially	time of day	spatially & time of day	none		
Pedestrians						
Pedestrianisation	X				0/1	Intended
Public Transport						
New PT-Infrastructure	X				0/1	Applied and tested
Fares		X			-50% to +200%	Applied and tested
Frequency		X			-50% to +100%	Applied and tested
Private Car						
New Roads	X				0/1	Applied and tested
Road Pricing			X		0 to +5 €	Applied and tested
Parking charges			X		0 to +5 €	Applied and tested
Road capacity increase/decrease		X			-20% to +20%	Applied and tested
Fuel tax				X	0 to +200%	Applied and tested
Parking supply	X				0/1	Intended
Land use measures						
Controls on development	X				0/1	Manual
Land use charges	X				0 to +5 €/m²	Intended

- **Fuel price**

The policy instrument fuel price affects the costs to travel by car. Normally fuel price does not fall under the competence of city authorities. Nevertheless there is at least on example of a local fuel tax in Tromso, Norway (KonSult, 2002). Although this policy instrument is rather hypothetical, it is included in the case study. No investments or operation costs are associated with the instrument fuel price.

- **Road charge**

The policy instrument road charging affects the costs to travel by car. No road charging regime is currently in use or planned for the city of Vienna. MARS considered road charging in the form of an area licensing, i.e. each car driving into a defined area is charged. Road charging as applied in MARS has effects rather similar to the instrument parking charges. Unlike for parking charges investment and operation costs are necessary to install a road charging regime. As the Vienna city authorities rely strongly on parking charges and as the effects are rather similar, road charging is not considered in the Vienna case study.

- **Parking charge**

The policy instrument parking charges affects the costs to travel by car. Currently parking charges are applied in the Viennese inner city districts 1 to 9 and 20. All public parking space is short term charged parking space. Residents can apply for an exemption from short term parking in their district of residence. A charge has to be paid for this exemption (Stadtentwicklung Wien, 2003). The height of the charge is given in the annex section 12.6.1 Transport related data p. 241. The policy instrument short and long term parking charges as used in MARS can either be an extension of the charged area or an increase of charge in the current area. The parking situation in uncharged areas neighbouring charged areas is tense due to car users trying to evade the charges. Local decision makers therefore want to introduce parking charges in these districts too. Nevertheless the city government strongly opposes against an extension of the charged area. It is very unlikely that the charged area will be extended even in the long run. Therefore an increase of the charge in the existing area is used as policy instrument in the case study. No investment or additional operating costs are associated with this policy instrument.

- **Road capacity**

The policy instrument road capacity changes the supply for car traffic and affects the average car driving speed. Road capacity increases in MARS are meant as the application of soft measures like car optimised traffic signals, telematics etc. Reductions are meant as traffic calming. Pedestrians are affected too by road capacity changes. Car optimised traffic signal programmes imply longer waiting times at signals for pedestrians. Wider roads or not allowing pedestrian crossings at all arms implies detours on pedestrians. On the contrary traffic calming reduces their waiting times and detours. Investment and operation costs for the instrument road capacity are shown in the annex section 12.6.4 Policy instrument data.

- **Road infrastructure**

The city of Vienna is planning a highway like ring road connecting its South-Eastern and North-Eastern parts (PGO, 2003). Figure 7.4 sketches the implications of this ring road for the MARS model. The main affected model zones are the districts 10, 11 and 22. The additional supply with road infrastructure affects driving speed in the MARS model. The estimated effects and costs can be found in the annex section 12.6.4 Policy instrument data.

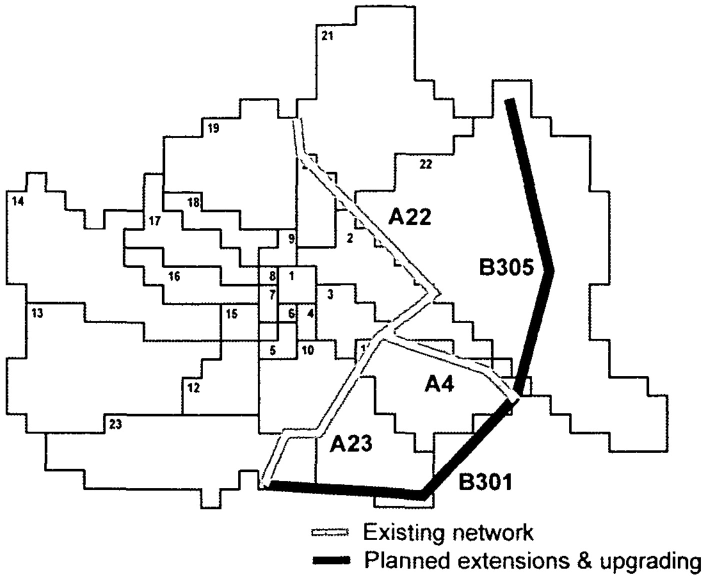


Figure 7.4: Policy instrument road infrastructure – ring road

- **PT fare**

The policy instrument PT fare affects the costs to travel by PT. Vienna has an integrated fare structure. A single ticket for any trip within Vienna has the same fare. Most PT users in Vienna own monthly or yearly season tickets. This makes it difficult to estimate the fare for a single trip (see in the annex section 12.6.1 Transport related data). MARS is capable of considering a differentiated fare structure. In the optimisation procedure the policy instrument PT fare is considered as a percentage change of the existing structure, i.e. the same percentage change is applied to the fare for each OD-pair. For single runs it is of course possible to change fare structure and height. No investments or operational costs are associated with the instrument PT fare.

- **PT frequency**

The policy instrument PT frequency affects the supply with public transport, i.e. headway times, waiting times and changing times. In the optimisation routing MARS considers the instrument PT frequency as a percentage change of the do-minimum headway times. For single runs it is possible to change PT frequency OD-pair wise. For an increase in frequency investment costs for additional rolling stock and additional operation costs arise. In the case of a frequency decrease benefits from selling rolling stock and a reduction of operation costs might arise. In Vienna most of the staff of the PT operator Wiener Linien has the status of civil servants, i.e. they can't be sacked unless they are found guilty of real severe offences. That means that today no direct reductions in personal costs can be associated with PT frequency decreases in the Vienna case study. New employees do not get the civil servant status anymore. So this issue will change in the long run. For the estimation of investment and operating costs see in the annex section 12.6.4 Policy instrument data.

- **PT infrastructure**

The city of Vienna currently plans to extend the three metro lines U1, U2 and U6 within the next years (Stadtentwicklung Wien, 2002; Stadtentwicklung Wien, 2003; Stadtentwicklung Wien, 2003; Stadtentwicklung Wien, 2003). Work is already ongoing on the lines U1 and U2. The U1 extension should be opened in 2006 (Wiener Linien, 2000). The U2 extension should be opened before the European football championships in 2008 (Stadtentwicklung Wien, 2003). The U6 extension should be finished in the period 2013 To 2015 (Stadtentwicklung Wien, 2003). Figure 7.5 sketches the implications for the Viennese MARS model. The main beneficiaries are the districts 21 and 22, North of the river Danube, and the districts 2 and 10. The metro line extensions affect the transport supply: access and egress time, waiting time, travel speed and changing time. The estimates for the quantified effects as well as for the infrastructure investments and operating costs are shown in the annex section 12.6.4 Policy instrument data. In the current version of MARS only one infrastructure project can be considered. For the model calculations in the case study it is therefore assumed that all metro extensions operate from 2006 on.

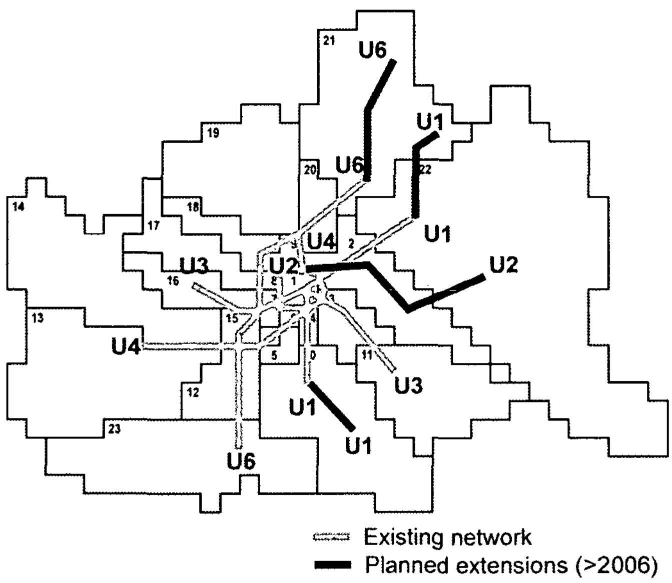


Figure 7.5: Policy instrument PT infrastructure – planned Viennese metro extensions

7.4 The optimisation method

Given a broad set of policy instruments numerous combinations are possible. The number of combinations increases exponentially with the number of instruments. To find the best strategy the use of formal optimisation routines was suggested (Fowkes, A. S. et al., 1998). The formal optimisation process results in second-best strategies as opposed to "first-best" strategies which assume that social marginal costs can be charged across all modes by some future GPS based system. Two different optimisation routines are presented in the following sections: the regression analysis based approach as suggested by (Fowkes, A. S. et al., 1998) and an automated optimisation routine as suggested by (Minken, H. et al., 2003).

7.4.1 The regression method

Figure 7.6 to Figure 7.11 illustrates how the regression based optimisation routine works. First an initial set of objective function values with different policy instrument combinations has to be calculated. (Fowkes, A. S. et al., 1998) suggest (2*n + m + 5) initial model runs. Where n is the number of continuous policy instruments and m is the number of discrete policy instruments. The regression method uses linear and quadratic approximations for continuous instruments. Therefore the degree of freedom is two. Dummy variables are used for the discrete instruments.

In Figure 7.6 the two continuous instruments

- *percentage change of public transport fares and*
- percentage of public transport frequency

are considered. The minimum number of initial runs should therefore be nine. The ten grey diamonds show the initial objective function values and their associated policy instrument levels.

Figure 7.7 shows the surface of the regression model resulting from the ten initial values. The white point shows the maximum objective function value predicted by this regression model. An additional transport model run using the policy instrument values suggested by the regression model is performed. The resulting objective function value (the black point) is in this case far from being near to the predicted objective function value.

The strategic transport models developed at TUW-IVV are suitable for the calculation of "policy surfaces" (May, A. D. et al., 2001). The resulting surface is shown in different shades of grey in Figure 7.8. In the example shown here the policy surface is very rugged. The reason is that a "deregulated" objective function (Knoflacher, H. et al., 2000) is used. Deregulated means that the public transport is operated privately and the operator requires a return of about 15%. If this target is not met the objective function is penalised. It could be easily seen in Figure 7.8 that it is hard or even impossible to get reasonable estimates for a highly penalised objective function using a quadratic regression model.

After the comparison of the predicted maximum and the model output, additional policy instrument combinations are specified by the user. The calculated objective function values are shown as grey stars in Figure 7.9. This additional information is used to estimate a new regression model (Figure 7.10). Once again the suggested best performing instrument combination is tested in a model run. Now the prediction and the model result are quite near. The convergence criterion is fulfilled (Figure 7.11) and the regression approach succeeded.

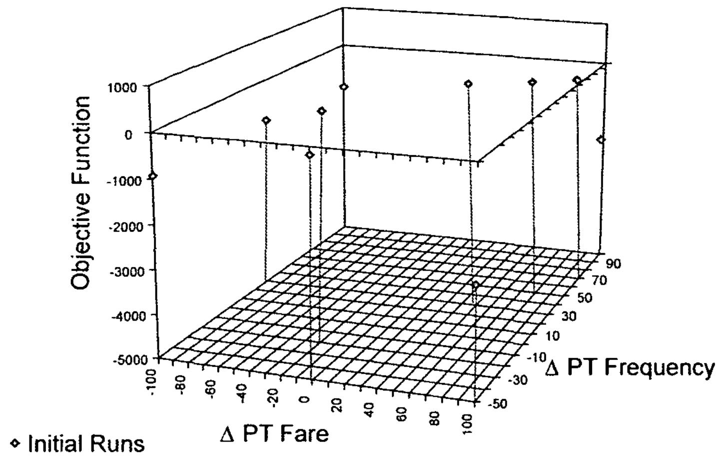


Figure 7.6: The regression method – initial runs

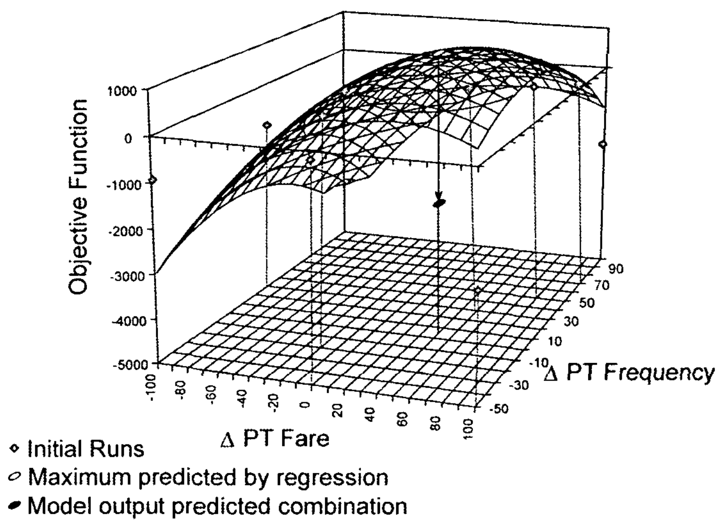


Figure 7.7: The regression method – prediction and model run

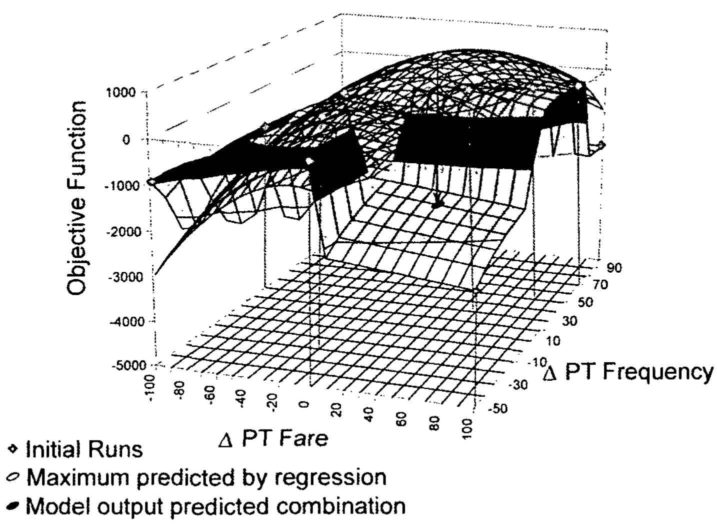


Figure 7.8: The regression method – prediction and policy surface

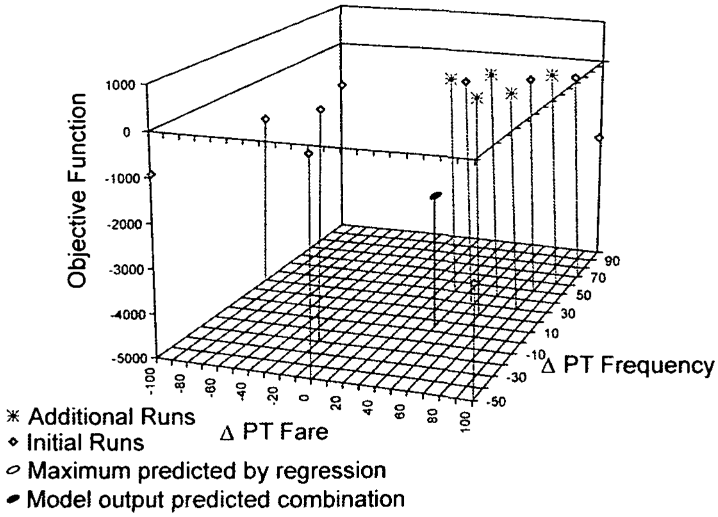


Figure 7.9: The regression method – additional runs

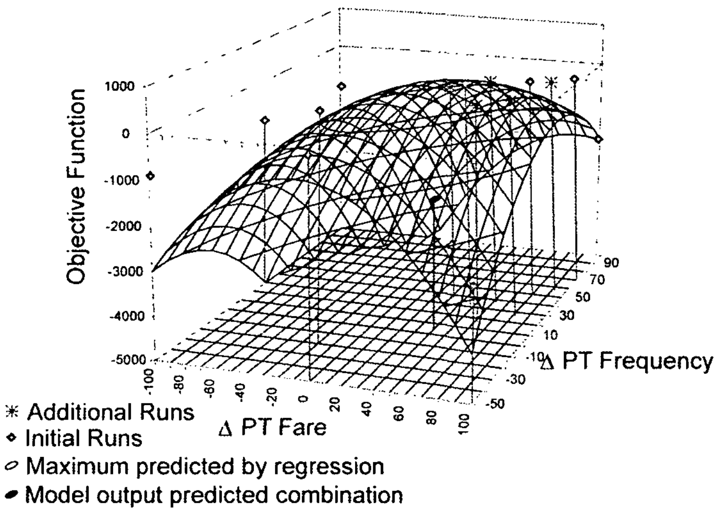


Figure 7.10: The regression method – new prediction

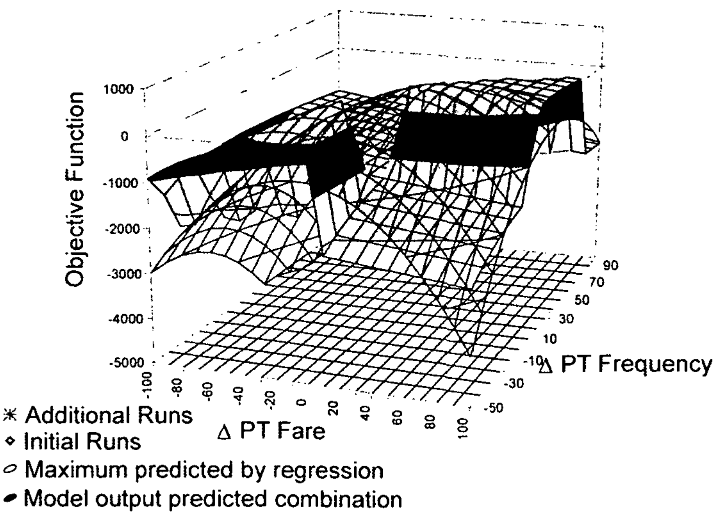


Figure 7.11: The regression method – convergence

7.4.2 The automated method

The method applied within MARS is based on the downhill simplex method in multi-dimensions (Nelder, J. A. and Mead, R., 1965). It solves a multidimensional minimisation, i.e. finding the minimum of a function of more than one independent variable. The method requires only function evaluations, not derivatives. The method is applied to MARS thus allowing an automated optimisation. A more detailed description is given in the annex section 12.4 Optimisation framework and (Minken, H. et al., 2003). Figure 7.12 illustrates how AMOEBA calculates new policy instrument values.

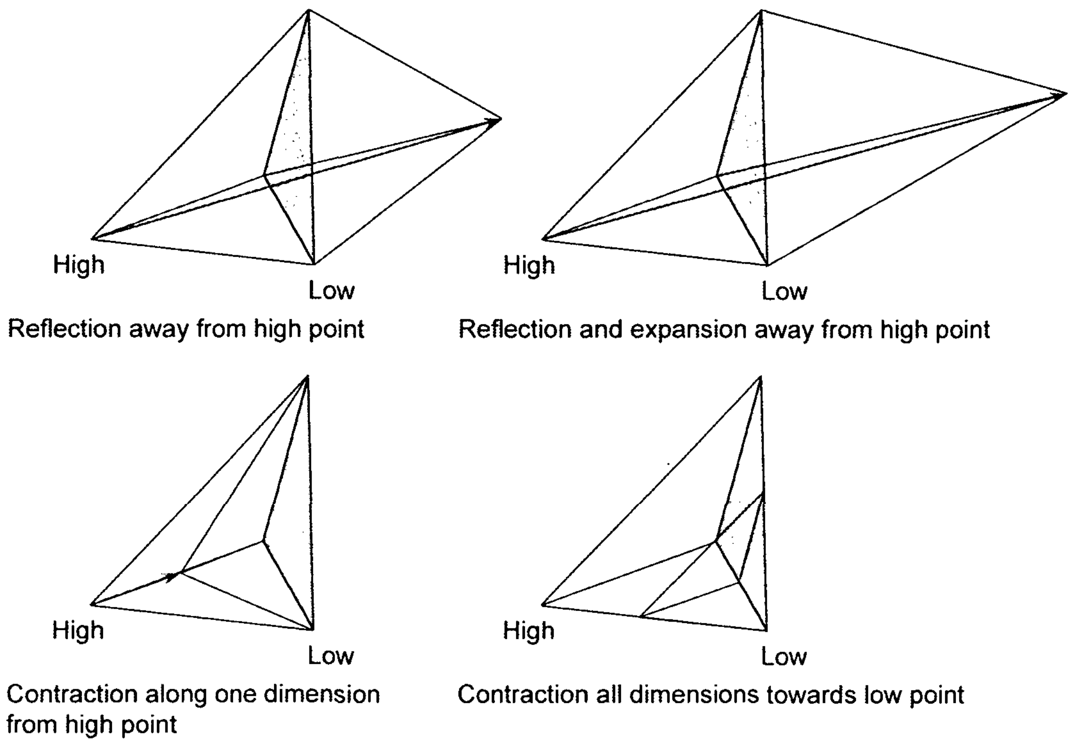


Figure 7.12: The four possibilities to calculate new policy instrument values using the AMOEBA algorithm

To start an optimisation the MARS user has to specify the implementation and long run years, the upper and lower bounds of the policy instruments and which constraints, if any, should be considered in the objective function. An initial set of policy instrument values used as input vectors is calculated by the optimisation routine (see Figure 7, Init). MARS calculates the behavioural changes and the objective function values for each policy instrument vector. These are used to suggest new policy instrument values. As the instruments can vary by the period of time and in the implementation and the long run year the total number of variables to be optimised in this example is 18. In Figure 7.13 the thick line shows the convergence of the objective function. The thin black lines show the development of the corresponding relative policy instrument values within the allowed range[95]. The convergence criterion was fulfilled after about 320 MARS runs. The tolerance chosen in this optimisation was 0.05.

[95] I.e.: The lower bound is equal to 0, the upper bound is equal to 1.

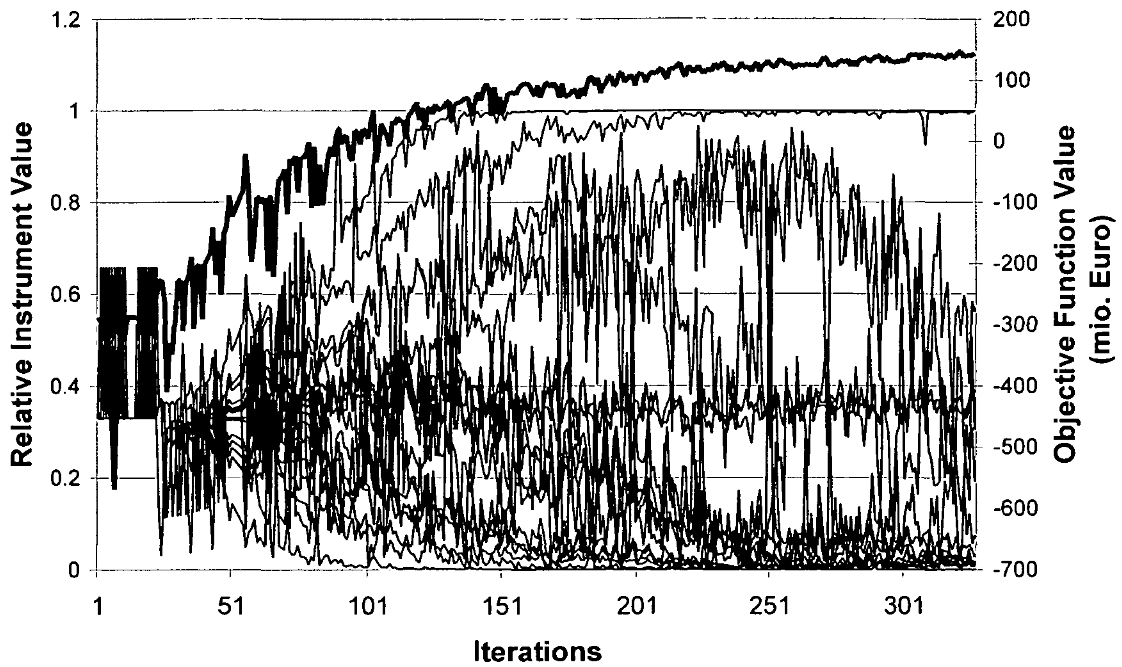


Figure 7.13: Example convergence of the optimisation procedure

8. VIENNA CASE STUDY

8.1 Introduction

A predecessor of the MARS version presented here was applied to six European cities within the project PROSPECTS[96]. The cities are Edinburgh, Helsinki, Madrid, Oslo, Stockholm and Vienna. A series of benchmarking tests was performed for the different case study cities. The calibrated models were used to perform case studies using the assessment framework presented in chapter 7. A framework for finding optimal policy packages. A common set of policy instruments was tested in all six cities. These instruments are: public transport fares and frequency both for peak and off-peak and fuel price for private car. Individual tests using a wider set of instruments (infrastructure investments, road charging, parking charging, etc.) were performed in some of the cities. Results of this case studies are presented in (Pfaffenbichler, P. and Emberger, G., 2003).

The Vienna MARS model used in the case studies was set up for the base year 2001. Data from the year 2001 were not available for all parameters. If this was the case, the most current data available have been used instead. The data used in the MARS model are summarised in section 12.6 Data used in the Vienna MARS.

8.1.1 Objectives of the city of Vienna

Fundamental Viennese objectives, policies and measures of urban and transport planning are formulated in the Urban Development Plan (Stadtplanung Wien, 1994) and the Traffic Concept (Stadtplanung Wien, 1994). The Traffic Concept includes objectives such as reduction of traffic impacts on the environment and health, an increase of traffic safety and a reallocation of urban space for pedestrians and cyclists. To achieve these objectives, a reduction in urban sprawl and traffic volumes and an increase in the share of public transport and the slow modes pedestrian and cycling are necessary. Several indicators have been defined to monitor the achievement of the objectives, such as modal split, traffic safety (number of accidents, injuries, fatalities), noise level, air pollutants and CO_2 (May, A. D. et al., 2003). A quantitative target formulated in the Traffic Concept 1994 is a reduction of car shares to 25% by the year 2010[97] (Figure 8.1).

The membership in the climate alliance for the protection of the atmosphere commits the city of Vienna to reduce its CO_2-emissions by 50% by the year 2010 (compared to 1987)[98] (Herry, M. et al., 1998).

In 2001 the project Transport Management Vienna (*Verkehrsmanagement Wien: VEMA*) was started (Hermann, E., 2000). A major task of this project is the

[96] 5th RTD framework: PROSPECTS (**P**rocedures for **R**ecommending **O**ptimal **S**ustainable **P**lanning of **E**uropean **C**ity **T**ransport **S**ystems).

[97] Resolution by the local council by 12/03/1993. Stadtplanung Wien (1994). step 1994 - Stadtentwicklungsplan für Wien; *Beiträge zur Stadtforschung, Stadtentwicklung, Stadtgestaltung,* **Band 53**, p. 167.

[98] My paraphrase. Original in German: *Durch den Beitritt zum "Klimabündnis zum Schutz der Erdatmosphäre" verpflichtete sich die Stadt Wien dazu, die CO_2-Emissionen bis zum Jahr 2010 (bezogen auf 1987) um 50% zu senken.*

renewal of the traffic control computer system. VEMA has the following overall objectives (VEMA, 2003)[99]:

- *Intelligent, environmentally and socially compatible regulation (control) of the transport system in Vienna as living space and location for businesses and firms following the guidelines of the Urban Development Plan (STEP).*
- *Reinforcing the trend in modal share in the inner districts and stabilising modal share in the outer districts.*

A specific objective under the topic *Optimising by control*[100] is:

- *... increase the capacity of transport infrastructure (bottlenecks, intersections, conflict points) ...*[101]

Targets process indicator modal share

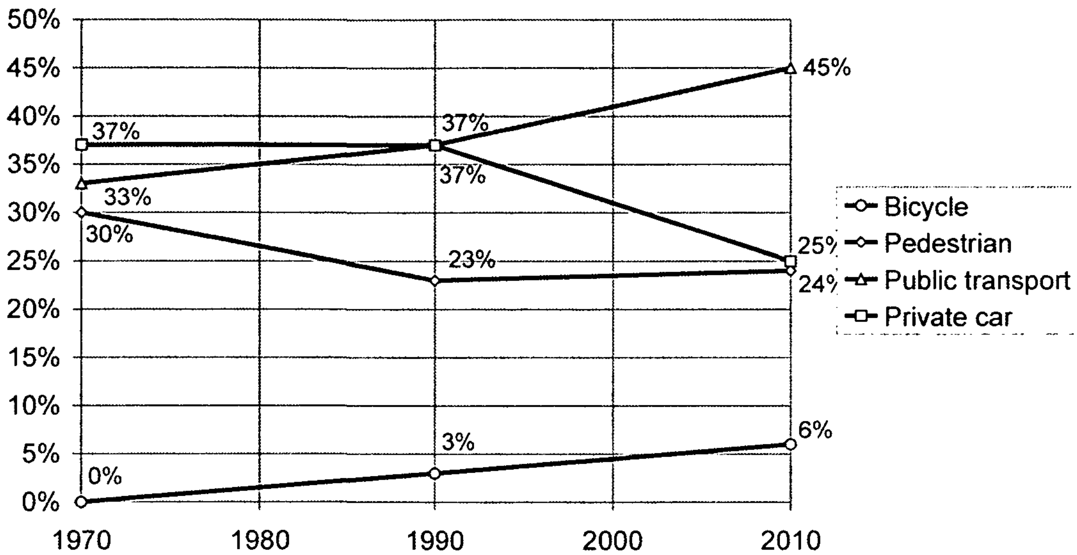


Figure 8.1: Modal split objectives city of Vienna (Stadtplanung Wien, 1994) p. 12

8.1.2 Transport projects in Vienna

Two major transport infrastructure projects are currently in the planning and/or construction phase: a metro line extension and a highway like ring road. A brief description of these projects is already given in section 7.3.2 Specific policy instruments considered in MARS. The ongoing Transport Management Vienna programme will renew the traffic control computer system and install traffic

[99] My paraphrase. Original in German:
- *Intelligente, umwelt- und sozialverträgliche Regelung (Steuerung) des Verkehrsverhaltens in Wien als Lebensraum und Wirtschaftsstandort nach den Vorgaben des Stadtentwicklungsplanes (STEP).*
- *Verstärkung des Trends des Modal Split in den Innenbezirken und Stabilisierung in den Außenbezirken.*

[100] My paraphrase. Original in German: *Optimierung durch Steuerung.*

[101] My paraphrase. Original in German: ... *die Erhöhung des Durchsatzes einzelner Verkehrseinrichtungen (Engpässe, Knoten, Konfliktpunkte)...*

management measures (see section 8.1.1). It is assumed that these measures will increase peak period capacity by 10%.

8.1.3 Study area

The city of Vienna is situated in the east of Austria, not far from the borders to Hungary, Slovakia and the Czech Republic (Figure 8.2). Vienna, the capital of Austria, has a population of about 1.6 million (city area: 415 km²). It is by far the largest city of the country (1/5 of the population of Austria live in Vienna). The Vienna MARS uses the 23 municipal districts as analysis zones. The Vienna model consists of 23 zones as shown in Figure 8.3. These zones correspond with the Viennese administrative districts.

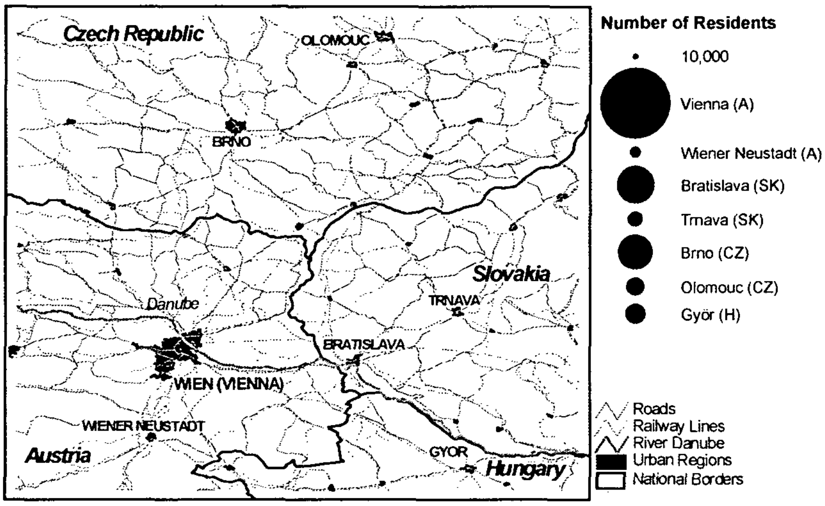


Figure 8.2: The greater Vienna region

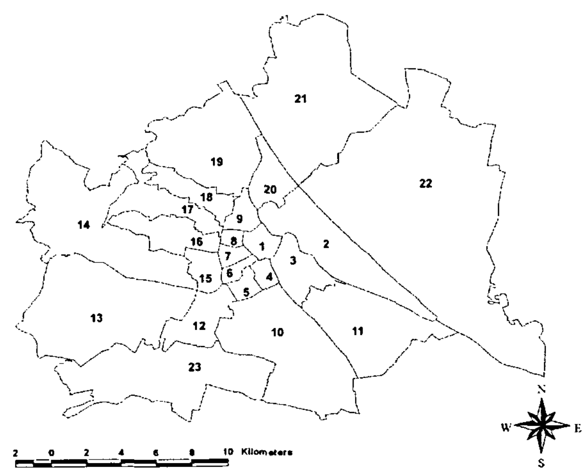


Figure 8.3: Vienna case study area and analysis zones

8.1.4 Aim of the case study

The effects of the planned and ongoing transport projects are estimated using the MARS model. The results are compared with objectives of the city of Vienna. It is assessed whether the projects contribute to the achievement of the objectives or not. Furthermore the case study assesses whether it is possible to achieve the official objectives of the city of Vienna and what kind of action would be needed to do so.

The last part of the case study searches for the strategy resulting in the highest sustainability objective function value (section 7.2 and 12.5). An automated optimisation algorithm (section 7.4.2 and 12.4) is used for this task. The resulting policy is compared with the official Viennese objectives and targets.

8.2 Do-minimum scenario

In the do-minimum scenario in principle nothing on the transport supply and cost side changes over the forecast period. The situation in the base year is kept constant. There are two exceptions: there might be endogenous road infrastructure development following substantial developments in housing business stock and fuel costs change with travel speed and therefore traffic volumes.

The do-minimum situation is characterised by an outward migration of workplaces as well as residents. Figure 8.5 illustrates the location changes over the simulation period of 30 years in 6 years steps. Workplace and population densities are plotted over a sketch of Vienna. I.e. the volume over a district represents the number of workplaces or residents. As well workplaces as residents move from the inner city into the outskirts, especially the southern district 23 and the northern district 22. The workplace and household movements in the do-minimum scenario contradict the Viennese goal of stopping urban sprawl.

The do-minimum mode split development over time is characterised by an increasing share of car trips and a decreasing share of slow mode and public transport trips (Figure 8.4). The official targets as described in section 8.1.1 not met, neither in the base year 2001 not in the final target year 2010. The target and the MARS prediction show opposite trends. The share of car trips in 2010 is about 60% higher than the target value of 25%.

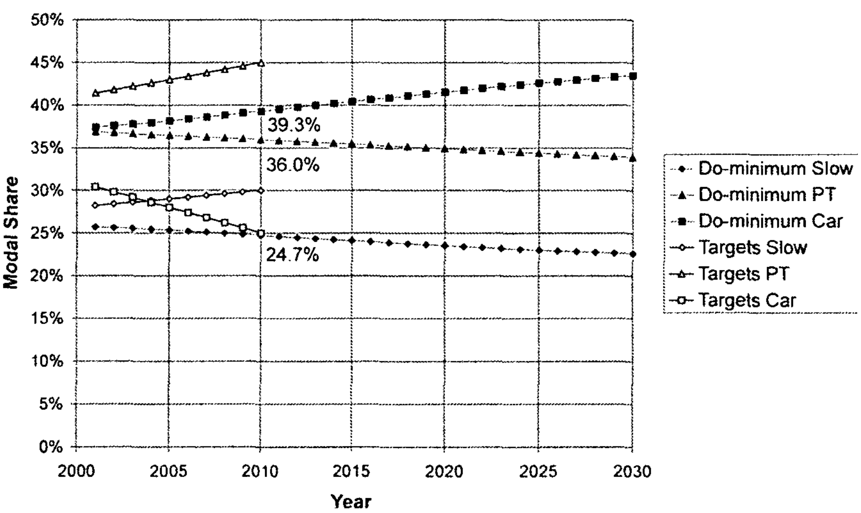


Figure 8.4: Development of modal share in the Vienna do-minimum scenario in comparison with the official targets (Stadtplanung Wien, 1994)

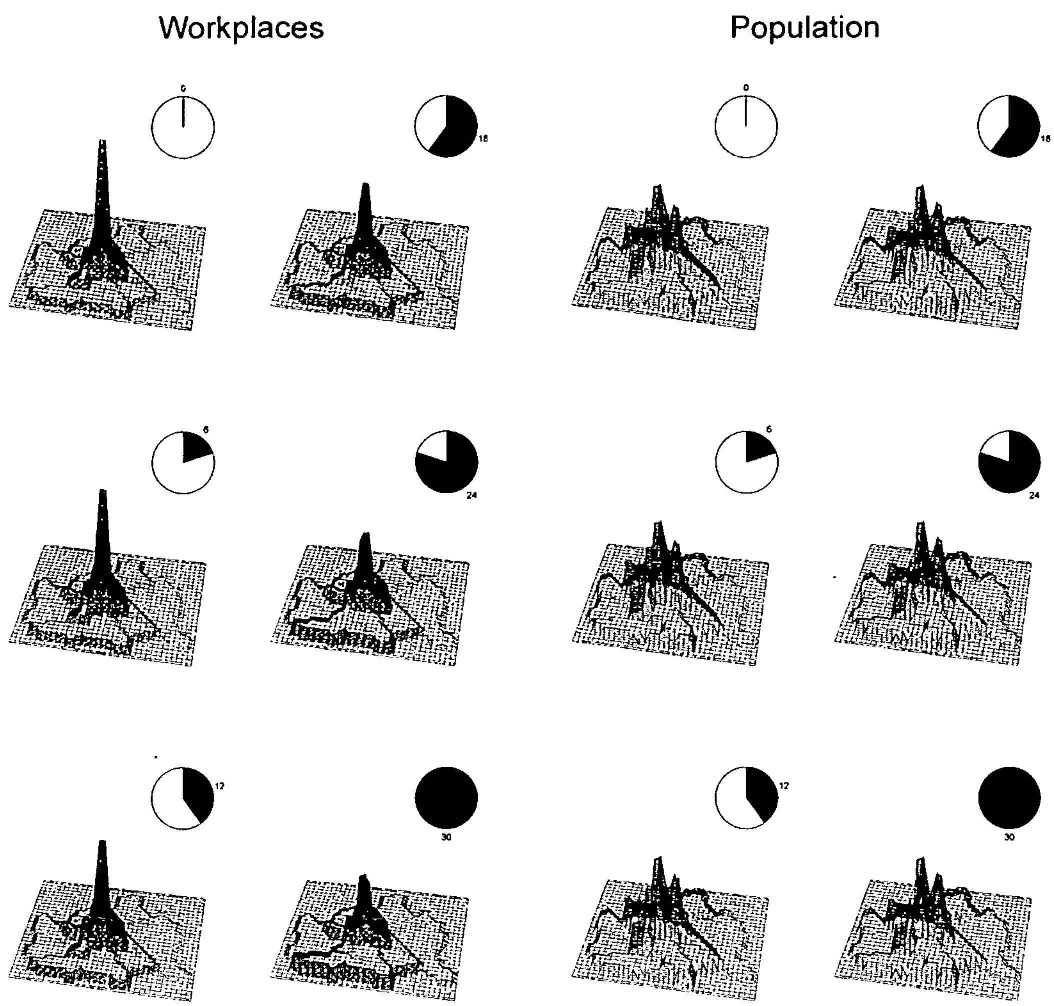


Figure 8.5: Temporal changes in workplace and population location Vienna do-minimum scenario

Figure 8.6 shows the development of transport caused CO_2-emissions in the Vienna do-minimum scenario. As there are no changes in public transport infrastructure or service there are no changes in public transport CO_2-emissions. CO_2-emissions caused by car traffic increase continuously. The 50% reduction target cited in section 8.1.1 is highly unrealistic, if achievable at all, in the transport sector. Therefore holding CO_2-emissions at least constant at the 2001 level is used as target in the case study.

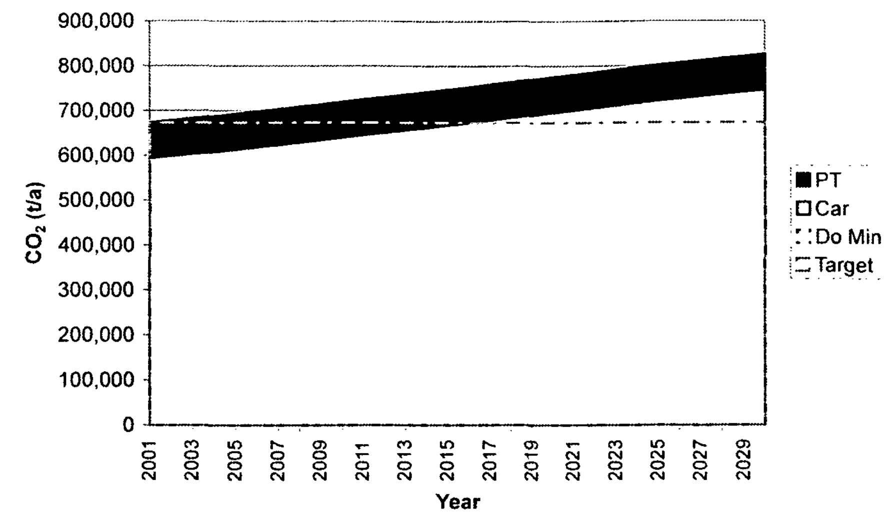


Figure 8.6: Development of CO_2-emissions in the Vienna do-minimum scenario

8.3 Metro line extension

The planned metro extensions increase the share of public transport slightly (Figure 8.7). The shares of slow modes and car trips are reduced slightly. The instrument metro line extension contributes to the target of reducing car share, but the difference to the do-minimum scenario is nearly insignificant. Additional public transport trips mainly substitute former slow mode trips.

The metro line extension contributes to the target of reducing CO_2-emissions. Nevertheless the contribution is marginal (Figure 8.8). The reduction is about 4,500 tons in 2010, which is just about 0.6% of the do-minimum emissions in 2010.

The metro line extension initialises a migration of households into the districts 21 and 22 north of the river Danube (Figure 8.9). The instrument metro line extension therefore contradicts the target of reducing urban sprawl. The effects on workplace location are marginal.

Table 8.1 presents the results of the cost benefit analysis for the instrument metro line extension. Public transport users benefit from substantial time savings. Car uses benefit slightly in the form of time and money savings due to less car trips and the speed flow relationship. Households have small losses due to rent changes.

On the operator and government side public transport operators have high losses due to the expensive investments and additional operation costs. There are small losses for operators and government due to a decrease in fuel taxes and parking charges. Landlords gain small benefits. External costs are slightly positive.

As well the present value of finance PVF[102] (-1,931 mio. Euro) as the economic efficiency objective function EEF[103] (-1,458 mio. Euro) and the sustainability objective function SOF[104] (-126.1 mio. Euro) are highly negative. The summary of the cost benefit analysis is that public transport operators and public authorities have to pay a high price for some time benefits for public transport and car users[105]. From a strategic viewpoint the metro line extension cannot be recommended.

[102] ***Present value of finance:***
The annual value of finance of a strategy is the net result of the government budget (revenue minus payments). The present value of this (see discounting) is the present value of finance (PVF). In strategic planning, there will usually be a constraint on the present value of finance, stemming from the need to balance government budgets in the long run and the need to keep public expenditure on transport within certain bounds.
Minken, H., Jonsson, D., Shepherd, S. P., Järvi, T., May, A. D., Page, M., Pearman, A., Pfaffenbichler, P. C., Timms, P. and Vold, A. (2003). Developing Sustainable Land Use and Transport Strategies - A Methodological Guidebook; *TOI Report*, **619**; Institute of Transport Economics, Oslo. p. 198.
The Viennese public transport operators are still more or loss under control of the public authorities. Therefore their revenues and losses are part of the present value of finance. Private transport operators are only occupying some niches.

[103] ***Economic efficiency:***
Economic efficiency as used in this guidebook is measured by a utilitarian welfare function (the Economic Efficiency Function, EEF). It includes external costs of accidents, noise and pollution. Generally, however, the term economic efficiency is used in three different meanings, one related to Pareto improvement and the other two related to the Kaldor-Hicks criterion or a welfare function, respectively.
(1) A Pareto improvement increases the utility of at least one individual without reducing the utility of any other individual. There is economic efficiency in the first sense if no Pareto improvements are possible. One might also speak of a Pareto improvement as constituting an increase in economic efficiency (towards the fully efficient state).
(2) A strategy is however often said to increase economic efficiency if the winners would be able to fully compensate the losers and still be winners. This is economic efficiency according to the Kaldor-Hicks criterion.
(3) If a welfare function has been specified, any increase in this function might also be said to improve economic efficiency. Unless the welfare function is utilitarian (giving equal weight to an euro more, regardless of who gets it), this usage of the word should be avoided.
Ibid., p. 192.

[104] See section 12.5 Objective function.

[105] The consideration of time savings in the cost benefit analysis is not undisputed. There are several points of criticism. Due to constant travel time budgets the total travel time spent in the system stays constant. But due to the way of calculation user benefits (rule of a half) time savings occur in the cost benefit analysis. Other points of criticism concern the value of time and summing up very small individual time savings.

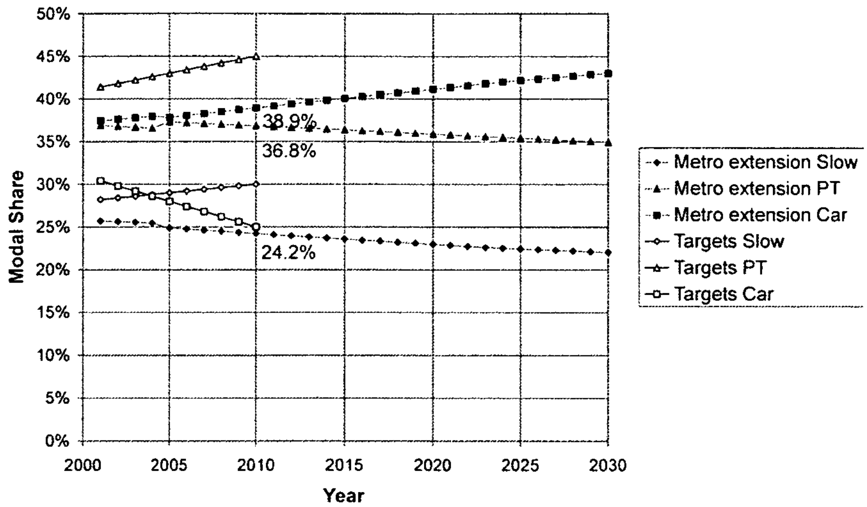


Figure 8.7: Development of modal share in the Vienna metro line extension scenario in comparison with the official targets (Stadtplanung Wien, 1994)

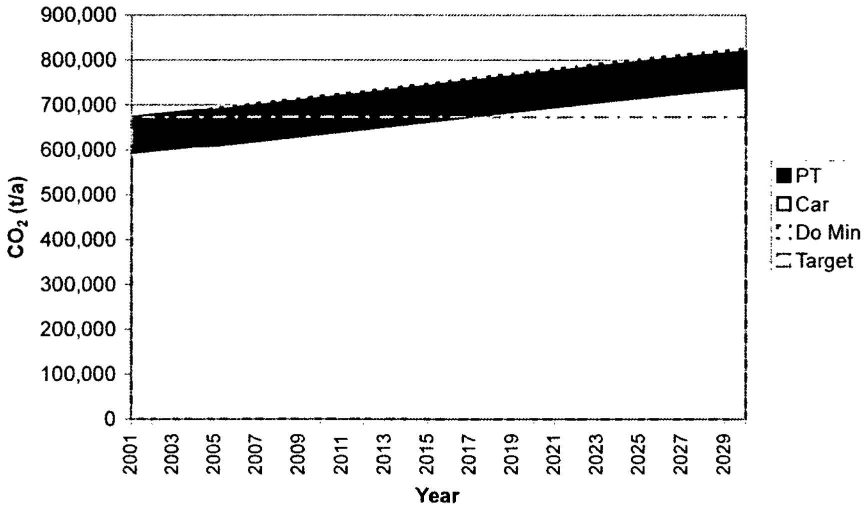


Figure 8.8: Development of CO_2-emissions in the Vienna metro line extension scenario

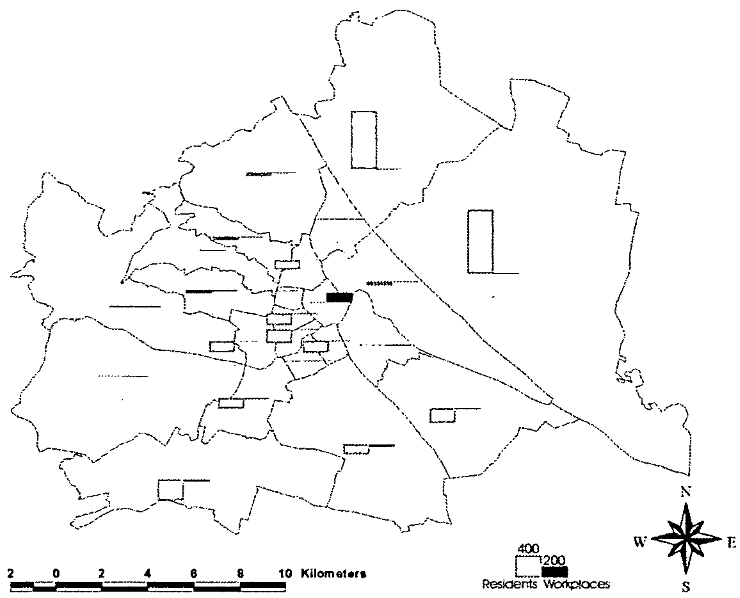


Figure 8.9: Difference in number of residents and workplaces between metro line extension and do-minimum scenario in the year 2015

Table 8.1: Results cost benefit analysis metro line extension

Users						Operators, government			External costs
Slow	PT		Car		Housing	PT	Car	Housing	
Time	Time	Money	Time	Money	Money				
0.0	442.5	0.0	13.0	4.7	-16.9	-2,031.6	-12.2	16.1	13.2

8.4 Ring road

The planned ring road increase the share of car trips (Figure 8.10). The shares of slow modes and public transport are reduced. The instrument ring road contradicts the target of reducing car share to 25%.

The ring road also contradicts the target of reducing CO_2-emissions (Figure 8.11). The increase in CO_2-emissions is about 8,500 tons in 2010, which is about 1.2% of the do-minimum emissions in 2010.

The ring road initialises a migration of households and workplaces into the districts 21 and 22 north of the river Danube and the most southern district 23 (Figure 8.12). The instrument ring road therefore contradicts the target of reducing urban sprawl.

Table 8.2 presents the results of the cost benefit analysis for the instrument ring road. Public transport users benefit from time savings. This benefits occur as the additional road capacity increases the speed of the bus based public transport. Car uses benefit in the form of time and money savings due to the increase in road capacity. Households have losses due to rent changes.

On the operator and government side public transport operators have no benefits or losses. There are high losses for operators and government due to the infrastructure investment costs and the additional maintenance costs. Landlords gain benefits. External costs are highly negative.

As well the present value of finance PVF[102] (-986.5 mio. Euro) as the economic efficiency objective function EEF[103] (-785.0 mio. Euro) and the sustainability objective function SOF[104] (-14.2 mio. Euro) are negative. The summary of the cost benefit analysis is that public authorities have to pay a high price for some time benefits for public transport and some time and cost benefits for car users[105]. From a strategic viewpoint the construction of the highway type ring road cannot be recommended.

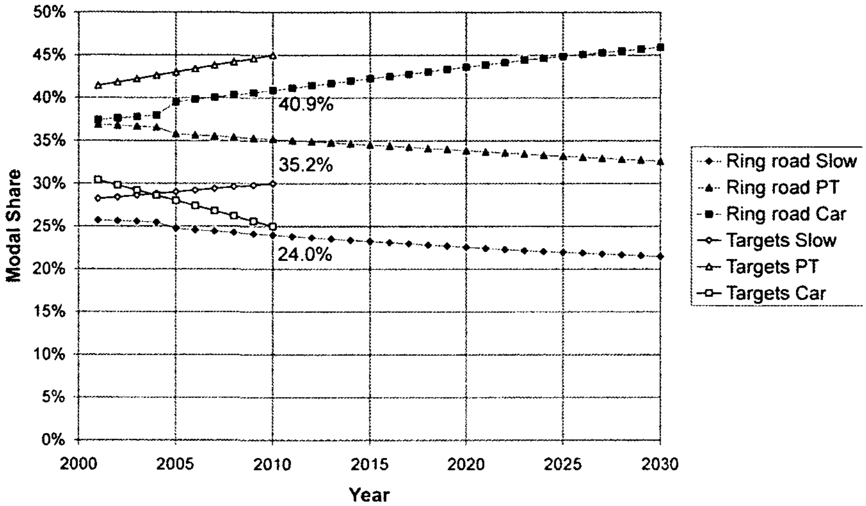


Figure 8.10: Development of modal share in the Vienna highway ring road scenario in comparison with the official targets (Stadtplanung Wien, 1994)

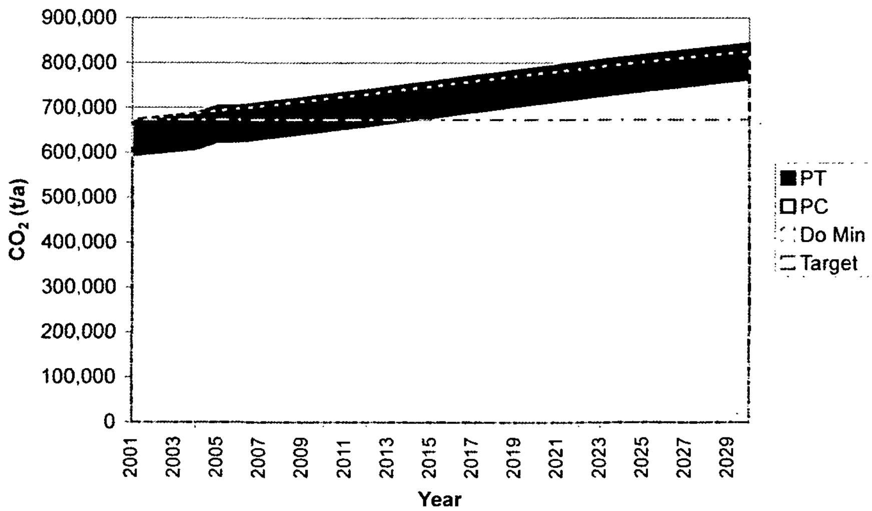


Figure 8.11: Development of CO_2-emissions in the Vienna highway ring road scenario

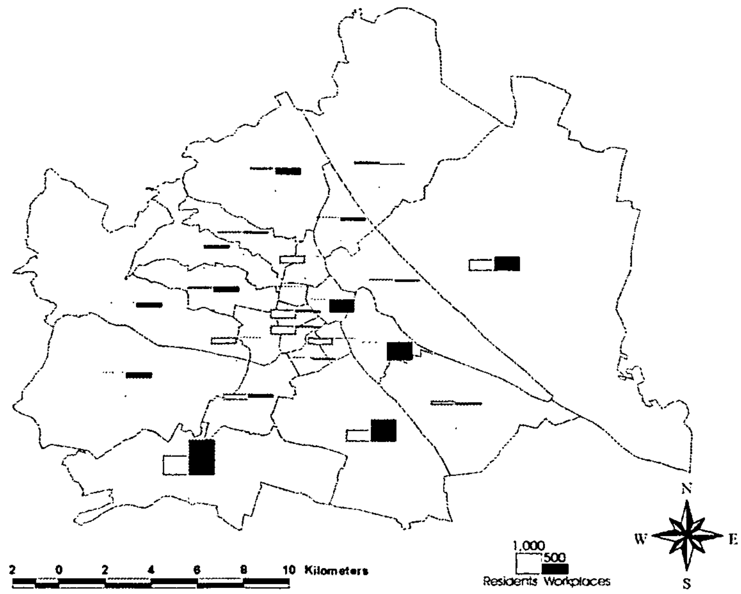


Figure 8.12: Difference in number of residents and workplaces between ring road and do-minimum scenario in the year 2015

Table 8.2: Results cost benefit analysis ring road

Users						Operators, government			External costs
Slow	PT		Car		Housing	PT	Car	Housing	
Time	Time	Money	Time	Money	Money				
0.0	123.1	0.0	275.4	144.8	-30.8	0.0	-1,008.2	31.4	-342.5

8.5 Traffic management

The planned road capacity increase by traffic management increases the share of car trips slightly (Figure 8.13). The shares of slow modes and public transport are reduced slightly. The instrument road capacity improvement by traffic management contradicts the target of reducing car share to 25%.

The road capacity increase by traffic management also contradicts the target of reducing CO_2-emissions in the long run (Figure 8.14). There is a slight decrease in the earlier years (e.g. –170 tons in 2010, which is –0.02% compared to the do-minimum). But there is an increase in the long run years (e.g. +1,619 tons in 2030 which is +0.2% compared to the do-minimum).

The road capacity increase by traffic management initialises a migration of households and workplaces into the districts 21 and 22 north of the river Danube and the most southern district 23 (Figure 8.15). The instrument road capacity increase by traffic management therefore contradicts the target of reducing urban sprawl.

Table 8.3 presents the results of the cost benefit analysis for the instrument capacity increase by traffic management. Slow mode users have rather high time losses, Public transport users benefit from time savings. This benefits occur as the additional road capacity increases the speed of the bus based public transport. Car uses benefit in the form of time and money savings due to the increase in road capacity. Households have losses due to rent changes.

On the operator and government side public transport operators have no benefits or losses. There are some losses for operators and government due to the investment costs and maintenance costs for the traffic management system. Landlords gain benefits. External costs are negative.

As well the present value of finance PVF[102] (-33.0 mio. Euro) as the economic efficiency objective function EEF[103] (-91.4 mio. Euro) and the sustainability objective function SOF[104] (-12.6 mio. Euro) are negative. The summary of the cost benefit analysis is that public authorities and slow mode users have to pay for time benefits for public transport and some time and cost benefits for car users. From a strategic viewpoint the road capacity increase by traffic management cannot be recommended.

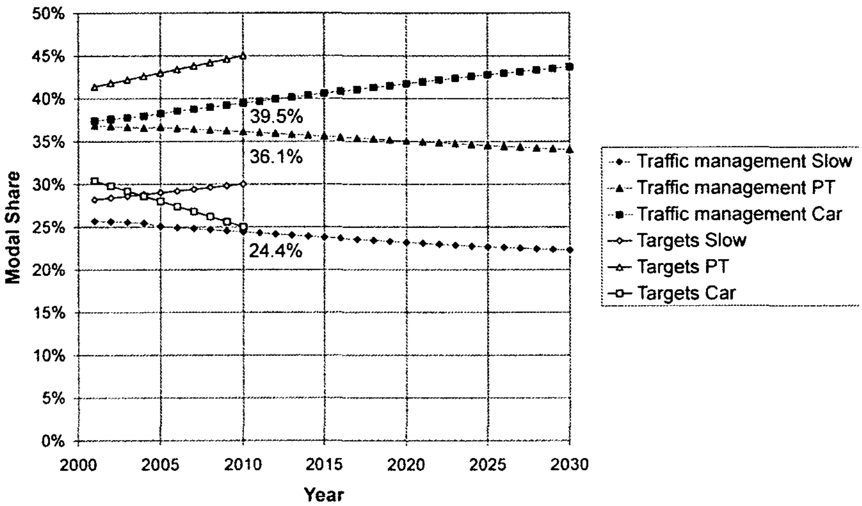


Figure 8.13: Development of modal share in the Vienna traffic management scenario in comparison with the official targets (Stadtplanung Wien, 1994)

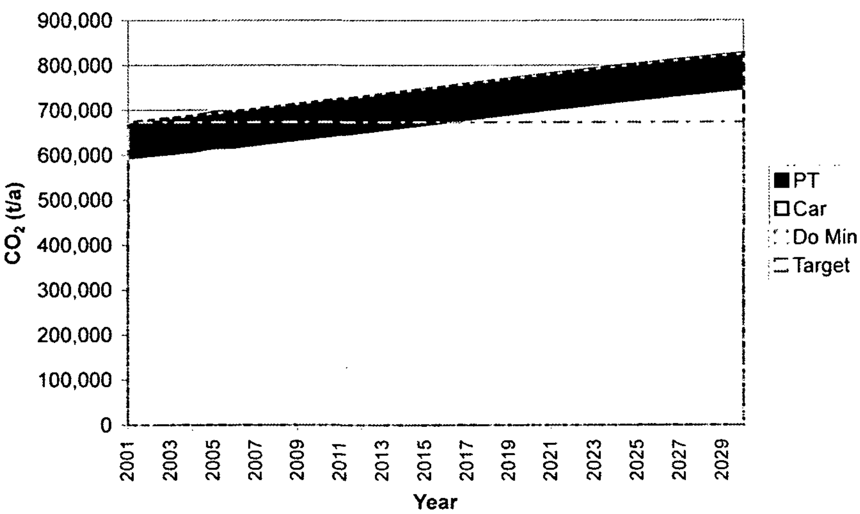


Figure 8.14: Development of CO_2-emissions in the Vienna traffic management scenario

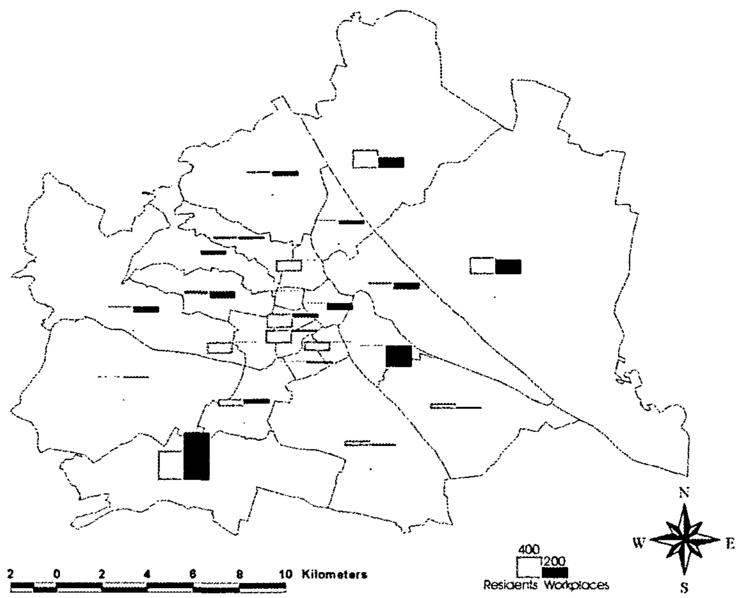


Figure 8.15: Difference in number of residents and workplaces between traffic management and do-minimum scenario in the year 2015

Table 8.3: Results cost benefit analysis road capacity increase by traffic management

Users						Operators, government			External costs
Slow	PT		Car		Housing	PT	Car	Housing	
Time	Time	Money	Time	Money	Money				
-238.5	53.2	0.0	101.0	55.5	-17.1	0.0	-68.6	17.5	-30.0

8.6 All planned transport investments

This section describes the MARS results of a combination of the three single instruments described above. The combination of the three instruments increases the share of car trips and public transport trips (Figure 8.16). The share of slow modes is decreased. The combination of the three instruments contradicts the target of reducing car share to 25%.

The combination of the three instruments also contradicts the target of reducing CO_2-emissions (Figure 8.17). The increase in CO_2-emissions is about 3,800 tons in 2010, which is about 0.5% of the do-minimum emissions in 2010.

The combination of the three measures initialises a migration of households and workplaces into the south eastern district 10, the districts 21 and 22 north of the river Danube and the most southern district 23 (Figure 8.18). The combination of the three instruments therefore contradicts the target of reducing urban sprawl.

Table 8.4 presents the results of the cost benefit analysis for the instrument combination. Slow mode users have rather high time losses. Public transport users benefit from time savings. This benefits occur as a combination of the additional public transport infrastructure and the additional road capacity which increases the speed of the bus based public transport. Car uses benefit in the form of time and money savings due to the increase in road capacity. Households have losses due to rent changes.

On the operator and government side public transport operators have high losses from investment and additional operation costs for the extended metro lines. There are also high losses for operators and government due to the investment costs and maintenance costs for the traffic management system and the new road capacity. Landlords gain benefits. External costs are negative.

As well the present value of finance PVF[102] (-2,946.0 mio. Euro) as the economic efficiency objective function EEF[103] (-2,239.7 mio. Euro) and the sustainability objective function SOF[104] (-134.6 mio. Euro) are negative. The summary of the cost benefit analysis is that public authorities and slow mode users have to pay for time benefits for public transport and some time and cost benefits for car users[105]. From a strategic viewpoint the combination of the three instruments cannot be recommended.

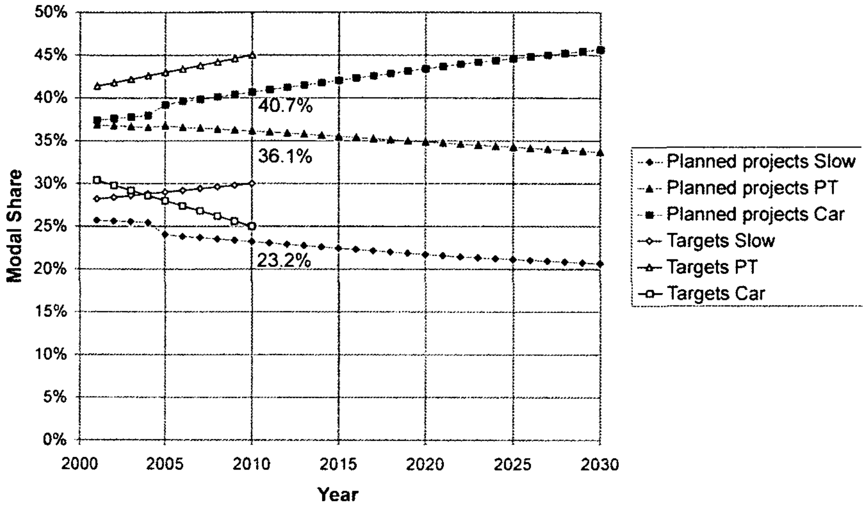


Figure 8.16: Development of modal share in the Vienna all planned transport investments scenario in comparison with the official targets (Stadtplanung Wien, 1994)

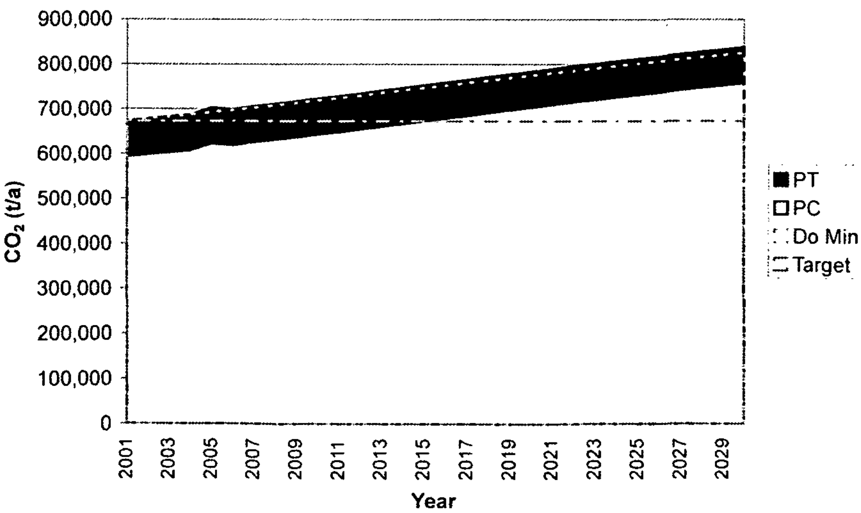


Figure 8.17: Development of CO_2-emissions in the Vienna all planned transport investments scenario

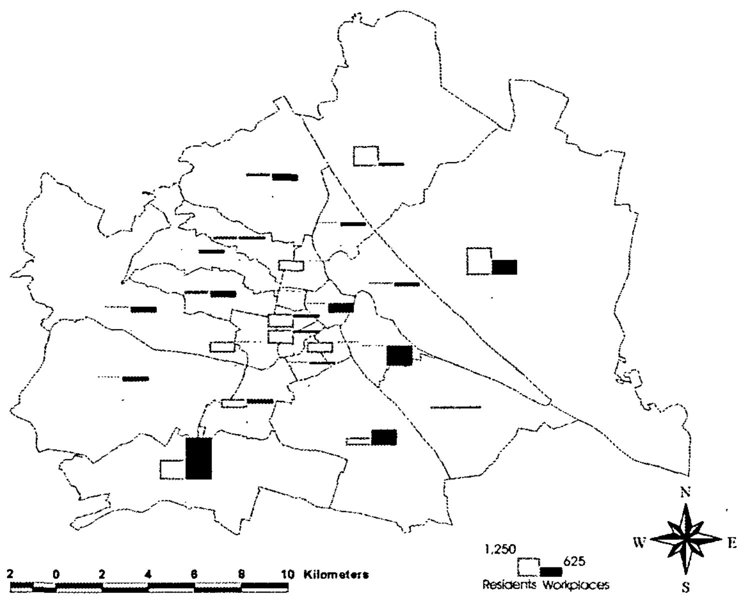


Figure 8.18: Difference in number of residents and workplaces between all planned transport investments and do-minimum in the year 2015

Table 8.4: Results cost benefit analysis all planned transport investments

Users						Operators, government			External costs
Slow	PT		Car		Housing	PT	Car	Housing	
Time	Time	Money	Time	Money	Money				
-237.0	724.0	0.0	385.7	202.3	-60.5	-2,031.6	-1,082.8	60.9	-369.1

8.7 What is necessary to meet the Transport Concept 1994 targets?

This section describes which strategy would be necessary to achieve the Transport Concept 1994 target of reducing car share to 25%[106]. The optimisation routine AMOEBA, which is described in section 7.4.2 The automated method, was used to find a potential strategy. Equation 8.1 shows the objective function used to measure the target achievement. Table 8.5 shows the policy instruments and their bounds as used in this optimisation. The implementation year is for all instruments iteration 4 (2005). The long run year for all instruments is iteration 19 (2020). Table 8.6 shows the policy instrument combination resulting from the optimisation process. Nearly all instruments hit the externally defined boundaries. A very extreme strategy is needed to come at least near to the Transport Concept 1994 target (Figure 8.19).

CO_2-emissions are substantially reduced over the whole simulation period (Figure 8.20). The decrease in CO_2-emissions is about 214,000 tons in 2010, which is about 27% of the do-minimum emissions in 2010.

[106] See section 8.1.1 Objectives of the city of Vienna p. 187.

Compared to the do-minimum scenario the inner city gains residents and workplaces while the outskirts (districts 10, 11, 21, 22 and 23) loose residents and workplaces (Figure 8.21).

Table 8.7 presents the results of the cost benefit analysis for the strategy to meet the Transport Concept 1994 targets. Slow mode users have rather high time benefits. Public transport users benefit from time and money savings. Car uses have some time losses and high money losses. Households have losses due to rent changes.

On the operator and government side public transport operators have high losses from investment and additional operation costs for the frequency increase. High revenues for the public hand are generated from car traffic. Landlords gain benefits. External costs are positive.

As well the present value of finance PVF[102] (-5,430 mio. Euro) as the economic efficiency objective function EEF[103] (-10,343 mio. Euro) and the sustainability objective function SOF[104] (-1,463 mio. Euro) are negative. The summary of the cost benefit analysis is that public transport operators and car users have to pay for the strategy. Slow mode and public transport users as well as the environment are the beneficiaries of the strategy. The case study shows quite clearly that the car share reduction target will hardly ever be reached unless the land use and transport system changes radically.

$$OF = -10^6 * \left[p_n^{car}(t_t) - p_t^{car}(t_t)\right]^2$$

Equation 8.1: Objective function mode split target

OF..............Objective function value

t_t..................Target year 2010 (iteration 9)

$p_n^{car}(t_t)$.........Percentage of car trips run n in the target year t_t

$p_t^{car}(t_t)$..........Target percentage of car trips in the target year t_t (=25%)

Table 8.5: Policy instruments available to achieve the Transport Concept 1994 target

Policy instrument		Lower bound	Upper bound
PT fare	peak	-50%	+100%
	off peak	-50%	+100%
PT frequency	peak	-50%	+100%
	off peak	-50%	+100%
Parking charge	long term	0	5 €
	short term	0	5 €
Road capacity		-20%	+20%
Fuel tax		0%	+300%

Table 8.6: Policy instruments values to achieve the Transport Concept 1994 target

Policy instrument		Implementation year	Long run year
PT fare	peak	-50%	-50%
	off peak	-50%	-50%
PT frequency	peak	+99%	+100%
	off peak	+100%	+100%
Parking charge	long term	5.0 €	0.0 €
	short term	4.9 €	5.0 €
Road capacity		-20%	-20%
Fuel tax		+300%	+300%

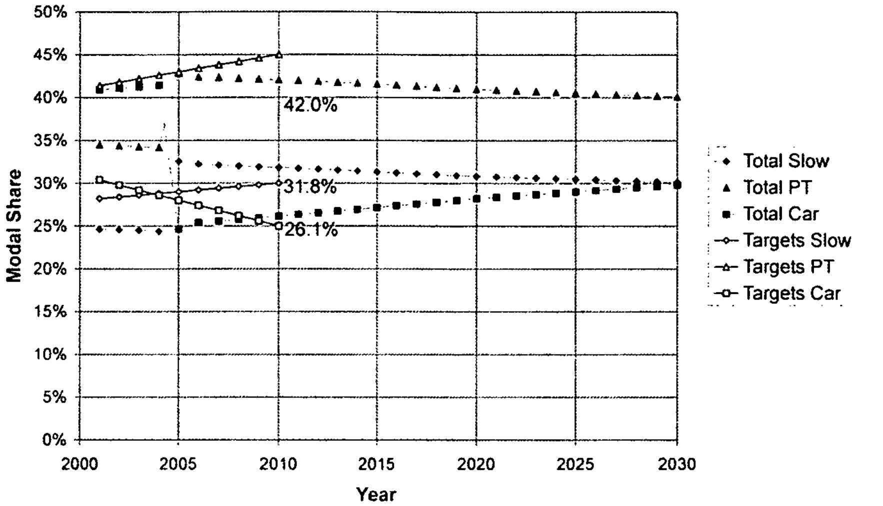


Figure 8.19: Development modal share strategy to meet the Transport Concept 1994 target

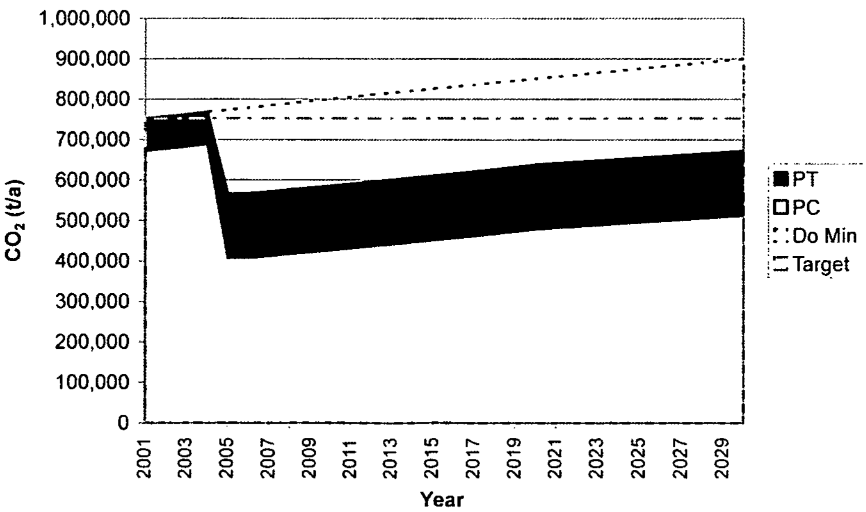


Figure 8.20: Development of CO_2-emissions in the strategy to meet the Transport Concept 1994 targets

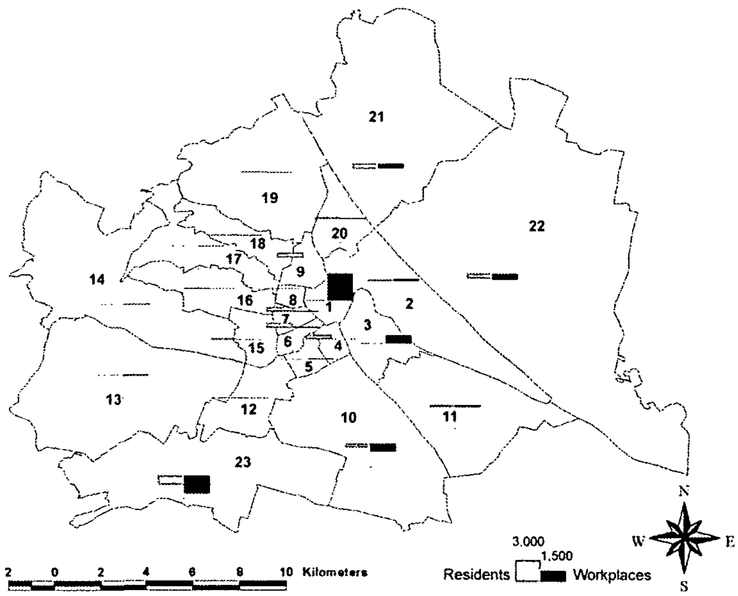


Figure 8.21: Difference in number of residents and workplaces between the strategy to meet the Transport Concept 1994 targets and do-minimum in the year 2015

Table 8.7: Results cost benefit analysis strategy to meet Transport Concept 1994 targets

Users						Operators, government			External costs
Slow	PT		Car		Housing	PT	Car	Housing	
Time	Time	Money	Time	Money	Money				
2,407	1,933	2,160	-585.9	-11,625	-2.5	-11,724	6,294	2.7	798.3

8.8 Optimisation sustainability objective function

This section presents the results of an optimisation using the sustainability objective function described in section 12.5 Objective function. No constraints were used in the objective function. The same policy instruments as in section 8.8 Optimisation sustainability objective function were used. The boundaries used in this optimisation are shown in Table 8.5. The implementation year is for all instruments iteration 4 (2005). The long run year for all instruments is iteration 19 (2020).

Table 8.9 shows the policy instrument combination resulting from the optimisation process. The suggested strategy includes a significant reduction of public transport fares of about 50% for both periods and for the implementation and the long run year. A public transport frequency reduction of about 20% is suggested for the implementation and the long run year. Nevertheless this reduction leads to overcrowding effects on some of the OD pairs[107]. For the off peak period an

[107] The endogenous overcrowding mechanism is not strong enough to avoid overcrowding in any case. A more detailed representation of overcrowding is suggested for future MARS improvements. See chapter 9.3 Suggestions for future MARS improvements. Probably by now such solutions should be excluded either by penalising the objective function or by changing the exogenous lower bound.

increase in public transport frequency by about 50% is suggested for the implementation and the long run year. A long term parking charge increase from 1 to 6 Euro per stay is suggested in the implementation year. The charge is reduced to about 1.3 Euro in the long run year. Short term parking charge changes can be neglected. Traffic calming is suggested. Road capacity should decrease by about 6% in the implementation year and by about 19% in the long run year. Only small increases of about 15% are suggested.

The effects of the proposed strategy on mode shares are shown in Figure 8.22. The share of car trips is significantly decreased in the implementation year. But it is still far from reaching the reduction target of the Transport Concept 1994[108]. Additionally the share of car trips starts to increase again after the implementation year. The share of public transport trips is increased significantly. The additional public transport trips mainly substitute former slow mode trips. After the implementation year both slow modes and public transport a declining trend.

The target of reducing CO_2-emissions from transport is only met for a view years after the implementation of the strategy (Figure 8.23). CO_2-emissions are reduced by about 62,000 tons in 2010, which is about 8% of the do-minimum emissions in 2010.

Figure 8.24 shows the difference in number of residents and workplaces between the strategy for a maximum sustainability objective function value and the do minimum scenario. The suggested strategy results in a relative migration of households and workplaces from the outskirts into the city centre.

Table 8.10 presents the results of the cost benefit analysis for the strategy with the maximum sustainability objective function value. Slow mode users have rather high time benefits. Public transport users benefit as well from of high time as high money savings. Car uses have small time losses and high money losses. Households have benefits due to rent changes.

On the operator and government side public transport operators have high losses from investment and additional operation costs for the frequency increase in off peak. Revenues for the public hand are generated from car traffic. Landlords have losses. External costs are positive.

The present value of finance PVF[102] is negative (-2,087 mio. Euro). The economic efficiency objective function EEF[103] (+453.6 mio. Euro) and the sustainability objective function SOF[104] (+147.0 mio. Euro) are positive. The summary of the cost benefit analysis is that public transport operators and car users have to pay for the strategy. Slow mode and public transport users as well as the environment are the beneficiaries of the strategy.

[108] See section 8.1.1 Objectives of the city of Vienna p. 187.

Table 8.8: Policy instruments available optimisation unconstrained sustainability objective function

Policy instrument		Lower bound	Upper bound
PT fare	peak	-20%	+100%
	off peak	-50%	+100%
PT frequency	peak	-50%	+100%
	off peak	-50%	+200%
Parking charge	long term	0	5 €
	short term	0	5 €
Road capacity		-20%	+20%
Fuel tax		0%	+300%

Table 8.9: Policy instruments values optimisation unconstrained sustainability objective function

Policy instrument		Implementation year	Long run year
PT fare	peak	-48%	-49%
	off peak	-43%	-49%
PT frequency	peak	-20%	-20%
	off peak	+46%	+47%
Parking charge	long term	5.0 €	0.3 €
	short term	0.1 €	0.0 €
Road capacity		-6%	-19%
Fuel tax		12%	15%

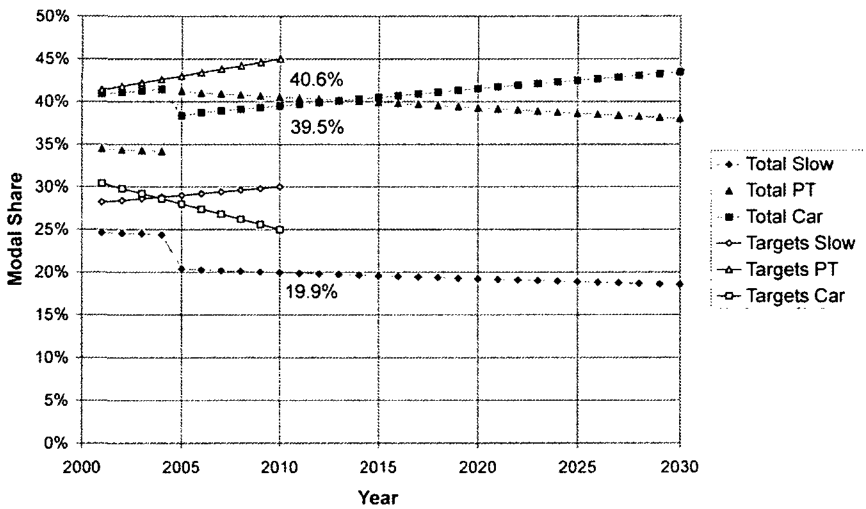


Figure 8.22: Development modal share optimum sustainability objective function

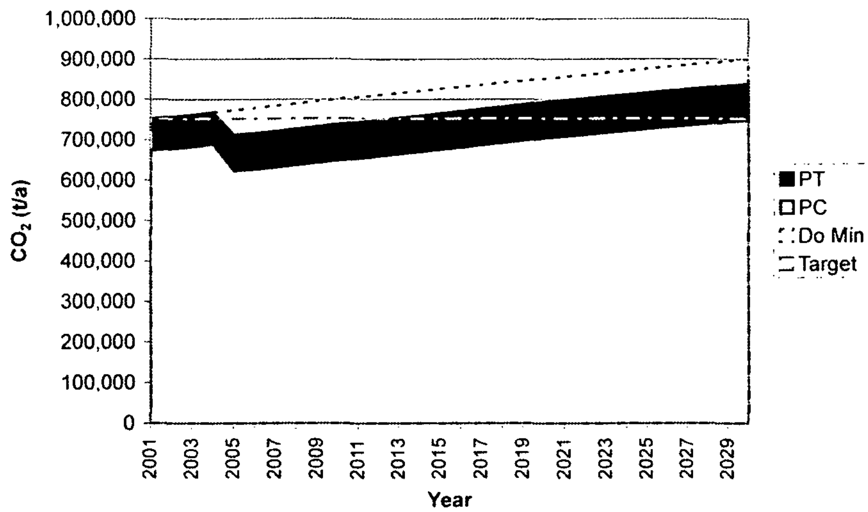


Figure 8.23: Development of CO_2-emissions optimum sustainability objective function

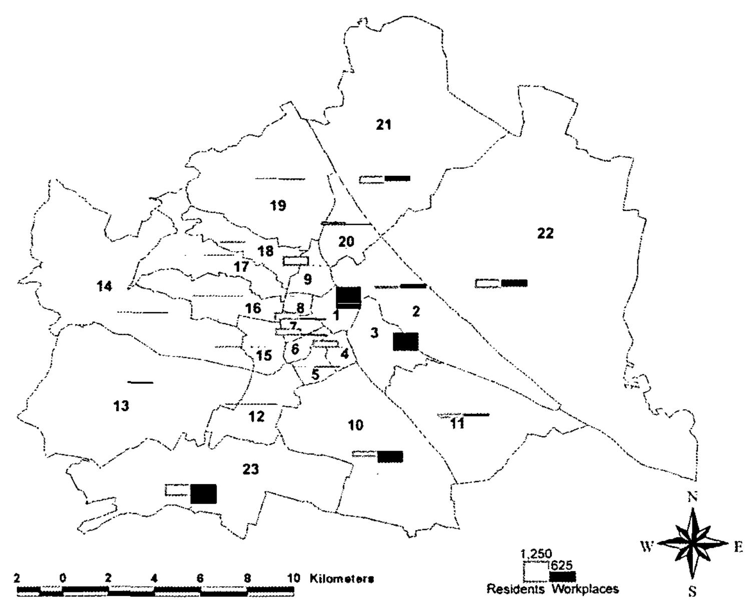


Figure 8.24: Difference in number of residents and workplaces between the strategy for an optimum sustainability objective function value and do-minimum in the year 2015

Table 8.10: Results cost benefit analysis strategy for an optimum sustainability objective function value

Users						Operators, government			External costs
Slow	PT		Car		Housing	PT	Car	Housing	
Time	Time	Money	Time	Money	Money				
358.7	1,084	2,001	-70.5	-1,075	20.6	-2,659	572.2	-20.6	358.7

8.9 Conclusions

At the beginning of this chapter official urban and transport planning objectives of the city of Vienna were presented.

Three different investments into the transport system, currently planned or already ongoing, were tested with MARS as well as single policy instruments as in the form of a combined strategy. The results were compared with the official Viennese urban planning objectives. All three instruments, a metro extension, a highway type ring road and road capacity improvements by traffic management, contradict the objectives. Only the metro extension contributes partly to the official targets. The outcome of the cost benefit analysis is significantly negative for all instruments. The same is true for the combination of the three instruments. From a strategic viewpoint neither the single projects nor their combination can be recommended.

An optimisation algorithm was used to search for strategies which are able to achieve the target of reducing car share to 25% by 2010. The policy instruments considered in this optimisation are public transport fares, public transport frequency, parking charges, fuel tax and road capacity. A strategy coming very near to the target was identified. This strategy includes extreme changes like a 300% increase in fuel tax, a 100% increase in public transport frequency, a 5 Euro increase in parking charges per stay, a 50% reduction of public transport fares and a 20% reduction of road capacity. The outcome of the cost benefit analysis is for all indicators highly negative. The case study demonstrates that the official target from the Transport Concept 1994 is hardly ever achievable. Radical changes in the transport and land use system would be required to cause a lasting effect on car use.

Finally an optimisation using the sustainability objective function described in section 7.2 and 12.5 was performed. The same policy instruments as in the previous case study were used. The suggested strategy includes a public transport fare reduction of about 50%, a slight decrease of public transport peak frequency, an increase of public transport frequency in off peak, a 5 Euro increase of long term parking charges in the implementation year, but decreasing the long term parking charges continuously until the long run year (+0.3 Euro), a slight increase in fuel tax and traffic calming.

The present value of finance PVF[102] is negative for this strategy. That means that the public hand has a deficit from the transport system compared to the do-minimum scenario. This might be unacceptable. If this is the case, an optimisation constrained by the condition that PVF has to be positive could be carried out. The economic efficiency function EEF[103] and the sustainability objective function SOF[104] are positive. Beneficiaries of the proposed strategy are slow mode and public transport users. Car users and public transport operators are on the loser side. The public hand gains revenues from road traffic, but in total these are more than compensated by losses from the public transport sector.

The sustainability objective function SOF used in the case study is an important progress in the assessment of the sustainability of urban land use and transport policies. Nevertheless the case study has shown that an optimisation employing SOF does not necessarily result in a sustainable strategy in a strict sense. For all instruments and strategies tested, car traffic and CO_2-emissions started to rise again after the implementation year. The only strategy resulting in final year CO_2-emissions lower than in the base year was the extreme strategy to achieve the Transport Concept 1994 targets. The case studies show that, especially if emission reduction targets are used in the assessment framework, dynamic models are essential. Models predicting only one target year cannot give any evidence whether the reduction targets are fulfilled or violated beyond the target year.

Some important issues essential for sustainability seem to be underrepresented in the sustainability objective function. On the one hand this are the benefits and losses of the slow mode users. The appraisal framework is very much in favour of public transport oriented strategies. Indeed there seems to be a strong bias towards public transport. On the other hand it is the consumption of land. Land is a non-renewable, (or at least hardly renewable) resource and therefore should be given a high weight in a sustainability assessment. Therefore a refinement of the sustainability objective function is suggested as a topic for future research (see section 9.3 Suggestions for future MARS improvements).

9. CONCLUSIONS

9.1 The position of MARS within the range of land use and transport modelling approaches

The trip generation model of MARS is based on a constant trip rate for tours home – work – home and a constant travel time budget for total travel. The trip distribution and mode choice is treated simultaneously. A combination of the analogy to the law of gravity and Kirchoff's law from electrical engineering is used. Currently no assignment stage is applied with MARS. Road traffic supply side effects are taken into account by an area speed flow relationship. Accessibility is measured in terms of time.

The land use sub-model consists of two parts: a residential and a workplace model. Both parts use the same basic structure. The workplace sub-models are partially simpler than the residential sub-models. The basic structure consists of a stock development model, an activity model and a relocation model. The activity model consists of a moving out (household and workplace mobility) model and a moving in (household and workplace location) model. In general the land use sub-models are based on LOGIT models. If there is not enough floor space available in a zone, a relocation to sites of second best choice is performed.

In contrary to the common trend of an increasing level of spatial detail, MARS relies on an aggregated approach. As the issue of concern is the strategic objective of sustainability, this approach is seen as appropriate. The justification for this approach is found in the theories of self organising systems and synergetics (see section 2.7.2).

MARS is an integrated land use and transport model. Unlike many other models MARS fully considers the non motorised modes in its transport sub-model[109]. The four stage model has been extensively criticised. A major point of criticism was addressed to the sequential structure of the four stage models. *However, once this assumption is loosened, and the possibility of feedback is allowed (...), this criticism substantially falls away* (Bates, J., 2000) p. 17. Figure 9.1 shows the principle model structure allowing a feedback. MARS, although not employing an assessment stage, includes such a feedback from the supply side up to destination and mode choice and trip generation. (Cerwenka, P., 2002) p. 282 criticises that common transport demand models do not take into account captive riders[110]. In MARS the existence of captive riders is modelled. Furthermore (Cerwenka, P., 2002) p. 282 criticises that the common practice does not take into

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[109] One point of criticism of today's modelling practice is indeed the omission of the non motorised modes.

(3) there is usually no treatment of walk or cycle modes, apart from the role that walking plays in accessing public transport routes...

Bates, J. (2000). History of Demand Modelling. Handbook of Transport Modelling. D. A. Hensher and K. J. Button, Pergamon. **1:** 11-33. p. 20.

[110] *In der überwiegenden Anzahl aller praktischen Anwendungsfälle wird bei Modal-Split Modellen davon ausgegangen, dass ein in einer bestimmten Quelle-Ziel-Relation in einer bestimmten Zeiteinheit beobachtetes Personenverkehrsaufkommen vollständig einer nutzenabwägenden Wahlfreiheit unterliegt.*

account induced traffic[111]. MARS is able to respond to transport system changes with induced ("new") traffic. The MARS transport sub-model overcomes several of the points criticised in today's transport modelling practise.

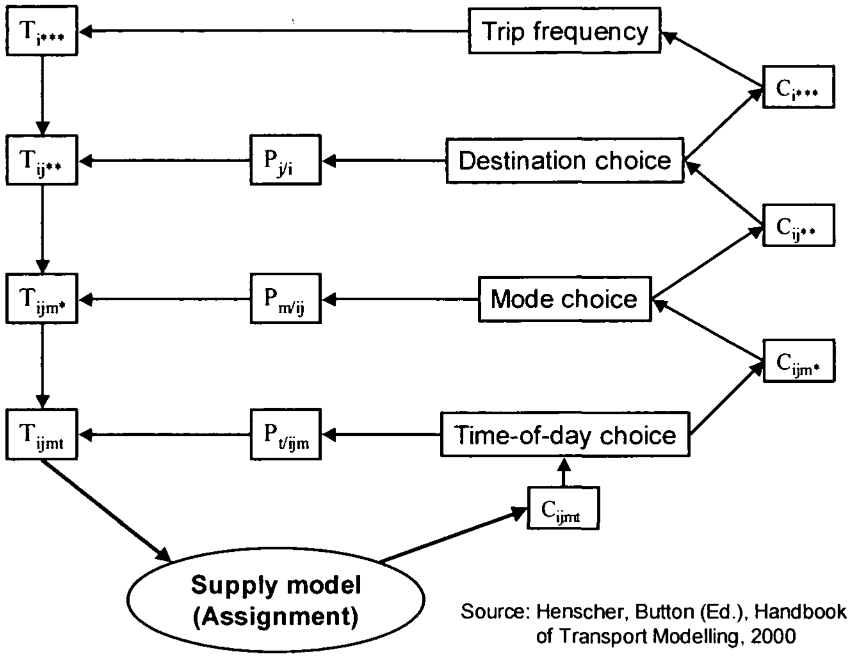

Figure 9.1: Hierarchical demand model allowing feedback (Bates, J., 2000) p.15

T_{ijmt}.............Trips from source i to destination j by mode m in time of day t

c_{ijmt}.............Generalised cost for a trip from source i to destination j by mode m in time of day t

$P_{j/i}$..............Probability of a trip from source i to choose destination j

$P_{m/ij}$.............Probability of a trip from source i to destination j to choose mode m

$P_{t/ijm}$............Probability of a trip from source i to destination j by mode m to choose time of day t

In section 2. Review of land use and transport modelling MARS is compared with other operational land use and transport models. MARS is comprehensive as it covers seven of the eight sub-systems defined by (Wegener, M., 2003)[112]. Unlike many other models MARS does not rely on cross sectional modelling. On the contrary MARS models changes of land use and transport over time. MARS models the development of stock (floor space, road network) and activities (location choices, transport choices). Due to its aggregated and strategic character MARS takes into account a relative small number of different actors and sectors. But its segmentation is comparable with other models [113]. The position of MARS is on a high step in the evolution of urban land use and transport models[114]. In general the MARS modelling approach and its different sub-parts are in line with theories and approaches established in international land use and transport modelling research.

[111] *..., wird die Berücksichtigung von induzierten Verkehr ("Neuverkehr") unabdingbar, ...*

[112] See section 2.5 A brief review of land use modelling, Table 2.1.

[113] See section 2.6.7 METROSIM, Table 2.5.

[114] See section 2.7.1Outlook, Figure 2.18.

9.2 Results of model testing

A wide variety of model tests is presented in chapter 6. Model Testing. MARS is intended to be a transparent model rather than a "Black box" model. The model tests start with a description of the purpose and scope of MARS. A boundary chart lists the endogenous, exogenous and excluded variables. Extensive empirical testing was performed. MARS simulations were compared with observed data from different sources. The results of the back casting simulations are satisfying. Nevertheless some areas, where the conformity between observed and simulated data was not that convincing, were identified. Explanations for the lower correspondence could be found in any case. Suggestions for future improvements are made in section 9.3. Plausibility of effects caused by the implementation of policy instruments was tested. All instruments used in the case study give plausible results. The MARS performance was benchmarked with examples from the reviewed literature.

The model tests presented in section 6.2 have shown that MARS is able to reproduce the development of the city of Vienna between 1981 and 2001 with reasonable accuracy. The final conclusion from the model tests is therefore that MARS is a useful tool to predict future urban development paths. Transferability issues are addressed in section 9.3.3.

9.3 Suggestions for future MARS improvements

Several potential issues and fields for future MARS developments and research arise from the extensive model testing programme. Suggestions for future work are made for the topics model structure, data and general research.

9.3.1 MARS structure

The following suggestions for future MARS developments are ranked by their importance as seen by the author, starting with the most important one.

- **Ageing i.e. household and business transition model**

In the current version of MARS each person moving out gives room for another person moving into the zone. This assumption is a bit weak. If grown up children leave their home or if people are dying, housing units will or might still be occupied. The non consideration of household transition gives the explanation for the systematic overestimation of the household location model in some Viennese zones (see section 6.2.7). The inclusion of a household and a business transition model is seen as the development with the highest potential to improve the quality of the land use sub-models predictions.

- **Include a fourth mode**

The original intention was to model four distinct modes: pedestrian, bicycle, public transport[115] and car. Due to software problems[35] pedestrians and bicycle were combined to the mode "slow modes". There are plans to use MARS for case studies with Asian cities. Motorcycles are an important means of transport in Asian cities. Therefore a fourth mode is important to be able to apply MARS adequately

[115] Public transport includes the two sub-modes bus and metro. The split between these two modes is exogenously defined by the model user for each OD-pair.

to Asian cities. The fourth mode is intended to be used alternatively to represent either bicycle or motorcycle use.

- **Subdivide population into at least two distinct household income groups**

If household location choice is concerned, rent is an ambiguous indicator. On the one side households try to minimise their rent. On the other side high rents imply a high quality of living in the zone. In the Oslo case study (Pfaffenbichler, P. and Emberger, G., 2003) one zone had very low rents. Therefore the model located a high number of households in this zone. But in reality the area was run down and had a poor neighbourhood quality. The observed balance of households over the calibration period was therefore negative. The consideration household groups with different location behaviour would help to overcome this issue. A subdivision into two different household income groups is suggested for a further MARS development.

- **Improve the employment move out model (i.e. employment mobility model)**

Currently the employment mobility model is very simple. A certain percentage of workplaces moves out from each zone in each year. A model similar to the household mobility model would be rather easy to implement but substantial improvement of MARS.

- **Time of the day model**

Missing consideration of time of day choice is one of the criticisms of common transport modelling practice[116]. The basic structure of MARS allows to implement such a sub-model. The representation of effects of policy instruments would significantly benefit from this improvement.

- **Car availability model**

Car availability is one of the parameters which change significantly during the simulated period of time. Currently changes in car availability are considered by exogenously defined yearly growth rates. The performance of MARS would benefit from an endogenous car availability model.

- **Accessibility based on generalised costs rather than time**

Generalised costs are already calculated in MARS. A change from time to generalised cost based accessibility indicators requires not much effort. Therefore this development is suggested to be included in the very next version of MARS. The land use response to instruments like road pricing and parking charges will be more distinct using the new accessibility indicator definition.

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[116] *(1) no account is usually taken of changes in the time of day profile, either on a "micro" basis ("peak spreading") or as a result of more specific shifts in behaviour, possibly induces by pricing policies, etc.;*
Bates, J. (2000). History of Demand Modelling. Handbook of Transport Modelling. D. A. Hensher and K. J. Button, Pergamon. **1:** 11-33.

- **Improve endogenous road construction model, 7.2.5 footnote**

At the beginning of the model development it was not intended to include an endogenous road construction model. The study area of the case studies in Madrid and Oslo (Pfaffenbichler, P. and Emberger, G., 2003) included some large zones with very low population and workplace densities. As there was a lot of land available, the model developed a lot of housing units and workplaces in these zones. This causes very high relative changes in the number of trips starting and ending in these zones and the car speed dropped near to zero. The result was an unstable, oscillating model behaviour.

If substantial developments are made on greenfields in the real world, then additional road infrastructure will be necessary to make them accessible. It was decided to try to mimic this process in the model. If developments in a zone are over relative threshold value and if car speed falls below a relative threshold value, then additional road capacity is provided. The percentage of additional road capacity is equal to the percentage change in the number of housing units and workplaces.

No attempts to calibrate this sub-model have been made so far. Model testing has shown that the road construction sub model should be revised and calibrated. See also section 9.3.2 Data.

- **Include an assignment stage**

The representation of speed flow effects in MARS would benefit from an additional assignment stage. Currently speed flow relationships are considered OD-pair wise. Some the OD-pairs might not be independent from each other in reality. E.g. in Vienna all trips from the Northern districts 21 and 22 to the other districts have to cross the river Danube over five bridges.

The inclusion of an assignment stage would require a lot of effort and resources. The same is true for developing an interface to link MARS to an external assignment model. That is the main reason for not giving a higher priority to this improvement.

9.3.2 Data

- **Survey access/egress times, parking place searching times**

Model calibration and testing have shown that MARS has a tendency to underestimate short trips and overestimate long trips. Modifying the definition of intra-zonal trip length helped to decrease these tendency. The MARS transport sub-model is sensitive to changes in access/egress and parking place searching times. Currently the numbers used for these parameters are only reasonable estimates. No observed data are available. The model performance would benefit from more detailed data about access/egress times and parking place searching times. Access/egress times for public transport can be estimated using the number of public transport stops per zone and the built up area per zone. The situation is much more difficult for parking place access/egress and searching times. A survey to collect data about parking place access/egress and searching times is therefore suggested for future projects.

- **Calibration endogenous road construction model**

As mentioned in section 9.3.1 the road construction model was not yet calibrated. The data used for model testing (section 6.2.5) were not really appropriate as they covered all transport infrastructure, including e.g. railway stations. Data about road capacity changes for at least two points in time have to be collected to be able to calibrate the road construction model.

9.3.3 Basic research

- **Investigate the transferability of the land use models**

The land use part of MARS was developed based on data and research from Vienna. In the first phase of the development of MARS case studies and benchmarking tests were performed in six European cities[117]. Nevertheless extensive model testing and comparisons with observed data over a longer period of time were only carried with the Vienna MARS model. To test the transferability of the MARS land use sub-models a study performing a model testing programme similar to that shown in chapter 6. Model Testing in the cities Edinburgh, Helsinki, Madrid, Oslo and Stockholm is suggested.

- **Investigate the transferability of the used friction factors**

The friction factors which are used in the transport sub-model stem from German research. Arguments that they are transferable are presented in section 12.2. Nevertheless it would be very useful to test the transferability in a study. There are two ways of doing so. The first is similar to what is suggested to test the transferability of the land use model. If the land use model is tested, no additional effort is needed to test the transferability of the friction factors.

The second possibility is to perform a study similar to that of (Walther, K. et al., 1997) in cities in different countries. This approach requires substantial, but would nevertheless be of great scientific interest.

- **Refinement of the sustainability objective function**

The case studies have shown that the optimisation of the sustainability objective function does not guarantee sustainable solutions in a strict sense. There seems to be a bias towards public transport oriented strategies. Slow modes and the consumption of land seem to be underrepresented. Therefore future research to redefine and refine the sustainability objective function is suggested.

[117] See e.g. Pfaffenbichler, P. and Emberger, G. (2003). Are European cities becoming similar? CORP2003, 8. internationales Symposion zur Rolle der IT in der und für die Planung sowie zu den Wechselwirkungen zwischen realem und virtuellem Raum, Wien, iemar - Institut für EDV-gestützte Methoden in Architektur und Raumplanung.

9.4 Vienna case study results and recommendations

The results of Vienna case studies are summarised in more detail in section 8.9. Three currently planned or already ongoing transport investments, a metro extension, a highway type ring road and road capacity improvements by traffic management, were tested with MARS. All three instruments, as well as single instrument as in combination, contradict the official Viennese objectives. Only the metro extension contributes partly to the targets. The outcome of the cost benefit analysis is significantly negative for all instruments. The same is true for the combination of the three instruments. From a strategic viewpoint neither the single projects nor their combination can be recommended.

An optimisation algorithm was used to find a strategy which can achieve the target of reducing car share to 25% by 2010. This strategy includes extreme changes like a 300% increase in fuel tax, a 100% increase in public transport frequency, a 5 Euro increase in parking charges per stay, a 50% reduction of public transport fares and a 20% reduction of road capacity. The outcome of the cost benefit analysis is for all indicators highly negative. The case study demonstrates that the official target from the Transport Concept 1994 is hardly ever achievable. Radical changes in the transport and land use system would be required to cause a lasting effect on car use.

Finally an optimisation with the sustainability objective function was performed. The suggested strategy includes a public transport fare reduction of about 50%, a slight decrease of public transport peak frequency, an increase of public transport frequency in off peak, a 5 Euro increase of long term parking charges in the implementation year, but decreasing the long term parking charges continuously until the long run year (+0.3 Euro), a slight increase in fuel tax and traffic calming. This strategy produces a deficit in public spending on transport compared to the do-minimum scenario. Beneficiaries of the proposed strategy are slow mode and public transport users and the environment. Car users and public transport operators are on the loser's side. Strictly speaking this strategy is not sustainable. CO_2-emissions and car use increase again after the implementation year. CO_2-emissions are higher than in the base year from about 2012 on. Decentralisation is slowed down in comparison with the do-minimums scenario but the trend was not reversed, not even neutralised.

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11. ABBREVIATIONS

CLD .... Causal loop diagram

EEF .... Economic efficiency objective function

FUR .... Functional urban region

H-O .... Home – others

H-W .... Home – work

LUTI .... Land use and transport integrated model

OD .... Origin – destination

PC .... Private car

PT .... Public transport

PVF .... Present value of finance

RUT .... Random utility theory

SOF .... Sustainability objective function

TAZ .... Travel analysis zone

TUW-IVV .... Technische Universität Wien- Institut für Verkehrsplanung und Verkehrstechnik (Vienna University of Technology – Institute for Transport Planning and Traffic Engineering)

VBA .... Visual basic for applications, VBA is the property of Microsoft Corp.

12. ANNEX

12.1 Causal loop diagramming (CLD)

Source: (Pfaffenbichler, P. C., 2001)

The method of CLD[118] was used for a qualitative analysis. A causal loop diagram consists of entities connected by arrows denoting the causal influences among variables. Entities - in the context of system dynamics - are elements which affect other elements and are themselves affected. An entity represents an unspecified quantity. Entities are related by causal links, shown by arrows. Each causal link is assigned the characteristic *same* (s) or *opposite* (o) to indicate how the dependent entity changes when the independent entity changes. A link "s" means that if the cause increases, the effect increases above what it would otherwise have been, and if the cause decreases, the effect decreases below what it would otherwise have been. In the example (Figure 12.1) an increase in births means the population will increase above what it would have been, and a decrease in births means the population will fall below what it would have been. A link "o" means that if the cause increases, the effect decreases below what it would otherwise have been, and if the cause decreases, the effect increases above what it would otherwise have been. In the example (Figure 12.1), an increase in deaths means the population will fall below what it would have been, and a decrease in deaths means that the population will rise above what it would have been.

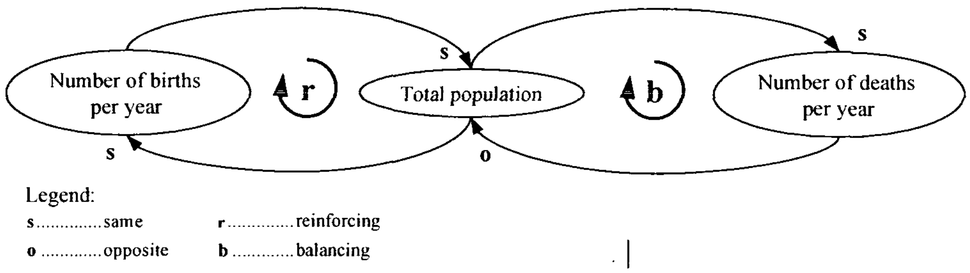

Figure 12.1: System with two feedback loops

A reinforcing loop (r) indicates that the loop continues going in the same direction, causing systematic growth. This behaviour moves away from an equilibrium point in an unstable matter. A balancing loop (b) indicates that the loop changes direction, causing the system to fluctuate or to move towards equilibrium.

[118] A more detailed description of the method of CLD could be found in:
Emberger, G. and Fischer, P. (2001). Easy Understanding of Causal Loop Inherent Dynamics - EUCLID Method. Vienna, Institute for Transport Planning and Traffic Engineering, Vienna University of Technology: 4.
An application of CLD to describe the interaction between economy, transport and land-use planning could be found in:
Emberger, G. (2000). Causal Loop To Describe Transport System's Effects on Socio-Economic Systems. 18th International Conference of the Systems Dynamic Society, Bergen, Norway.
and
Emberger, G. (2001). Interdisziplinäre Betrachtung der Auswirkungen verkehrlicher Maßnahmen auf sozioökonomische Systeme; *Beiträge zu einer ökologisch und sozial verträglichen Verkehrsplanung*, **1**; Institut für Verkehrsplanung und Verkehrstechnik, Technische Universität Wien, Wien.

12.2 Constant travel time budgets

12.2.1 Theory

(Kölbl, R., 2000) gives a comprehensive summary of travel budget approaches (p. 33 to 39). Explanations for the observation of constant travel time budgets over a long period of time and across different societies and cultures are given from and economic and an evolutionary angle. (Knoflacher, H., 1995) has shown that constant travel budgets can be derived from two basic laws: the Sensation Law by Weber-Fechner and the Travel Law by Lill.

The perception of travel time determines human travel behaviour. (Knoflacher, H., 1981; Knoflacher, H., 1987) has shown that the perception of travel time is based on the physiological energy consumption during travelling. Based on these findings (Kölbl, R., 2000) advocates in his thesis the hypothesis of constant physiological energy consumption budgets.

Figure 12.2 shows that the use of constant travel time budgets corresponds better to observed data than the use of constant trip rates. The observed data furthermore justify the use of a constant trip rate for the purpose work (Figure 12.2, right side). Nevertheless the use of constant physiological energy consumption budgets for trip generation is seen as a potential future development of MARS.

12.2.2 Observations

This section summarises some empirical observations, which show the stability of travel time budgets over time and across countries, societies and cultures.

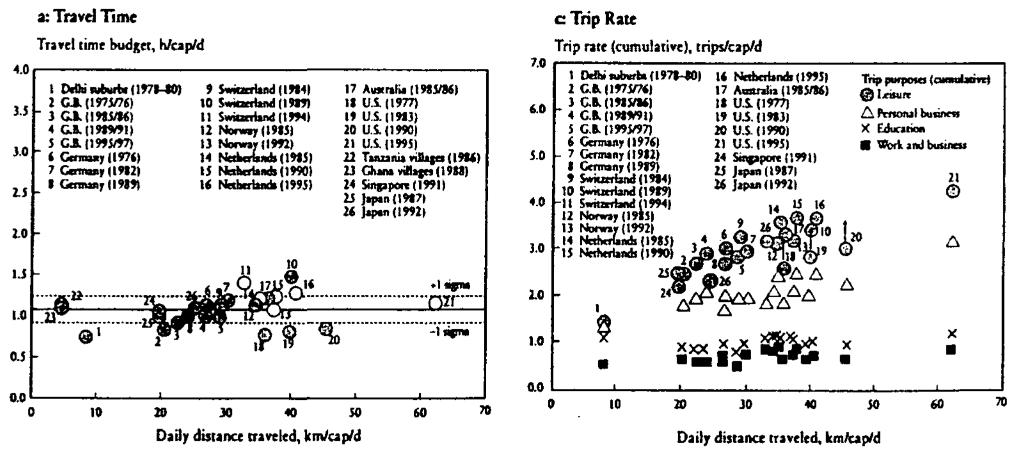

Figure 12.2: Basic variables of human mobility as functions of daily distance travelled (Schafer, A., 2000)

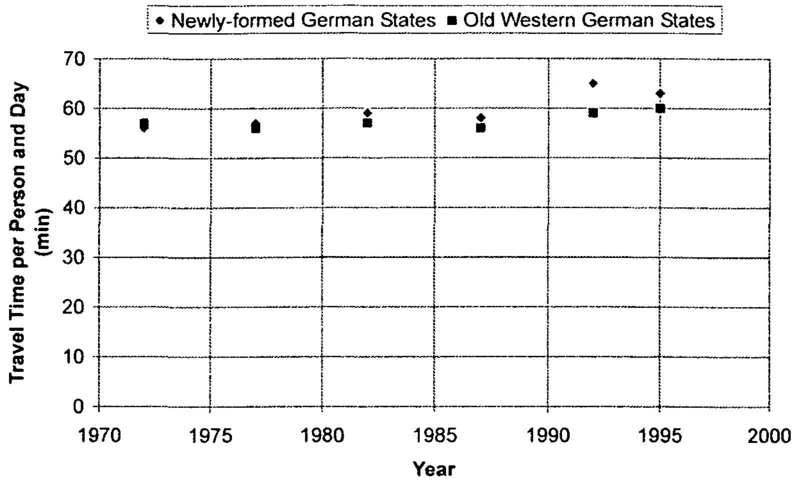

Figure 12.3: Travel time budget per person and day on city level (Brög, W. and Erl, E., 1999)

The display of constancy in trip duration over the study period (and even back to 1957), despite increasing trip distances and worsening congestion, is the primary finding of this paper (Levinson, D. M. and Kumar, A., 1994).

12.3 Friction factors

12.3.1 Basics

Abstract from (Walther, K., 1991) p. III-IV:

The objektive[119] *of the research project was to demonstrate the feasibility of establishing the traffic resistance*[120] *in urban traffic deterministically from the supply parameters of the different transport modes (car, local public transport (bus/tram, light rail/underground, regional express system), pedestrian and cycle traffic) and the fundamental subjective human attitude to these supply parameters, in order to permit direct inferences on behaviour and, amongst other factors, on the selection of a particular mode of transport. ...*

The method used to verify the above hypothesis for formulating traffic resistance is as follows: on the basis of previous before/after counts in the context of demand-modifying measures for urban traffic areas, the modal split for the before and after situation is modelled, taking into account all the parameters mentioned below; the resulting change in demand is then compared with the count data.

The following parameters were included in the model:

- ***motorized individual traffic***
    - *distance on foot from house to car*
    - *in-vehicle time/speed*
    - *parking-spot search time*
    - *distance on foot from car to destination*

[119] sic!

[120] In this thesis called friction factor.

    - *speed-dependent fuel consumption (according to car population)*
    - *fuel price*
    - *car operating costs (excluding tax and insurance)*
    - *car occupancy*
- ***public transport***
    - *mode of transport (bus/tram, light rail/underground, regional express system)*
    - *walking distance (local availability)*
    - *frequency of service (temporal availability)*
    - *in-vehicle time/speed*
    - *transfers involved/transfer times*
    - *type of season ticket (transferable/non-transferable)*
    - *fare levels*
- ***pedestrian and cycle traffic***
    - *area-typical resistance function*

*The **time components** are weighted according to subjektive[121] responses, using so-called time-evaluation functions. This reveals that in public transport the non-transportation components of journey-time (walking times, waiting times and transfer times) are perceived as much more disagreeable and therefore much more resistance-enhancing, i.e. they tend to be overrated.*

*The various **cost components** of the resistances are transformed to time equivalents. Among other factors, mean net household income is used for valueting[122].*

The total transport-mode-specific resistances for a relationship are formed by adding together the evaluated cost and time components, and are then combined with the distance-dependent, area-typical resistance values for pedestrian and cycle traffic to achieve a modal split calculation using Kirchhoff's law (electrical engineering)....

The results of comparative calculations are documented for a single relation (H-Bahn Dortmund) and for global studies in larger traffic areas. ....

12.3.2 Validation

(Walther, K., 1991) used several German real life before and after studies to validate the results of the friction factor definition (Table 12.1).

[121] sic!

[122] sic!

Table 12.1: Comparison model results and traffic counts (Walther, K., 1991) p. 91

Example	Year	Policy instruments	Changes in demand PT	
			Model	Counts/surveys
Tübingen	1985 to 1989	Improved route structure, Increased frequency, tariffs (temporal graduated)	+42.0%	+40.8%
H-Bahn Dortmund	1984	Introduction of the system (initially free use)	49.9% former car users; 33.5% former pedestrians and 16.6% former cyclists	44.5% former car users; 38.9% former pedestrians and 16.6% former cyclists
	1985	Paid use	-4.1%	-4.4%
S-Bahn Düsseldorf	1967/ 1968	System change, decreasing headway times (30 to 15 min), 11 stops instead of 6, reduction of speed from 54 km/h to 40 km/h (caused by more stops)	+29.8%	+30%
Mannheim Rheinau-Süd	1985	Decreasing headway times (30 to 15 min, free weekly tickets	+31.3% (incr. frequency) +44.1% incr. frequency & free tickets)	between 33% and 46% (depending on the share of free tickets)
Hamm	1988/ 1989	no changes on the transport supply side	+1.1%	+1.3%

12.3.3 Transferability

During the development of MARS the question about the transferability of friction factor definitions to other countries e.g. the UK was raised. Suggestions for future research work to test the transferability of the friction definitions are made in section 9.3 Suggestions for future MARS improvements. (Knoflacher, H., 1981; Knoflacher, H., 1987) first recognised that human behaviour in the transport system follows Weber-Fechners law of perception.

$$P = \alpha * \ln(I)$$

Equation 12.1: Weber-Fechners law

P........................ Human perception

α................. Constant factor

I..................... Intensity of the stimulus

For destination and mode choice the intensity of the stimulus can be interpreted as the friction factor or resistance to travel by a certain mode or to a certain destination. The transformation of Equation 12.1 gives:

$$I = e^{(P/\alpha)}$$

Equation 12.2: Weber-Fechners law transformed

Equation 12.2 is formal equivalent to the time dependent part of the friction factor definitions developed by (Walther, K., 1991; Walther, K. et al., 1997). The friction factors are therefore based on basic physiological laws of human behaviour. They should be transferable as long as the urban environment is roughly comparable[123]. The part of the friction factors which is most likely to differ between countries and cities is the cost part. Different sensitivity to costs can be considered be adopting the factor for the value of time.

12.4 Optimisation framework

12.4.1 The core optimisation algorithm

The method applied with MARS is based on the downhill simplex method in multi-dimensions due to (Nelder, J. A. and Mead, R., 1965). It solves a multidimensional minimisation, i.e. finding the minimum of a function (which is in our case $-OF$, Equation 12.10) of more than one independent variable (which is in our case $X(t)$). The method requires only function evaluations, not derivatives.

A simplex is the geometrical figure consisting, in N dimensions, of N+1 points (or vertices) and all their interconnecting line segments, polygonal faces etc. In two dimensions, a simplex is a triangle. In three dimensions it is a tetrahedron, not necessarily the regular tetrahedron.

In general the method is only interested in simplexes that are nondegenerate, i.e. which enclose a finite inner N-dimensional volume. If any point of a nondegenerate simplex is taken as the origin, then the N other points define vector directions that span the N-dimensional vector space.

The method requires an initial starting point, that is, an N-vector of independent variables. The algorithm is then supposed to make its own way downhill through the N-dimensional topography, until it encounters a (at least local) minimum.

The downhill simplex method must be started not just with a single point, but with $N+1$ points, defining an initial simplex. If one of these points is taken to be the initial starting point X_0, then the other N points can be expressed as:

$$X_n^k = X_n^0 + \lambda_n * e_n$$

Equation 12.3

Where k is row number of the initial matrix ($0<=k<=N+1$) and n is the column number ($1<=n<=N$) (Equation 12.4), where the e_n is 1 if $k = n$ and otherwise 0, and where λ_n is a constant which is a guess at the problem's characteristic length or scale (λ_n could be different for each vector direction).

For example with 3 dimensions then the initial simplex defined by Equation 12.3 would be a tetrahedron made up as follows:

[123] Research at the Institute for Transport Planning and Traffic Engineering has shown that the perception of time is influenced by the quality of the urban environment.
Peperna, O. (1982). Die Einzugsbereiche von Haltestellen öffentlicher Nahverkehrsmittel im Straßenbahn- und Busverkehr. Masterthesis. Institut für Verkehrsplanung. Technische Universität Wien.

$$X = \begin{pmatrix} X_1^0 \, X_2^0 \, X_3^0 \\ X_1^1 \, X_2^1 \, X_3^1 \\ X_1^2 \, X_2^2 \, X_3^2 \\ X_1^3 \, X_2^3 \, X_3^3 \end{pmatrix} = \begin{pmatrix} X_1^0 & X_2^0 & X_3^0 \\ X_1^0 + \lambda_1 & X_2^0 & X_3^0 \\ X_1^0 & X_2^0 + \lambda_2 & X_3^0 \\ X_1^0 & X_2^0 & X_3^0 + \lambda_3 \end{pmatrix}$$

Equation 12.4

Where:

X_1^0, X_2^0, X_3^0 Policy instruments 1 to 3

$\lambda_1, \lambda_2, \lambda_3$ ... Initial guesses at the scale of the simplex which depends upon the ranges considered for each measure.

The policy instruments to be optimised can be defined by the user along with feasible input ranges for each measure. The initial simplex is then generated automatically from the minimum and maximum for each measure as follows:

$$X_n^0 = X_n^{\min} + \frac{X_n^{\max} - X_n^{\min}}{3}$$

Equation 12.5

and

$$\lambda_n = \frac{X_n^{\max} - X_n^{\min}}{3}$$

Equation 12.6

Where: X_n^{min}, X_n^{max} are the minimum and maximum values for policy measure X_n.

This is equivalent to assuming that the initial guess X^0_n is one third of the feasible range and that the scale of the problem λ_n is also one third of the feasible range. This then ensures that the movement of the simplex is initially within the bounds of the problem as defined by the user. It also removes the onus of defining the initial simplex from the user and is easily generalised for N dimensions.

The downhill simplex method now takes a series of steps, most steps just moving the point of the simplex where the function is largest ("highest point") through the opposite face of the simplex to a lower point. These steps are called reflections, and they are constructed to conserve the volume of the simplex (hence maintain its nondegeneracy). When it can do so, the method expands the simplex in one or another direction to take larger steps. When it reaches a "valley floor", the method contracts itself in the transverse direction and tries to ooze down the valley. If there is a situation where the simplex is trying to "pass through the eye of a needle", it contracts itself in all directions, pulling itself in around its lowest (best) point. The routine name AMOEBA is intended to be descriptive of this kind of behaviour (Press, W. H. et al., 1990).

12.4.2 Re-parameterisation

To deal with upper and lower bounds on policy instruments re-parameterisation was used. Policy instruments X_n, *(n=1,...,N)* are economically interpretable and constrained between a lower and an upper limit, $X_n^{\min} \le X_n \le X_n^{\max}$. Unconstrained optimisation with respect to X may give meaningless estimates that are beyond the limits. However, transformation of the parameters (policy instruments) with the re-parameterisation by (Vold, A. et al., 1999):

$$\xi(X) = \log((X - X^{\min})/(X^{\max} - X)),$$

Equation 12.7: Transformation

Equation 12.7 ensures that an original parameter *p* stays within its definition area during unconstrained estimation. Since $e^{\xi} = (X - X^{\min})/(X^{\max} - X)$, which is equivalent to $X*(e^{\xi}+1) = e^{\xi} * X^{\max} + X^{\min}$, we have the unique inverse transformation:

$$p(\xi) = (X^{\max} * e^{\xi} + X^{\min})/(1 + e^{\xi})$$

Equation 12.8: Transformation

Now, we can transform the maximisation problem to

$$\max_{\xi \in R_m} f(\xi)$$

and use an unconstrained optimisation algorithm to find

$$f(\hat{\xi}) = \max_{\xi \in R_m} f(\xi)$$

where the elements of the initial simplex defined by the section "The core optimisation algorithm" are transformed by

$$\xi_i(X_n^0 + \lambda_n \cdot e_n) = \log((X_n^0 + \lambda_n \cdot e_n - X^{\min})/(X^{\max} - X_n^0 + \lambda_n \cdot e_n))$$

Equation 12.9

It is guaranteed then that function evaluations at the final estimate and at the algorithmic search path are such that the values of the original parameters (policy instruments) are within their lower and upper limits.

12.5 Objective function

12.5.1 General form

The general form of the objective function can be written as follows :-

$$OF[X(t)] = \sum_{t=0}^{30} \alpha(t) * [b(\mathbf{X}(t)) - c(\mathbf{X}(t)) - I(\mathbf{X}(t)) - \gamma(t) * g(\mathbf{X}(t))] + \sum_{k \in M} \sum_{t=0}^{30} \mu_k(t) * y_k(t)$$

Equation 12.10: Objective function

Equation 12.10 is subject to constraints on some of the indicators of the form $\sum_{t=0}^{30} \mu_k(t) * y_k(t) \le C_k$ or the form $y_k(t) \le C_k(t)$.

OF is the overall objective function[124] and the first term represents economic efficiency where:

$X(t)$ .... Vector of levels of policy instruments which can be used to maximise the objective function OF

$b(\mathbf{X}(t))$ .... Sum of all benefits in year t (€)

$c(\mathbf{X}(t))$ .... Sum of all costs in year t (€)

$I(X(t))$ .... Sum of capital investments in year t (€)

$\gamma(t)$ .... Shadow cost of CO_2 emission, reflecting national CO_2 targets for year t (€/t)

$g(\mathbf{X}(t))$ .... Amount of CO_2 emissions in year t (t)

k .... Represents the remaining indicators ($k \in$ M)

$\mu_k(t)$ .... Weight in year t for indicator k (€/Unit of indicator k)

$y_k(t)$ .... Level of indicator k in year t (Unit of indicator k)

$C_k(t)$ .... Constraint/target for indicator k in year t (Unit of indicator)

C_k .... Overall constraint/target for indicator k (for instance, a financial constraint) (€)

The annual cost and benefit terms are weighted by α_t. We use

$$\alpha_t = \alpha \frac{1}{(1+r)^t}$$

for all years between 0 and 29. Here, r is a (country specific) discount rate and α, the intergenerational equity constant, is a constant between 0 and 1, reflecting the relative importance of welfare at present as opposed to the welfare of future generations. So for these years, $\alpha(t)$ is an ordinary discount factor. For year 30,

$$\alpha_{30} = \alpha \frac{1}{(1+r)^{30}} + (1-\alpha)$$

Furthermore,

i .... represents the remaining indicators ($i \in$ M)

y_{it} .... is the level of indicator i in year t

μ_{it} .... is the weight in year t for indicator i

C_{it} .... is the constraint/target for indicator i in year t

C_i .... is the overall constraint/target for indicator i (for instance, a financial constraint)

X_t .... is the vector of levels of policy instruments which can be used to maximise the objective function OF.

124 See Minken, H., Jonsson, D., Shepherd, S. P., Järvi, T., May, A. D., Page, M., Pearman, A., Pfaffenbichler, P. C., Timms, P. and Vold, A. (2003). Developing Sustainable Land Use and Transport Strategies - A Methodological Guidebook; *TOI Report*, **619**; Institute of Transport Economics, Oslo. p. 52

12.5.2 Application for the MARS case studies

Equation 12.11 illustrates the policy instrument vector used in the framework presented here.

$$X(t) = \left| {}^{p}F^{PT}(t)\, {}^{op}F^{PT}(t) \quad {}^{p}Fr^{PT}(t) \quad {}^{op}Fr^{PT}(t) \quad \ldots\ldots \quad {}^{st}P_j^{PC}(t) \quad {}^{lt}P_j^{PC}(t) \right|$$

Equation 12.11: Policy instrument vector

$X(t)$ .... Policy instrument vector

${}^{p}F^{PT}(t)$ ..... Public transport fare peak period (% change relative to do nothing)

${}^{op}F^{PT}(t)$ .... Public transport fare off peak period (% change relative to do nothing)

${}^{p}Fr^{PT}(t)$ .... Public transport frequency peak period (% change relative to do nothing)

${}^{op}Fr^{PT}(t)$ ... Public transport frequency off peak period (% change relative to do nothing)

${}^{st}P_j^{PC}(t)$ ..... Short term parking charge (€/stay)

${}^{lt}P_j^{PC}(t)$ ..... Long term parking charge (€/stay)

Equation 12.12 illustrates the policy instrument profile for the example public transport peak fare.

$$\text{If } {}^{p}F^{PT}(t) < \text{ then } {}^{p}F^{PT}(t) = 0$$

$$\text{If } {}^{p}F^{PT}(t) = t_{im} \text{ then } {}^{p}F^{PT}(t) = {}^{p}F_{im}^{PT}$$

$$\text{If } {}^{p}F^{PT}(t) > t_{im} \text{ and } {}^{p}F^{PT}(t) < t_{lr} \text{ then } {}^{p}F^{PT}(t) = {}^{p}F_{im}^{PT} + \frac{{}^{p}F_{lr}^{PT} - {}^{p}F_{im}^{PT}}{t_{lr} - t_{im}} * (t - t_{im})$$

$$\text{If } {}^{p}F^{PT}(t) >= t_{lr} \text{ then } {}^{p}F^{PT}(t) = {}^{p}F_{lr}^{PT}$$

Equation 12.12: Policy instrument profile

t_{im} .... Implementation year; user defined

${}^{p}F_{im}^{PT}$ .... Public transport peak fare in the implementation year; user defined for a single MARS run, suggested by the optimisation routine in an optimisation

t_{lr} .... Long run year; user defined

${}^{p}F_{lr}^{PT}$ .... Public transport peak fare in the long run year; user defined for a single MARS run, suggested by the optimisation routine in an optimisation

Benefits, costs, emissions and other indicator values required in Equation 12.10 are calculated from MARS output values. The balance of yearly benefits and costs comes from two groups: the users and the operators (including government) of the land use and transport system.

$$b(X(t)) - c(X(t)) = \sum_k {}^{k}U(X(t)) + \sum_k {}^{k}O(X(t))$$

Equation 12.13: Benefits and costs

${}^{k}U(X(t))$........Balance of user benefits and losses for user group k in year t. User groups are pedestrians, cyclists, public transport and car users from the transport perspective and residents and businesses from the land use perspective.

${}^{k}O(X(t))$........Balance of operator benefits and losses for group k in year t. The groups are public transport operators, parking facility operators, toll operators, land and property owners and public authorities.

$$^{PT}U^{T}(t) = -\frac{1}{2}\sum_{ij} VoT * \left[t_{ij}^{PT}(t)\Big|_{X(t)} - t_{ij}^{PT}(t)\Big|_{0}\right] * \left[T_{ij}^{PT}(t)\Big|_{X(t)} + T_{ij}^{PT}(t)\Big|_{0}\right]$$

Equation 12.14: User time benefits and losses

${}^{PT}U^{T}$ ....Balance of user time benefits and losses for public transport users in year t

VoT.............Value of time; specified by the MARS user (€/min)

$t_{ij}^{PT}(t)\big|_{X(t)}$ ...Travel time for a public transport trip from i to j in year t if the vector of policy instrument levels X_t is applied; output of MARS (min)

$t_{ij}^{PT}(t)\big|_{0}$ ....Travel time for a public transport trip from i to j in year t in the do nothing scenario; input to MARS (min)

$T_{ij}^{PT}(t)\big|_{X(t)}$ ..Public transport trips from i to j in year t if the vector of levels instrument levels X_t is applied; output of MARS

$T_{ij}^{PT}(t)\big|_{0}$ ......Public transport trips from i to j in year t in the do nothing scenario output of MARS

The balance of operating benefits and losses is a function of the trips made in the do something ${}^{k}T(X(t))$ and the do nothing scenario ${}^{k}T(0)$ and the policy instrument vector $X(t)$ applied in the do something scenario (Equation 12.15).

$${}^{k}O(t) = f\left({}^{k}T(t)\Big|_{X(t)}, {}^{k}T(t)\Big|_{0}, X(t)\right) + g(X(t))$$

Equation 12.15: Operator benefits and losses

${}^{k}O(t)$...........Balance of benefits and losses for the operator type k in year t

Equation 12.16 shows revenues from changes in fare levels as an example for the first type. An example for the second type are operating costs for additional public transport frequency (Equation 12.17).

$$f\left({}^{k}T(t)\Big|_{X(t)}, {}^{k}T(t)\Big|_{0}, X(t)\right) = \sum_{ij} F_{ij}^{PT}(t)\Big|_{X(t)} * T_{ij}^{PT}(t)\Big|_{X(t)} - F_{ij}^{PT}(t)\Big|_{0} * T_{ij}^{PT}(t)\Big|_{0}$$

Equation 12.16: Revenues from PT fare level changes

$F_{ij}^{PT}(t)\big|_{X(t)}$ ....Public transport fares for a trip from i to j and year t when the vector of levels of policy instruments $X(t)$ is applied; output of MARS (€/trip)

$F_{ij}^{PT}(t)\big|_{0}$ ....Public transport fares for a trip from i to j and year t in the do nothing scenario; input in MARS (€/trip)

$T_{ij}^{PT}(t)\big|_{X(t)}$ .....Public transport trips from i to j in year t when the vector of levels of policy instruments $X(t)$ is applied; output of MARS

$T_{ij}^{PT}(t)\big|_{0}$........Public transport trips from i to j in year t in the do nothing scenario; output of MARS

$$g(X(t)) = {}^{Fr}o^{PT} * {}^{Fr}p^{PT}(t)$$

Equation 12.17: Operating costs PT frequency

${}^{Fr}o^{PT}$ ....Operating costs for an additional percent of public transport frequency (k€/%)

${}^{Fr}p^{PT}(t)$.......Percentage change in public transport frequency change year t; specified by the user for a single model run or the optimisation routine in an optimisation (%)

- **Emissions**

The emissions from car traffic are calculated using results from (Samaras, Z. and Ntziachristos, L., 1998).

Carbon dioxide

$${}^{CO_2}e_{ij}^{PC}(t) = a_2 * \left(V_{ij}^{PC}(t)\right)^2 + a_1 * V_{ij}^{PC}(t) + a_0$$

Equation 12.18: Specific carbon dioxide emissions private car

${}^{CO_2}e_{ij}^{PC}(t)$ ...Specific carbon dioxide emissions of the mode car for a trip from i to j in year t (g/Vh-km)

$V_{ij}^{PC}(t)$ ....Average speed for a car trip from i to j in year t; depending of the applied policy instrument vector; output of MARS (km/h)

a_n................Parameters; Source: MEET project (Samaras, Z. and Ntziachristos, L., 1998)

Table 12.2: Parameter values specific carbon dioxide emissions PC

Parameter	a_0	a_1	a_2
Value	416.1	-6.9808	0.0431

Source: MEET project (Samaras, Z. and Ntziachristos, L., 1998) p. 73

$${}^{CO_2}E^{PC}(t) = \frac{270}{10^6} * \left| \sum_{ij} {}^{CO_2}e_{ij}^{PC}(t) * \frac{T_{ij}^{PC}(t) * D_{ij}^{PC}(t)}{o^{PC}} \right|_{HWH} + \frac{365}{10^6} * \left| \sum_{ij} {}^{CO_2}e_{ij}^{PC}(t) * \frac{T_{ij}^{PC}(t) * D_{ij}^{PC}(t)}{o^{PC}} \right|_{HOH}$$

Equation 12.19: Total carbon dioxide emissions private car

${}^{CO_2}E^{PC}(t)$ ..Carbon dioxide emissions of the mode car in year t (t/a)

$T_{ij}^{PC}(t)$........Trips by the mode car from zone i to zone j in year t; output o f MARS

$D_{ij}^{PC}(t)$.......Distance of a car trip from i to j in year t including search for parking place; output of MARS (km)

o^{PC} ....Occupancy rate car (people per car); specified by the user

HWH...........Tour Home - Work - Home

HOH...........Tour Home - Others - Home

$$D_{ij}^{PC}(t) = \frac{t_{ij}^{PC,inVh}(t)}{60} * V_{ij}^{PC}(t)$$

Equation 12.20: Driving distance private car trip

$t_{ij}^{PC,inVh}(t)$ ...In vehicle time for a car trip from i to j and year t; output of MARS (min)

$V_{ij}^{PC}(t)$ ....Average speed by car from *i* to *j* and year *t*; output of MARS (km/h)

The emissions of public transport are calculated as follows.

$${}^{CO_2}E^{PT}(t) = {}^{CO_2}E^{PT}(0) * \left(1 + {}^{Fr}p^{PT}(t)\right)$$

Equation 12.21: Carbon dioxide emissions public transport

${}^{CO_2}E^{PT}(t)$ ..Carbon dioxide emissions mode *PT* in year *t* (t/a)

${}^{CO_2}E^{PT}(0)$ ..Carbon dioxide emissions mode *PT* in base year *0* (t/a); from statistical data

${}^{Fr}p^{PT}(t)$ .....Percentage change in public transport frequency change in year *t*; specified by the user for a single model run or the optimisation routine in an optimisation (%)

Nitrogen oxide

$${}^{NO_X}e_{ij}^{PC}(t) = a_2 * \left(V_{ij}^{PC}(t)\right)^2 + a_1 * V_{ij}^{PC}(t) + a_0$$

Equation 12.22: Specific nitrogen oxide emissions private car

${}^{NO_X}e_{ij}^{PC}(t)$ ..Specific nitrogen oxide emissions of the mode car for a trip from *i* to *j* in year *t* (g/Vh-km)

$V_{ij}^{PC}(t)$ ....Average speed for a car trip from *i* to *j* in year *t*; depending of the applied policy instrument vector; output of MARS (km/h)

a_n ....Parameters; Source: MEET project (Samaras, Z. and Ntziachristos, L., 1998)

Table 12.3: Parameter values specific nitrogen oxide emissions car

Parameter	a_0	a_1	a_2
Value	0.526	-8.5*10^{-3}	8.54*10^{-6}

Source: MEET project (Samaras, Z. and Ntziachristos, L., 1998) p. 72

$${}^{NO_X}E^{PC}(t) = \frac{270}{10^6} * \left| \sum_{ij} {}^{NO_X}e_{ij}^{PC}(t) * \frac{T_{ij}^{PC}(t) * D_{ij}^{PC}(t)}{o^{PC}} \right|_{HWH} + \frac{365}{10^6} * \left| \sum_{ij} {}^{NO_X}e_{ij}^{PC}(t) * \frac{T_{ij}^{PC}(t) * D_{ij}^{PC}(t)}{o^{PC}} \right|_{HOH}$$

Equation 12.23: Total nitrogen oxide emissions private car

${}^{NO_X}E^{PC}(t)$. Nitrogen oxide emissions of the mode car in year *t* (t/a)

$T_{ij}^{PC}(t)$ ....Trips by the mode car from zone *i* to zone *j* in year *t*; output of MARS

$D_{ij}^{PC}(t)$ ....Distance of a car trip from *i* to *j* in year *t* including search for parking place; output of MARS (km), Equation 12.20

o^{PC} ....Occupancy rate car (people per car); specified by the user

HWH ....Tour Home - Work - Home

HOH............Tour Home - Others - Home

Hydrocarbon

$${}^{VOC}e_{ij}^{PC}(t) = a_2 * \left(V_{ij}^{PC}(t)\right)^2 + a_1 * V_{ij}^{PC}(t) + a_0$$

Equation 12.24: Specific hydrocarbon emissions private car

${}^{VOC}e_{ij}^{PC}(t)$ ...Specific hydrocarbon emissions of the mode car for a trip from *i* to *j* in year *t* (g/Vh-km)

$V_{ij}^{PC}(t)$ ....Average speed for a car trip from *i* to *j* in year *t*; depending of the applied policy instrument vector; output of MARS (km/h)

a_n ....Parameters; Source: MEET project (Samaras, Z. and Ntziachristos, L., 1998)

Table 12.4: Parameter values specific hydrocarbon emissions car

Parameter	a_0	a_1	a_2
Value	0.4494	-8.88*10^{-3}	5.21*10-6

Source: MEET project (Samaras, Z. and Ntziachristos, L., 1998) p. 73

$${}^{VOC}E^{PC}(t)=\frac{270}{10^6}*\left|\sum_{ij}{}^{VOC}e_{ij}^{PC}(t)*\frac{T_{ij}^{PC}(t)*D_{ij}^{PC}(t)}{o^{PC}}\right|_{HWH}+\frac{365}{10^6}*\left|\sum_{ij}{}^{VOC}e_{ij}^{PC}(t)*\frac{T_{ij}^{PC}(t)*D_{ij}^{PC}(t)}{o^{PC}}\right|_{HOH}$$

Equation 12.25: Total hydrocarbon emissions private car

${}^{CO_2}E^{PC}(t)$ ..Hydrocarbon emissions of the mode car in year *t* (t/a)

$T_{ij}^{PC}(t)$........Trips by the mode car from zone *i* to zone *j* in year *t*; output o f MARS

$D_{ij}^{PC}(t)$ ....Distance of a car trip from *i* to *j* in year *t* including search for parking place; output of MARS (km), Equation 12.20

o^{PC} ....Occupancy rate car (people per car); specified by the user

HWH ....Tour Home - Work - Home

HOH............Tour Home - Others - Home

- **External costs**

Accidents

$$C_{Acc}^{PC}=c_{Acc}^{PC}*u_R^{PC}*Vh-km$$

Equation 12.26: General definition accident costs private car

C_{Acc}^{PC} ....Accident costs car per year (M€/a)

c_{Acc}^{PC} ....Costs per accident with car involvement (€/accident)

u_R^{PC} ....Accident rate car (10^{-6} km)

Vh-km..........Vehicle kilometres per year (km/a)

$$c_{Acc,t}^{PC}=c_{Acc,0}^{PC}*\frac{V_t^{PC}}{V_0^{PC}}$$

Equation 12.27: Costs per accident with car involvement

$c_{Acc,t}^{PC}$ ....Costs per accident with car involvement in iteration *t* (€/accident)

V_t^{PC} ....Average speed car in iteration *t* (km/h)

$$u_{R,t}^{PC} = u_{R,0}^{PC} * \frac{V_t^{PC}}{V_0^{PC}}$$

Equation 12.28: Accident rate private car

$u_{R,t}^{PC}$ ....Accident rate car in iteration t (10^{-6} km)

V_t^{PC} ....Average speed car in iteration t (km/h)

$$C_{Acc,t}^{PC} = \left[c_{Acc,0}^{PC} * \sum_{ij} \left(\frac{V_{ij,t}^{PC}}{V_{ij,0}^{PC}} \right)^2 * \frac{T_{ijPC,t} * D_{ijPC,t}}{o_{PC}} * \frac{365}{10^6} \right]_{peak} + \left[c_{Acc,0}^{PC} * \sum_{ij} \left(\frac{V_{ij,t}^{PC}}{V_{ij,0}^{PC}} \right)^2 * \frac{T_{ijPC,t} * D_{ijPC,t}}{o_{PC}} * \frac{365}{10^6} \right]_{off-peak}$$

Equation 12.29: Accident costs private car

$C_{Acc,t}^{PC}$ ....Accident costs car per year in iteration t (M€/a)

$c_{Acc,0}^{PC}$ ....Costs per accident with car involvement in the base year 0 (€/accident)

$V_{ij,t}^{PC}$ ....Average speed car from i to j in iteration t (km/h)

$T_{ijPC,t}$ ....Trips by the mode car from TAZ i to TAZ j year t (-)

$D_{ijPC,t}$ ....Distance of a car trip from i to j year t (km), Equation 12.20

o_{PC} ....Occupancy rate car (people per car)

Local emissions

$$C_{Em,t}^{PC} = c_{NO_X} *^{VOC} E^{PC}(t) + c_{VOC} *^{VOC} E^{PC}(t)$$

Equation 12.30: External costs from atmospheric emissions

$C_{Em,t}^{PC}$ ....External costs emissions caused by the mode car year t (k€/a)

c_{NO_X} ....Specific external costs nitrogen oxide emissions (8 €/kg NO_X; Task 21 report p. 71)

c_{VOC} ....Specific external costs hydrogen emissions (8 €/kg VOC; Task 21 report p. 71)

${}^{NO_X}E^{PC}(t)$. Nitrogen oxide emissions of the mode car in year t (t/a)

${}^{CO_2}E^{PC}(t)$ .. Hydrocarbon emissions of the mode car in year t (t/a)

12.6 Data used in the Vienna MARS models

12.6.1 Transport related data

The average trip rate for a trip Home - Work is 0,85 trips per employed and workday[125]. The daily travel time budget per person is assumed to be 65 minutes[126].

[125] The trip rate is calculated as follows: 365 d/a minus 52 weekends is 261 weekdays/a. 261 weekdays /a minus 5 weeks holidays and minus 13 bank holidays gives 223 workdays per employee and year. 223 workdays per 261 weekdays is 0.85 trips Home - Work per employee and weekday.

- **Car ownership**

Table 12.5: Car ownership in cars per 1,000 residents by district Vienna in the years 1981 and 1991

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23
80	849	269	322	379	296	345	348	310	324	288	291	283	319	287	266	273	283	286	328	276	280	294	327
91	915	297	372	401	321	348	344	327	370	343	373	337	370	348	314	322	329	340	386	309	371	397	435
99	919	336	422	502	376	423	405	393	438	392	397	377	457	405	351	355	377	399	444	333	410	423	503

Source: (Magistratsabteilung 66 - Statistisches Amt, 1981), (Magistratsabteilung 66 - Statistisches Amt, 1992)

The data for travel analysis zone 1[127] calculated in Table 12.5 are not valid. Zone 1 is the central business district and many companies have their headquarters in this district. That means that their car fleet is registered in district 1. The average car ownership of the other zones, which is about 303 (1981) and 353 (1991) cars per inhabitant, is used for zone 1 in MARS. The spatial distribution of car ownership can be seen in Figure 12.5.

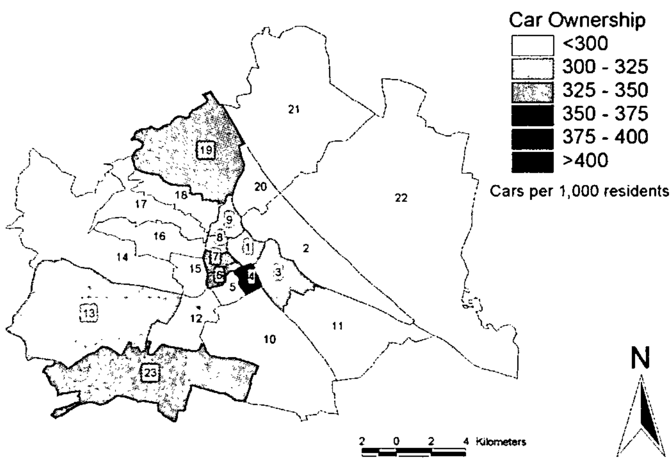

Figure 12.4: Car ownership Vienna 1981 (Magistratsabteilung 66 - Statistisches Amt, 1981)

[126] The average daily travel time budget is according to the Viennese travel survey of the year 1993 about 69 minutes (Socialdata (1993). Mobilität in Wien; *Beiträge zur Stadtforschung, Stadtentwicklung und Stadtgestaltung*, **Band 45**, Wien. p. 12)

[127] 1st District - Innere Stadt

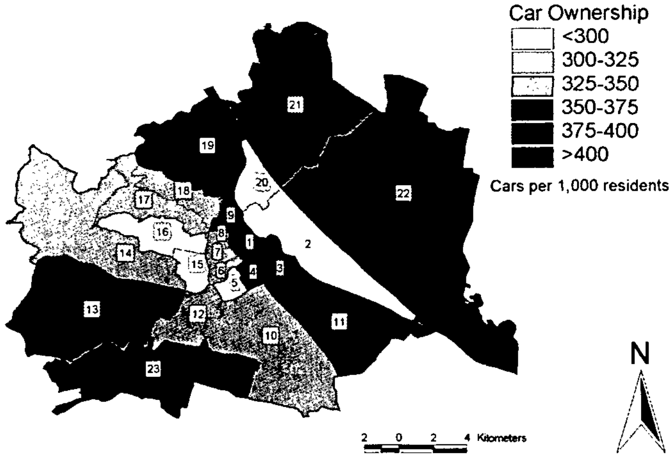

Figure 12.5: Car ownership Vienna 1991 (Magistratsabteilung 66 - Statistisches Amt, 1992)

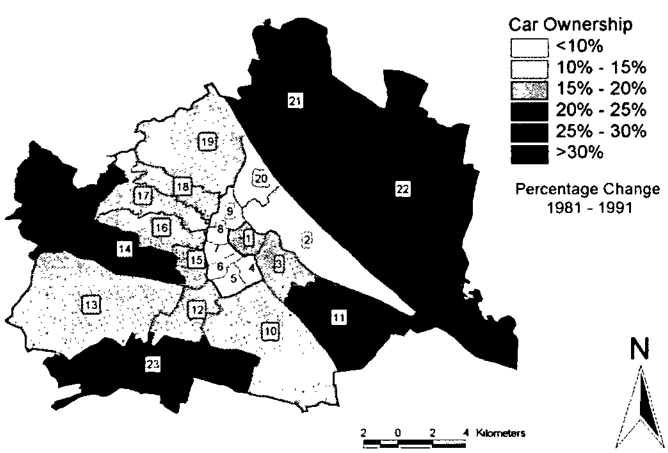

Figure 12.6: Percentage change in car ownership 1981 to 1991

- **Car occupancy rate**

The car occupancy rate is assumed with 1.3 passengers per car for tours HWH and with 1.5 passengers per car for tours HOH[128].

- **Distance matrices**

The distance matrices for slow modes, public transport and car are shown in Table 12.20 to Table 12.22 in section OD Matrices.

[128] The year 1977 census gives the following results for Vienna: Work, business 1.2, shopping, children, school 2.0, leisure, holidays 1.5 and others 1.5. Source: ÖSTAT (1979). Fahrleistungen der Kraftfahrzeuge, Führerscheine - Ergebnisse des Mikrozensus 1977; *Beiträge zur Österreichischen Statistik*, **Heft 553**; Österreichisches Statistisches Zentralamt, Wien. p. 49

- **Travel speed**

The travel speed of slow modes is assumed with 6 km/h for HWH tours and 4 km/h for HOH tours. The speed matrix public transport separated from individual road traffic is given in Table 12.23. The free flow speed matrix for car trips is given in Table 12.24. The speed matrices for HWH and HOH tours in the base year are given in Table 12.25 and Table 12.26.

- **Average distance to a PT stop**

Table 12.6: Average walking distance to a PT stop (min)

1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23
1.3	3.6	2.2	1.7	1.7	1.6	1.4	1.4	1.7	3.9	3.6	2.3	7.0	6.2	1.9	3.1	4.8	2.9	4.3	2.4	4.8	6.6	4.6

The average distance to a PT stop is calculated as described in Equation 12.31.

$$t_{il}^{PT,w} = \sqrt{\frac{A_i}{n_i^{PT} * \pi}} * \frac{60}{V^w} * \alpha_d$$

Equation 12.31: Average walking distance to a PT stop

$t^{PT,w}_{il}$............Walking time from source i to public transport stop l (min)

A_i................Area of zone i (km²)

n^{PT}_i.............Number of public transport stops in zone i

V^w...............Walking speed (4 km/h)

α_d................Detour factor (1.2)

Table 12.7: Area per zone (km²)

1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23
3.0	19.3	7.4	1.8	2.0	1.5	1.6	1.1	3.0	31.8	23.2	8.2	37.7	33.8	3.9	8.6	11.3	6.3	24.9	5.7	44.5	102.3	32.0

Source: (Magistratsabteilung 66 - Statistisches Amt, 1992)

Table 12.8: Number of PT stops per zone

1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23
197	156	164	64	71	61	79	57	109	213	183	156	79	91	113	92	50	79	139	99	202	240	154

Source: Counted from a city map

- **PT headway times**

The PT headway time matrices (Table 12.27 and Table 12.28) are needed to calculate the average waiting times at PT stops. The headway times are estimated by aggregating the relevant PT lines per OD pair. Source: Timetables

- **PT Changing times**

The assumptions for the PT changing time matrices for HWH and HOH tours are shown in Table 12.29 and Table 12.30.

- **PT Fares**

Vienna has an integrated PT fare structure. The majority of the PT users own season tickets.

Table 12.9: Public transport fare in the year 2000

Ticket	Share	Price (€)
Yearly season ticket	36%	377.90[129]
Monthly season ticket	19%	40.70
Weekly season ticket	9%	11.26
Educational ticket	22%	5.09[130]
Single ticket	6%	1.38
Others	8%	4.36[131]

Source: (VOR, 2000), (Wiener Linien, 2000)

Under the assumption that season ticket owners are using their ticket twice each day and that "Others" are using their ticket four times a day the average PT fare per trip in the years 2000/2001 is about 0.58 Euro. Data for 1995 were used as a proxy to calculate an aggregated fare level for the year 1991 (VOR, 1995). The PT fare in 1991 is assumed with 0.51 Euro per trip. The growth rate for PT fares between 1981 and 1991 was about 64% (VCÖ, 1993). The PT fare in 1981 is assumed with 0.31 Euro per trip.

- **Average distance to a parking place**

The average walking distance to a parking place is estimated by expert judgement.

Table 12.10: Average walking distance to a parking place (min)

1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23
3.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0	0.0	1.0	1.0	0.0	0.0	0.0

- **Average time to find a parking place**

The average time to find a parking place is estimated by expert judgement.

Table 12.11: Average time to find a parking place (min)

1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23
6.0	6.0	6.0	6.0	6.0	6.0	6.0	6.0	6.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0

- **Parking charges**

Table 12.12: Parking charge long term (€/stay)

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23
81	0.3	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
91	0.9	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
01	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	1.0	0.0	0.0	0.0

Source: (Dorner A. et al., 1997), (Stadtentwicklung Wien, 2003)

Table 12.13: Ratio of charged long term parking places (%)

1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23
70	70	70	70	70	70	70	70	70	50	50	50	50	50	50	50	50	50	50	50	50	50	50

[129] Cash payment.

[130] Educational tickets are in principal free for the OD pair home – school. For the given monthly fee the educational ticket is extended to the core zone 100, which covers the whole city of Vienna.

[131] Assumed as the 24 hours runaround ticket "24 Stunden Wien"

Table 12.14: Parking charge short term (€/stay)

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23
81	0.3	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
91	0.9	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
01	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	1.0	0.0	0.0	0.0

Source: (Dorner A. et al., 1997), (Stadtentwicklung Wien, 2003)

Table 12.15: Ratio of charged short term parking places (%)[132]

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23
81	30	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
91	70	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
01	70	70	70	70	70	70	70	70	70	50	50	50	50	50	50	50	50	50	50	50	50	50	50

Table 12.16: Ratio of long term to short term parking for HWH tours (%)

1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23
100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100

Table 12.17: Ratio of long term to short term parking for HOH tours (%)

1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23
0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0

- **Fuel costs**

The fuel price at the petrol station is assumed with 0.9 Euro per litre. The fuel price was about the same in the years 1981 and 1991 (VCÖ, 1993)). The fuel tax is assumed with 70%.

$$f(V) = 0.295 - 8.62 * 10^{-3} * V + 1.19 * 10^{-4} * V^2 - 7.13 * 10^{-7} * V^3 + 1.76 * 10^{-9} * V^4$$

Equation 12.32: Fuel consumption car

f(V)............. Speed dependent fuel consumption car (l/km)

V................ Speed (km/h)

- **Other operating costs car**

The other operating costs for a car trip are assumed with 0.26 Euro per kilometre. 10% of these costs are relevant for transport user behaviour.

- **Intra-zonal distances**

In a first version the intra-zonal distances were assumed as the radius of a circle with an area equal to that of the residential area of a zone (see Table 12.19 row (1)). With these distances the fit of the OD matrix was not very satisfying. MARS significantly underestimated the number of intra-zonal trips in the bigger zones (see section 6). Therefore another method to calculate the intra-zonal trip distance was employed. Service sector businesses were assumed as destinations for intra-zonal trips. An average catchment area per service sector business is calculated (Equation 12.33). A hypothetical radius for a circular catchment area is calculated (Equation 12.34).

[132] To be able to predict the effects of the potential policy instrument parking charge a share of charged parking places has to be given for zones with actually no charging for the base year 2001.

$$A_i^{c,sv} = \frac{A_i^b}{B_i^{sv}}$$

Equation 12.33: Catchment area for a service sector business

$A_i^{c,sv}$ .... Catchment area for a service sector business in zone i (m²)

A_i^b .... Built-up area in zone i (m²)

B_i^{sv} .... Number of service sector businesses in zone i

$$r_i^{c,sv} = \sqrt{A_i^{c,sv}/\pi}$$

Equation 12.34: Hypothetical radius

$r_i^{c,sv}$ .... Hypothetical radius for a service sector business in zone i (m)

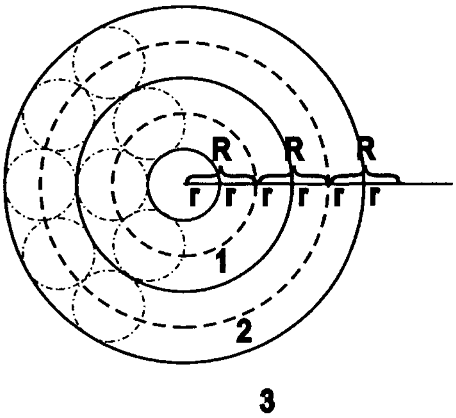

Figure 12.7: Hypothetical distribution of service sector businesses

Table 12.18: Hypothetical distribution of service sector businesses

k	Radius R (m)	Circumference U (m)	Number of businesses b in ring k	b*R (m)
0	0	0	1	0
1	$2*r$	$4*r*\pi$	$2*\pi$	$4*r*\pi$
2	$4*r$	$8*r*\pi$	$4*\pi$	$16*r*\pi$
3	$6*r$	$12*r*\pi$	$6*\pi$	$32*r*\pi$
...	...	...	...	...
k	$R=2*k*r$	$U=2*R*\pi$	$b=2*k*\pi$	$b*R=(2*k)^2*r*\pi$

$$b_{k,i} = \frac{U_{k,i}}{2*r_i}$$

Equation 12.35: Number of businesses service sector per ring

$b_{k,i}$ .... Number of service sector businesses in ring k

$U_{k,i}$ .... Circumference of the centre line of ring k (m)

r_i .... Radius (m), see Equation 12.34

$$B_i^{sv} = 1 + \sum_k b_{k,i} = 1 + \sum_k 2 * k * \pi$$

Equation 12.36: Number of service sector businesses

k .... Index ring

$$B_i^{sv} = 1 + \int_0^K 2 * k * \pi * dk = 1 + \pi * K^2$$

Equation 12.37: Number of service sector businesses

$$K_i \approx \sqrt{\frac{B_i^{sv}}{\pi}}$$

Equation 12.38: Number of rings zone i

$$D_i^{sv} = \sum_k b_{k,i} * 2 * r_i = \sum_k (2 * k)^2 * r * \pi$$

Equation 12.39: Total distance to service sector businesses

D_i^{sv} .... Sum of distances to service sector businesses

$$D_i^{sv} = \int_0^K 4 * k^2 * r * \pi * dk = \frac{4}{3} * \pi * K^3$$

Equation 12.40: Total distance to service sector businesses

$$d_{ii} = \frac{D_i^{sv}}{B_i^{sv}} = \frac{4}{3} * K_i * r_i$$

Equation 12.41: Intra zonal distance

d_{ii} .... Intra-zonal distance zone i (m)

The results of these calculations are shown in Table 12.19 row (2).

Table 12.19: Intra-zonal distances (m)

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23
(1)	726	1068	1090	776	817	713	789	645	793	1841	1272	1369	2011	2050	1031	1407	1389	1389	2203	903	2411	2838	2396
(2)	504	862	879	468	484	415	458	371	567	1301	1158	895	1204	1264	609	842	781	770	1266	615	1705	2015	1712

- **OD Matrices**

Table 12.20: Distance matrix slow modes

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23
1	0.81	5.47	2.74	3.06	4.86	3.10	2.70	2.48	3.17	7.70	8.03	7.56	11.88	7.20	5.26	6.48	5.11	5.83	6.48	3.38	10.66	9.25	13.07
2	2.59	2.13	3.78	5.31	7.29	5.67	5.58	4.77	4.14	9.18	8.28	9.27	11.07	9.72	7.83	8.64	7.11	7.02	6.57	2.88	8.82	6.84	15.66
3	2.74	3.78	1.29	2.34	4.59	3.78	4.14	4.68	5.84	5.31	5.31	7.20	13.32	8.64	6.57	8.55	7.29	8.46	9.18	5.94	12.60	8.37	12.78
4	3.06	5.31	2.34	0.63	2.34	1.80	2.61	3.60	5.67	4.95	6.57	4.95	11.16	6.48	4.50	6.84	5.67	7.65	9.00	6.39	13.68	11.34	10.53
5	4.86	7.29	4.59	2.34	0.68	1.89	2.88	4.05	6.48	5.40	8.28	2.79	9.18	4.86	3.15	5.76	5.49	7.74	9.63	7.74	15.21	13.59	8.37
6	3.10	5.67	3.78	1.80	1.89	0.58	1.08	2.25	4.68	6.48	8.46	3.69	9.54	4.77	2.79	5.04	4.23	6.12	7.83	5.94	13.32	12.24	9.99
7	2.70	5.58	4.14	2.61	2.88	1.08	0.60	1.26	3.69	7.47	9.09	4.05	9.27	4.59	2.61	4.32	3.33	5.13	6.84	5.04	12.42	11.97	10.71
8	2.48	4.77	4.68	3.60	4.05	2.25	1.26	0.50	2.52	8.55	9.90	4.95	9.54	4.86	3.15	4.05	2.70	4.05	5.58	4.05	11.34	11.52	11.70
9	3.17	5.47	5.84	5.67	6.48	4.68	3.69	2.52	0.82	10.62	11.16	7.20	10.80	6.66	5.31	5.04	3.42	2.88	3.33	1.98	9.00	10.44	14.04
10	7.70	9.18	5.31	4.95	5.40	6.48	7.47	8.55	10.62	2.72	4.23	7.83	14.13	10.17	8.55	11.16	10.71	12.60	13.95	10.98	18.00	13.23	10.35
11	8.03	8.28	5.31	6.57	8.28	8.46	9.09	9.90	11.16	4.23	2.29	10.98	17.46	12.96	11.07	13.41	12.42	13.77	14.40	10.89	16.65	10.08	14.40
12	7.56	9.27	7.20	4.95	2.79	3.69	4.05	4.95	7.20	7.83	10.98	1.36	6.21	2.52	2.07	4.41	4.86	7.29	9.72	9.00	16.20	15.93	6.84
13	11.88	11.07	13.32	11.16	9.18	9.54	9.27	9.54	10.80	14.13	17.46	6.21	2.96	4.68	6.75	5.76	7.38	9.00	11.61	12.78	18.72	20.97	8.28
14	7.20	9.72	8.64	6.48	4.86	4.77	4.59	4.86	6.66	10.17	12.96	2.52	4.68	2.84	1.98	2.25	3.51	5.85	8.46	9.63	15.39	16.47	8.19
15	5.26	9.22	6.57	4.50	3.15	2.79	2.61	3.15	5.31	8.55	11.07	2.07	6.75	1.98	0.93	2.79	5.31	5.31	7.74	7.02	14.22	14.58	8.82
16	6.48	10.08	8.55	6.84	5.76	5.04	4.32	4.05	5.04	11.16	13.41	4.41	5.76	2.25	2.79	1.40	1.62	3.51	6.21	6.93	13.32	15.30	10.53
17	5.11	8.64	7.29	5.67	5.49	4.23	3.33	2.70	3.42	10.71	12.42	4.86	7.38	3.51	5.31	1.62	1.53	2.43	5.04	5.04	11.88	13.77	11.43
18	5.83	9.07	8.46	7.65	7.74	6.12	5.13	4.05	2.88	12.60	13.77	7.29	9.00	5.85	5.31	3.51	2.43	1.20	2.70	4.50	9.90	13.23	13.95
19	6.48	7.92	9.18	9.00	9.63	7.83	6.84	5.58	3.33	13.95	14.40	9.72	11.61	8.46	7.74	6.21	5.04	2.70	2.40	3.69	7.20	11.79	16.47
20	3.38	4.32	5.94	6.39	7.74	5.94	5.04	4.05	1.98	10.98	10.89	9.00	12.78	9.63	7.02	6.93	5.04	4.50	3.69	1.16	7.38	8.73	15.66
21	10.66	8.82	12.60	13.68	15.21	13.32	12.42	11.34	9.00	18.00	16.65	16.20	18.72	15.39	14.22	13.32	11.88	9.90	7.20	7.38	3.19	9.18	22.95
22	9.25	6.84	8.37	11.34	13.59	12.24	11.97	11.52	10.44	13.23	10.08	15.93	20.97	16.47	14.58	15.30	13.77	13.23	11.79	8.73	9.18	4.86	21.78
23	13.07	15.66	12.78	10.53	8.37	9.99	10.71	11.70	14.04	10.35	14.40	6.84	8.28	8.19	8.82	10.53	11.43	13.95	16.47	15.66	22.95	21.78	2.71

Table 12.21: Distance matrix public transport

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23
1	0.68	4.56	2.28	2.55	4.05	2.58	2.25	2.07	2.64	6.42	6.69	6.30	9.90	6.00	4.38	5.40	4.26	4.86	5.40	2.82	8.88	7.71	10.89
2	2.16	1.77	3.15	4.43	6.08	4.73	4.65	3.98	3.45	7.65	6.90	7.73	9.23	8.10	6.53	7.20	5.93	5.85	5.48	2.40	7.35	5.70	13.05
3	2.28	3.15	1.08	1.95	3.83	3.15	3.45	3.90	4.87	4.43	4.43	6.00	11.10	7.20	5.48	7.13	6.08	7.05	7.65	4.95	10.50	6.98	10.65
4	2.55	4.43	1.95	0.53	1.95	1.50	2.18	3.00	4.73	4.13	5.48	4.13	9.30	5.40	3.75	5.70	4.73	6.38	7.50	5.33	11.40	9.45	8.78
5	4.05	6.08	3.83	1.95	0.57	1.58	2.40	3.38	5.40	4.50	6.90	2.33	7.65	4.05	2.63	4.80	4.58	6.45	8.03	6.45	12.68	11.33	6.98
6	2.58	4.73	3.15	1.50	1.58	0.48	0.90	1.88	3.90	5.40	7.05	3.08	7.95	3.98	2.33	4.20	3.53	5.10	6.53	4.95	11.10	10.20	8.33
7	2.25	4.65	3.45	2.18	2.40	0.90	0.50	1.05	3.08	6.23	7.58	3.38	7.73	3.83	2.18	3.60	2.78	4.28	5.70	4.20	10.35	9.98	8.93
8	2.07	3.98	3.90	3.00	3.38	1.88	1.05	0.42	2.10	7.13	8.25	4.13	7.95	4.05	2.63	3.38	2.25	3.38	4.65	3.38	9.45	9.60	9.75
9	2.64	4.56	4.87	4.73	5.40	3.90	3.08	2.10	0.69	8.85	9.30	6.00	9.00	5.55	4.43	4.20	2.85	2.40	2.78	1.65	7.50	8.70	11.70
10	6.42	7.65	4.43	4.13	4.50	5.40	6.23	7.13	8.85	2.26	3.53	6.53	11.78	8.48	7.13	9.30	8.93	10.50	11.63	9.15	15.00	11.03	8.63
11	6.69	6.90	4.43	5.48	6.90	7.05	7.58	8.25	9.30	3.53	1.91	9.15	14.55	10.80	9.23	11.18	10.35	11.48	12.00	9.08	13.88	8.40	12.00
12	6.30	7.73	6.00	4.13	2.33	3.08	3.38	4.13	6.00	6.53	9.15	1.14	5.18	2.10	1.73	3.68	4.05	6.08	8.10	7.50	13.50	13.28	5.70
13	9.90	9.23	11.10	9.30	7.65	7.95	7.73	7.95	9.00	11.78	14.55	5.18	2.47	3.90	5.63	4.80	6.15	7.50	9.68	10.65	15.60	17.48	6.90
14	6.00	8.10	7.20	5.40	4.05	3.98	3.83	4.05	5.55	8.48	10.80	2.10	3.90	2.36	1.65	1.88	2.93	4.88	7.05	8.03	12.83	13.73	6.83
15	4.38	7.68	5.48	3.75	2.63	2.33	2.18	2.63	4.43	7.13	9.23	1.73	5.63	1.65	0.78	2.33	4.43	4.43	6.45	5.85	11.85	12.15	7.35
16	5.40	8.40	7.13	5.70	4.80	4.20	3.60	3.38	4.20	9.30	11.18	3.68	4.80	1.88	2.33	1.16	1.35	2.93	5.18	5.78	11.10	12.75	8.78
17	4.26	7.20	6.08	4.73	4.58	3.53	2.78	2.25	2.85	8.93	10.35	4.05	6.15	2.93	4.43	1.35	1.27	2.03	4.20	4.20	9.90	11.48	9.53
18	4.86	7.56	7.05	6.38	6.45	5.10	4.28	3.38	2.40	10.50	11.48	6.08	7.50	4.88	4.43	2.93	2.03	1.00	2.25	3.75	8.25	11.03	11.63
19	5.40	6.60	7.65	7.50	8.03	6.53	5.70	4.65	2.78	11.63	12.00	8.10	9.68	7.05	6.45	5.18	4.20	2.25	2.00	3.08	6.00	9.83	13.73
20	2.82	3.60	4.95	5.33	6.45	4.95	4.20	3.38	1.65	9.15	9.08	7.50	10.65	8.03	5.85	5.78	4.20	3.75	3.08	0.97	6.15	7.28	13.05
21	8.88	7.35	10.50	11.40	12.68	11.10	10.35	9.45	7.50	15.00	13.88	13.50	15.60	12.83	11.85	11.10	9.90	8.25	6.00	6.15	2.66	7.65	19.13
22	7.71	5.70	6.98	9.45	11.33	10.20	9.98	9.60	8.70	11.03	8.40	13.28	17.48	13.73	12.15	12.75	11.48	11.03	9.83	7.28	7.65	4.05	18.15
23	10.89	13.05	10.65	8.78	6.98	8.33	8.93	9.75	11.70	8.63	12.00	5.70	6.90	6.83	7.35	8.78	9.53	11.63	13.73	13.05	19.13	18.15	2.26

Table 12.22: Distance matrix car

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23
1	0.68	4.56	2.28	2.55	4.05	2.58	2.25	2.07	2.64	6.42	6.69	6.30	9.90	6.00	4.38	5.40	4.26	4.86	5.40	2.82	8.88	7.71	10.89
2	2.16	1.77	3.15	4.43	6.08	4.73	4.65	3.98	3.45	7.65	6.90	7.73	9.23	8.10	6.53	7.20	5.93	5.85	5.48	2.40	7.35	5.70	13.05
3	2.28	3.15	1.08	1.95	3.83	3.15	3.45	3.90	4.87	4.43	4.43	6.00	11.10	7.20	5.48	7.13	6.08	7.05	7.65	4.95	10.50	6.98	10.65
4	2.55	4.43	1.95	0.53	1.95	1.50	2.18	3.00	4.73	4.13	5.48	4.13	9.30	5.40	3.75	5.70	4.73	6.38	7.50	5.33	11.40	9.45	8.78
5	4.05	6.08	3.83	1.95	0.57	1.58	2.40	3.38	5.40	4.50	6.90	2.33	7.65	4.05	2.63	4.80	4.58	6.45	8.03	6.45	12.68	11.33	6.98
6	2.58	4.73	3.15	1.50	1.58	0.48	0.90	1.88	3.90	5.40	7.05	3.08	7.95	3.98	2.33	4.20	3.53	5.10	6.53	4.95	11.10	10.20	8.33
7	2.25	4.65	3.45	2.18	2.40	0.90	0.50	1.05	3.08	6.23	7.58	3.38	7.73	3.83	2.18	3.60	2.78	4.28	5.70	4.20	10.35	9.98	8.93
8	2.07	3.98	3.90	3.00	3.38	1.88	1.05	0.42	2.10	7.13	8.25	4.13	7.95	4.05	2.63	3.38	2.25	3.38	4.65	3.38	9.45	9.60	9.75
9	2.64	4.56	4.87	4.73	5.40	3.90	3.08	2.10	0.69	8.85	9.30	6.00	9.00	5.55	4.43	4.20	2.85	2.40	2.78	1.65	7.50	8.70	11.70
10	6.42	7.65	4.43	4.13	4.50	5.40	6.23	7.13	8.85	2.26	3.53	6.53	11.78	8.48	7.13	9.30	8.93	10.50	11.63	9.15	15.00	11.03	8.63
11	6.69	6.90	4.43	5.48	6.90	7.05	7.58	8.25	9.30	3.53	1.91	9.15	14.55	10.80	9.23	11.18	10.35	11.48	12.00	9.08	13.88	8.40	12.00
12	6.30	7.73	6.00	4.13	2.33	3.08	3.38	4.13	6.00	6.53	9.15	1.14	5.18	2.10	1.73	3.68	4.05	6.08	8.10	7.50	13.50	13.28	5.70
13	9.90	9.23	11.10	9.30	7.65	7.95	7.73	7.95	9.00	11.78	14.55	5.18	2.47	3.90	5.63	4.80	6.15	7.50	9.68	10.65	15.60	17.48	6.90
14	6.00	8.10	7.20	5.40	4.05	3.98	3.83	4.05	5.55	8.48	10.80	2.10	3.90	2.36	1.65	1.88	2.93	4.88	7.05	8.03	12.83	13.73	6.83
15	4.38	7.68	5.48	3.75	2.63	2.33	2.18	2.63	4.43	7.13	9.23	1.73	5.63	1.65	0.78	2.33	4.43	4.43	6.45	5.85	11.85	12.15	7.35
16	5.40	8.40	7.13	5.70	4.80	4.20	3.60	3.38	4.20	9.30	11.18	3.68	4.80	1.88	2.33	1.16	1.35	2.93	5.18	5.78	11.10	12.75	8.78
17	4.26	7.20	6.08	4.73	4.58	3.53	2.78	2.25	2.85	8.93	10.35	4.05	6.15	2.93	4.43	1.35	1.27	2.03	4.20	4.20	9.90	11.48	9.53
18	4.86	7.56	7.05	6.38	6.45	5.10	4.28	3.38	2.40	10.50	11.48	6.08	7.50	4.88	4.43	2.93	2.03	1.00	2.25	3.75	8.25	11.03	11.63
19	5.40	6.60	7.65	7.50	8.03	6.53	5.70	4.65	2.78	11.63	12.00	8.10	9.68	7.05	6.45	5.18	4.20	2.25	2.00	3.08	6.00	9.83	13.73
20	2.82	3.60	4.95	5.33	6.45	4.95	4.20	3.38	1.65	9.15	9.08	7.50	10.65	8.03	5.85	5.78	4.20	3.75	3.08	0.97	6.15	7.28	13.05
21	8.88	7.35	10.50	11.40	12.68	11.10	10.35	9.45	7.50	15.00	13.88	13.50	15.60	12.83	11.85	11.10	9.90	8.25	6.00	6.15	2.66	7.65	19.13
22	7.71	5.70	6.98	9.45	11.33	10.20	9.98	9.60	8.70	11.03	8.40	13.28	17.48	13.73	12.15	12.75	11.48	11.03	9.83	7.28	7.65	4.05	18.15
23	10.89	13.05	10.65	8.78	6.98	8.33	8.93	9.75	11.70	8.63	12.00	5.70	6.90	6.83	7.35	8.78	9.53	11.63	13.73	13.05	19.13	18.15	2.26

Table 12.23: Speed matrix public transport separated from individual road traffic

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23
1	20.0	20.0	20.0	20.0	20.0	20.0	20.0	20.0	20.0	30.0	30.0	30.0	30.0	30.0	30.0	30.0	30.0	30.0	30.0	30.0	30.0	30.0	30.0
2	20.0	20.0	20.0	20.0	20.0	20.0	20.0	20.0	20.0	30.0	30.0	30.0	30.0	30.0	30.0	30.0	30.0	30.0	30.0	30.0	30.0	30.0	30.0
3	20.0	20.0	20.0	20.0	20.0	20.0	20.0	20.0	20.0	30.0	30.0	30.0	30.0	30.0	30.0	30.0	30.0	30.0	30.0	30.0	30.0	30.0	30.0
4	20.0	20.0	20.0	20.0	20.0	20.0	20.0	20.0	20.0	30.0	30.0	30.0	30.0	30.0	30.0	30.0	30.0	30.0	30.0	30.0	30.0	30.0	30.0
5	20.0	20.0	20.0	20.0	20.0	20.0	20.0	20.0	20.0	30.0	30.0	30.0	30.0	30.0	30.0	30.0	30.0	30.0	30.0	30.0	30.0	30.0	30.0
6	20.0	20.0	20.0	20.0	20.0	20.0	20.0	20.0	20.0	30.0	30.0	30.0	30.0	30.0	30.0	30.0	30.0	30.0	30.0	30.0	30.0	30.0	30.0
7	20.0	20.0	20.0	20.0	20.0	20.0	20.0	20.0	20.0	30.0	30.0	30.0	30.0	30.0	30.0	30.0	30.0	30.0	30.0	30.0	30.0	30.0	30.0
8	20.0	20.0	20.0	20.0	20.0	20.0	20.0	20.0	20.0	30.0	30.0	30.0	30.0	30.0	30.0	30.0	30.0	30.0	30.0	30.0	30.0	30.0	30.0
9	20.0	20.0	20.0	20.0	20.0	20.0	20.0	20.0	20.0	30.0	30.0	30.0	30.0	30.0	30.0	30.0	30.0	30.0	30.0	30.0	30.0	30.0	30.0
10	30.0	30.0	30.0	30.0	30.0	30.0	30.0	30.0	30.0	30.0	30.0	30.0	30.0	30.0	30.0	30.0	30.0	30.0	30.0	30.0	30.0	30.0	30.0
11	30.0	30.0	30.0	30.0	30.0	30.0	30.0	30.0	30.0	30.0	30.0	30.0	30.0	30.0	30.0	30.0	30.0	30.0	30.0	30.0	30.0	30.0	30.0
12	30.0	30.0	30.0	30.0	30.0	30.0	30.0	30.0	30.0	30.0	30.0	30.0	30.0	30.0	30.0	30.0	30.0	30.0	30.0	30.0	30.0	30.0	30.0
13	30.0	30.0	30.0	30.0	30.0	30.0	30.0	30.0	30.0	30.0	30.0	30.0	30.0	30.0	30.0	30.0	30.0	30.0	30.0	30.0	30.0	30.0	30.0
14	30.0	30.0	30.0	30.0	30.0	30.0	30.0	30.0	30.0	30.0	30.0	30.0	30.0	30.0	30.0	30.0	30.0	30.0	30.0	30.0	30.0	30.0	30.0
15	30.0	30.0	30.0	30.0	30.0	30.0	30.0	30.0	30.0	30.0	30.0	30.0	30.0	30.0	30.0	30.0	30.0	30.0	30.0	30.0	30.0	30.0	30.0
16	30.0	30.0	30.0	30.0	30.0	30.0	30.0	30.0	30.0	30.0	30.0	30.0	30.0	30.0	30.0	30.0	30.0	30.0	30.0	30.0	30.0	30.0	30.0
17	30.0	30.0	30.0	30.0	30.0	30.0	30.0	30.0	30.0	30.0	30.0	30.0	30.0	30.0	30.0	30.0	30.0	30.0	30.0	30.0	30.0	30.0	30.0
18	30.0	30.0	30.0	30.0	30.0	30.0	30.0	30.0	30.0	30.0	30.0	30.0	30.0	30.0	30.0	30.0	30.0	30.0	30.0	30.0	30.0	30.0	30.0
19	30.0	30.0	30.0	30.0	30.0	30.0	30.0	30.0	30.0	30.0	30.0	30.0	30.0	30.0	30.0	30.0	30.0	30.0	30.0	30.0	30.0	30.0	30.0
20	30.0	30.0	30.0	30.0	30.0	30.0	30.0	30.0	30.0	30.0	30.0	30.0	30.0	30.0	30.0	30.0	30.0	30.0	30.0	30.0	30.0	30.0	30.0
21	30.0	30.0	30.0	30.0	30.0	30.0	30.0	30.0	30.0	30.0	30.0	30.0	30.0	30.0	30.0	30.0	30.0	30.0	30.0	30.0	30.0	30.0	30.0
22	30.0	30.0	30.0	30.0	30.0	30.0	30.0	30.0	30.0	30.0	30.0	30.0	30.0	30.0	30.0	30.0	30.0	30.0	30.0	30.0	30.0	30.0	30.0
23	30.0	30.0	30.0	30.0	30.0	30.0	30.0	30.0	30.0	30.0	30.0	30.0	30.0	30.0	30.0	30.0	30.0	30.0	30.0	30.0	30.0	30.0	30.0

Table 12.24: Free flow speed matrix car

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23
1	30.0	30.0	30.0	30.0	30.0	30.0	30.0	30.0	30.0	40.0	40.0	40.0	40.0	40.0	40.0	40.0	40.0	40.0	40.0	40.0	40.0	40.0	40.0
2	30.0	30.0	30.0	30.0	30.0	30.0	30.0	30.0	30.0	40.0	40.0	40.0	40.0	40.0	40.0	40.0	40.0	40.0	40.0	40.0	40.0	40.0	40.0
3	30.0	30.0	30.0	30.0	30.0	30.0	30.0	30.0	30.0	40.0	40.0	40.0	40.0	40.0	40.0	40.0	40.0	40.0	40.0	40.0	40.0	40.0	40.0
4	30.0	30.0	30.0	30.0	30.0	30.0	30.0	30.0	30.0	40.0	40.0	40.0	40.0	40.0	40.0	40.0	40.0	40.0	40.0	40.0	40.0	40.0	40.0
5	30.0	30.0	30.0	30.0	30.0	30.0	30.0	30.0	30.0	40.0	40.0	40.0	40.0	40.0	40.0	40.0	40.0	40.0	40.0	40.0	40.0	40.0	40.0
6	30.0	30.0	30.0	30.0	30.0	30.0	30.0	30.0	30.0	40.0	40.0	40.0	40.0	40.0	40.0	40.0	40.0	40.0	40.0	40.0	40.0	40.0	40.0
7	30.0	30.0	30.0	30.0	30.0	30.0	30.0	30.0	30.0	40.0	40.0	40.0	40.0	40.0	40.0	40.0	40.0	40.0	40.0	40.0	40.0	40.0	40.0
8	30.0	30.0	30.0	30.0	30.0	30.0	30.0	30.0	30.0	40.0	40.0	40.0	40.0	40.0	40.0	40.0	40.0	40.0	40.0	40.0	40.0	40.0	40.0
9	30.0	30.0	30.0	30.0	30.0	30.0	30.0	30.0	30.0	40.0	40.0	40.0	40.0	40.0	40.0	40.0	40.0	40.0	40.0	40.0	40.0	40.0	40.0
10	40.0	40.0	40.0	40.0	40.0	40.0	40.0	40.0	40.0	40.0	40.0	40.0	40.0	40.0	40.0	40.0	40.0	40.0	40.0	40.0	40.0	40.0	40.0
11	40.0	40.0	40.0	40.0	40.0	40.0	40.0	40.0	40.0	40.0	40.0	40.0	40.0	40.0	40.0	40.0	40.0	40.0	40.0	40.0	40.0	40.0	40.0
12	40.0	40.0	40.0	40.0	40.0	40.0	40.0	40.0	40.0	40.0	40.0	40.0	40.0	40.0	40.0	40.0	40.0	40.0	40.0	40.0	40.0	40.0	40.0
13	40.0	40.0	40.0	40.0	40.0	40.0	40.0	40.0	40.0	40.0	40.0	40.0	40.0	40.0	40.0	40.0	40.0	40.0	40.0	40.0	40.0	40.0	40.0
14	40.0	40.0	40.0	40.0	40.0	40.0	40.0	40.0	40.0	40.0	40.0	40.0	40.0	40.0	40.0	40.0	40.0	40.0	40.0	40.0	40.0	40.0	40.0
15	40.0	40.0	40.0	40.0	40.0	40.0	40.0	40.0	40.0	40.0	40.0	40.0	40.0	40.0	40.0	40.0	40.0	40.0	40.0	40.0	40.0	40.0	40.0
16	40.0	40.0	40.0	40.0	40.0	40.0	40.0	40.0	40.0	40.0	40.0	40.0	40.0	40.0	40.0	40.0	40.0	40.0	40.0	40.0	40.0	40.0	40.0
17	40.0	40.0	40.0	40.0	40.0	40.0	40.0	40.0	40.0	40.0	40.0	40.0	40.0	40.0	40.0	40.0	40.0	40.0	40.0	40.0	40.0	40.0	40.0
18	40.0	40.0	40.0	40.0	40.0	40.0	40.0	40.0	40.0	40.0	40.0	40.0	40.0	40.0	40.0	40.0	40.0	40.0	40.0	40.0	40.0	40.0	40.0
19	40.0	40.0	40.0	40.0	40.0	40.0	40.0	40.0	40.0	40.0	40.0	40.0	40.0	40.0	40.0	40.0	40.0	40.0	40.0	40.0	40.0	40.0	40.0
20	40.0	40.0	40.0	40.0	40.0	40.0	40.0	40.0	40.0	40.0	40.0	40.0	40.0	40.0	40.0	40.0	40.0	40.0	40.0	40.0	40.0	40.0	40.0
21	40.0	40.0	40.0	40.0	40.0	40.0	40.0	40.0	40.0	40.0	40.0	40.0	40.0	40.0	40.0	40.0	40.0	40.0	40.0	40.0	40.0	40.0	40.0
22	40.0	40.0	40.0	40.0	40.0	40.0	40.0	40.0	40.0	40.0	40.0	40.0	40.0	40.0	40.0	40.0	40.0	40.0	40.0	40.0	40.0	40.0	40.0
23	40.0	40.0	40.0	40.0	40.0	40.0	40.0	40.0	40.0	40.0	40.0	40.0	40.0	40.0	40.0	40.0	40.0	40.0	40.0	40.0	40.0	40.0	40.0

Table 12.25: Speed matrix car base year HWH tours

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23
1	12.0	15.0	15.0	15.0	15.0	15.0	15.0	15.0	15.0	20.0	20.0	20.0	20.0	20.0	20.0	20.0	20.0	20.0	20.0	20.0	20.0	20.0	20.0
2	15.0	20.0	20.0	20.0	20.0	20.0	20.0	20.0	20.0	30.0	30.0	30.0	30.0	30.0	30.0	30.0	30.0	30.0	30.0	30.0	30.0	30.0	30.0
3	15.0	20.0	20.0	20.0	20.0	20.0	20.0	20.0	20.0	30.0	30.0	30.0	30.0	30.0	30.0	30.0	30.0	30.0	30.0	30.0	30.0	30.0	30.0
4	15.0	20.0	20.0	20.0	20.0	20.0	20.0	20.0	20.0	30.0	30.0	30.0	30.0	30.0	30.0	30.0	30.0	30.0	30.0	30.0	30.0	30.0	30.0
5	15.0	20.0	20.0	20.0	20.0	20.0	20.0	20.0	20.0	30.0	30.0	30.0	30.0	30.0	30.0	30.0	30.0	30.0	30.0	30.0	30.0	30.0	30.0
6	15.0	20.0	20.0	20.0	20.0	20.0	20.0	20.0	20.0	30.0	30.0	30.0	30.0	30.0	30.0	30.0	30.0	30.0	30.0	30.0	30.0	30.0	30.0
7	15.0	20.0	20.0	20.0	20.0	20.0	20.0	20.0	20.0	30.0	30.0	30.0	30.0	30.0	30.0	30.0	30.0	30.0	30.0	30.0	30.0	30.0	30.0
8	15.0	20.0	20.0	20.0	20.0	20.0	20.0	20.0	20.0	30.0	30.0	30.0	30.0	30.0	30.0	30.0	30.0	30.0	30.0	30.0	30.0	30.0	30.0
9	15.0	20.0	20.0	20.0	20.0	20.0	20.0	20.0	20.0	30.0	30.0	30.0	30.0	30.0	30.0	30.0	30.0	30.0	30.0	30.0	30.0	30.0	30.0
10	20.0	30.0	30.0	30.0	30.0	30.0	30.0	30.0	30.0	30.0	30.0	30.0	30.0	30.0	30.0	30.0	30.0	30.0	30.0	30.0	30.0	30.0	30.0
11	20.0	30.0	30.0	30.0	30.0	30.0	30.0	30.0	30.0	30.0	30.0	30.0	30.0	30.0	30.0	30.0	30.0	30.0	30.0	30.0	30.0	30.0	30.0
12	20.0	30.0	30.0	30.0	30.0	30.0	30.0	30.0	30.0	30.0	30.0	30.0	30.0	30.0	30.0	30.0	30.0	30.0	30.0	30.0	30.0	30.0	30.0
13	20.0	30.0	30.0	30.0	30.0	30.0	30.0	30.0	30.0	30.0	30.0	30.0	30.0	30.0	30.0	30.0	30.0	30.0	30.0	30.0	30.0	30.0	30.0
14	20.0	30.0	30.0	30.0	30.0	30.0	30.0	30.0	30.0	30.0	30.0	30.0	30.0	30.0	30.0	30.0	30.0	30.0	30.0	30.0	30.0	30.0	30.0
15	20.0	30.0	30.0	30.0	30.0	30.0	30.0	30.0	30.0	30.0	30.0	30.0	30.0	30.0	30.0	30.0	30.0	30.0	30.0	30.0	30.0	30.0	30.0
16	20.0	30.0	30.0	30.0	30.0	30.0	30.0	30.0	30.0	30.0	30.0	30.0	30.0	30.0	30.0	30.0	30.0	30.0	30.0	30.0	30.0	30.0	30.0
17	20.0	30.0	30.0	30.0	30.0	30.0	30.0	30.0	30.0	30.0	30.0	30.0	30.0	30.0	30.0	30.0	30.0	30.0	30.0	30.0	30.0	30.0	30.0
18	20.0	30.0	30.0	30.0	30.0	30.0	30.0	30.0	30.0	30.0	30.0	30.0	30.0	30.0	30.0	30.0	30.0	30.0	30.0	30.0	30.0	30.0	30.0
19	20.0	30.0	30.0	30.0	30.0	30.0	30.0	30.0	30.0	30.0	30.0	30.0	30.0	30.0	30.0	30.0	30.0	30.0	30.0	30.0	30.0	30.0	30.0
20	20.0	30.0	30.0	30.0	30.0	30.0	30.0	30.0	30.0	30.0	30.0	30.0	30.0	30.0	30.0	30.0	30.0	30.0	30.0	30.0	30.0	30.0	30.0
21	20.0	30.0	30.0	30.0	30.0	30.0	30.0	30.0	30.0	30.0	30.0	30.0	30.0	30.0	30.0	30.0	30.0	30.0	30.0	30.0	30.0	30.0	30.0
22	20.0	30.0	30.0	30.0	30.0	30.0	30.0	30.0	30.0	30.0	30.0	30.0	30.0	30.0	30.0	30.0	30.0	30.0	30.0	30.0	30.0	30.0	30.0
23	20.0	30.0	30.0	30.0	30.0	30.0	30.0	30.0	30.0	30.0	30.0	30.0	30.0	30.0	30.0	30.0	30.0	30.0	30.0	30.0	30.0	30.0	30.0

Table 12.26: Speed matrix car base year HOH tours

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23
1	18.0	22.5	22.5	22.5	22.5	22.5	22.5	22.5	22.5	30.0	30.0	30.0	30.0	30.0	30.0	30.0	30.0	30.0	30.0	30.0	30.0	30.0	30.0
2	22.5	30.0	30.0	30.0	30.0	30.0	30.0	30.0	30.0	45.0	45.0	45.0	45.0	45.0	45.0	45.0	45.0	45.0	45.0	45.0	45.0	45.0	45.0
3	22.5	30.0	30.0	30.0	30.0	30.0	30.0	30.0	30.0	45.0	45.0	45.0	45.0	45.0	45.0	45.0	45.0	45.0	45.0	45.0	45.0	45.0	45.0
4	22.5	30.0	30.0	30.0	30.0	30.0	30.0	30.0	30.0	45.0	45.0	45.0	45.0	45.0	45.0	45.0	45.0	45.0	45.0	45.0	45.0	45.0	45.0
5	22.5	30.0	30.0	30.0	30.0	30.0	30.0	30.0	30.0	45.0	45.0	45.0	45.0	45.0	45.0	45.0	45.0	45.0	45.0	45.0	45.0	45.0	45.0
6	22.5	30.0	30.0	30.0	30.0	30.0	30.0	30.0	30.0	45.0	45.0	45.0	45.0	45.0	45.0	45.0	45.0	45.0	45.0	45.0	45.0	45.0	45.0
7	22.5	30.0	30.0	30.0	30.0	30.0	30.0	30.0	30.0	45.0	45.0	45.0	45.0	45.0	45.0	45.0	45.0	45.0	45.0	45.0	45.0	45.0	45.0
8	22.5	30.0	30.0	30.0	30.0	30.0	30.0	30.0	30.0	45.0	45.0	45.0	45.0	45.0	45.0	45.0	45.0	45.0	45.0	45.0	45.0	45.0	45.0
9	22.5	30.0	30.0	30.0	30.0	30.0	30.0	30.0	30.0	45.0	45.0	45.0	45.0	45.0	45.0	45.0	45.0	45.0	45.0	45.0	45.0	45.0	45.0
10	30.0	45.0	45.0	45.0	45.0	45.0	45.0	45.0	45.0	45.0	45.0	45.0	45.0	45.0	45.0	45.0	45.0	45.0	45.0	45.0	45.0	45.0	45.0
11	30.0	45.0	45.0	45.0	45.0	45.0	45.0	45.0	45.0	45.0	45.0	45.0	45.0	45.0	45.0	45.0	45.0	45.0	45.0	45.0	45.0	45.0	45.0
12	30.0	45.0	45.0	45.0	45.0	45.0	45.0	45.0	45.0	45.0	45.0	45.0	45.0	45.0	45.0	45.0	45.0	45.0	45.0	45.0	45.0	45.0	45.0
13	30.0	45.0	45.0	45.0	45.0	45.0	45.0	45.0	45.0	45.0	45.0	45.0	45.0	45.0	45.0	45.0	45.0	45.0	45.0	45.0	45.0	45.0	45.0
14	30.0	45.0	45.0	45.0	45.0	45.0	45.0	45.0	45.0	45.0	45.0	45.0	45.0	45.0	45.0	45.0	45.0	45.0	45.0	45.0	45.0	45.0	45.0
15	30.0	45.0	45.0	45.0	45.0	45.0	45.0	45.0	45.0	45.0	45.0	45.0	45.0	45.0	45.0	45.0	45.0	45.0	45.0	45.0	45.0	45.0	45.0
16	30.0	45.0	45.0	45.0	45.0	45.0	45.0	45.0	45.0	45.0	45.0	45.0	45.0	45.0	45.0	45.0	45.0	45.0	45.0	45.0	45.0	45.0	45.0
17	30.0	45.0	45.0	45.0	45.0	45.0	45.0	45.0	45.0	45.0	45.0	45.0	45.0	45.0	45.0	45.0	45.0	45.0	45.0	45.0	45.0	45.0	45.0
18	30.0	45.0	45.0	45.0	45.0	45.0	45.0	45.0	45.0	45.0	45.0	45.0	45.0	45.0	45.0	45.0	45.0	45.0	45.0	45.0	45.0	45.0	45.0
19	30.0	45.0	45.0	45.0	45.0	45.0	45.0	45.0	45.0	45.0	45.0	45.0	45.0	45.0	45.0	45.0	45.0	45.0	45.0	45.0	45.0	45.0	45.0
20	30.0	45.0	45.0	45.0	45.0	45.0	45.0	45.0	45.0	45.0	45.0	45.0	45.0	45.0	45.0	45.0	45.0	45.0	45.0	45.0	45.0	45.0	45.0
21	30.0	45.0	45.0	45.0	45.0	45.0	45.0	45.0	45.0	45.0	45.0	45.0	45.0	45.0	45.0	45.0	45.0	45.0	45.0	45.0	45.0	45.0	45.0
22	30.0	45.0	45.0	45.0	45.0	45.0	45.0	45.0	45.0	45.0	45.0	45.0	45.0	45.0	45.0	45.0	45.0	45.0	45.0	45.0	45.0	45.0	45.0
23	30.0	45.0	45.0	45.0	45.0	45.0	45.0	45.0	45.0	45.0	45.0	45.0	45.0	45.0	45.0	45.0	45.0	45.0	45.0	45.0	45.0	45.0	45.0

Table 12.27: Headway time matrix base year for HWH tours

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23
1	4	4	4	4	4	4	4	4	4	4	4	4	5	5	4	4	4	5	5	4	6	6	6
2	4	4	4	4	4	4	4	4	4	4	4	4	5	5	4	4	4	5	5	4	6	6	6
3	4	4	4	4	4	4	4	4	4	4	4	4	5	5	4	4	4	5	5	4	6	6	6
4	4	4	4	4	4	4	4	4	4	4	4	4	5	5	4	4	4	5	5	4	6	6	6
5	4	4	4	4	4	4	4	4	4	4	4	4	5	5	4	4	4	5	5	4	6	6	6
6	4	4	4	4	4	4	4	4	4	4	4	4	5	5	4	4	4	5	5	4	6	6	6
7	4	4	4	4	4	4	4	4	4	4	4	4	5	5	4	4	4	5	5	4	6	6	6
8	4	4	4	4	4	4	4	4	4	4	4	4	5	5	4	4	4	5	5	4	6	6	6
9	4	4	4	4	4	4	4	4	4	4	4	4	5	5	4	4	4	5	5	4	6	6	6
10	4	4	4	4	4	4	4	4	4	4	4	4	5	5	4	4	4	5	5	4	6	6	6
11	4	4	4	4	4	4	4	4	4	4	4	4	5	5	4	4	4	5	5	4	6	6	6
12	4	4	4	4	4	4	4	4	4	4	4	4	5	5	4	4	4	5	5	4	6	6	6
13	5	5	5	5	5	5	5	5	5	5	5	5	6	6	5	5	5	6	6	5	7	7	7
14	5	5	5	5	5	5	5	5	5	5	5	5	6	6	5	5	5	6	6	5	7	7	7
15	4	4	4	4	4	4	4	4	4	4	4	4	5	5	4	4	4	5	5	4	6	6	6
16	4	4	4	4	4	4	4	4	4	4	4	4	5	5	4	4	4	5	5	4	6	6	6
17	4	4	4	4	4	4	4	4	4	4	4	4	5	5	4	4	4	5	5	4	6	6	6
18	5	5	5	5	5	5	5	5	5	5	5	5	6	6	5	5	5	6	6	5	7	7	7
19	5	5	5	5	5	5	5	5	5	5	5	5	6	6	5	5	5	6	6	5	7	7	7
20	4	4	4	4	4	4	4	4	4	4	4	4	5	5	4	4	4	5	5	4	6	6	6
21	6	6	6	6	6	6	6	6	6	6	6	6	7	7	6	6	6	7	7	6	8	8	8
22	6	6	6	6	6	6	6	6	6	6	6	6	7	7	6	6	6	7	7	6	8	8	8
23	6	6	6	6	6	6	6	6	6	6	6	6	7	7	6	6	6	7	7	6	8	8	8

Table 12.28: Headway time matrix base year for HOH tours

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23
1	6	8	7	8	7	7	7	7	7	9	9	9	10	10	7	7	9	9	9	9	11	11	11
2	8	10	9	10	9	9	9	9	9	11	11	11	12	12	9	9	11	11	11	11	13	13	13
3	7	9	8	9	8	8	8	8	8	10	10	10	11	11	8	8	10	10	10	10	12	12	12
4	8	10	9	10	9	9	9	9	9	11	11	11	12	12	9	9	11	11	11	11	13	13	13
5	7	9	8	9	8	8	8	8	8	10	10	10	11	11	8	8	10	10	10	10	12	12	12
6	7	9	8	9	8	8	8	8	8	10	10	10	11	11	8	8	10	10	10	10	12	12	12
7	7	9	8	9	8	8	8	8	8	10	10	10	11	11	8	8	10	10	10	10	12	12	12
8	7	9	8	9	8	8	8	8	8	10	10	10	11	11	8	8	10	10	10	10	12	12	12
9	7	9	8	9	8	8	8	8	8	10	10	10	11	11	8	8	10	10	10	10	12	12	12
10	9	11	10	11	10	10	10	10	10	12	12	12	13	13	10	10	12	12	12	12	14	14	14
11	9	11	10	11	10	10	10	10	10	12	12	12	13	13	10	10	12	12	12	12	14	14	14
12	9	11	10	11	10	10	10	10	10	12	12	12	13	13	10	10	12	12	12	12	14	14	14
13	10	12	11	12	11	11	11	11	11	13	13	13	14	14	11	11	13	13	13	13	15	15	15
14	10	12	11	12	11	11	11	11	11	13	13	13	14	14	11	11	13	13	13	13	15	15	15
15	7	9	8	9	8	8	8	8	8	10	10	10	11	11	8	8	10	10	10	10	12	12	12
16	7	9	8	9	8	8	8	8	8	10	10	10	11	11	8	8	10	10	10	10	12	12	12
17	9	11	10	11	10	10	10	10	10	12	12	12	13	13	10	10	12	12	12	12	14	14	14
18	9	11	10	11	10	10	10	10	10	12	12	12	13	13	10	10	12	12	12	12	14	14	14
19	9	11	10	11	10	10	10	10	10	12	12	12	13	13	10	10	12	12	12	12	14	14	14
20	9	11	10	11	10	10	10	10	10	12	12	12	13	13	10	10	12	12	12	12	14	14	14
21	11	13	12	13	12	12	12	12	12	14	14	14	15	15	12	12	14	14	14	14	16	16	16
22	11	13	12	13	12	12	12	12	12	14	14	14	15	15	12	12	14	14	14	14	16	16	16
23	11	13	12	13	12	12	12	12	12	14	14	14	15	15	12	12	14	14	14	14	16	16	16

Table 12.29: Changing time matrix base year for HWH tours

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23
1	0.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0
2	2.0	0.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0
3	2.0	2.0	0.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0
4	2.0	2.0	2.0	0.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0
5	2.0	2.0	2.0	2.0	0.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0
6	2.0	2.0	2.0	2.0	2.0	0.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0
7	2.0	2.0	2.0	2.0	2.0	2.0	0.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0
8	2.0	2.0	2.0	2.0	2.0	2.0	2.0	0.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0
9	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0	0.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0
10	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0	0.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0
11	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0	0.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0
12	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0	0.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0
13	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0	0.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0
14	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0	0.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0
15	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0	0.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0
16	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0	0.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0
17	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0	0.0	2.0	2.0	2.0	2.0	2.0	2.0
18	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0	0.0	2.0	2.0	2.0	2.0	2.0
19	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0	0.0	2.0	2.0	2.0	2.0
20	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0	0.0	2.0	2.0	2.0
21	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0	0.0	2.0	2.0
22	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0	0.0	2.0
23	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0	0.0

Table 12.30: Headway time matrix base year for HOH tours

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23
1	0.0	3.0	3.0	3.0	3.0	3.0	3.0	3.0	3.0	3.5	3.5	3.5	3.0	3.0	3.0	3.0	3.5	3.5	3.5	4.0	4.0	4.0	4.0
2	2.0	0.0	3.0	3.0	3.0	3.0	3.0	3.0	3.0	3.5	3.5	3.5	3.0	3.0	3.0	3.0	3.5	3.5	3.5	4.0	4.0	4.0	4.0
3	2.0	3.0	0.0	3.0	3.0	3.0	3.0	3.0	3.0	3.5	3.5	3.5	3.0	3.0	3.0	3.0	3.5	3.5	3.5	4.0	4.0	4.0	4.0
4	2.0	3.0	3.0	0.0	3.0	3.0	3.0	3.0	3.0	3.5	3.5	3.5	3.0	3.0	3.0	3.0	3.5	3.5	3.5	4.0	4.0	4.0	4.0
5	2.0	3.0	3.0	3.0	0.0	3.0	3.0	3.0	3.0	3.5	3.5	3.5	3.0	3.0	3.0	3.0	3.5	3.5	3.5	4.0	4.0	4.0	4.0
6	2.0	3.0	3.0	3.0	3.0	0.0	3.0	3.0	3.0	3.5	3.5	3.5	3.0	3.0	3.0	3.0	3.5	3.5	3.5	4.0	4.0	4.0	4.0
7	2.0	3.0	3.0	3.0	3.0	3.0	0.0	3.0	3.0	3.5	3.5	3.5	3.0	3.0	3.0	3.0	3.5	3.5	3.5	4.0	4.0	4.0	4.0
8	2.0	3.0	3.0	3.0	3.0	3.0	3.0	0.0	3.0	3.5	3.5	3.5	3.0	3.0	3.0	3.0	3.5	3.5	3.5	4.0	4.0	4.0	4.0
9	2.0	3.0	3.0	3.0	3.0	3.0	3.0	3.0	0.0	3.5	3.5	3.5	3.0	3.0	3.0	3.0	3.5	3.5	3.5	4.0	4.0	4.0	4.0
10	2.0	3.0	3.0	3.0	3.0	3.0	3.0	3.0	3.0	0.0	3.5	3.5	3.0	3.0	3.0	3.0	3.5	3.5	3.5	4.0	4.0	4.0	4.0
11	2.0	3.0	3.0	3.0	3.0	3.0	3.0	3.0	3.0	3.5	0.0	3.5	3.0	3.0	3.0	3.0	3.5	3.5	3.5	4.0	4.0	4.0	4.0
12	2.0	3.0	3.0	3.0	3.0	3.0	3.0	3.0	3.0	3.5	3.5	0.0	3.0	3.0	3.0	3.0	3.5	3.5	3.5	4.0	4.0	4.0	4.0
13	2.0	3.0	3.0	3.0	3.0	3.0	3.0	3.0	3.0	3.5	3.5	3.5	0.0	3.0	3.0	3.0	3.5	3.5	3.5	4.0	4.0	4.0	4.0
14	2.0	3.0	3.0	3.0	3.0	3.0	3.0	3.0	3.0	3.5	3.5	3.5	3.0	0.0	3.0	3.0	3.5	3.5	3.5	4.0	4.0	4.0	4.0
15	2.0	3.0	3.0	3.0	3.0	3.0	3.0	3.0	3.0	3.5	3.5	3.5	3.0	3.0	0.0	3.0	3.5	3.5	3.5	4.0	4.0	4.0	4.0
16	2.0	3.0	3.0	3.0	3.0	3.0	3.0	3.0	3.0	3.5	3.5	3.5	3.0	3.0	3.0	0.0	3.5	3.5	3.5	4.0	4.0	4.0	4.0
17	2.0	3.0	3.0	3.0	3.0	3.0	3.0	3.0	3.0	3.5	3.5	3.5	3.0	3.0	3.0	3.0	0.0	3.5	3.5	4.0	4.0	4.0	4.0
18	2.0	3.0	3.0	3.0	3.0	3.0	3.0	3.0	3.0	3.5	3.5	3.5	3.0	3.0	3.0	3.0	3.5	0.0	3.5	4.0	4.0	4.0	4.0
19	2.0	3.0	3.0	3.0	3.0	3.0	3.0	3.0	3.0	3.5	3.5	3.5	3.0	3.0	3.0	3.0	3.5	3.5	0.0	4.0	4.0	4.0	4.0
20	2.0	3.0	3.0	3.0	3.0	3.0	3.0	3.0	3.0	3.5	3.5	3.5	3.0	3.0	3.0	3.0	3.5	3.5	3.5	0.0	4.0	4.0	4.0
21	2.0	3.0	3.0	3.0	3.0	3.0	3.0	3.0	3.0	3.5	3.5	3.5	3.0	3.0	3.0	3.0	3.5	3.5	3.5	4.0	0.0	4.0	4.0
22	2.0	3.0	3.0	3.0	3.0	3.0	3.0	3.0	3.0	3.5	3.5	3.5	3.0	3.0	3.0	3.0	3.5	3.5	3.5	4.0	4.0	0.0	4.0
23	2.0	3.0	3.0	3.0	3.0	3.0	3.0	3.0	3.0	3.5	3.5	3.5	3.0	3.0	3.0	3.0	3.5	3.5	3.5	4.0	4.0	4.0	0.0

12.6.2 Socio economic data

- **Residents**

Table 12.34 shows the number of residences from the censuses in the years 1981, 1991 and 2001[(ÖSTZ, 1984), (ÖSTAT, 1993) and (Statistisches Amt der Stadt Wien, 2003)] by zone as used in the MARS validation. Figure 12.8 to Figure 12.10 illustrates the spatial distribution of density and the changes between 1981 and 1991.

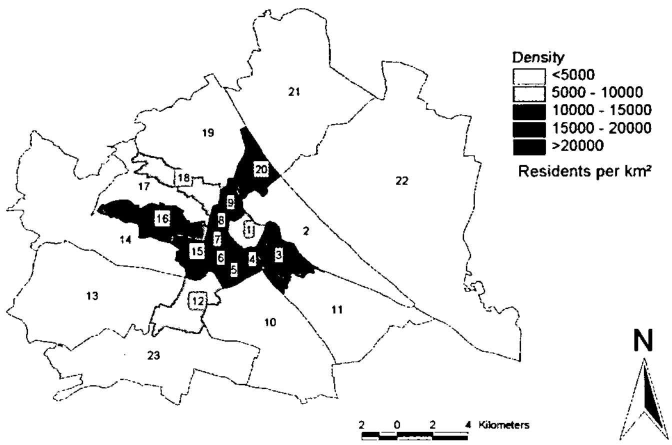

Figure 12.8: Density in residents per km² in 1981 (ÖSTZ, 1984)

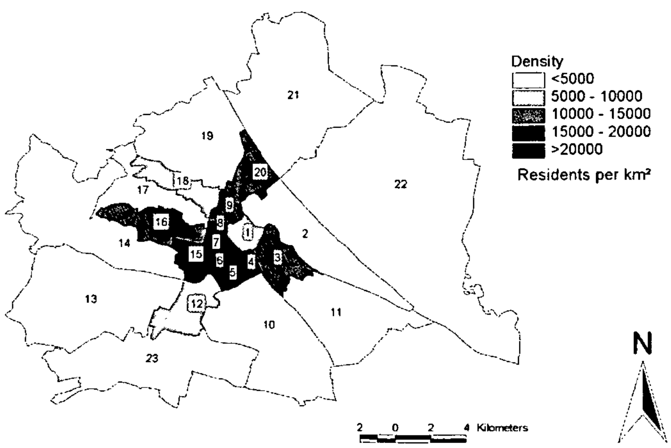

Figure 12.9: Density in residents per km² in 1991 (ÖSTAT, 1993)

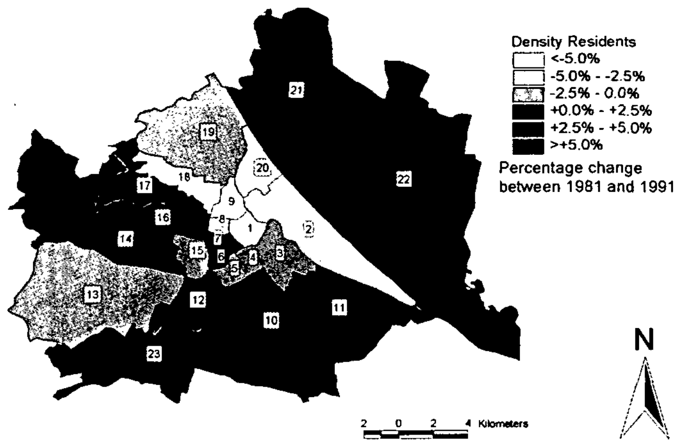

Figure 12.10: Percentage change density residents per km² from 1981 to 1991 (ÖSTZ, 1984), (ÖSTAT, 1993)

- **Employees**

Table 12.34 shows the number of employees from the 1991 census (ÖSTAT, 1995) by zone as used in the MARS validation.

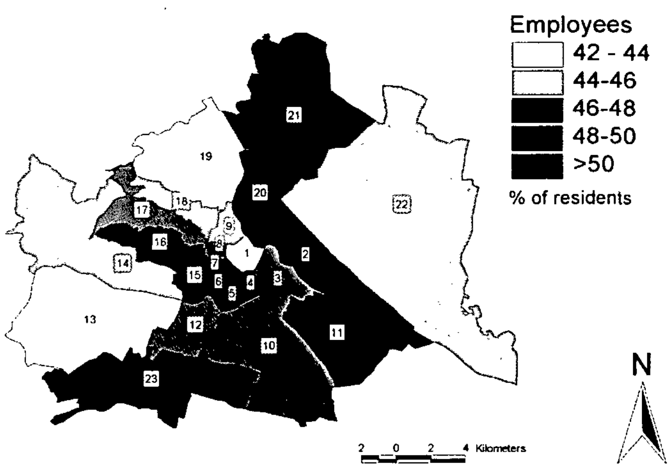

Figure 12.11: Employees per residents in the year 1991

- **Workplaces**

Table 12.34 shows the number of workplace from the 1981 and 1991 census [(ÖSTZ, 1985), (ÖSTAT, 1995)] by zone as used in MARS validation.

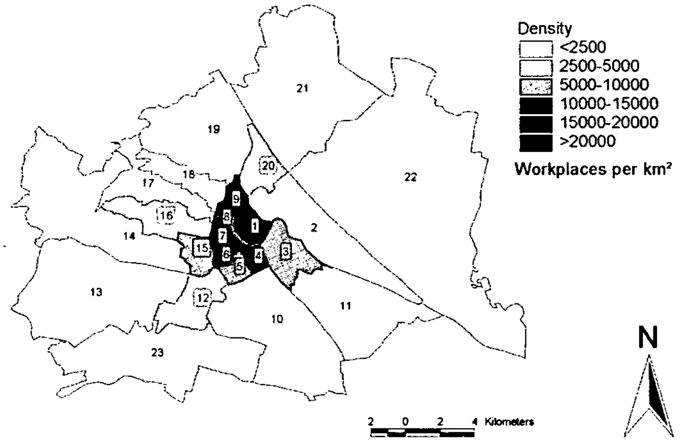

Figure 12.12: Density workplaces per km² in 1991

- **Household size**

Table 12.31: Persons per household by district Vienna year 1991

1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23
1.89	2.09	1.94	1.92	1.90	1.95	1.90	1.90	1.90	2.04	2.16	1.97	2.01	2.00	1.96	1.94	1.99	1.95	1.99	1.98	2.16	2.32	2.24

Source: (MA 66 Wien Statistik, 2001) p. 42

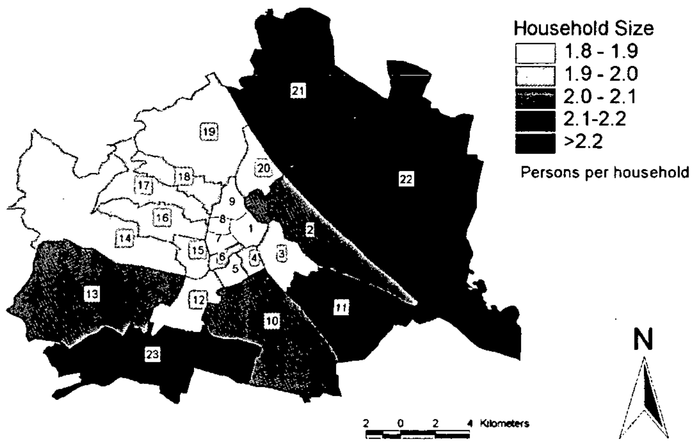

Figure 12.13: Persons per household by district Vienna year 1991 (MA 66 Wien Statistik, 2001)

- **Household income**

Household income data by Viennese districts are not available for the year 1991. The main purpose of household income in MARS is to distinguish between wealthier and poorer districts. Therefore data for net income per employee from 1999 are used as an approximation for household income (Table 12.35).

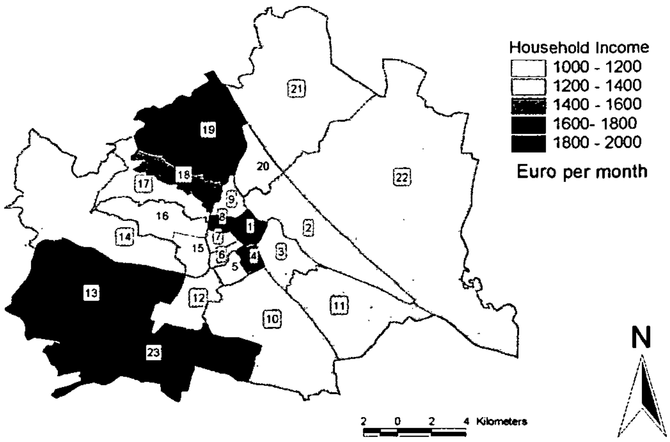

Figure 12.14: Net income per employee as an approximation for household income in the year 1991 (MA 66 Wien Statistik, 2001)

- **Rent**

Table 12.32: Average rent for housing units (€/m² and month) by district Vienna year 1991

1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23
3.08	2.52	2.51	2.63	2.51	2.67	2.67	2.64	2.50	2.54	2.67	2.60	2.93	2.58	2.51	2.62	2.61	2.69	3.10	2.43	2.78	2.82	3.24

Source: (Magistratsabteilung 66 - Statistisches Amt, 1994)

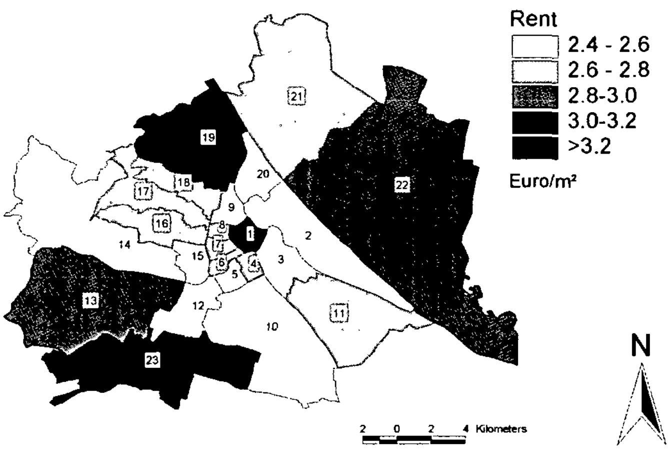

Figure 12.15: Average rent for housing units (€/m² and month) by district Vienna year 1991

- **Land price**

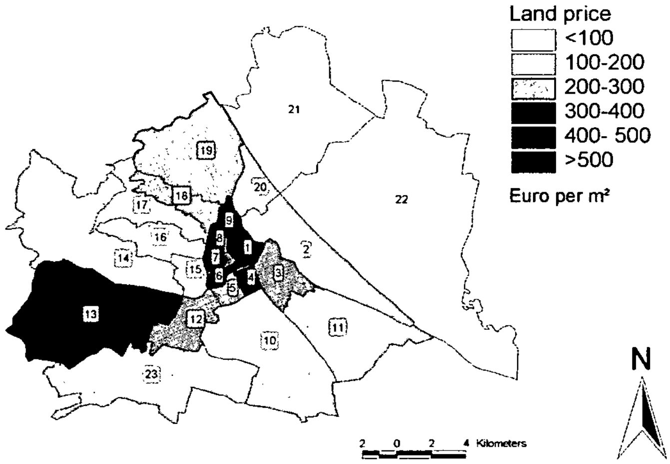

Figure 12.16: Land price (€/m²)

- **Floor space per housing unit**

Table 12.33: Floor space per housing unit (m²) by district Vienna year 1991

1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23
97.1	65.7	68.9	79.1	59.7	74.1	74.0	77.3	71.8	57.9	63.0	59.9	78.2	64.6	55.2	54.6	59.1	71.1	74.9	56.7	66.4	72.4	75.5

Source: (Magistratsabteilung 66 - Statistisches Amt, 1994)

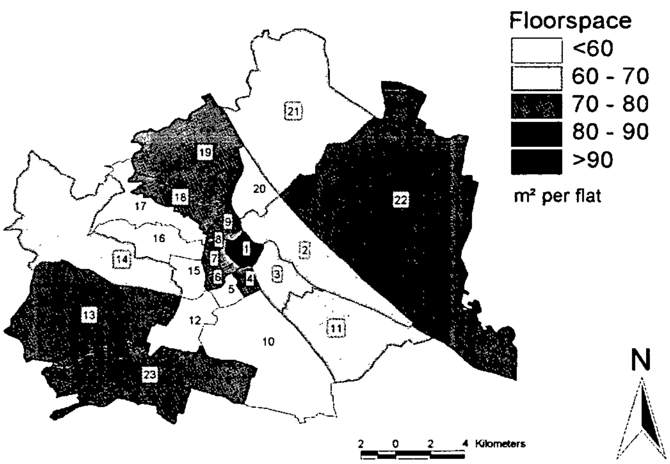

Figure 12.17: Floor space per housing unit (m²) by district Vienna year 1991

- **Share of business sectors**

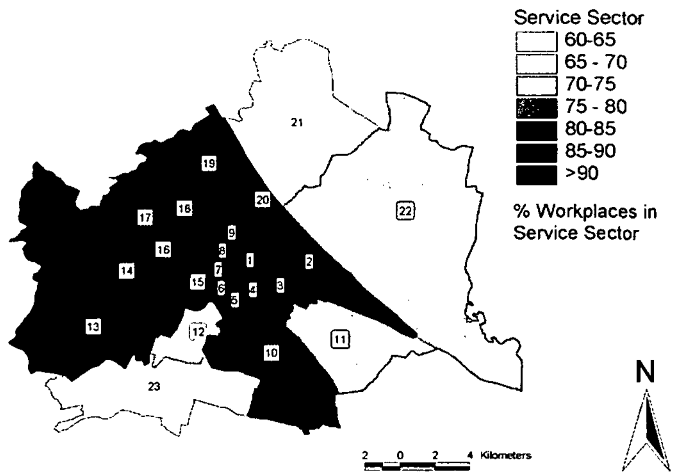

Figure 12.18: Percentage of workplaces in the service sector 1991 (Magistratsabteilung 66 - Statistisches Amt, 1999)

- **Workplaces per premise**

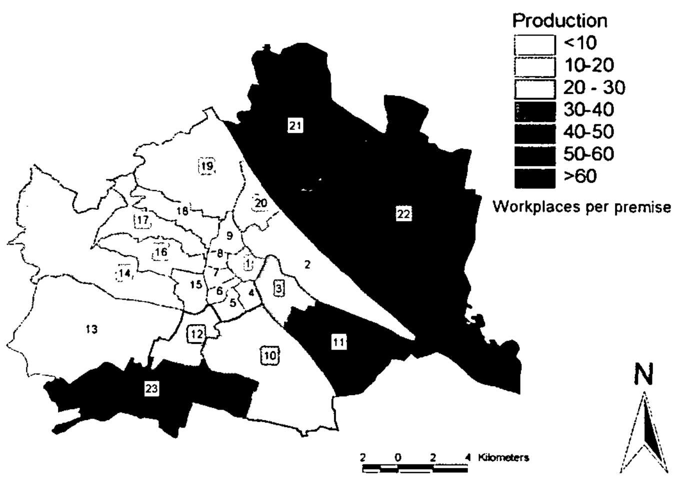

Figure 12.19: Workplaces per premise in the production sector 1991 (Magistratsabteilung 66 - Statistisches Amt, 1999)

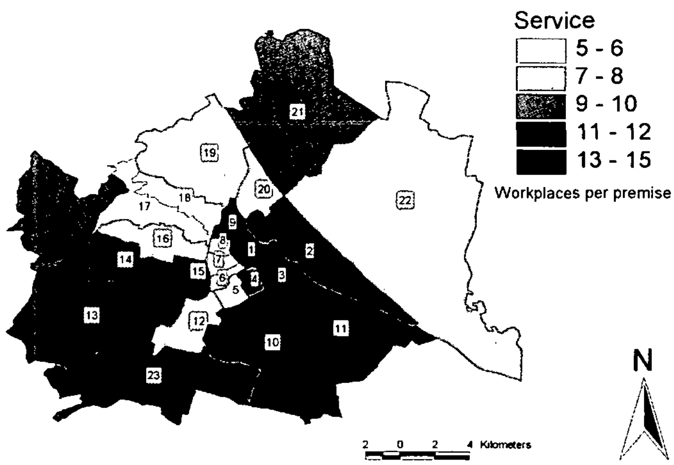

Figure 12.20: Workplaces per premise in the service sector 1991 (Magistratsabteilung 66 - Statistisches Amt, 1999)

- **Floor space per premise**

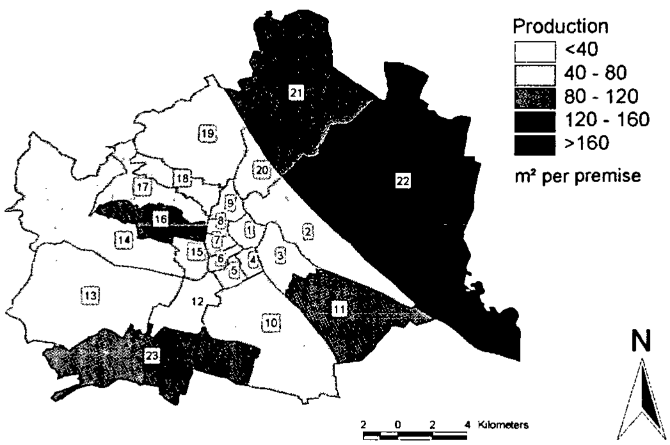

Figure 12.21: Floor space per premise in the production sector

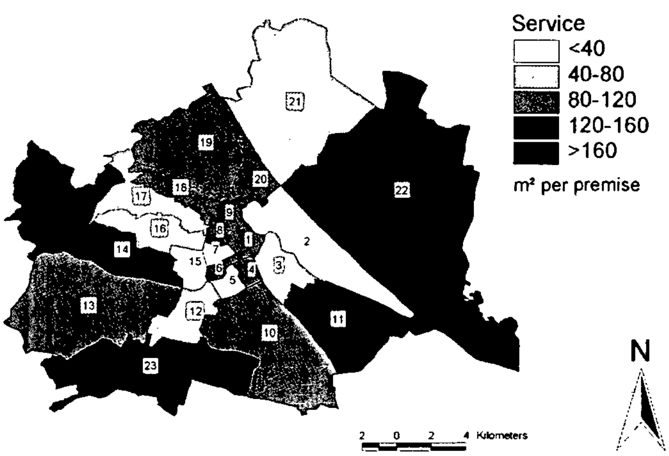

Figure 12.22: Floor space per premise in the production sector

- **Tables**

Table 12.34: Socio economic data by district Vienna in the years 1981 and 1991

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23
Residents																							
1981	19,537	95,892	86,054	31,800	52,436	28,771	29,490	24,769	45,314	147,101	65,859	79,408	55,331	78,996	70,066	88,587	49,337	52,548	67,522	73,696	116,033	99,801	72,998
1991	18,002	93,542	84,500	31,410	51,521	30,298	30,396	23,850	40,416	147,636	66,881	79,592	54,909	80,822	69,309	88,931	50,944	49,761	67,377	71,876	119,415	106,589	81,871
2001	17,056	90,914	81,281	28,354	49,111	27,867	28,292	22,572	37,816	150,636	76,899	78,268	49,574	78,169	64,895	86,129	47,610	44,992	64,030	76,268	128,228	136,444	84,718
Employed																							
1981	8,498	43,474	37,549	13,799	23,542	12,904	12,918	10,586	19,535	71,116	31,718	34,922	22,040	33,175	31,292	39,778	21,803	21,549	28,344	34,454	53,923	47,359	34,992
1991	8,457	47,334	41,795	14,790	26,404	15,351	15,516	11,318	19,663	76,565	36,167	39,475	23,226	39,131	36,607	45,342	25,556	22,464	30,580	36,889	62,822	57,402	41,616
Workplaces																							
1981	121,368	41,254	64,157	29,954	22,804	22,822	28,096	17,222	45,091	52,912	28,523	35,273	22,184	32,227	31,486	27,295	17,890	15,645	25,958	21,917	41,418	30,167	40,390
1991	112,770	42,791	70,148	28,627	20,396	21,129	23,605	18,126	50,244	57,480	30,032	33,630	26,232	29,947	33,316	28,102	18,073	16,048	25,882	20,931	45,336	37,350	52,217

Source: (ÖSTZ, 1984), (ÖSTZ, 1985), (ÖSTAT, 1993), (ÖSTAT, 1995), (Statistisches Amt der Stadt Wien, 2003)

Table 12.35: Net income per employee by district Vienna year 1999

Household	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23
income (€/m)	1,782	1,215	1,296	1,458	1,134	1,296	1,296	1,620	1,296	1,215	1,215	1,215	1,701	1,377	1,053	1,134	1,215	1,458	1,620	1,134	1,296	1,296	1,863

Source: (MA 66 Wien Statistik, 2001)

Table 12.36: Land price (€/m²)

Land price	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23
(€/m²)	1,000.0	139.1	205.9	354.4	217.4	536.7	390.6	324.5	500.0	139.0	115.2	226.7	330.2	179.6	159.0	179.0	184.0	300.0	300.0	188.6	91.2	74.5	159.1

Source: Database of Municipal Department 40 – Real estate evaluation and assessment (MA 40)[133]

[133] No empirical data are available for the districts 1, 9, 18 and 19. The values used in MARS are plausible estimates.

Table 12.37: Share of business sectors by Viennese districts 1991

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23
Production	4%	11%	14%	7%	18%	15%	14%	8%	4%	19%	28%	32%	5%	16%	12%	19%	19%	12%	13%	15%	40%	29%	36%
Services	96%	89%	86%	93%	82%	85%	86%	92%	96%	81%	72%	68%	95%	84%	88%	81%	81%	88%	87%	85%	60%	71%	64%

Source: (Magistratsabteilung 66 - Statistisches Amt, 1999) p.138 ff.

Table 12.38: Workplaces per premise by Viennese districts 1991

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23
Production	11	14	24	9	10	10	9	7	8	27	49	29	8	16	9	11	11	7	15	15	65	44	53
Services	15	9	12	9	6	7	7	7	15	11	12	7	10	9	10	7	6	5	7	8	9	8	10

Source: (Magistratsabteilung 66 - Statistisches Amt, 1999) p.135 ff.

Table 12.39: Floor space per premise by Viennese districts (m^2)

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23
Production	78	78	76	78	57	78	78	78	78	47	107	34	78	59	42	87	78	78	78	79	107	146	96
Services	81	16	65	81	23	81	23	81	81	104	179	63	81	155	34	51	46	81	81	101	47	149	160

Source: Data WWFF (Wiener Wirtschaftsförderungsfond), own calculations

12.6.3 Spatial data

- **Area**

Table 12.40: Area (km²) by district Vienna year 1991

1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23
3.0	19.3	7.4	1.8	2.0	1.5	1.6	1.1	3.0	31.8	23.2	8.2	37.7	33.8	3.9	8.6	11.3	6.3	24.9	5.7	44.5	102.3	32.0

Source: (Magistratsabteilung 66 - Statistisches Amt, 1992)

- **Share of green land**

Table 12.41: Share of green land (%) by district Vienna

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23
85	11.4	35.5	13.1	8.7	4.1	1.9	3.3	2.0	6.1	49.4	48.5	18.3	72.3	64.0	8.6	36.3	59.9	31.5	48.6	6.9	46.8	61.7	37.6
88	10.5	25.7	11.8	5.4	3.9	2.4	3.3	1.9	5.4	26.1	33.4	16.2	71.6	62.1	6.2	33.9	57.0	29.9	38.2	6.8	25.3	41.5	26.8

Source: (Magistratsabteilung 66 - Statistisches Amt, 1990), (Magistratsabteilung 66 - Statistisches Amt, 1992)

- **Land availability for developments**

Table 12.42: Estimated percentage of green land (%) available for residential developments

1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23
1.0	0.1	20.0	1.0	1.0	5.0	1.0	2.0	1.0	50.0	40.0	40.0	20.0	20.0	0.0	40.0	40.0	40.0	40.0	80.0	50.0	60.0	40.0

Table 12.43: Estimated percentage of green land (%) available for business developments

1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23
0.0	10.0	40.0	0.0	0.0	0.0	0.0	0.0	0.0	50.0	40.0	40.0	10.0	20.0	0.0	40.0	40.0	40.0	40.0	10.0	30.0	30.0	40.0

Table 12.44: Estimated percentage of protected green land (%)

1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23
99.0	89.9	40.0	99.0	99.0	95.0	99.0	98.0	99.0	0.0	20.0	20.0	70.0	60.0	100.0	20.0	20.0	20.0	20.0	10.0	20.0	10.0	20.0

12.6.4 Policy instrument data

- **Road infrastructure**

Table 12.45: Estimated percentage change car driving speed (%)

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23
1																							
2										40	40												40
3																							
4																							
5																							
6																							
7																							
8																							
9																							
10		40									40										40	80	40
11		40								40											40	80	40
12																							
13																							
14																							
15																							
16																							
17																							
18																							
19																							
20																							
21										40	40											40	
22										80	80										40	80	80
23		40								40	40											80	

The investment costs for the construction of the ring road are estimated with about 1.2 billion Euro[134]. The yearly maintenance costs for the additional road infrastructure are estimated with 2.75 million Euro per year[135].

- **PT infrastructure**

The investment cost for the metro line extension are estimated with 1,600 mio. Euro[136]. The operating costs are estimated with 42 mio. Euro per year[137].

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[134] B301 about 6 billion ATS or about 0.44 billion Euro; Source: Macoun, T. (2001). Gutachten für das Bürgerforum gegen Transit B301. Wien, Institut für Verkehrsplanung und Verkehrstechnik, Technische Universität Wien.
B305 about 8 billion ATS or about 0.58 billion Euro; Source: PGO (2003). Nordostumfahrung Wien. Planungsgemeinschaft Ost. Last Update. Access: 05/09/2003. http://www.pgo.wien.at/projekte/v_nordostumfahrung_trassenstudie.htm

[135] Length about 25 km. Structural costs about 55,000 Euro per km and year. Operational costs about 55,000 Euro per km and year. BmWA (2001). Fernmündliche Auskunft Bundesministerium für wirtschaftliche Angelegenheiten, Preisstand Mai 2001.

[136] Source: Stadtentwicklung Wien (2003). Verlängerung der U-Bahn-Linie U2 von Schottentor/Schottenring nach Stadlau/Aspern. Internet-Support-Gruppe Stadtentwicklung. Last Update: 25/04/2003. Access: 25/07/2001. www.magwien.gv.at/stadtentwicklung/02/02/01.htm;
Wiener Linien (2000). "Von Ottakring nach Simmering - Die leistungsfähige U-Bahnstrecke quer durch Wien." *24 Stunden für Wien* **Sonderheft**.
Statistik Austria (2001). Statistisches Jahrbuch Österreichs, Wien.

Table 12.46: Estimated percentage change PT stop access and egress time (%)

1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23
-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-10	-20	-

Table 12.47: Estimated percentage change waiting time (%)

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23
1																					-20	-20	
2		-5																				-20	
3																							
4																						-20	
5																							
6																						-20	
7																					-20	-20	
8																					-20	-20	
9																					-20	-20	
10										-5												-20	
11																							
12																					-20		
13																							
14																							
15																					-20	-20	
16																					-20	-20	
17																					-20		
18																					-20		
19																					-20		
20																					-20		
21	-20						-20	-20	-20			-20			-20	-20	-20	-20	-20	-20	-20	-20	-20
22	-20	-20		-20		-20	-20	-20	-20	-20					-20	-20					-20		
23																					-20		

Table 12.48: Estimated percentage change changing time (%)

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23
1																					-50	-50	
2		0																				-50	
3																							
4																						-50	
5																							
6																						-50	
7																					-50	-50	
8																					-50	-50	
9																					-50	-50	
10										0												-50	
11																							
12																					-50		
13																							
14																							
15																					-50	-50	
16																					-50	-50	
17																					-50		
18																					-50		
19																					-50		
20																					-50		
21	-50						-50	-50	-50			-50			-50	-50	-50	-50	-50	-50	-50	0	-50
22	-50	-50		-50		-50	-50	-50	-50	-50					-50	-50					0		
23																					-50		

[137] Source: Schönbeck, W., Kosz, M., Mayer, S., Reishofer, M., Titz, T. and Winkelbauer, S. (1994). Kosten und Finanzierung des öffentlichen Personenverkehrs in Wien - Ausgewählte Befunde und Optionen zur Umsetzung des Wiener Verkehrskonzepts; *Stadtpunkte*; AK Wien, Wien.
Stadtentwicklung Wien (2003). Verlängerung der U-Bahn-Linie U2 von Schottentor/Schottenring nach Stadlau/Aspern. Internet-Support-Gruppe Stadtentwicklung. Last Update: 25/04/2003. Access: 25/07/2001. www.magwien.gv.at/stadtentwicklung/02/02/01.htm
Statistik Austria (2001). Statistisches Jahrbuch Österreichs, Wien.
Statistik Austria (2002). Statistisches Jahrbuch Österreichs, Wien.

Table 12.49: Estimated percentage change driving speed (%)

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23
1																					30	30	
2		30																				30	
3																							
4																						30	
5																							
6																						30	
7																					30	30	
8																					30	30	
9																					30	30	
10										80												20	
11																							
12																					20		
13																							
14																							
15																					20	20	
16																					30	20	
17																					30		
18																					30		
19																					30		
20																					40		
21	30						30	30	30			20			20	30	30	30	30	40	45	80	10
22	30	30		30		30	30	30	30	20					20	20					80		
23																					10		

Table 12.50: Estimated percentage change share of PT separated from road (%)

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23
1																					50	50	
2		50																				50	
3																							
4																						50	
5																							
6																						50	
7																					50	50	
8																					50	50	
9																					50	50	
10										50												50	
11																							
12																					50		
13																							
14																							
15																					50	50	
16																					50	50	
17																					50		
18																					50		
19																					50		
20																					50		
21	50						50	50	50			50			50	50	50	50	50	50	50	50	50
22	50	50		50		50	50	50	50	50					50	50					50		
23																					50		

- **PT frequency**

Table 12.51: Operating costs public transport Vienna in the year 2001

2001 (mio. Euro)	Bus	Tramway	Underground	Total
Driving staff	39.0	49.5	7.8	96.4
Other variable costs	38.7	73.2	43.6	155.4
Total	77.7	122.7	51.4	251.8

Source: (Schönbeck, W. et al., 1994), (ÖSTAT, 2002), own calculations

It is assumed that in the case of a frequency decrease only other variable costs can be reduced. A one percent increase therefore increases PT operation costs by 2.5 mio. Euro per year. A one percent decrease decreases PT operation costs by 1.6 mio. Euro per year.

Table 12.52: Investment costs PT frequency

Investments	Bus	Tramway	Underground	Total
Buying (Euro/veh.)	300,000	1,900,000	7,000,000	
Selling (Euro/veh.)	60,000	380,000	1,400,000	
# Vehicles	495	898	299	1692
Increase (Euro/100%)	148.5	1,706.2	2,093.0	3,947.7
Decrease (Euro/100%)	29.7	341.2	418.6	789.5

Source: Number of vehicles (Wiener Linien, 2002), costs for buying vehicles (Ossberger, M., 2003), selling vehicles: own assumption 20% of value as new

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