Universität Stuttgart

Institut für Straßen- und Verkehrswesen
Lehrstuhl für Verkehrsplanung und Verkehrsleittechnik
Univ.-Prof. Dr.-Ing. M. Friedrich

Development of a Virtual City Model for Urban Land Use and Transport Planning

Lu Liu

Veröffentlichungen aus dem
Institut für Straßen- und Verkehrswesen

Heft 55 (August 2016)

ISSN 0932 - 402X
ISBN 978 - 3 - 9816754 - 5 - 0
D 93 (Dissertation der Universität Stuttgart)

Veröffentlichungen aus dem Institut für Straßen- und Verkehrswesen

Universität Stuttgart

55

Universität Stuttgart

Institut für Straßen- und Verkehrswesen
Lehrstuhl für Verkehrsplanung und Verkehrsleittechnik
Univ.-Prof. Dr.-Ing. M. Friedrich

Development of a Virtual City Model for Urban Land Use and Transport Planning

Lu Liu

Veröffentlichungen aus dem
Institut für Straßen- und Verkehrswesen

Heft 55 (August 2016)

Herausgeber	:	Institut für Straßen- und Verkehrswesen Universität Stuttgart
Copyright	:	Das Copyright liegt beim Verfasser.
Eigenverlag und Vertrieb	:	Institut für Straßen- und Verkehrswesen Universität Stuttgart Lehrstuhl für Verkehrsplanung und Verkehrsleittechnik Pfaffenwaldring 7 70569 Stuttgart

Hinweis / Note:

Diese Veröffentlichung ist auch als "Elektronische Dissertation" online unter **http://elib.uni-stuttgart.de** verfügbar und kann dort im PDF-Format heruntergeladen werden.

This paper is also published online as "Electronic Dissertation" at **http://elib.uni-stuttgart.de** and can be downloaded there as PDF file.

Development of a Virtual City Model for Urban Land Use and Transport Planning

Von der Fakultät Bau- und Umweltingenieurwissenschaften der Universität Stuttgart zur Erlangung der Würde eines Doktors der Ingenieurwissenschaften (Dr.-Ing.) genehmigte Abhandlung

Vorgelegt von

Lu Liu

aus Yuci

Hauptberichter: Prof. Dr.-Ing. Markus Friedrich

Mitberichter: Prof. Dr.-Ing. Stefan Siedentop

Tag der mündlichen Prüfung: 02. August 2016

Institut für Straßen- und Verkehrswesen

Lehrstuhl für Verkehrsplanung und Verkehrsleittechnik

Universität Stuttgart

2016

Preface

This dissertation was written based on the doctoral research during my time at the Institute for Road and Transport Science, Chair of Transport Planning and Traffic Engineering at the University of Stuttgart.

Prof. Dr-Ing Markus Friedrich at the Chair of Transport Planning and Traffic Engineering opened the door of transport science for me. He motivated me during my entire study with his passion and competence for research; and his cares for students and employees. I cannot thank him more for his generous supports, valuable teachings and positive influences in terms of both personality and professionality.

Prof. Dr-Ing Stefan Siedentop at the Research Institute for Regional and Urban Development co-advised this dissertation. We shared the same love for science of geography. I would also like to take this opportunity to thank him for his encouragements and supports in many aspects.

My colleagues during my stay at the Chair of Transport Planning and Traffic Engineering are like a big family for me despite of the impedance due to cultural difference and language gap. Especially I would like to thank Charlotte Ritz, Juliane Pilat and Matthias Schmaus for uncountable exchanges of personal experiences and various opinions. My deep thank goes also to Alice Lorenz for her nice caring for me and improving the language of my dissertation. Last but not the least I appreciate the helps from Maximilian Hartl for developing new functions of the network generator tool and offering fresh ideas in our discussions.

My parents accepted and supported my decision of studying and living so far away from them. Without their understanding and unconditional love I cannot reach where I am. At the end, I would like to thank my beloved husband for accompanying me through these years, always supporting me and keeping faith with me, in good or bad times.

Lu Liu

Contents

List of Tables

List of Figures

Abstract

Travel demand in person transport is the result of decisions of individuals. These travel-related decisions are subject to the characteristics of individuals (age, employment status and car ownership), the characteristics of the land use structure (distribution of land uses) and of transport supply (road network and public transport lines). Measures in land use planning and transport planning can have an impact on the land use structure and the transport supply. For a better understanding of the influences of land use structure and transport supply on travel demand, a virtual city model (VCM) is developed in this work.

A VCM is a travel demand model of a synthetically designed city that replicates the same characteristics of travel demand as a real city. The VCM in this work is embedded in a tour-based travel demand model (VISEM) and is developed with the software VISUM from PTV Group. The travel demand model of Region Stuttgart is the reference model for VCM. Three areas, i.e. city, region and rest of the world, are modelled in VCM on the different aggregation levels. Trips within and between these three areas are correspondingly modelled with different methods.

The three substantial inputs of VCM, i.e. transport supply, land use structure and behavioural pattern, should have comparable characteristics as the reference model. The modelling of these three inputs in VCM is listed in the following:

- Transport supply is represented by network models for both private and public transport. The road network is generated with the help of a network generator tool.
- Land use structure is defined by distribution of residents per person groups and activity locations per activity. The land use structure in the reference model is transferred to VCM applying different methods for the city area, the region area and for commuting trips.
- The behavioural pattern is modelled by parameters in sub-models of the travel demand model, such as generation rates and parameters in utility functions. These parameters are taken directly from the reference model.

In order to obtain characteristics of the travel demand (e.g. number of trips and person kilometre per modes) in VCM comparable to the reference model, the network model and the land use structure in VCM are calibrated with different methods. For example, adjusting detour factors of links for travel distance, and considering topography for travel time by bike. After the process of calibration, VCM is able to generate comparable characteristics as the reference model. Certain simplifications, such as the highly aggregated zones in the region area of VCM, are responsible for the result that not all of the characteristics can be calibrated, as for instance the frequency distribution of travel time for trips within the region area. The usability of the calibrated VCM is examined again through the process of validation. In this process, a series of changes on transport supply (e.g. free-flow speed on roads in the city area) and land use structure (e.g. residential density) are implemented in the same way to both VCM and the reference model. The influences on travel demand in both models are investigated and compared. VCM is adjusted until it is able to generate the same change on characteristics of the travel demand with the same modification of inputs as the reference model.

After the processes of calibration and validation VCM can be applied for studying influences of measures in urban land use planning and transport planning on travel demand. This work gives some application examples of VCM. Influences of the following scenarios are experimented with VCM:

- Function-separated land use distribution,
- Ideal mixture of land uses,
- New developments located in different areas,
- Ideal scenario of no congestion on the roads in the city area,
- Improvement of PuT service in the city area.

The methodological processes can be applied to develop a new virtual city model (e.g. with another network form or with a new reference model). The VCM generated from this work is available for further research in urban land use and transport planning.

Zusammenfassung

Die Verkehrsnachfrage im Personenverkehr ist die Folge individueller Entscheidungsprozesse, die von den Eigenschaften der Menschen (Alter, Beruf, Verfügbarkeit des Pkws) und von der Siedlungsstruktur (Verteilung der Nutzung) und dem Verkehrsangebot (Straßen- und ÖPNV Liniennetz), beeinflusst werden. Siedlungsstruktur und Verkehrsangebot sind zwei Einflussfaktoren auf die Verkehrsnachfrage, die Raum- und Verkehrsplaner mit Maßnahmen beeinflussen können. Zum besseren Verständnis der Wirkungen von Siedlungsstruktur und Verkehrsangebots auf die Verkehrsnachfrage wird in meiner Arbeit ein Planstadtmodell entwickelt.

Unter einem Planstadtmodell versteht man ein abstraktes Modell einer virtuell gestalteten Stadt, die jedoch die gleichen verkehrlichen Wirkungen wie eine reale Stadt aufweist. Das Planstadtmodell wird in einem tourbasierten Nachfragemodell (VISEM) mit der PTV Software VISUM abgebildet. Das Verkehrsnachfragemodell der Region Stuttgart dient als Referenzmodell für das Planstadtmodell. Das Planstadtmodell umfasst drei Gebiete: die Stadt, die Region und den Rest der Welt. Die Wege zwischen diesen Gebieten werden mit unterschiedlichen Methoden modelliert.

Die drei wesentlichen Eingangsgrößen des Planstadtmodells, i.e. Verkehrsangebot, Siedlungsstruktur, Verhaltensweise, sollen vergleichbare Eigenschaften wie das Referenzmodell aufweisen.

- Das Verkehrsangebot ist durch ein Straßennetzmodell und ein ÖPNV Liniennetzmodell abgebildet mithilfe vom Netzgeneratortool.
- Die Siedlungsstruktur ist von der Verteilung der Einwohner je Personengruppe und von der Verteilung der Aktivitätenorte je Aktivität abhängig. Die Verteilung im Planstadtmodell erfolgt anhand von Nutzungskategorien (z.B. Wohnen, Arbeiten), von Nutzungsdichten und von der Entfernung zur Stadtmitte.
- Die Parameter des Nachfragemodells (z.B. Erzeugungsraten und Parameter der Nutzenfunktionen) entsprechen die Verhaltensweise. Diese Parameter im Planstadtmodell werden direkt aus dem Referenzmodell übernommen.

Um die gleichen verkehrlichen Kenngrößen (Zahl der Wege je Verkehrsmittel, Personenkilometer) wie das Referenzmodell liefern zu können, wurden das Netzmodell und die Siedlungsstruktur mit unterschiedlichen Methoden kalibriert, z.B. Umweg Faktoren der Strecken einstellen für Reiseweiteverteilung, und Steigung für Reisezeitversteilung des Rades. Nach der Kalibrierung liefert das Planstadtmodell bei vielen Kenngrößen vergleichbare Werte mit dem Referenzmodell. Einige Vereinfachungen, z.B. die Zahl der Orte in der Region, führen jedoch dazu, dass nicht alle Kenngrößen vergleichbar sind. Die Verwendbarkeit des kalibrierten Planstadtmodells wird nochmal durch eine Validierung sichergestellt. Dazu werden im Planstadtmodell und im Referenzmodell Veränderungen im Verkehrsangebot (z.B. pauschale Erhöhung der Geschwindigkeit) und in der Siedlungsstruktur (z.B. pauschale

Erhöhung der Einwohnerzahl) vorgenommen. Dann werden die Wirkungen auf die Verkehrsnachfrage ermittelt und verglichen. Das Planstadtmodell wird korrigiert bis die gleiche Veränderung der Nachfragekenngrößen wie im Referenzmodell generiert werden kann, basierend auf der gleichen Veränderung der Eingangsdaten.

Das validierte Planstadtmodell wird zur Untersuchung des Einflusses von Maßnahmen in Raumplanung und Verkehrsplanung auf die Verkehrsnachfrage genutzt. Einige Anwendungen des Planstadtmodells, i.e. Einfluss von den folgenden Szenarien auf Verkehrsnachfrage, werden beispielhaft durchgespielt.

- Die Trennung der Flächennutzung
- Die Mischung der Flächennutzung,
- Lagerung der Neuentwicklung in unterschiedlichen Gebieten,
- Keine Überlastung auf dem Straßennetz in der Stadt,
- Verbesserung der städtischen ÖV Qualität.

Die methodologischen Prozesse können für zukünftige Planstadtmodelle mit z.B. einer neuen Straßennetzform oder einem neuen Referenzmodell verwendet werden. Das in meiner Arbeit beschriebene Planstadtmodell steht für weitere Anwendungen und wissenschaftliche Fragestellungen zur Verfügung.

1 Introduction

1.1 Motivation

Travel demand is an aggregation of individual movements that are made because people need to move between different locations of activities. Travel demand has a variety of different characteristics around the world. These differences result from the composition of the population (with respect to car ownership), the necessity of activities and the features of settlement locations. Two main features of settlement locations that influence travel demand are land use and transport supply.

Notwithstanding differences of characteristics of travel demand worldwide the same trend of more cars travelling longer distances is shared around the world. Individual motorized traffic generates negative effects such as air pollution, energy consumption, and congestion in cities. The negative effects generated by the high share of individual motorized vehicles lead to the desire for reduction of travel demand by avoiding travelling, by reducing trip length and by shifting trips with individual motorized vehicles to non-motorized trips or public transport. Since the purpose of travelling is to participate in activities, unless activities are located at the same place, avoiding trips is usually not desirable. Reducing trip length and promoting modal shift can be reached through urban land use planning (e.g. by bringing activity locations close to one another so that the trip length reduces and non-motorized trips are preferable); and through transport planning (e.g. by offering good PuT infrastructure and service so that the car can be replaced by PuT).

This work focuses on urban areas. Services and facilities are concentrated in urban areas, 53% of the global population lived in urban areas in 2014 (THE WORLD BANK). Compared to rural areas, urban areas offer better PuT infrastructure and thus better preconditions for sustainable transport. However, urban areas generate accordingly more congestion and environmental problems because of the concentration of services and facilities. Notwithstanding the importance of urban areas a city is never isolated, therefore the hinterland of a city and the interactions between the city and other areas are also considered in this work.

Planning means developing measures. These measures should transform a current state with a deficiency into an improved state which is close to the desired state (KIRCHHOFF, 2002). Therefore whether a measure is appropriate for reaching a desired state is the core of planning. Before determining measures in urban land use and transport planning in order to change travel demand, the influence of land use and transport supply on travel demand should be investigated. The relationship between land use and travel demand in literature is studied mainly with methods of statistics focusing on quantitative elasticities or causal relationships. Travel demand models replicate travel demand by modelling a sequence of travel-related decision-making processes with the given external conditions. Since both land use and transport supply function as inputs (external conditions) for travel demand models, their influences on travel demand can be investigated in travel demand models.

Travel demand models are built normally referring to a specific area for purposes of forecasting in transport planning. Nowadays with the help of big data and advanced modelling methods, travel demand of an area can be modelled on a high level of details. In opposition to this trend, a virtual city model (VCM), i.e. a travel demand model of a synthetic city, is generated in this work and applied to investigate systematically the influence of land use and transport supply on travel demand. For such an investigation, a VCM provides the following advantages:

- Fastness: It demands less computing effort because of the high level of aggregation.
- Generality: The modelling framework can be applied to variable types of cities, rather than only for a specific area. A virtual city can be designed for variable research purposes, such as research of different networks or land use forms.
- Flexibility: Inputs of land use structure and transport supply can be modified systematically, such as headways and stop densities of PuT lines.
- Simplification: It is not necessary to consider the specific characteristics of a real city, e.g. a river.

1.2 Research goals

The objective of this work is the development of a VCM for purposes of both land use planning and transport planning. This VCM is intended to deliver answers to the two main research questions:

- Is it possible to develop a VCM that can deliver reasonable and reliable results by representing a real city in spite of its artificiality?
- How do changes on land use and transport supply influence travel demand according to the developed VCM?

Based on the above research questions, the two main research goals are summarized as follows:

- To develop, calibrate and validate a VCM that can represent travel demand in a real city as closely as possible. The following methods should be developed:
  - Method to transfer characteristics of land use structure and transport supply from a real city to VCM.
  - Method to calibrate inputs of land use structure, transport supply and result of travel demand in VCM based on the reference model.
  - Method to validate VCM in order to ensure the reliability of VCM for possible changes.

- To model the influences of several measures in urban land use planning and transport planning in VCM and evaluate these measures.

The changes of land use structure and transport supply applied to VCM should be on the macroscopic level. For example, the street design for an improvement of walking safety and comfort cannot be modelled in VCM.

1.3 Outline of work

This work presents the processes of developing, calibrating and validating a VCM and several examples applied to VCM to investigate the influence of measures in land use planning and transport planning on travel demand.

Chapter 2 provides fundamentals in literature related to indicators of travel demand, factors of influence on travel demand, and modelling of these factors of influence and travel demand. To understand travel demand, chapter 2.1 gives an overview of worldwide differences of travel demand. These differences can be explained by influencing factors which are introduced in chapter 2.2. These influencing factors represent the input data for the travel demand modelling. After understanding how these factors influence travel demand, chapter 2.3 summarizes measures in both land use planning and transport planning, the effectiveness of these measures and an ideal urban land use-transport system. Chapter 2.4 prepares modelling of a VCM by introducing how the influencing factors and their influence on travel demand are modelled.

The core of this work is the development of a VCM, which is introduced in chapter 3. The methods used to transfer the characteristics of a reference model to VCM are generally introduced in chapter 3.1. Chapter 3.2 briefly introduces population, land use, transport supply and travel demand in the reference region: Stuttgart Region. The tool applied to generate the network model of VCM is described in chapter 3.3. Aggregations of space, population and activity are presented correspondingly in chapter 3.4 and chapter 3.5. Chapter 3.6 portrays the three methods used to transfer the land use structure of the reference model into VCM. The core method of the most important transfer for the land use structure in the city is the cross-classification of land use categories, rings and densities. Modelling the transport supply, and the evaluation of the road and PuT network in VCM are introduced in chapter 3.7. Last but not the least chapter 3.8 describes the modelling of travel behaviour, i.e. how the above factors influence travel demand.

In chapter 4 the processes of calibration and validation of the developed VCM are addressed. Chapter 4.1 gives an overview of the process of calibration with respect to the applied indicators and the process of validation. The calibration of transport supply (represented by travel time, distance and cost) is introduced in detail in chapter 4.2. The calibration of number of trips with consideration of adjustment of land use structure and freight transport is addressed in chapter 4.3. After calibration, VCM is validated through a series of sensitivity tests of both transport supply and land use structure. Adjustments are conducted in VCM until it can deliver the same change of travel demand as SCM in the validation process. The final results of changed travel demands in these tests are analysed and displayed in chapter 4.4. Results of travel demand in VCM after both processes of calibration and validation are presented in chapter 4.5.

Chapter 5 examines the impact of selected scenarios. Seven scenarios are generated and applied to VCM: two scenarios with a different degree of land use mixture (chapter 5.1.1), three scenarios with different locations of new developments (chapter 5.1.2), one scenario with the improvement of road network (chapter 5.2.1) and the last scenario with the improvement of PuT service (chapter 5.2.2). Changes of travel demand are shown in each sub-chapter.

The methodological accomplishment of this work, major findings from application examples, further improvements of VCM, and potential applications are summarized as conclusion of this work in chapter 6.

2 Fundamentals

2.1 Travel demand

Combining the explanations of travel demand from KIRCHHOFF (2002) and WERMUTH (2005) the generation process of travel demand is shown in Figure 1. Needs are the inner human incitements for their behaviours, i.e. travel behaviour is need-driven as all other behaviours. Travel behaviour reflexes the complex individual decision processes with consideration of constrains from external factors. Needs lead to the necessity to participate in activities. As activity locations are distributed in space, travellers need to move between different locations for variable activities. Travel demand is the sum of all realised necessities of movements with the help of the transport supply.

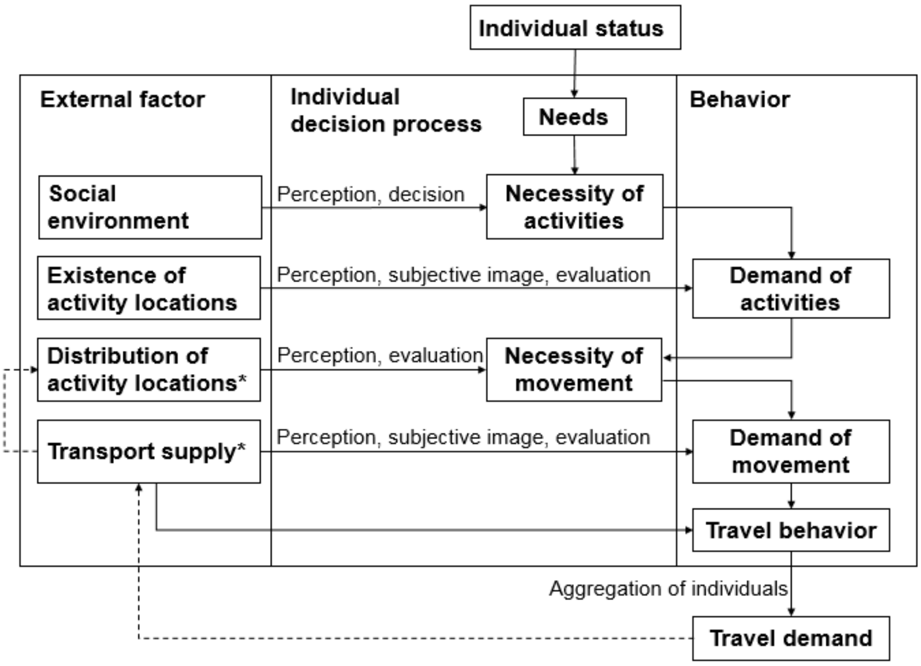


Figure 1: Formation of travel demand (KIRCHHOFF, 2002; WERMUTH, 2005).

In this work, travel demand is at the core of the investigation. The following delimitations are confined:

- When travel demand is referred, person transport rather than freight transport or information flows is concerned;
- Aggregated travel behaviours instead of individual decisions are in the focus of attention;
- The generated travel demand is looked upon as a result of certain external factors and individual characteristics. Mechanisms of decision processes (e.g. learning process with “mental map”) are not addressed.

Travel demand has different characteristics around the world. Characteristics of travel demand are quantified by several indicators. The following three categories of indicators are applied to describe travel demand in this work:

- The number of trips refers to the total number of movements in an area for a given time period. It may also refer to the average number of trips per person in a day (trip rate). Modal split of trips is the share of trip numbers of each mode.
- The travel distance can be combined with the number of trips to describe the total distance travelled in an area and a time period. In order to compare the travel distance of different areas, both the travel distance for all the trips per person in a day and the average distance of a trip can be applied. Modal split of the distance travelled is the share of total distance travelled of each mode. The total distance travelled influences energy consumption for trips.
- The travel time expenditure is the total time travelled of all persons in an area and a time period. Similar to the travel distance, the average daily travel time per person is applied for comparison of different areas.

Number of trips

Travel demand is different all over the world. The worldwide average number of person trips per day is 3.5, according to AXHAUSEN and FRICK (2005). A person makes 2-5 trips per day on average. Based on data from national surveys, trip rates aggregated by (part of) country are explored: 2.5 trips in South Africa (DEPARTMENT OF TRANSPORT IN SOUTH AFRICA, 2005), 2.6 trips in England (DEPARTMENT FOR TRANSPORT IN UK, 2015), 3.4 trips in Germany (INFAS and DLR, 2010), whereas 3.8 trips in the USA (U.S. DEPARTMENT OF TRANSPORTATION, 2011). Trip rates aggregated by persons with specific characteristics show differences, for example commuters make more trips than an average person: commuters make 4.5 trips in Washington D.C, the USA (KUPPAM and PENDYALA, 2001).

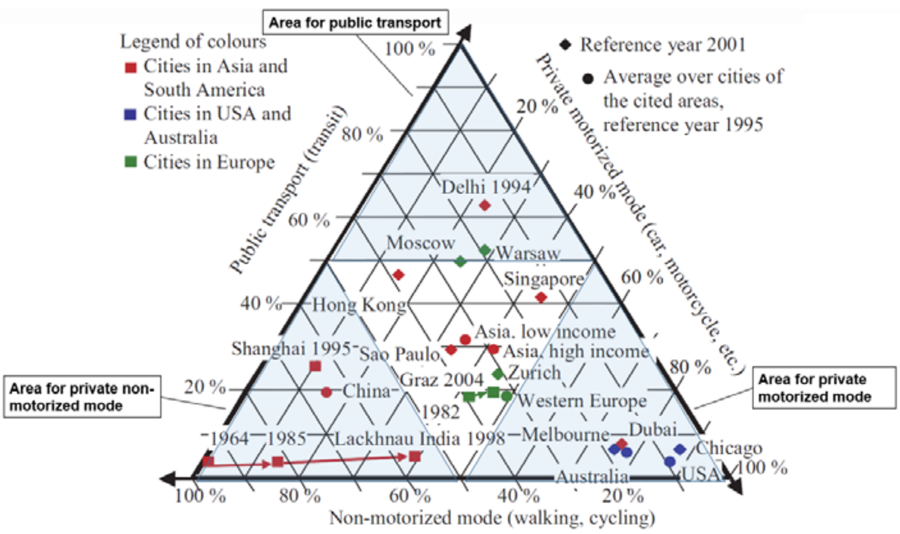


Figure 2: Modal split around the world (GEA, 2012).

Not only the number of trips differs globally, but also the modal split of trips. For example, the share of car trips in the US is 40% higher than in Germany (BUEHLER, 2009). Figure 2 shows characteristics of modal split in selected cities and countries using data mainly from KENWORTHY and LAUBE (2001) and PADAM and SINGH (2001) in GEA (2012). The three edges of a triangle represent the non-motorized mode, the private motorized mode and public transport. Modal-split points in the middle area show an average distribution of trips to three modes. Points near 100% of any mode represent the dominant share of this mode. Cities in USA and Australia show the most dominant share of car trips with approx. 78% and 88%. And the USA has 7% fewer trips with non-motorized mode than Australia. European cities are located in the central area with balanced modal splits: the share of the private motorized mode is between 30% and 50%, and the rest of 50% to 70% are either PuT trips or non-motorized trips. Asian cities have diverse modal splits, however, in most Asian cities, the car is not the dominant mode except for Dubai. For example in Delhi PuT is dominant and in Lackhnau of India (also Lucknow) in1964 walk and bike are the main modes. The shift from the non-motorized mode to the private motorized mode of Lackhnau along the time scale shows the progress of motorization in the cities in developing countries.

Travel distance

Travel distance per trip depends to a great extent on the applied means of transport. It is also different all around the world: the average distance covered per trip in both Germany and England is 11 km (INFAS and DLR, 2010; DEPARTMENT FOR TRANSPORT IN UK, 2015), whereas a person in the USA covers a distance of 15 km per trip on average (U.S. DEPARTMENT OF TRANSPORTATION, 2011). In countries where the car is not widely used yet people make shorter trips, for example the average trip distances in 25 Chinese cities are between 2 km and 6 km (MAO, 2005).

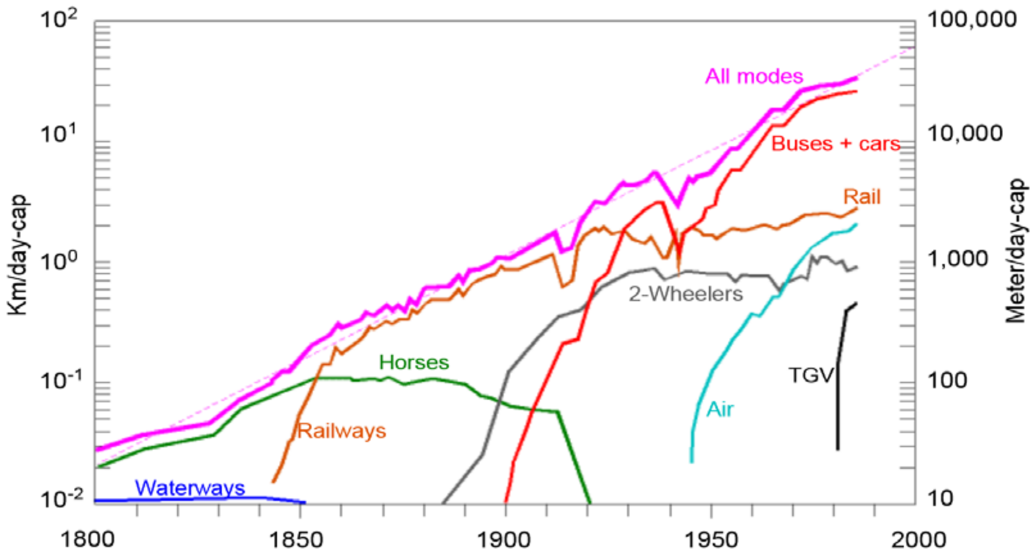


Figure 3: Temporal changes of daily travel distance in France (GRÜBLER, 1990).

The difference of travel distances is not only spatial but also temporal. Figure 3 shows the temporal growth of travel distances per capita for France. Travel distance per capita increases from only a few metres in 1800, to 1 km in 1900, up to 10 km in 1950 and 35 km in 1990. The increase of travel distance is associated with the existence of faster means of transport. For example by the end of 19th century railways accounted for 90% of all the distance travelled (GRÜBLER, 1990). With the use of cars, the distance travelled increases from 1 km in 1900 to 10 km in 1950.

Aside from spatiotemporal differences of travel distance, the distribution of travel distance follows the Lill's law of travel (Lillsches Reisegesetz). This law indicates that the number of trips depends on not only the characteristics of origin and destination, but also the travel distance (LILL, 1889). Their relation is described with a gravity model, which reveals that there are fewer trips for longer distances. This relation can be proved by distributions of trip frequency by trip distance in both Switzerland and Germany (AXHAUSEN and FRICK, 2005).

Travel time

A travel time between 75 min and 85 min per day is observed in the last 40 years in national and regional surveys (AXHAUSEN and FRICK, 2005). GRÜBLER (1990) concludes that travel time over the history happens to be similar in spite of the development of technology. Figure 4 illustrates an range of daily travel time between 50 min and 100 min in a wide range of cities and countries with geographic, economic, social differences (SCHAFER and VICTOR, 2000). These data are collected from two African villages, 36 cities and 20 national surveys between the years of 1965 and 1993. Some examples of average daily travel time based on recent statistics are 90 min in the USA of 2009 (U.S. DEPARTMENT OF TRANSPORTATION, 2011), 79 min in Germany of 2008 (INFAS and DLR, 2010), 60 min in England of 2014 (DEPARTMENT FOR TRANSPORT IN UK, 2015) and 55 min in 66 cities of China (MAO, 2005). Considering average time per trip, inhabitants of all the above countries (the USA, Germany, England and China) travel approx. 23 min per trip.

The phenomenon of the stability of the travel time over decades was first described by ZAHAVI and RYAN (1980). They proposed that a fixed amount of time is assigned to travel and there is a travel time budget of 1.1 h. The term “travel time budget” implies stability when compared to the term “travel time expenditure”. This stability is a result of the fact that the tolerance with respect to travel time expenditure for fulfilling activities at different locations remains similar. For example, an increase in travel speed may induce more trips with longer distances because the new travel time is still within the tolerance of travel time expenditure.

Travel time expenditure varies within a certain range and the degree of stability of travel time is related to the level of aggregation. Taking the examples in Figure 4, the range of travel time on the national level is 55 min - 70 min; whereas the longest daily travel time on the city level is 100 min, twice as long as the shortest time of 50 min. Travel time varies according to the sociodemographic characteristics of the traveller and the physical environment. For example, SCHAFER and VICTOR (2000) conclude that travel times are generally the highest for the largest cities, such as Paris with 90 min. MAO (2005) offers evidence from China that the total travel time in large cities (>2 million inhabitants) is 63 min whereas in small cities (<0.2 million inhabitants) it amounts to 54 min.

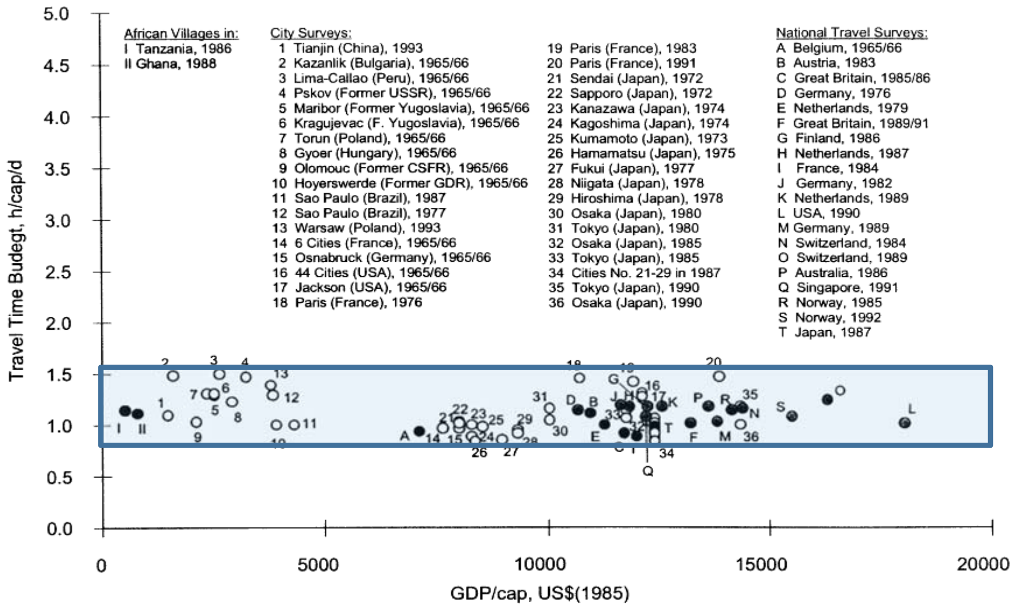


Figure 4: Worldwide daily travel time (SCHAFER AND VICTOR, 2000).

2.2 Factors of influence on travel demand

The characteristics of travel demand are different all over the world. As addressed in Figure 1 (see chapter 2.1), the following four aspects influence the formation of travel demand.

- Person-related factors: they describe different characteristics of individual status;
- External factors: they refer mainly to land use and transport supply. These can be influenced by the land use planner and the transport planner;
- Individual decision processes: external factors are perceived and analysed based on person-related factors. As a result, travel behaviour is generated;
- Total number of individuals in a specific area: travel demand is the aggregation of travel behaviour of individuals.

How both person-related factors and external factors (land use and transport supply) influence travel demand is discussed in the following.

2.2.1 Person related factors

Person-related factors are individual characteristics, most of which are socio-demographic or socio-economic features. The main person-related factors and interactions among them are shown in Figure 5. Car ownership is not a conventional person-related factor, but it is a key individual factor in matters of travel behaviour, especially of car usage. Socio-demographic factors, i.e. age, gender, employment and household structure, determine different necessities of activities and travels. Socio-economic factors, i.e. employment and income, offer resources to cover costs for movements and accordingly provide choices of means of transport. Car-related factors, i.e. driving license and car ownership, depend on the above factors and influence the choice of car use. Inhabitants with different features influence the land use through their residence choices. Residence choices describe the different preferences to choose residence places. For example, the possibility for a working-age person to live in the inner city is higher than for a retiree, as shown in Stuttgart City that in the peripheral city there live 4% more retirees but 8% fewer working-age persons (18-65 years old) than in the inner city (STATISTISCHES AMT STUTTGART, 2012).

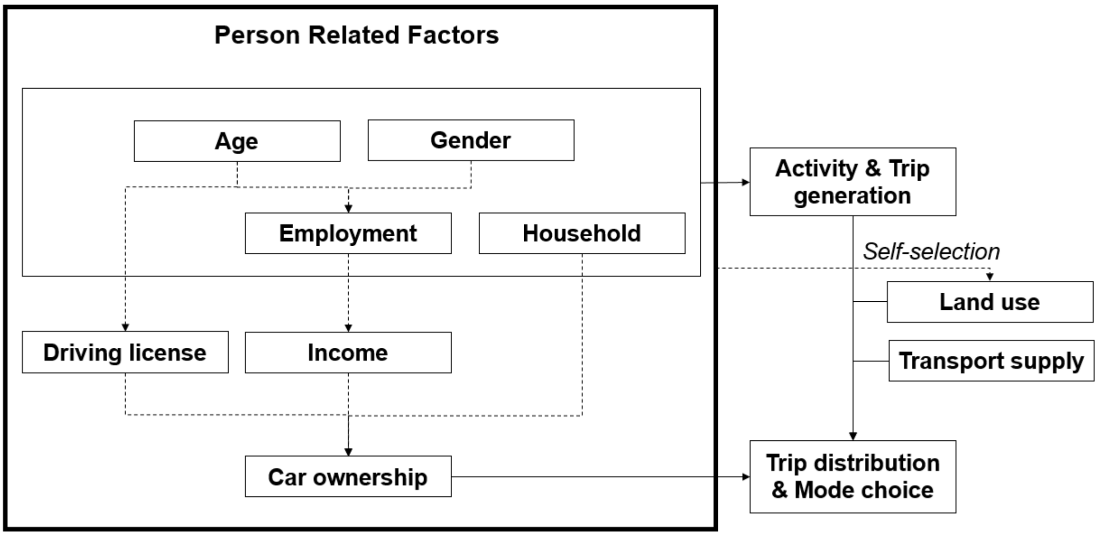


Figure 5: Overview of person related factors influencing travel demand.

As illustrated in Figure 5, the person-related factors do not only influence travel demand, but also show interdependencies, as for instance between age and employment. These interdependencies among person-related factors are complex and are discussed in the following.

People with the same sociodemographic and socio-economic features could also behaviour differently, for which life style or preference are responsible. However, these individual differences are excluded from this work.

Age, gender and employment

Age, gender and status of employment are basic characteristics of a human being. The influence of age and employment on travel behaviour reflects the necessities of activities during different stages of life. Employment status determines whether going to work is included into daily trip purposes; it additionally influences the income and the money available for travel. Life begins with in-home activities and incapability of car driving; then together with necessities of education and work, more out-of-home activities are integrated in daily life and people make more trips with longer distance; in case of not going to work, more trips are made for private business or leisure purposes; life ends with participating in fewer out-of-home activities. Different from biologically-classified sex, gender refers to differences in behaviour by sex, according to MONEY and EHRHARDT (1972) from UDRY (1994). Gender is explained by differences in social experiences and constrains in social structure, explained by the first principle of gender theory introduced in his work “The nature of gender” (UDRY, 1994). Travel behaviour is a gendered behaviour mainly due to gender role in the social structure that determines different necessities of activities and differences in income, rather than because of biological dimorphism. The degree to which travel demand by gender differs depends on differences in the employment structure and the division of responsibilities within a household. Historically seen females take up more responsibility for private business for household than males do, while males work full-time.

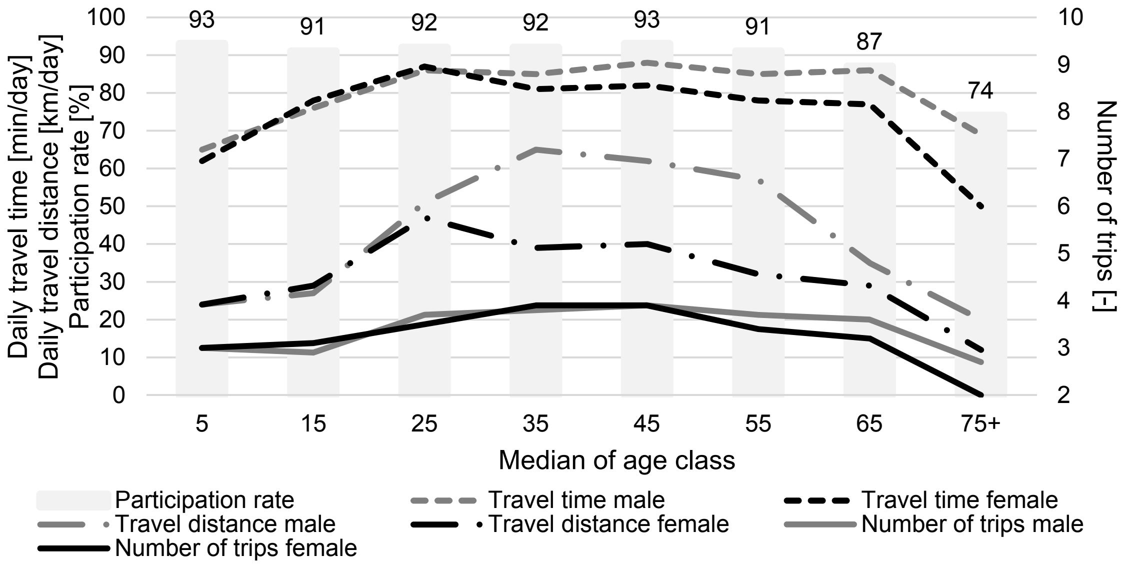


Figure 6: Travel demand by age and gender in Germany (INFAS and DLR, 2010).

Figure 6 shows the aggregated indicators of travel demand by age and gender derived from MiD 2008 (INFAS and DLR, 2010). The participation rate of people older than 75 years decreases to the lowest value compared to other age groups. The number of trips, daily travel time and distance increase from the age of 18 years, and they begin to decrease from the age of 50 years. The number of daily trips ranges from two of female retirees to four of people around 45 years (no difference between male and female).

People between 35 and 55 make the most trips. Children and teenagers make fewer trips compared to adults between 18 and 59. Travel time of young people around 25 is the longest of almost 90 min. The most significant difference by gender lies in the travel distance for people of 30-60 years: males travel 30% further than females. It infers that males make more car trips than females whereas females travel more with non-motorized mode or PuT. It also reflexes the different employment structure by gender, as full-time employees travel the longest distance, while unemployed or house-wives/men make shorter trips. Differences of trips and travel time by gender become more significant for elderly people: elderly females make fewer trips and spend shorter time on travel.

Besides the above illustrated travel demands by age and gender, INFAS and DLR (2010) also show the difference of travel demand according to employment: part-time employees make the highest number of trips per day: four trips. Students travel with the longest time: 95 min. Of all age groups teenagers under 18 years are responsible for the biggest share of trips covered with both bike and PuT: 14% (INFAS and DLR, 2010).

In addition to the characteristics extracted from MiD 2008, studies with various statistic or modelling methods have found different characteristics of travel demand by age, gender and employment. For example, a study in Edinburgh concludes that people in working age travel the most and are most likely to drive a car, whereas students and unemployed cycle more than employees (RYLEY, 2006). A modelling study in Washington D.C. shows that full-time out-of-home employees make fewer trips than other commuters and elderly travellers make fewer trips, travel with shorter distance and time, and are unlikely to make complex work trip chains (KUPPAM and PENDYALA, 2001). VAN ACKER and WITLOX (2010) summarize that elderly people older than 60 years have lower car ownership and make fewer car trips. POLK (2004) delivers the evidence of different car use by gender in Sweden with the conclusion that females use the car less than males after controlling employment, household structure, car access and income. KUPPAM and PENDYALA (2001) find that females travel more, and are more likely to make complex work trip chains. The reviewing study by MOKHTARIAN and CHEN (2004) summarizes the contradictory results of travel time by gender in a wide range of studies. Some studies compare the same characteristics in different years, such as the studies from SCHOTT (2014) and NEWBOLD et al. (2005). SCHOTT (2014) finds that the motorisation degree of people aged 18-24 and 25-39 decreases by respectively 60% and 30% from 1980 to 2010 in Germany. However, he argues that car ownership of the young generation could increase with the increase of age and income. NEWBOLD et al. (2005) applies cohort analysis and concludes that the number of car trips for older Canadians increase from 2.7 in 1986 to 3.3 in 1998.

There are interactions between the influencing factors. For example, different characteristics by gender are often relevant to employment and household structure. NOBIS and LENZ (2005) explore individuals with an age range of 30-49 years and conclude that single men and women share similarities, but the difference of gender increases in multi-person households.

Furthermore, there is sometimes more than one way of influence. For example, elder people tend to travel shorter; however, they tend to live in areas with low density, which leads possibly to more car use and longer travel distance. To sum up, direct influence for elder people results shorter distance, whereas indirect influence through residence location leads to longer distance. The result is that elder people drive shorter, as direct influence is stronger.

Household structure

In comparison with an individual, household is a more aggregated unit in terms of observation of travel behaviour. The household structure refers to the number of persons within a household emphasizing especially on the presence of children. The household structure influences travel demand in the following aspects:

- Substitution of activities within a household especially for private business trips;
- Different necessities of activities due to presence of children, e.g. to bring & pick up;
- Strong influence of number of drivers and children in a household on car ownership;
- Indirect influence of household size on travel demand through residence location.

There is a substitution of activities among household members. A theory is that certain activities of each household are assigned to household members (SCOTT and KANAROGLOU, 2002). Aside from individual trips such as going to school, some trips are on household level, such as private business trips. For example, in a multi-person household if one has done shopping or bring & pick up trips, the other can save these trips, and they are more likely to make more work or leisure trips. As found by NOBIS and LENZ (2005), those private business and child caring trips are mainly done by females. Following this theory, travellers in single households make more trips than travellers in multi-person households. This conclusion complies with the data of MiD 2008 that a person in one-adult household makes the most trips (4.5 for person under 30 years) and travels the longest distances (56 km for person under 30 years) among individuals of all the household groups (INFAS and DLR, 2010).

The presence of children leads to differences on both activities and car usage. Child-care-related trips are additional tasks for households with children. Households with children are particularly car dependent, proved in Edinburgh by RYLEY (2006). Research in the Netherlands shows similar results that families with children are more likely to use cars than one-person families do (DIELEMAN et al., 2002). However, this dependence of car usage and presence of children is also determined by household income. For example, 23% of single-parent-households do not own a car, whereas there are only 2% of couple-with-children-household without car in Germany (INFAS and DLR, 2010), as the household income of single-parent-households is generally less than the household income of couple-with-children-households. Larger households tend to own more than one car (VAN ACKER and WITLOX, 2010). It is also proved by MiD 2008 that 40% of two-adult households, and 76% of three-or-more-adult households own two or more cars (INFAS and DLR, 2010). The number of drivers is the prerequisite for more cars in a household.

Similar to age, household size influences also residence location. For example, large families tend to choose low-density residence areas, which in turn increases total distance travelled. KIM and BROWNSTONE (2010) find a significant relationship between number of children and location of residence in lower-density areas.

To sum up, the influence of household structure on travel demand is a mixture of substitution within a household, necessities of child-caring trips, and preference of residence area.

Income, driving license and car ownership

Income determines the potential available financial resources. These resources can be used to fulfil necessities of travel and the freedom to choose residence area based on the housing market. Driving license and car ownership are two factors directly influencing car use: the driving license is a prerequisite for car usage; and car ownership tends to increase car uses. Income influences both driving license and car ownership. People with driving license make 50% more trips and travel 250% further than people without driving license in Germany (INFAS and DLR, 2010). Although cars can be shared and activities can be substituted within a household, two persons cannot use a car for different trips at the same time. Thus it is meaningful to observe influence of these factors on individual level.

Studies in different regions find a strong relationship between income and travel behaviour, especially car use and distance travelled (BADOE and MILLER, 2000). Commuters with higher income would spend more time on out-of-home recreation activities and make more complex work trip chains, thus, it is possible that they travel more and further (KUPPAM and PENDYALA, 2001; SCOTT and KANAROGLOU, 2002). Data from NHTS 2009 show the positive relationship between household yearly income and daily trips per person (U.S. DEPARTMENT OF TRANSPORTATION, 2011). SCHAFER and VICTOR (2000) summarize the historical data and find that the annual distance travelled per capita using motorized modes rises with average income by roughly the same proportion throughout the world, as shown in Figure 7. It indicates that a certain share of individual income of around 5% - 15% worldwide is spent to cover travel costs (SCHAFER and VICTOR, 2000).

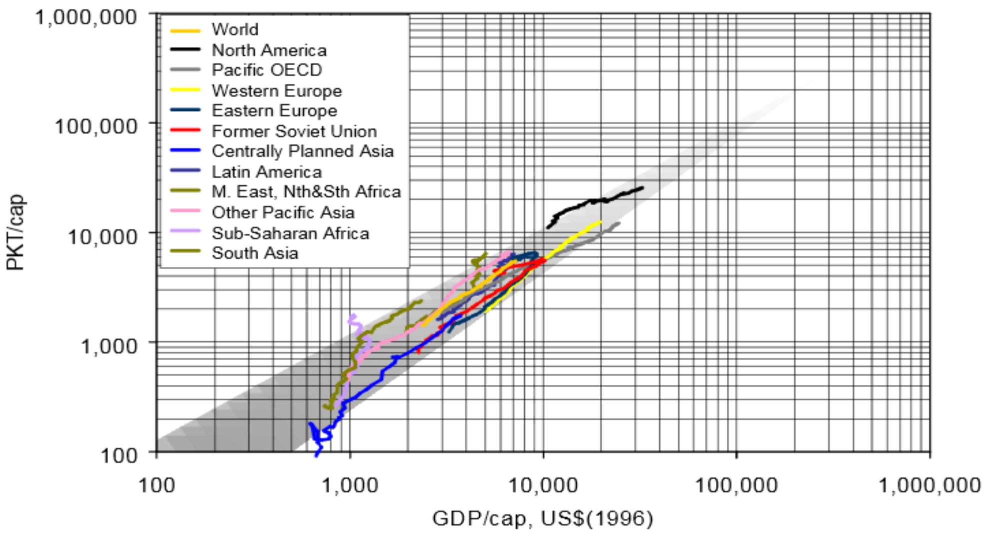


Figure 7: Relationship between income and distance travelled (SCHAFER and VICTOR, 2000).

Income influences car ownership and car use. DIELEMAN et al. (2002) argue that people with higher income are more likely to own and use a car. Data from MiD 2008 verify that a higher household income leads to more cars, as shown in Figure 8. Over 60% of the two lowest income groups have no car in their households. For household with the income more than € 3000, almost all the households have cars, and the share of households with two cars starts to exceed the share of households with one cars. The relationship between household income and car use is also proved by RYLEY (2006) that almost all high-earning households (>20,000 pound) in Edinburg have cars and are car dependent, especially for the working trips.

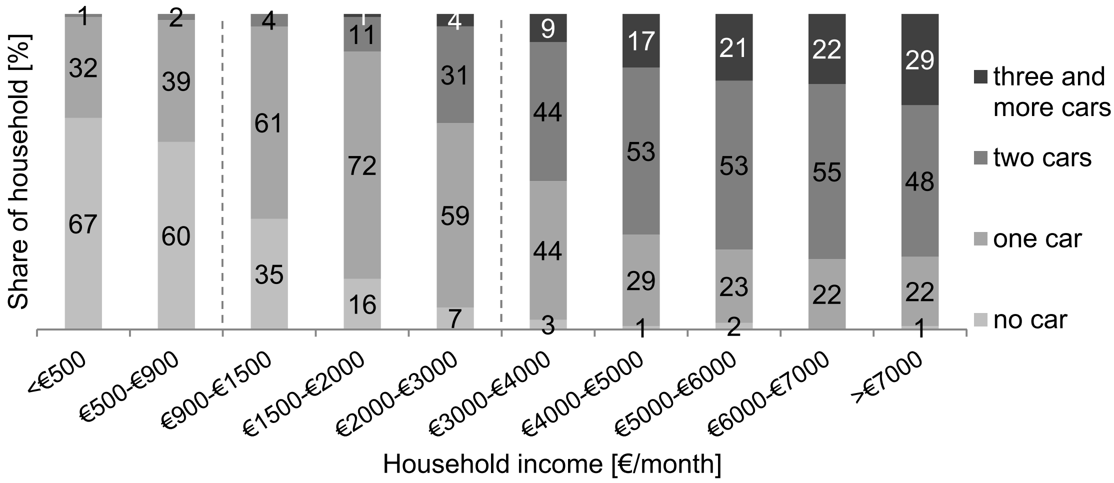


Figure 8: Relationship between income and car ownership (INFAS and DLR, 2010).

The influence of income on travel time shows diversity. ROTH and ZAHAVI (1981) explore travel time in cities in developing countries. In both Bogotá (Columbia) and Santiago

(Chile) daily travel time decreases with increasing income: motorized traveller with lowest income travel two hour whereas those with highest income travel one hour. In Singapore travel time for vehicle-owning households is stable over a wide range of incomes. In Salvador (Brazil) travel time tends to rise with increasing income because of spatial distribution of residences: high-income residences are located in the peripheral areas of the city whereas low-income residences in the inner city.

Car ownership is a medium-term travel-related decision, which is influenced by both socio-economic factors such as income and long-term decision like residence choice and work location. Car ownership influences short-term decisions as for instance daily car use (VAN ACKER and WITLOX, 2010). Although car sharing systems make car ownership no longer a prerequisite for car use, car ownership tends to induce more car trips and further distance travelled. Based on approx. 5,000 observations in the USA, household income, household car ownership and annual distance travelled in areas with different housing densities are illustrated in Figure 9. In this example, the households with the highest income are located in areas with moderate housing density. Car ownership does not change with income, but decreases slowly with increasing housing density. In the areas with lowest and highest densities, household income is comparable, but car ownership is respectively two and one, and the annual distances travelled are respectively 40,000 km and 20,000.

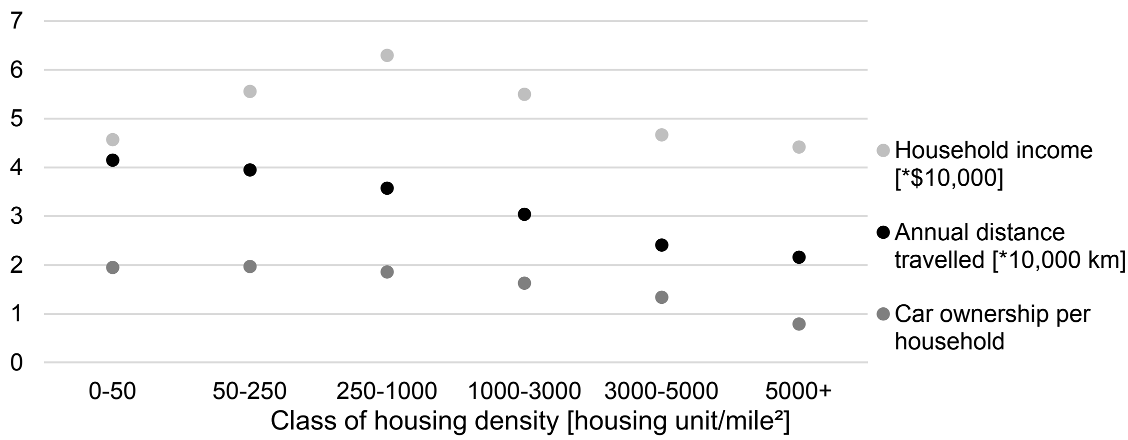


Figure 9: Income, car ownership, distance travelled and housing density (data from KIM and BROWNSTONE (2010)).

2.2.2 External factors

In addition to person-related factors, external factors also influence travel demand. The external factors include land use and transport supply, Instead of influencing activities, they affect characteristics of trips such as travel distance. The influence of these external factors on travel demand is introduced firstly with a short review of historical development, and then by means of influencing mechanisms and empirical evidences.

Development of cities and transportation

The history of cities, as a matter of development of its residents, of land use and network forms, goes along with the development of means of transport. In the process of development of cities and transport technology, characteristics of travel demand have changed, especially the distance travelled. “The Marcheti Constant” indicates that the size of cities is based on a travel time budget of one hour (NEWMAN and KENWORTHY, 2006). The exemplary developments of cities in both literature from the USA and Germany are displayed in Figure 10, distinguishing three city types based on the main mode applied in a city: walking city, transit city and automobile city. The development of cities according to NEWMAN and KENWORTHY (1996) focuses on the typology of cities, whereas the development of cities according to GATHER et al. (2008) concentrates on the development of spatial scales.

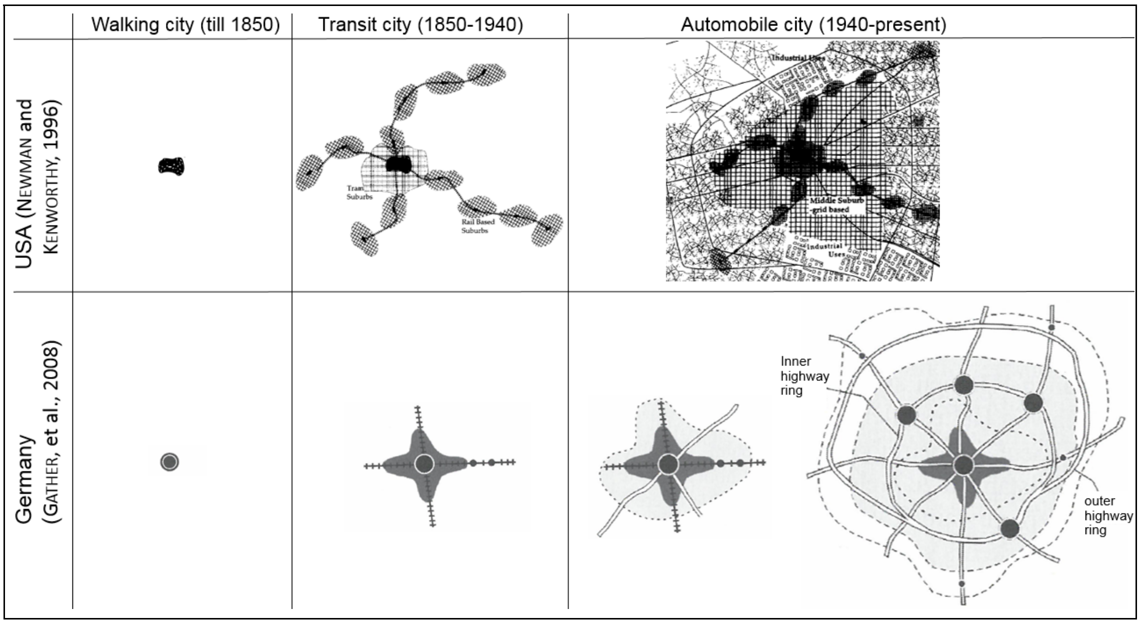


Figure 10: Exemplary development of cities (NEWMAN and KENWORTHY, 1996; GATHER et al., 2008).

The walking city originally refers to the cities before industrialization in 19th century. High density and mixed use are its characteristics. In most cases, a market or a church is located in the centre. A typical walking city lies within a limited spatial scale, i.e. with a diameter of four to five kilometre, so that every person can reach the centre within 30 min. These cities share the similar size in their blooming times, for instance, old Rome had 0.8 Million inhabitants within an area of 12 km² and a radius of 2 km in 13 B.C.. Road networks of these old Roman cities (e.g. Miler) had a grid form due to military reasons. Ancient cities (e.g. Babylon, Alexandria, Peking), and cities of the middle age are all walking cities. Nowadays such walking areas can be found in European and Asian cities, but rarely in the U.S. nor Australian cities (NEWMAN and KENWORTHY, 1996).

Railway has been developed and implemented in cities in western countries since the industrial revolution in the middle of the 19th century. It extends the hinterland of cities and allows the process of urbanization. In this process the core city attracts new work places and inhabitants from surrounding areas. At the same time, areas near railway stations and along railways are developed. The scale of such cities is extended to 20-30 km (NEWMAN and KENWORTHY, 1996) and urban population reaches one million at the first time. Average travel distance increases accordingly compared to walking cities.

The widely used car use trigger a new phase of city development. Since the 1950s the mass motorization and the upgrading of infrastructure such as motorways have pushed individual motorized transport. The hinterland of cities without railway connection becomes accessible with the help of cars. An automobile city can reach a scale of 40-50 km. Compared to walking and transit cities people travel much further in automobile cities. The Athens Charter, published in 1933 by Le Corbusier, describes the spatial separation of functions in order to avoid bad living condition, noise and pollution. Four main functions are living, working, recreation and movement. This notion influences the urban planning after the 1950s. Due to the availability of cars, zoning of functions in cities, and disadvantages of centralization, decentralization is initiated by a process of suburbanization. In this process, the surrounding area is developed with radial PuT lines and major roads being built. Suburbanization is possibly linked with urban sprawl, if the development is not controlled such as in many regions in the USA. Suburbanization can be observed in examples of automobile cities in Figure 10. However, the example from NEWMAN and KENWORTHY (1996) is only a possible scenario of a car-dominated city with low density and widely spread urban areas. Other scenarios can result from different urban planning strategies.

Most cities nowadays display some characteristics of these three types in Figure 10. From the historical point of view, land use and transport supply infrastructure are developed in interaction with each other. The transport supply infrastructure influences accessibility and attractiveness of land uses, and the land use structure determines the distribution and efficiency of the transport supply infrastructure.

Land use

The distribution of land use, i.e. land use pattern, describes how land uses such as houses, workplaces are distributed in an area. The main influence of land use on transport is its function as generator or attractor of trips (RODRIGUE et al., 2006). The land use pattern, together with the accessibility of these land uses, determines possible travel distance to destinations and the corresponding means of transport, especially car use.

In studies of influence on travel behaviour, different terms related to land use and land use variables are applied. The frequently applied terms are built environment, urban form, and urban (spatial) structure. Both urban form and structure emphasize the morphologic configuration of streets and residences in urban spaces. There is no strict difference between these terms in this work. The relevant studies are cited, if a relevant term is approved to influence travel demand in these studies. Land use variables are applied to represent land use characteristics. WEGENER and FÜRST (1999) summarize five land use variables which are most likely to influence travel demand. They are: residential density, job density, size of city, local urban form and location factor. EWING and CERVERO (2010) name also five variables of built environment influencing travel demand, i.e. the five Ds: density, diversity, design, destination accessibility and distance to transit. The influences of some of these variables are introduced in the following, as for instance densities and the diversity. However, microscopic variables such as the local urban form or design are not discussed in this work.

The earliest investigation on the relation between land use and car-trip-based energy consumption is conducted by NEWMAN and KENWORTHY in 1980. They analyse a global sample of 32 cities, and find that energy consumption and residential density have an exponential relationship. As displayed in Figure 11, energy consumption increases with the decrease of residential density, especially for lower dense cities (<30 persons/ha). This research is the most frequently cited evidence of the relationship between urban density and distance travelled by car. They also propose that higher residential density tends to be associated with higher travelled distance by PuT (NEWMAN and KENWORTHY, 1989). Their further study of 58 high-income metropolitan areas in 2001 shows the similar relationship between energy consumption and the variable activity intensity (density of both residences and work places) (NEWMAN and KENWORTHY, 2006).

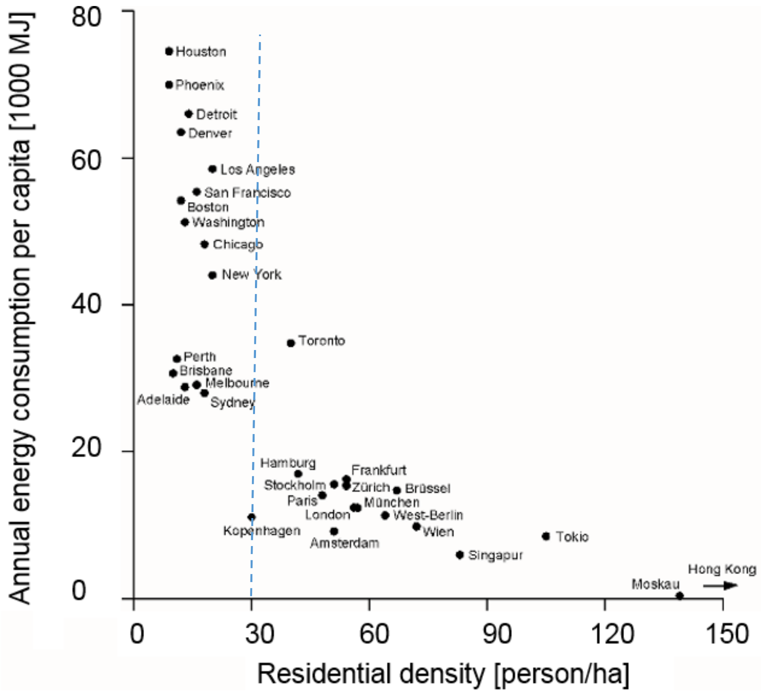


Figure 11: Relation of energy consumption and residential density (NEWMAN and KENWORTHY, 1989).

Diverse studies of impact of land use on travel behaviour use density as a variable and find a quantitative relation between residential density and travel demand. HOLTZCLAW (1994) studies 28 Californian communities and proves that an increase of residential density of 100% will decrease both car ownership and travelled distance by car per household by 25%. The influence of density on car ownership is also demonstrated by CERVERO and MURAKAMI (2010). EWING and CERVERO (2010) apply meta-analysis and find that a 100% increase of density leads to 5% fewer car trips and 5% shorter travelled distance by car. SCHIMEK (1996) applies the data of NPTS in 1990 and come to the similar conclusion that a 10% increase of density results in 0.7% reduction of car trips, all else being equal (BADOE and MILLER, 2000). KIM and BROWNSTONE (2010) apply the data of NPTS in 2001 to a simultaneous equation model and find that if the socio-demographic variables and urban/rural dimension are controlled, the household located in 50% more dense area drive 7% shorter distance per year than in less dense area. The difficulty in increasing the PuT share in the USA is confirmed by LU et al. (2008). They test different scenarios of residential density in an agent-based model and find that even the most aggressive scenarios of high residential density increase the PuT share insignificantly by 8%. This result might be caused by unchanged density of work place and incoordination of PuT lines with changed residential density. Further studies find that walking and cycling to work is strongly related to high-density accommodation (RYLEY, 2006) and higher work place density is associated with lower share of working trips by car (LECK, 2006).

Density itself does not count for the influence on travel demand. Density is a proxy for other characteristics of built environment, rather than a single, all-encompassing variable, seen from CERVERO and MURAKAMI (2010). They find with their model of 370 urbanized areas in the USA that higher residential density reduces distance travelled by car with a direct elasticity of -0.60. However, high residential density associates mostly with high road density, which offsets the high direct elasticity and makes the best net elasticity be -0.38. Furthermore, KIM and BROWNSTONE (2010) suggest a contextual density with consideration of urban and rural dimension. They prove that contextual density is highly correlated with residential density but is a more significant variable. For example the total yearly distance travelled of a household decreases by 35%, if it is moved from rural area to urban area. Although the densities of the rural and the urban area may be comparable, their distance to service locations could differ. Thus, the more it associates with phenomena like infrastructure quality and distance to service locations, the better it can represent land use in research of the influence on travel demand.

Mixture of land uses allows different activities to be completed within a limited spatial area. The distances between origins and destinations in mixed-use areas can be shorter than in single-use areas. Under this condition, travellers theoretically make shorter trips and are more likely to travel with non-motorized modes. EWING and CERVERO (2010) find out that a 10% increase of diversity leads to 0.3% fewer trips and 0.5% shorter distance travelled. The job-housing balance is frequently applied to represent the level of mixture. The study of San Francisco Bay are by CERVERO (1996) leads to the conclusion that an improved job-housing balance leads to a higher share of shorter internal trips and encourages non-motorized modes (DIELEMAN et al., 2002). Together with urban design, mixed-use promotes non-motorized modes (MILLER and SOBERMAN, 2003).

The size of city is another variable which leads to different characteristics of travel demand. The size of a settlement has a high correlation with density, mixed-use and PuT service. For example data from NHPS in 2009 show that both average travel time and distance are shorter in bigger urban areas. The differences of travel time and distance between the smallest and biggest settlements are respectively 6 min and 10 km (U.S. DEPARTMENT OF TRANSPORTATION, 2011). Modal splits of settlements with different sizes in Germany are shown in Figure 12. Big cities with more than 500,000 inhabitants have the highest shares of PuT, walk and bike trips, whereas rural areas/small cities have the highest share of car trips. The same characteristics of travel demand in big cities and towns are confirmed by examples in the Netherlands (DIELEMAN et al., 2002). Besides, residents in metropolitan areas are more likely to form complex trip chains than the residents in non-metropolitan areas (KUPPAM and PENDYALA, 2001).

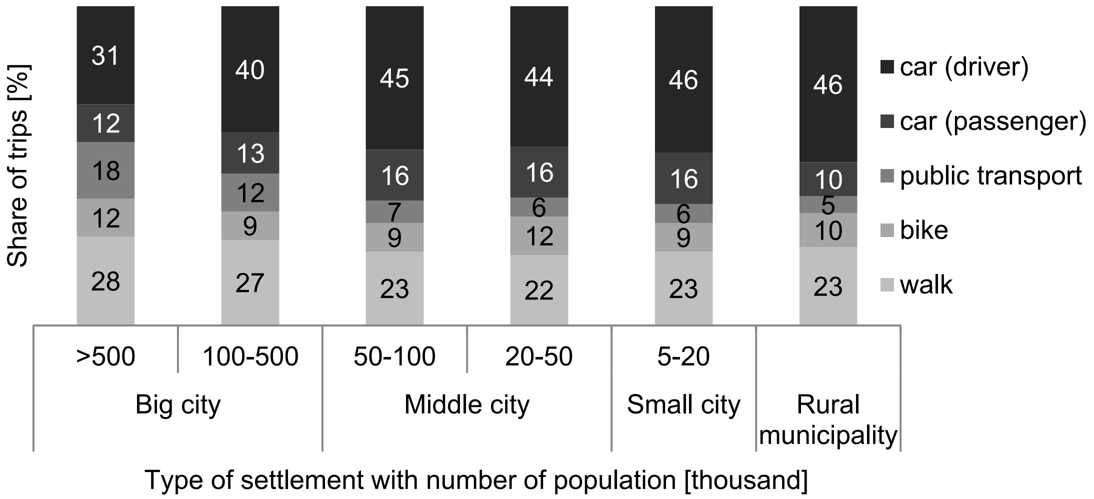


Figure 12: Relation of modal split and settlement size (data from (INFAS and DLR, 2010)).

The importance of the location factor is supported by the evidences from Norway and Denmark (NAESS, 2000). NAESS finds that the distance to the city centre from the residence location has a strong influence on travel distance and car use. This conclusion is based on the presence of an intensive city centre.

The above introduced land use variables are relevant to each other, and the influence of their combination on travel demand is significant. EWING and CERVERO (2010) conclude that the cumulative effects of regional accessibility, density, diversity, and design are large. WEGENER and FÜRST (1999) introduce the evidence from Munich (Germany) that both high density and mixed land use lead to reduced car travel.

Whether a city has monocentric or polycentric structure may also influence travel demand, especially the distance travelled. LE NÉCHET (2012) analyses urban structure and daily mobility in 34 European cities and finds out that energy consumption due to transport in the cities with polycentric configuration is higher than in the cities with monocentric configuration. It supports the study in Dutch cities from SCHWANEN et al. (2001). Besides, DIELEMAN et al. (2002) summarize some studies and figure out that the polycentric urban structure through relocating jobs leads to a shift of PuT trips to car trips. The opposite result is found in German cities that trip distance is longer in monocentric cities such as Munich than polycentric cities such as Stuttgart, however only under the condition that PuT lines in polycentric cities are well-developed (KUTTER and STEIN, 1998). This indicates the importance of the coordination of the transport supply (PuT lines) with the land use structure.

People with different characteristics may prefer to choose their residence place differently. Inconsideration of self-selection bias is a critical point in the research of land use and transport. Self-selection means that a person chooses to reside in an area where they could realize their preferred travel pattern. Travel behaviour of people is not caused by land use characteristics, but because of their preference and readiness. For example, people choose to reside in dense and mixed environment because they are ready to drive less. However, VOS et al. (2012) make surveys and show that more than 50% of respondents do not live in their preferred neighbourhood. Some persons prefer to drive car, but if they live in urban areas, their car usage is possibly constrained by limited urban spaces. On the other hand some persons prefer to take PuT, but if they live in rural areas where PuT services are limited, they tend to drive car. HANDY et al. (2005) find out that built environment still shows significant associations with travel behaviour with the consideration of the importance of self-selection, based on a quasi-longitudinal analysis.

The diversity of empirical studies that investigate the influences of the urban form on travel behaviour are reviewed and tabulated by CURTIS and PERKINS (2006) in detail.

Transport supply

Transport supply is the most direct factor of influence on travel demand. To what extent the necessities of movement can be fulfilled to be travel demand depends on the quality of transport supply. Their relationship is shown in Figure 13 borrowing the representation from economics. The intersection point between the two functions represents the travel demand fulfilled. The travel demand function is price-dependent: the lower the price, the more trips people make. This price stands for time and money spent for a trip. In the case of poor transport supply, represented by a parallel upturned shift of transport supply function, the travel demand fulfilled decreases. However, with a downturned shift of transport supply function, which represents faster speed or cheaper travel, there is more travel demand fulfilled. In contrast a change of travel demand requires also a corresponding change of transport supply with higher or lower costs.

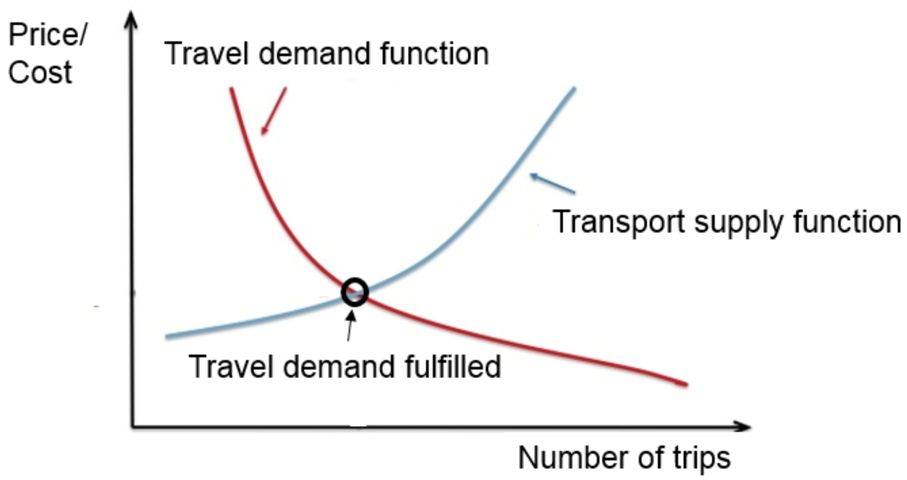


Figure 13: Relation between travel demand and transport supply (KIRCHHOFF, 2002).

According to FRIEDRICH (2013), transport supply includes mainly:

- means of transport,
- characteristics of networks,
- mode-specific facilities and their characteristics, e.g. parking places for car and stops for PuT.

The above aspects of transport supply are discussed in the following. Quality of transport supply is mainly evaluated with the aspects of fastness, availability, reliability, and benignity. Times and costs between origins and destinations are the most important criteria to evaluate the transport supply.

The means of transport of a trip influences the characteristics of this trip. From a historical point of view, the presence of railway and car triggers a dramatic increase in distances travelled. From a spatial point of view, it helps explaining the different characteristics of trips. For example, bikes and E-bikes are widely used respectively in Copenhagen and cities in China; motorcycles are popular in cities in south Asia, while cars are dominant in the USA and other industrial countries. The average distance of trips is directly influenced by different means of transport due to their different speeds. The availability of means of transport offers the choice pool for a trip. In this sense car ownership is a mediating variable of transport supply, as it is related to the availability for car use. There are more alternative transport systems nowadays as for instance sharing systems. These services may change the activity pattern but make no difference in travel demand, however, they may induce a shift of trips from car to other environmentally-friendly means of transport. Due to the competition among all the available means of transport, characteristics of all modes have an impact on the use of other modes.

The basic infrastructure for different means of transport is the network. Road length (or density) and service km of PuT lines are usually used to represent transport supply for car and PuT. From a historical point of view, an increase of the total distance travelled by railway or car can only be reached, if the corresponding networks and facilities, i.e. railway or roads especially motorway, are developed. Figure 14 shows the relation between the annual travel distance by car and PuT and their network length ratio. Network length ratio is defined as 1000 service kilometres of PuT divided by the road length with the unit of kilometre. NEWMAN and KENWORTHY (1996) list the service kilometres of PuT and road length by aggregating 32 countries into the continental level. These values are applied to calculate the network length ratio on the continental level, which is displayed in Figure 14. Assuming road length in all those cities is the same, longer service length of PuT leads to a longer distance travelled by PuT and shorter distance travelled by car such as in Asian cities. However it is notable that the change of distance travelled decreases with the increase of network length ratio. For example, the difference of network length ratio between the USA and European cities is smaller than the difference between European and Asian cities, however, both differences of distance travelled by car and PuT are bigger between the USA and European cities than between European and Asian cities. This trend coordinates with the relationship between density and distance travelled by car, as shown in Figure 11.

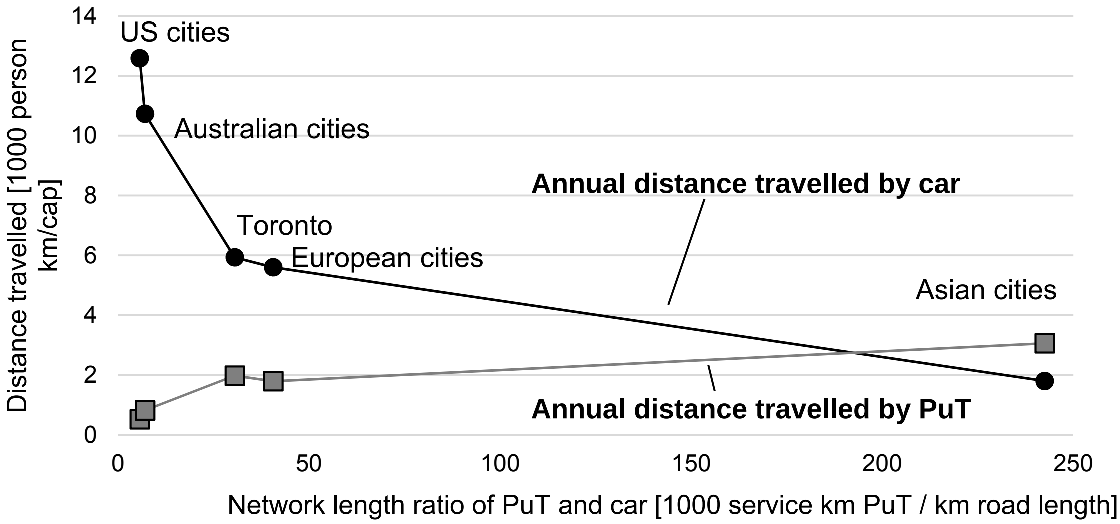


Figure 14: Annual travel distance by car and PuT dependent on network length ratio (data from NEWMAN and KENWORTHY (1996)).

Some studies show an influence of road network structure on travel demand. According to LECK (2006) and KULASH (1990), the traditional grid pattern reduces the total distance travelled by 57% as compared to other road network structures. However LECK (2006) concludes that the grid pattern contributes to a higher probability of commuting by car.

In addition to the characteristics of networks, other variables influencing travel time are:

- speeds of transport systems,
- road capacities and parking facilities for car,
- walking and waiting times for PuT.

FRIEDRICH and RITZ (2014) test a scenario with a goal speed limit of 30 km/h for all urban roads in the city of Stuttgart and find that the total distance travelled by car in the city area decreases by 10%. NAESS (2000) finds that high capacity urban motorways increase the total distance travelled by car in Norway and Denmark. WEGENER (1994) makes changes in both PuT and car speeds, and finds the following results under the specific conditions:

- Travel distance increases from 13 km to 14 km, if both speeds increase by 25%;
- Travel distance decreases from 13 km to 11 km, if PuT speed increases by 25% and car speed decreases by 40%. PuT share increases from 18% to 24%;
- Travel distance decreases from 13 km to only 10 km if both speeds decrease by 40%.

The cost of transport supply also influences travel demand. Increasing energy prices or parking cost should decrease car use while decreasing PuT fares raises the PuT attractiveness and induces more PuT trips. In the study of FRIEDRICH and RITZ (2014), the influences of several costs are investigated. For example a city toll of € 4 per car trip into the inner city results in a decrease of 50% total distance travelled in the inner city area. Besides, reduction of PuT fares by 50% decreases car distance travelled of internal trips in the region by 3%. Due to shifts from car or non-motorized trips to PuT trips the total distance travelled rises. WEGENER (1994) tests a PuT null-tariff scenario and finds that PuT share increases from 18% to 22% and average distance raises from 13 km to 14 km compared to the current scenario. His study also indicates that high parking fees in the inner city and high oil prices cause a reduction of average car distance from 15 km respectively to 13.5 km (16%) and 9.5 km (37%).

Transport supply is not isolated from land use. It provides accessibility to land uses. Its network structure depends on the land use structure. For example, the efficient operation of PuT is based on the certain density of population and the spatial distribution of activities.

2.3 Measures

Among all the factors of influence on travel demand introduced in chapter 2.2, land use structure and transport supply can be influenced by land use and transport planners by means of measures. The most common objective in terms of travel demand is to reduce total distance travelled by car in order to reduce energy consumption and air pollution. Urban land use and transport planning take effect through measures. The above objective is achievable mainly by shortening the average trip length per increasing closeness of activity locations and decrementing car use per raising relative advantages of other means of transport. The measures of land use and transport planning are introduced in the following.

The question whether people drive less if land use policies bring residents closer to destinations and transport policies provide viable alternatives to car trips is raised and answered by HANDY et al. (2005). They provide the positive answer to this question and find that the increased accessibility in new planned areas may lead to a decrease of car use. DIELEMAN et al. (2002) prove that car use is much higher in the new urban expansions on green-field sites, even if these new sites are compact. LECK (2006) reports the results from 1000 Friends of Oregon that an increase of 20,000 jobs within the 20 min car commuting distance will cause a 0.8 km reduction of travel distance by car but 10% more daily car trips; however, an increase of 20,000 jobs within the 30 min transit commuting distance leads to a 1 km reduction of travel distance by car and 10% fewer car trips.

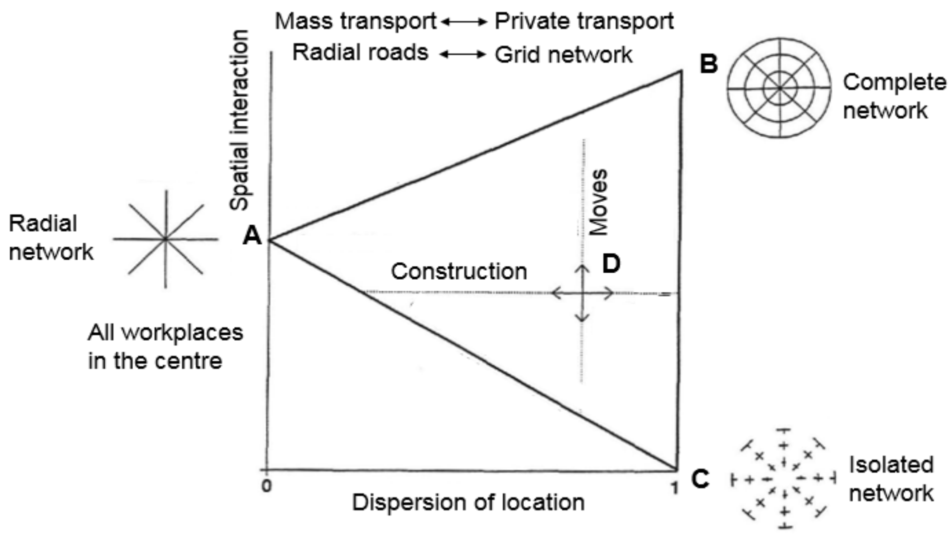


Figure 15: The Brotchie Triangle (BROTCHIE, 1984).

Allocation of work places in the city centre is recommended due to its outcome of a higher PuT share. The theoretic background of this phenomenon is displayed with the “Brotchie Triangle” (see Figure 15), which shows the relationship between spatial interaction and degree of dispersion. Take work places as an example, the horizontal axis represents the spatial dispersal of work places with zero meaning the concentration at the centre and one meaning the random distribution in the city. The vertical axis represents the spatial interaction, i.e. average travel distance of a work trip. Three following extreme situations are represented by three points in the figure:

- A: all the work places are located at the city centre, all the work trips are radial, which is suitable for PuT transit.
- B: all the work places are distributed randomly in the city, and people chose their residence locations without considering the distance to work places due to a complete network. Thus, they travel the maximum distance to work and car is widely used.
- C: all the work places are distributed randomly in the city, and people reside in direct vicinity to their work places, so that they travel minimum to work, i.e. they walk to work. An incomplete / isolated network supports such residence choices.

A real city is represented by point D inside the triangle that is formed by the above three points. A vertical shift is realized by changing the residence location, which is an individual decision based on preference, financial resources, land market and network status. The network status can be influenced by transport planners. A horizontal move means new construction of work places in dispersed places or redevelopment of the city centre, which can be influenced by land use planners. With the given preference of residence of an individual, the land use planner and the transport planner determine how the spatial interaction in a real city changes with the dispersion of location. However, demolition of road network in order to decrease car traffic is barely an option since it deteriorates the quality of mobility.

Measures of land use can only have a significant influence if the corresponding transport infrastructure supports these measures. For example, WEGENER and FÜRST (1999) conclude that land use policies of high-density and mixed-use have little effect if they do not accompany measures of transport supply for slower or more expensive car use.

A compact city form is widely believed to be the most efficient land-use transport system. It is characterized by the intensive land use pattern and a predominant city centre. The compact city model with an extensive use of the public transport system and short distances to work places is recommended (CERVERO and KOCKELMAN, 1997). They suggest to influence the travel patterns of Americans by a combination of more compact, diverse and pedestrian-orientated neighbourhoods. Since high residential density is also associated with high road density, CERVERO and MURAKAMI (2010) recommend that creating compact cities with below-average road network and more infrastructure for non-motorized modes could decrease distance travelled by car. A certain activity density is proposed by NEWMAN and KENWORTHY (2006). They argue that there is a threshold of urban density (residents and jobs): 3,500 per km², above which car dependence is significantly reduced. A strong centre is recommended to achieve less car use. Policies suggested by NAESS (2000) are the increase of proportions of population and work places in the inner and central areas of a city and the reduction or retaining of capacities of road and parking. In the comparison of cities in the USA, NEWMAN and KENWORTHY (1989) support the hypothesis that 120,000 work places in a city centre is the threshold for accessibility by car. Urban regeneration and improvement of PuT service over car infrastructure are needed to keep compact city lively (WEGENER and FÜRST, 1999).

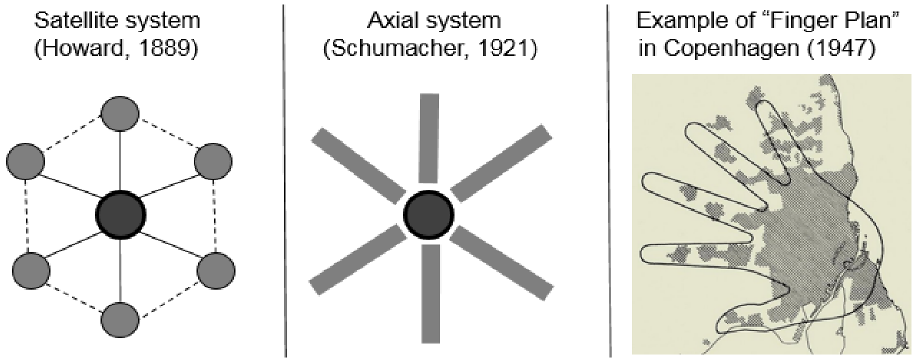


Figure 16: TOD: two land use systems and an example.

Another established successful land-use transport strategy is transit oriented development (TOD), i.e. new development happens along transit lines. It is a sustainable solution if a compact city is beyond a certain size and no longer efficient. The main features of TOD are the high density along transport corridors and city growth boundaries (BERTAUD, 2002). A growth boundary helps avoid low-density development. Figure 16 shows two TOD systems in satellite and axial forms, and an example of TOD. A satellite system, i.e. garden city model from HOWARD (1902), has a balanced spatial structure with a strong centre and centralized decentralization in the form of six sub-centres. These centres are connected by railway lines. Facilities such as PuT stops and work places are located within walking distance from residence areas. In case of continuous growth of sub-centres in a satellite system due to additional population, an axial system is formed. It is proposed by FRITZ SCHUMACHER for Hamburg and Cologne (WEGENER and FÜRST, 1999). In spite of the strong centre with high-order work places and facilities, mixed-used development runs along the railway axes in this system. Examples of TOD are Portland (USA), Curitiba (Brazil), Copenhagen (Denmark).

Dispersed development is not preferred as it represents low density expansion and provokes car use, although this form emphasizes citizen-orientation and freedom. For an already dispersed automobile city, NEWMAN and KENWORTHY (2006) raise a conceptual modification plan in Sydney by creating a strong centre and reconstructing the city into a series of cities that are linked by a fast PuT service. However, an unsuccessful example of the TOD measure in Atlanta (USA) is introduced by BERTAUD (2002). After investing PuT systems in order to implement TOD approx. 80% of new population and work places are located out of the area with PuT access. He argues that TOD is not a feasible strategy for a polycentric low-density city. Thus, the example of Atlanta shows that the prevention from dispersed development is more effective than the investment into the PuT system. Similarly, WEGENER and FÜRST (1999) conclude that preventing development of facilities with poor accessibility is more effective than promoting high-density, mixed-use pattern.

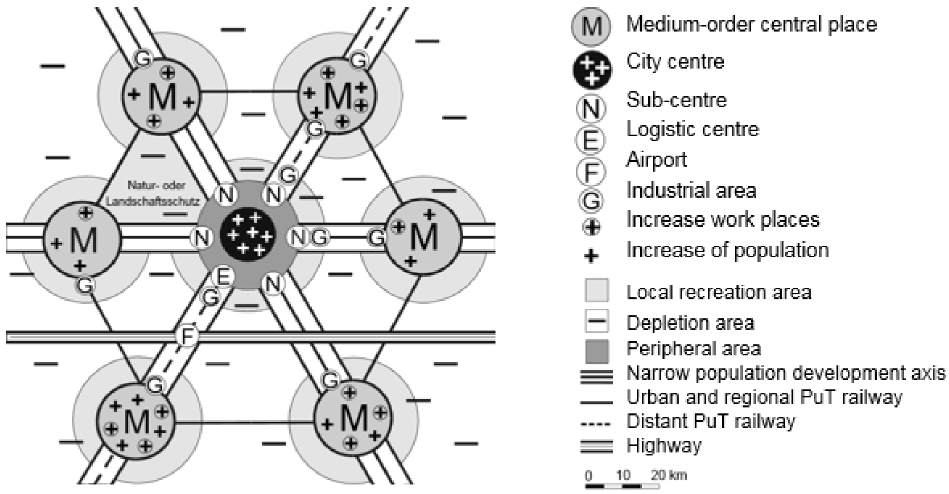


Figure 17: An urban form with light car traffic (SIEBER, 2000).

A concept of an urban form with light car traffic is raised by SIEBER (2000). This concept is based on the assumption that decentralized centralization can work against the dispersed development. Figure 17 illustrates this concept. A central city with a strong city centre and sub-centres is located in the middle. A series of medium-order central places are distributed around the central city at a distance of 30-80 km. These areas with central place function are mixed-used and offer a number of facilities and work places. New developments of work places and residences should be located in these medium-order central places. Narrow population development axes and the broad depletion areas ensure a boundary of development in the agglomeration area. This concept with light car traffic cannot be realized without a good PuT system. All the central city and medium-order central places are connected with PuT lines, including connections in tangential directions between medium-order central places. Transport infrastructure facilities like motorways and airports are also considered in this concept.

Several measures of transport planning can influence travel demand directly such as the adjustment of costs or the implementation of speed limits. For example, WEGENER (1994) concludes that the taxation of cars and the improvement of PuT service result in a significant reduction of car travel distance without any changes of land use, based on a model in Dortmund (Germany). Another example is Singapore that has introduced simultaneously economic restrictions on car ownership and car use (including parking), and improvements of both public transit and walking environments. However, both cities in the above examples already have a relatively dense and mixed land use pattern.

Measure influences… Measure (…-term)			Destination choice	Mode choice	Route choice	Traffic flow	Person km (car)
Measure of infrastructure	Extension of road network	long	x	x	x	x	x
	Improvement of PuT e.g. extension of rail network	long	x	x	x	x	x
Regulative measure	Tempo 30 (car)	medium	x	x	x	x	x
	No truck in inner city in daytime	medium	x	x	x	x	x
Monetary measure	Road pricing	medium	x	x	x	x	x
	Parking pricing	medium	x	x			
	PuT tariff	medium	x	x			x
Technical measure	Signal steerage	medium				x	
	Traffic guidance system (e.g. for parking)	short			x	x	
Mobility service	Car-, ride-sharing	medium		x			
	Networked mobility	medium		x			

Table 1: Measures of transport supply (FRIEDRICH, 2013; FRIEDRICH and RITZ, 2014).

Table 1 summarizes exemplary measures in transport planning and their qualitative impacts, based on FRIEDRICH (2013) and FRIEDRICH and RITZ (2014). Five categories of measures are listed. The measurable significance of a measure depends on the magnitude of this measure and its effective spatial area. Measures of infrastructure and regulative measures directly influence the travel time of different modes from A to B, thus, they have an impact on time-related choices, traffic flow and travel demand. The price has an impact on destination and mode choices. The sensitivity of travel demand to monetary measures depends on the income level of individuals and the degree to which prices change. Technical measures mainly improve traffic flows but their influence on travel demand is insignificant. Mobility services help organize movements in a more efficient way. For example electronic cars in car sharing systems help reduce energy consumption; and networked mobility integrates different services for the more efficient mobility. However, these mobility services do not have a significant influence on travel demand till now and they need to be supported by measures which restraint car use (WEIGELE, 2014).

Some measures are intended to solve a certain problem, however, they might lead to the opposite outcome. For example, the improvement of network capacity is intended to solve the congestion problem. But it induces more car traffic in the network as people like to take advantage of these improvements. Thus, improvement of network capacity is not a suitable measure, especially from the standpoint of energy consumption and air quality (MOKHTARIAN and CHEN, 2004).

Measures of transport supply also depend on land use measures for a long-term development, especially the measures of planning new PuT line routes and stops. For example, MILLER and SOBERMAN (2003) state that transit use is determined by both high-quality transit service and a transit-supportive land use policy. They argue that the difference of transit use between Great Toronto Area and Boston or Melbourne is caused by the coordinated land use-transportation policies in 1950s-1970s in Great Toronto Area, which lead to higher density in suburban areas. WEGENER and FÜRST (1999) argue that the measure of improving PuT cannot lead to a strong reduction of car trips. It should be combined with other measures.

In spite of the concept of an urban form with light car traffic from SIEBER (2000) and a number of measures of both land use planning and transport planning, there is no single measure which is feasible for all cities. In general, transport supply measures are more direct and efficient, but land use measures are vital in the long-term of sustainable city development (WEGENER and FÜRST, 1999).

2.4 Modelling

Travel demand models replicate decision-making processes of movements from travellers. Virtual city models in literature as yet are computer generated 3D geometric models with sufficient detail and accuracy as to portray both terrain and urban structures of a city (MORTON et al.). However there are hardly virtual city models in terms of travel demand research, whereas most virtual city models are applied for architecture, landscape planning and computer science. Virtual city model (VCM) in this work has a different definition and different application field compared to virtual city models in literature as yet. The VCM in this work is a framework of a macroscopic travel demand model with user-defined land use structure and network form. It is dedicated for travel demand research. The modelling basics are introduced in the following as a preparation to modelling the VCM.

2.4.1 Aggregation of modelling

VCM is a macroscopic travel demand model. Macroscopic models aggregate objects in the real world. The most important characteristics are replicated in the following ways:

- Describing spatial characteristics by traffic analysis zones (TAZ; short: zone);
- Representing the transport supply with a network model.
- Aggregating inhabitants to behaviourally homogenous person groups;

- Classifying all trip purposes into categories of activities;
- Simulating land use structure by means of number of inhabitants per person group and number of activity locations per activity in each zone.

Spatial segmentation

Land is divided into a set of zones (FRIEDRICH, 2016). Zones are the units for origins and destinations of trips in a travel demand model. Zoning describes how a study area is divided by zones, which represent blocks and buildings of a city. All the properties such as buildings of each zone are assumed to be concentrated on one point: the zone centroid. Characteristics such as architecture of buildings are of no relevance, whereas opening direction of buildings influences the accessibility to the network or characteristics of intra-zonal trips. Zone centroids are connected to networks by connectors. The nodes of connector on networks are the access and egress nodes for destination and origin trips of a zone.

A key parameter of a travel demand model is the number of zones. This parameter influences the size of zones in a given study area, thus, it plays an important role in the exactness of modelling results. The level of detail of zoning is a compromise between accuracy and cost (ORTÚZAR and WILLUMSEN, 2011). Larger zones are less demanding in terms of data provision and computation time, but they lead to less accurate indicators such as travel time and travel demand (FRIEDRICH, 2011). Smaller zones are desirable, but require a higher computational effort. However, the size of zones should match the corresponding research purposes. For example strategic studies require larger zones than studies for transport management (ORTÚZAR and WILLUMSEN, 2011). They propose that the following aspects should be considered in the process of zoning:

- The size of zones within the same model can differ, e.g. smaller zones for congested areas and larger zones for uncongested areas.
- The size of zones has a threshold value. It should ensure that the error caused by the assumption that zone centroids represent all properties of zones is insignificant.
- The shape of zones should be compatible with the administrative boundaries.
- The zones should be homogeneous in terms of land use and socio-economic characteristics of inhabitants.
- External zones can be built to represent “the rest of zones” in different directions.

The typical applications model 500-2000 zones and the large or detailed applications include up to 10.000 zones (FRIEDRICH, 2016). ORTÚZAR and WILLUMSEN (2011) give some examples of number of zones in a wide range of studies, such as 2200 zones for Washington DC (2008) with 6.5 million inhabitants; 2700 zones for Sydney (2006) with 3.6 million inhabitants, and 560 zones for Leeds UK (2009) with 0.7 million inhabitants.

Representation of transport supply

Transport supply is represented in a network model. The network model offers necessary information about network geometry and the evaluation of network elements with characteristics of impedance (WERMUTH, 2005). Similar to zoning, the network model can be built on different levels of detail and a higher degree of completeness of road network leads to a better representation of reality. ORTÚZAR and WILLUMSEN (2011) argue that a key parameter of a network model is the number of included road hierarchies in the model. Table 2 lists the various network objects and their attributes in a network model with current state of the aggregation level. The level of detail of a network model is determined for different applications. For example, capacity of links and waiting time at turns should be contained in a network model for an urban area (FRIEDRICH, 2016).

	Object in model	Object in reality	Selected attributes in model
Road network	Node	Intersection	Coordinates, height
	Turn	Movement at intersection	Waiting time
	Link	Road	Length, allowed speed, capacity
PuT network	Stop	Stop	Transfer walking time, allowed PuT system
	Links as carrier	Rail or road for PuT lines	Allowed PuT system
	PuT line routes based on carrier	PuT lines	Length, timetable or headway, connected stops

Table 2: Composition of a network model.

Person groups and activities

In a macroscopic model inhabitants are modelled not as individuals but as person groups, which are clustered based on homogeneous behavioural characteristics. Person groups are required to replicate specific obligations and preferences influencing travel behaviour. Person-related factors that influence travel demand (see chapter 2.2.1) are applied to characterize person groups. SCHMIEDEL (1984) implements a cluster analysis of homogeneous behavioural person groups in his dissertation based on behavioural data of Germany in 1976. He finds out that the generated trips from the division of the following seven person groups can reach the equivalent characteristics as trips in reality. These person groups are:

- employee with car,
- male employee without car,
- female employee without car,
- student,
- pupil / apprentice,
- unemployed (including housewife, househusband and retiree) with car,
- and unemployed (including housewife, househusband and retiree) without car.

Similar to person groups, the modelled activities are also an abstraction of diverse daily activities. These activities represent trip purposes. Typical trip purposes are for example working, education, shopping, private business, leisure and back home. Number of activity places represents capacity of possible activity locations as trip destinations. For example, the number of shopping places represents the potential attracted customers rather than the number of shops; and a school with a 100-study-place capacity can attract max. 100 pupils for their education trips.

Traveller and activity (also trip purpose) determine together the characteristics of movements (e.g. origin, destination, mode) in person transport. Thus travel demand is segmented into different classes with respect to person groups and trip purposes (FRIEDRICH, 2016). For example, the willingness to spend time for an activity and the influence of costs on choices are the same for each travel demand class.

The aggregation level of person groups and activities has a significant influence on the quality of a model. Detailed classified person groups and their corresponding activities ensure a high-quality replication of individuals with dispersed travel behaviour. The aggregation level of both activities and person groups should match with each other. For example, if workers are classified into several person groups such as part-time employee and freelance, appropriate types of work places should also be distinguished as corresponding trip purposes for these person groups.

2.4.2 Modelling network

Transport systems

Transport supply is composed of various transport systems. In terms of person transport, transport systems are means of transport with which movements are conducted. They are differentiated into private and public systems:

- Private systems: walk, bike, car, motorcycle, taxis;
- Public systems:
  - Rail-based systems: heavy rail (rail rapid transit), light rail, tramway (streetcar), cable car, as listed in Table 3;
  - Road-based systems: bus, bus rapid transit, trolleybus.

Transport systems require different infrastructures and financial investments. The differences between transport systems are characterized in a network model mainly by their speeds and costs. Additional characteristics for publicly operated systems are capacities and service frequencies. Characteristics of the same PuT transport system around the world might also be different. For example average stop intervals of the metro in Tokyo is 950 m and in Paris is 510 m; whereas the speed of the metro in Berlin is 24 km/h and in Stockholm is 33 km/h (LEIBBRAND, 1980).

Rail-based transport system	**Characteristics (Functions)**		**Examples**
Heavy rail (S-Bahn)	Mass transit systems, High passenger volumes, High performance	Connecting suburban areas with central areas	Stuttgart, Munich
Metro (U-Bahn)		Connecting conurbations with central areas	Berlin, Hamburg
Light rail (Stadtbahn)	Short headways	Connecting surrounding areas with central districts	Stuttgart, Frankfurt
Tramway (Straßenbahn)			Bonn, Cologne

Table 3: Urban rail-based transport systems in Germany (VERBAND DEUTSCHER VERKEHRSUNTERNEHMEN, 1997).

Transport supply is connected with travel demand by modes. One mode can consist of more than one systems, such as the mode PuT can include different systems, as listed above; one mode can also consist of both public and private transport system, such as park & ride, in complex models. Which transport systems and modes are modelled in a network model depends on both the existence of these transport systems and modes in the modelling area and also on the supposed level of detail required for applications. For example, distinguishing car and PuT is mainly sufficient for applications on national or regional levels; whereas in urban models in addition to car and PuT, walk and bike are also considered.

Hierarchy of road and rail

Road and rail hierarchies are the basis for the network design. The RIN (2008) distinguishes several categories of road and rail considering both connection hierarchies and category groups. Those categories for car, PuT, bike and walk are listed in Table 4.

The connection hierarchy of a road or a rail results from the hierarchies of the places which are connected by the road or the rail. The RIN (2008) distinguishes six categories of central place function and accordingly six connection hierarchies: continental, long-distance, medium-distance, regional, local, and vicinity connections. Category groups are characterized based on surrounding areas (inside or outside build-up areas) and type of the road (for car) or characteristics of the rail (for PuT). Not all the combinations of a connection hierarchy and a category group are reasonable, e.g. there is no rural road on continental level. In a network model these categories are defined by link types.

Which categories in Table 4 and the according link types should be included in a network model depends on the spatial scale of this model and the supposed level of detail required for research purposes. For example, a macroscopic urban transport model should exclude continental and vicinity connections.

Criteria & Category group					Continental 0	Long-distance I	Medium-distance II	Regional III	Local IV	Vicinity V
car	motorway			AS	AS 0	AS I	AS II	-	-	-
car	rural road			LS	-	LS I	LS II	LS III	LS IV	LS V
car	arterial road	without buildings		VS	-	-	VS II	VS III	-	-
car	arterial road	with buildings		HS	-	-	-	HS III	HS IV	-
car	collector road			ES	-	-	-	-	ES IV	ES V
PuT	long-distance			FB	FB 0	FB I	-	-	-	-
PuT	Short-distance	independent track	open area	NB	-	NB I	NB II	NB III	-	-
PuT	Short-distance	independent track	built-up area	UB	-	-	UB II	UB III	-	-
PuT	Short-distance	special track	built-up area	SB	-	-	SB II	SB III	SB IV	SB V
PuT	Short-distance	track in roads	built-up area	TB	-	-	TB II	TB III	TB IV	TB V
PuT	Short-distance	track in roads	open area	RB	-	-	RB II	RB III	RB IV	RB V
bike	outside built-up area			AR	-	-	AR II	AR III	AR IV	-
bike	inside built-up area			IR	-	-	IR II	IR III	IR IV	IR V
walk	outside built-up area			AF	-	-	-	-	AF IV	AF V
walk	inside built-up area			IF	-	-	-	-	IF IV	IF V

-: inappropriate

Table 4: Road and PuT categories (FORSCHUNGSGESELLSCHAFT FÜR STAßEN- UND VERKEHRSWESEN, 2008).

Road network configuration

Urban expressways, i.e. motorways or arterial roads, are on the top of road hierarchy for a city. These roads offer fast connections for through traffic, for a city to connect to other central places, or for internal trips within the city. Three ways how urban expressways are connected to a city are summarized by FEUCHTINGER (1956) and VOGT (2005), as shown in Figure 18. Characteristics and an example of each way are listed in the following:

- External bypass avoids the occupation of urban land use for expressways and negative impacts of traffics such as noises in the city (e.g. Berlin).
- Internal bypass increases traffic volumes in the city, but offers the better accessibility for inhabitants in the city (e.g. Stockholm).
- Central solution causes stark traffic volumes and is only suitable for a small-scale city with a strong centre or the topographic limit (e.g. Helsinki).

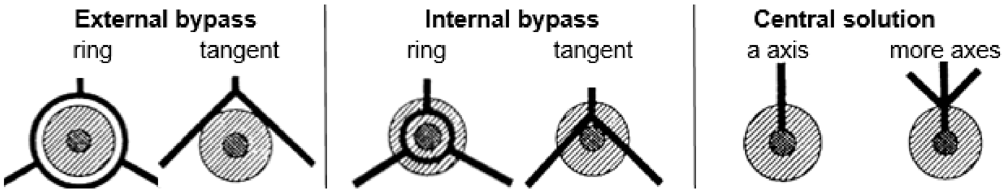


Figure 18: Relative location of expressway bypass referring to a city (VOGT, 2005).

The main road network in a city can also be differentiated into several forms. These forms depend largely on land use structures and their corresponding connection functions. LEIBBRAND (1980) introduces the following four basic network forms:

- Chessboard: also grid form; no central point; crossroads with similar spacing; example: Milet 450 B.C..
- Star: also radial form; a natural form; radiance of roads from a centre; being unsuitable for big cities, but suitable for cities with radial PuT lines; example: Karlsruhe.
- Ring road: a complement of radial form for cross linkage.
- Tangent: a complement of radial form to disperse congested radial traffic volumes by creating more intersections; tangent possibilities of triangle, hexagon, or more.

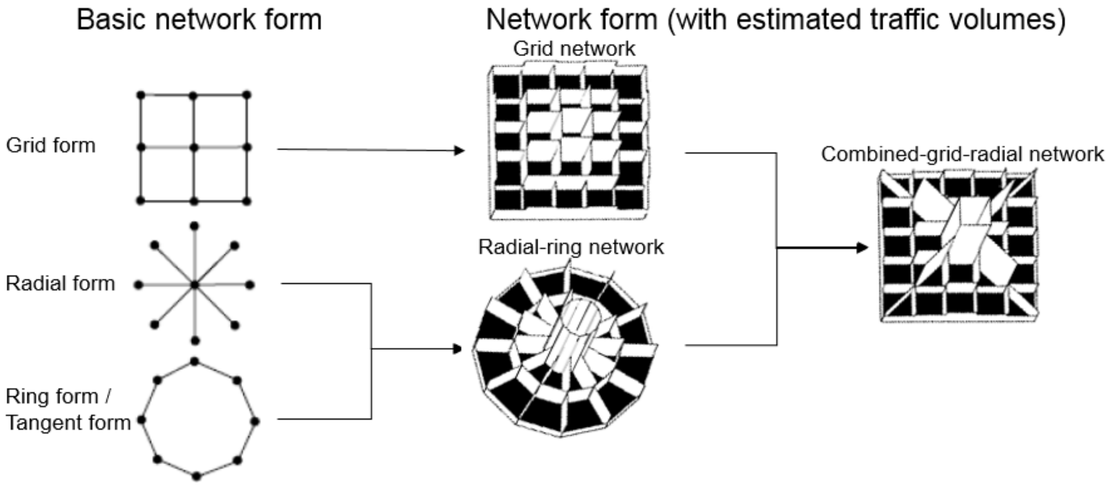


Figure 19: Road network forms (VOGT, 2005).

These basic forms can be combined to generate different network forms. Figure 19 shows three network forms and estimated traffic volumes, which are based on a study by FISHER and BOUKIDIS (1963) and VOGT (2005). Since a relatively strong centre is assumed in these three network forms, the highest concentration lies in the central area of the city for all these three network forms. These three network forms are:

- The grid network is based on grid roads. The grid network avoids traffic concentration to the largest degree (VOGT, 2005). An example is Phoenix (USA).
- The radial-ring network is a combination of radial and ring roads. The network in Munich (Germany) applies this form.

- The combined-grid-radial network is a combination of grid network and radial-ring network. It applies radial roads and the road capacity of ring roads from the radial-ring network, but keeps the basic grid form.

The further five types of network form in residential area, their advantages and disadvantages are introduced in FORSCHUNGSGESELLSCHAFT FÜR STAßEN- UND VERKEHRSWESEN (1995). The road network in a real city is influenced by topography, historical development and land use planning. The development of PrT and PuT network is the central part of the planning (LEIBBRAND, 1980).The above introduced external and internal expressway bypasses, the combined-grid-radial network form are all considered in the development of VCM.

PuT network configuration

Different from representing PrT network by road network as a carrier for PrT systems, the PuT network is represented by PuT lines rather than the carrier (i.e. rail and road) of PuT systems. PuT network configuration is described by the form of all PuT lines in a city. Combining both summarises from BONZ et al. (2005) and LEIBBRAND (1980), the basic forms of PuT lines are listed as follows and shown in Figure 20:

- Radius line (also radial line): association of star form of road network; intensive travel demand from and to the central area; possible requirement of turnaround facilities.
- Diameter line: an extension of radius lines; both starting and terminating stops outside central area; being applied in big cities; example: Zurich.
- Tangent line: not through central area; a complement of radial or diameter lines serving for activities which are not located in the central area.
- Ring line: an extension of tangent line; commonly interrupted due to the problem of reliable operating procedure; example: Rome, Vienna.

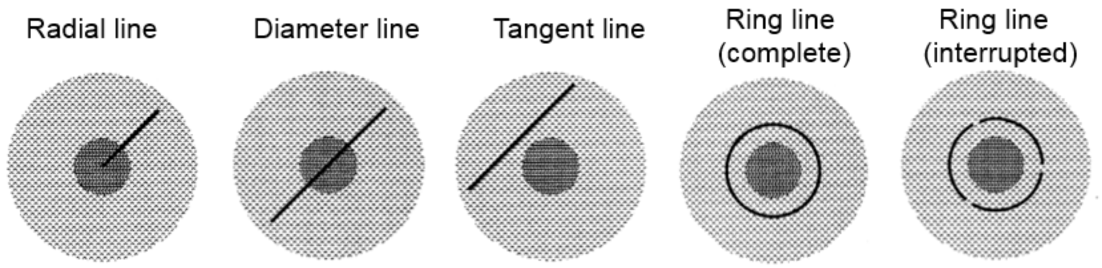


Figure 20: Basic forms of PuT lines (BONZ et al., 2005).

In most cases more than one form of PuT lines are applied in a city. For a monocentric city, radial and diameter lines are commonly applied; whereas for a polycentric city, tangent or ring lines aside from radial or diameter lines are used to connect different centres. For example, a heavy rail system with the diameter form is complemented with a light rail system with the ring form in Karlsruhe (KIRCHHOFF, 2002). Furthermore, in order to avoid possible accidents from diameter lines at the same central point, different points (e.g. in a form of triangle) in the central area are created for different diameter lines and these points are integrated and connected (KIRCHHOFF, 2002). Design of these PuT lines should not follow geometric form but rather follow function of connection. For example, PuT lines should be able to connect areas with central place function. Concerning designing PuT lines, LEIBBRAND (1980) suggests that fewer but oftener-driven lines are better than more but fewer-driven lines, given the same urban space. He also supposes that bus should not go parallel to a rail.

Skim values

Skim values describe the quality of transport supply for a network on the level of od-pairs. They are calculated based on the results of route choices in an empty network or a network with estimated trip tables (FRIEDRICH, 2016). Skim values are stored in skim matrices and are applied to evaluate alternatives of choices in a travel demand model. According to categories of characteristics of a network, skim values are differentiated into the following three types:

- Distance-related skim values represent spatial characteristics of od-pairs. The most commonly applied distance-related skims are direct distance, in-vehicle distance and travel distance (for different modes).
- Time-related skim values represent temporal characteristics of od-pairs. Travel time includes different skims for different modes. For example, car travel time is made up of access time, in-vehicle time, and egress time; whereas PuT travel time includes also (transfer) waiting time.
- Cost-related skim values represent monetary characteristics of od-pairs. Prices of travel, for instance parking cost for car and tickets for PuT, are represented by cost-related skims.

Skims are categorized into inter-zonal and intra-zonal skims according to the characteristics of od-pairs: whether trip origins and destinations are located in the same zone. Most of inter-zonal skim values are calculated based on the network model, whereas modellers define intra-zonal skim values mostly.

Skim values are applied to evaluate the transport supply by frequency distribution of skim values for a specific od-pair type. They can also be applied to represent characteristics of travel demand, if the skim values are weighted with number of trips per od-pairs. For example, the arithmetic mean of skim values weighted with the demand represent an average level of the aggregated trips. The skim values for evaluations of transport supply and travel demand are crucial for the processes of calibration and validation of VCM in chapter 4.

2.4.3 Modelling land use

The land use structure is quantified in a travel demand model by the number of inhabitants per person group and the number of activity places (e.g. work places, school places) per activity on the level of zones. In a model of a real city, data of residence distribution can be investigated through surveys of socio-demographic and socio-economic features of inhabitants; and data of activity places are extracted from administrative statistic information of land uses. In a VCM, the central place theory and land use models are contributed to transferring land use structure from a real city.

Central place theory explains the spatial distributions of facilities, work places and services by different levels of central place function. It is a theory in land use planning, but has a linkage to transport planning, as these land uses are activity locations which can be trip origins or destinations. CHRISTALLER (1933) discovers that the arrangement of settlements follows a certain spatial hierarchy and areas can be categorized into metropolitan region (MR), high-order central place (OZ), medium-order central place (MZ), low-order central place (GZ), community without central place (G). Areas with higher central place function have a wider influencing threshold, but the number of these areas is fewer than of areas with lower central place. Based on different principles (marketing, transport, administrative principles) different distribution forms of central places are generated (CHRISTALLER, 1933). Some of the above aspects of the central place theory can be applied to generate land use structure in VCM.

Land use models are abstractions of land use structures in real cities. They can be considered for the design of land use structure of a VCM. The development of land use models goes along the process of city development and the process of the improvement to replicate real cities. These models are summarized by RODRIGUE et al. (2006) and are shown in a temporal sequence in Figure 21. The burgess concentric model (1925) assumes that CBD is located in the city centre and all the homogenous socio-economic land uses are distributed following a concentric pattern. It is a typical monocentric model and is directly applied from Von Thunen Model of agricultural land use in Germany. In the sector model (1939) the urban development is located along transport axes (rail lines or major roads), and the nuclei model (1945) replicates the reality that a city does not grow around one single CBD. These two models represent new developments in a city due to the development of the motorization levels, such as growth of city size and presence of new axes or new centres. The further development of the nuclei model is a typical polycentric model. Hybrid models combine the above three models, as shown in an exemplary model from Isard (1956) in Figure 21. This hybrid model includes concentric effects of multi-centres in a city, development along axes, radial transport axes, a ring road around the inner city. Some aspects from these land use models are considered in developing a VCM.

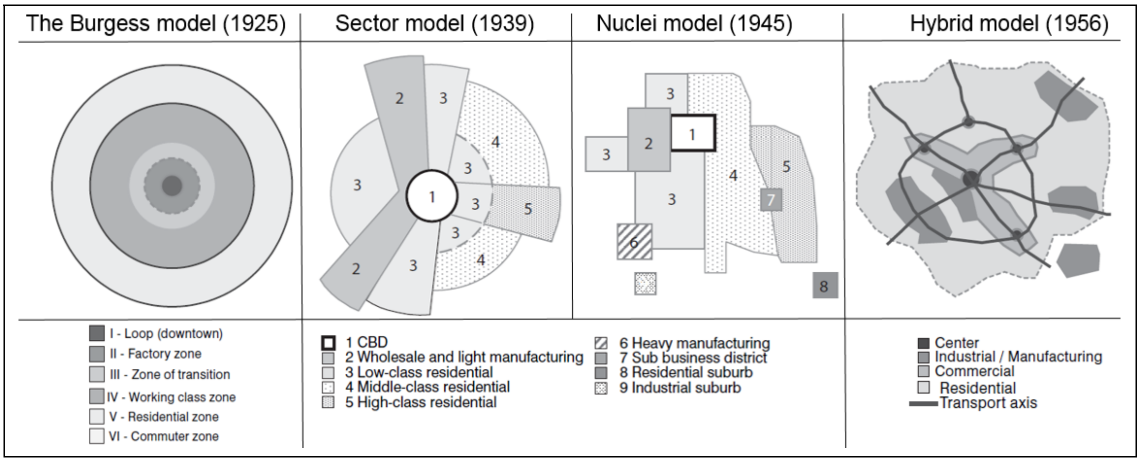


Figure 21: Urban land use models (RODRIGUE et al., 2006).

2.4.4 Modelling travel demand

Travellers perform a series of activities in a day from leaving home until returning home. The tour of these performed activities follows a sequence of activities, i.e. activity chain, as for instance home-working-shopping-home. Trip chains are derived from activity chains by assigning each activity a location in the destination choice model. Trip chains are modelled with different methods. Three distinguished methods are:

- Trip-based travel demand models take single trips (movements between two zones) as the modelling object without considering the sequence of activities of a day. Two types of trips can be distinguished: home-based trips and non-home-based trips.
- Tour-based travel demand models replicate the activity chains. Tour-based models are closer to reality than trip-based models, as they replicate the daily routine based on activity sequences rather than single trips. Thus, the tour-based model is an advanced disaggregated model compared to the traditional trip-based models (FELLENDORF et al., 1997). VCM is a tour-based travel demand model.
- Activity-based travel demand models focus on activities, e.g. activity sequence and the duration of activities. They are extensions of tour-based travel demand models (FRIEDRICH, 2016).

Four decisions of travellers are included in classical travel demand models. These four decisions are replicated by the corresponding four sub-models:

- Trip generation models
- Destination choice models
- Mode choice models
- Route choice models.

These four sub-models are discussed in the following. Their input data, their resulting output data and their basic formations are listed in Table 5. The parameters and variables in each sub-model are summarized in details by FRIEDRICH (2011).

Step	Input data	Resulting output	Exemplary equation (using Logit-Model)
Trip generation	• Land use data (χ) • Behavioural data (μ, η)	Trip q of group g produced (p) at origin zone o	$q_{go}^{p} = \sum_{k=1}^{K} \mu_{gk} \cdot x_{ko}$
		Trips q of group g attracted (a) at destination zone d	$q_{gd}^{a} = \sum_{k=1}^{K} \eta_{gk} \cdot x_{kd}$
Destination choice	• Land use data • Behavioural data (α) • Transport supply quality (skim values) (c)	Trips q of group g from origin zone o to destination zone d	$q_{god} = q_{go}^{p} \frac{q_{gd}^{a} \cdot exp\left(\alpha_g \cdot c_{od}\right)}{\sum_{d=1}^{D} q_{gd}^{a} \cdot exp\left(\alpha_g \cdot c_{od}\right)}$
Mode choice	• Behavioural data (β) • Transport supply quality (skim values) (c)	Trips q of group g from origin zone o to destination zone d using the mode m	$q_{godm} = q_{god} \cdot \frac{exp\left(\beta_{0,g} + \beta_{1,g} \cdot c_{odm}\right)}{\sum_{m=1}^{M} exp\left(\beta_{0,g} + \beta_{1,g} \cdot c_{odm}\right)}$
Route choice	• Behavioural data (δ) • Transport supply data (c)	Trips q of group g from origin zone o to destination zone d using mode m on route r	$q_{godmr} = q_{godm} \cdot \frac{exp\left(\delta_g \cdot c_{odmr}\right)}{\sum_{r=1}^{R} exp\left(\delta_g \cdot c_{odmr}\right)}$

g: demand groups (travel demand classes in respect to person groups and trip purposes)
c: costs of alternative between origin o and destination d

Table 5: Four-step travel demand model (FRIEDRICH, 2011).

The first sub-model is the trip generation model. The objective of this sub-model is to determine the number of trips generated and attracted in a zone within a specific time period such as a work day (WERMUTH, 2005). Land use data, i.e. number of inhabitants per person group and the number of activity places per activity, are the inputs for trip generation models and the variables in equations of trip generation models. Behavioural data are also the inputs serving as parameters in the equations describing the frequencies of activities. For tour-based travel demand models, behavioural data contain both observed trip chains and their frequencies. A critic is that the influence of changes in the quality of transport supply on the number of trips cannot be modelled, as trip generation model does not consider the transport supply (MOKHTARIAN and CHEN, 2004).

The rest three sub-models belong to decision models in which one of a set of alternatives should be selected based on the characteristics of alternatives and characteristics of travellers. In macroscopic models, an alternative is selected with a certain probability for each demand group. The probabilities of alternatives are modelled by decision functions. The Logit-Model determines the share of an alternative based on the differences in utility values (FRIEDRICH, 2010). The random utility theory assumes that individual chooses the alternative with the highest utility value. This theory is suitable for decision modelling (FRIEDRICH, 2013). Utilities are quantified by means of both the deterministic and stochastic utility values. The variable c_j in the equation 2.1 is the deterministic utility value representing the costs of alternatives for each demand group. From a wide range of distributions for the stochastic utility value the Gumbel-distribution is suitable to apply. The Logit-Model is applied for this distribution as decision functions for evaluation of probability, and it is the basic model concept for the following three sub-models. The basic from of the Logit-Model is shown in equation 2.1.

$$P_j = \frac{\exp(\alpha \cdot c_j)}{\sum_{n=1}^{N}(\exp(\alpha \cdot c_j))} \tag{2.1}$$

with	P_j	Probability of the alternative j
	c_j	Cost/utility of the alternative j
	α	Parameter that determinates the sensitivity of the cost of j
	N	Number of alternatives

The second sub-model is the destination choice model. The result of this sub-model is a trip table showing the number of trips between each origin and destination. Destination choice depends on characteristics of both origin and destination, and the evaluation of each alternative with a Logit-Model. Destination choices for some activities (e.g. shopping) apply single constraint models, which fulfil the condition that all trips generated from a zone are all assigned to a destination zone. However, for some activities whose number of destination places plays an important role (e.g. working), doubly constraint models are applied. The doubly constraint model indicates that the number of trips attracted by a zone should not exceed the activity places of this zone (FRIEDRICH, 2013).

The third sub-model is the mode choice model. This sub-model assigns the distributed trips to different modes. According to whether mode choice and destination choice are modelled simultaneously, sequential and simultaneous mode choice models are distinguished. For example, simultaneous destination choice and mode choice models ensure an individual without car choose only destinations that are reachable by other modes (FRIEDRICH, 2016). A good mode choice model should include the characteristics of travellers (e.g. car ownership), characteristics of the journey (e.g. trip purpose) and characteristics of the transport supply (e.g. travel time and cost). According to possibilities of choice three types of travellers can be distinguished: choice rider, captive rider, and captive driver (KIRCHHOFF, 2002). The difference of these types of travellers are made by distinguishing with and without car in person groups and by determining parameters in utility functions for each mode.

The fourth sub-model is the route choice model. In this step all the trips are assigned to the network. According to FRIEDRICH (2010), route choice models include three steps:

- Searching for a set of reasonable routes,
- Assigning the travel demand to routes,
- Replicating the vehicle movements and determining travel times in the actual network.

For private transport, deterministic user equilibrium assignment assumes that travellers are well-informed and leads to a stable state that all chosen routes have equal and minimum utility values (WARDROP, 1952). Stochastic user equilibrium assignment assumes that travellers have incomplete information and the distribution of demand is modelled with a discrete choice model (e.g. Logit-Model), as shown in Table 5 (FRIEDRICH, 2010). The other assignment methods can be found in FRIEDRICH (2013). The utility of an alternative, in this case a route, sums up the costs of all the network elements (e.g. links and turns) of this route. One phenomenon should be considered in the calculation of utilities of links: the quality of service on a link depends on the number of vehicles using this link. CR-function (capacity-restraint function) of links describes how the volume of vehicles influences the congested travel time. One basic CR-function, the BPR-function (NATIONAL RESEARCH COUNCIL (U.S.), 1985), has the following form.

$$t_{Con} = t_0\left(1 + a \cdot (\frac{q}{C})^b\right) \tag{2.2}$$

with	$t_{con}, t_0,$	Car travel time in congested or free-flow network
	$\frac{q}{C}$	Saturation of a link: volume (q) divided by capacity C
	a, b	Parameters

Public transport applies different route choice models from private transport due to its temporal constrains. For public transport, connections, which combine routes and departure times from timetables, are searched by either headway-based assignment or timetable-based assignment. Headway-based assignment does not consider the coordination of timetables of different lines and thus transfer time between lines cannot be calculated explicitly. In the opposite timetable-based assignment considers timetables with exact departure and arrival times. After searching for connections, connections are chosen based on utilities of each connection, including not only the time and costs, but also the number of transfers and waiting time for PuT. PuT demands are distributed by the Logit-Model, with the accordance of destination choice and mode choice models.

A travel demand model cannot be applied to evaluate all types of measures and developments relevant to transport. In order to be modelled in a travel demand model, measures or developments should have the same aggregation level as the travel demand model. For example, a network model with only roads of high hierarchy cannot analyse a measure of improving minor road network. The following developments and measures can be modelled in travel demand models (FRIEDRICH, 2011):

- Socio-demographic or economic developments:
  - Demographic development;
  - Price changes.
- Changes of land use structure.
- Measures in the transport supply:
  - Infrastructure related measures, e.g. construction of a new bypass;
  - Measures related to PuT lines and timetables;
  - Regulative and monetary measures such as road pricing;
  - Technical measures such as signal control.

3 Development of a Virtual City Model (VCM)

3.1 Objective and methodology

To analyse the influences of land use and transport supply on travel demand in a general way, a virtual city model (VCM) is developed. A VCM is a virtual city embedded in the framework of a travel demand model. Instead of representing a city as detailed and precisely as possible, VCM should be modelled as simply as possible. It describes an abstract and synthetic city with typical elements of a real city. Although a VCM is a model of an abstract city, it should replicate travel behaviour in a reasonable way by means of being calibrated and validated with a real city. The reference area in this work is Stuttgart Region, and the reference city is Stuttgart City. The reference area is introduced in chapter 3.2. The Stuttgart City Model (SCM) is derived from the original transport demand model of Stuttgart Region, that was developed with the help of the transport planning software VISUM by PTV Group in 2011 (HEIDL and SCHLAICH, 2012). VCM is developed in the same software environment as SCM.

Compared with the original travel demand model, SCM excludes unnecessary features and thus there is a slight difference between these two models. Table 6 lists the excluded features and their influences in SCM. These features are either specific for the Stuttgart Region (e.g. airport traffic and different adjustments) or of secondary importance (e.g. 0.1% of all the trips: Park+Ride trips). Because of these excluded features, fewer trips are modelled in SCM compared to the original model. Furthermore, without considering adjustment factors, the trips are distributed in a different way, and modal split differs slightly.

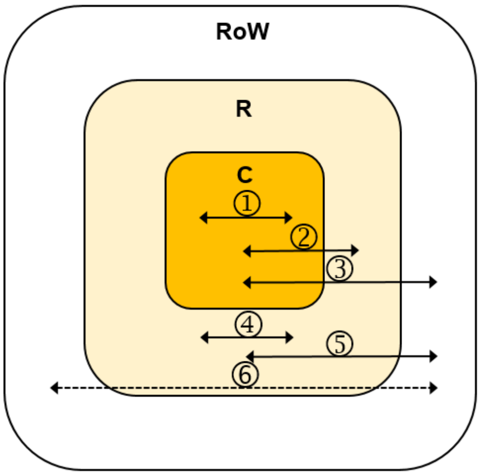
<table>
<tr><th colspan="2" rowspan="2">Excluded feature</th><th colspan="2">Change in SCM</th></tr>
<tr><th>Individual (example: car)</th><th>In total</th></tr>
<tr><td colspan="2">Additional trip tables (airport, fair, light-freight transport)</td><td>-7% (300,000) car trips</td><td rowspan="4">• Total trips -2%,
• Total distance -1%,
• Total time (car) -5%,
• More car-passenger trips (+0.6%),
• Fewer walk trips (-1%).</td></tr>
<tr><td colspan="2">Mode PR (Park + Ride)</td><td>+ 0.04% (2,000) car trips</td></tr>
<tr><td rowspan="2">Adjustment factors for…</td><td>work trip & non-work trip</td><td>+ 2% (106,000) car trips</td></tr>
<tr><td>car trip</td><td>+ 2% (90,000) car trips</td></tr>
</table>

Table 6: Excluded features in SCM from the original Stuttgart Region Modell.

The city is in the focus of VCM. However, a city is never isolated. For example on the network of Stuttgart City in SCM, only 30% of the total distance travelled are generated by internal trips of the city, whereas the remaining 70% are generated by trips relevant to neighbouring areas of the city. Therefore the neighbouring areas are also modelled in VCM, so that VCM replicates the congestion level on the network of the city in SCM.

The model area in VCM comprises three spatial areas: city area (C), region area (R) and rest of the world (RoW). The main area refers to both the city and region area. The region area, defined in both SCM and VCM, does not include the city area. However the administrative boundary of Stuttgart Region includes Stuttgart City. Figure 22 shows these three areas. C (city area) is modelled in VCM with a spatial resolution as high as in SCM. R (region area) in VCM is modelled with a lower spatial resolution. RoW represents all the areas outside the main area and is modelled in an even lower spatial resolution. Six trip types are distinguished between and within these three areas. Figure 22 also shows these six trip types. These trip types are clustered into the following three levels of importance in VCM:

- Trip type 1, 2, 4: the internal trips of the main area are modelled in detail with highly disaggregated person groups;
- Trip type 3, 5: the origin/destination trips of the main area are modelled in an aggregated way with a commuting travel demand model.
- Trip type 6: through traffic is modelled with an external trip table in VCM.



Trip types	Origin	Destination	Name of trips
1	C	C	Internal trips C
2	C R	R C	Origin / destination trips C-R
3	C RoW	RoW C	Origin / destination trips C-RoW
4	R	R	Internal trips R
5	R RoW	RoW R	Origin / destination trips RoW-R
6	RoW	RoW	Through traffic

(C: City R: Region RoW: Rest of the world)

Figure 22: Areas and trip types in VCM.

The city area of VCM is developed based on the characteristics of SCM. It is assumed that the most important characteristics of land use and transport supply in a travel demand model can be represented by aggregated indicators. These aggregated indicators are applied to transfer model elements from SCM to VCM. Figure 23 shows some examples of the aggregated indicators and how these indicators are applied to generate model elements in the city area of VCM.

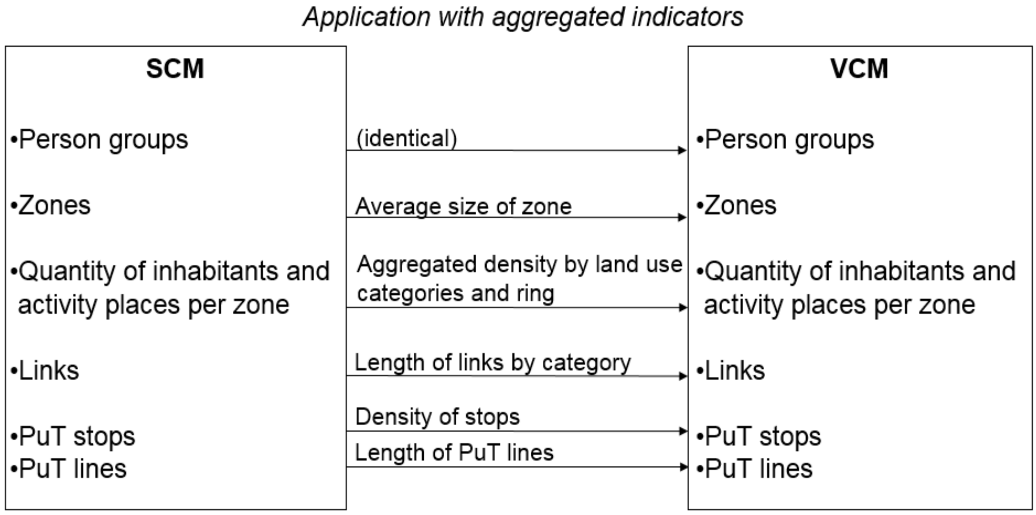


Figure 23: Application of aggregated indicators to VCM (city area).

Unlike the city area, the region area in VCM is not generated based on the above aggregated indicators in SCM. Model elements in the region area of VCM are designed and generated based on mainly the central place theory and corresponding connection hierarchies. Aside from the total number of inhabitants and activity places in the region area of SCM and VCM, the model elements in Figure 23 in the region area of VCM are not developed on the same quantity basis as for SCM, i.e. these model elements in VCM have a higher aggregation level than in SCM. For example, zones in the area of VCM are much larger than zones in SCM. Thus the method to transfer land use structure in the city area cannot be applied in the region area.

VCM requires the following three main inputs:

- The land use structure is represented by land use data, consisting of a zoning system (see chapter 3.4), the number of inhabitants and of activity places (e.g. work places, school places) per zone (see chapter 3.6).
- The transport supply is displayed by means of a network model including both road and PuT networks. The network model is developed with a network generator tool (see chapter 3.3), and is introduced in chapter 3.7.
- Mobility behavioural data describe the travel behaviour of travellers. These data in SCM are extracted from the database of a household interview survey in Stuttgart Region in 2009/2010 (VRS, 2011). The behavioural data in VCM are directly adopted from SCM.

The core of VCM is an impact model through which the impacts of these inputs on travel demand are modelled (see chapter 3.8). The development process of VCM is introduced in this chapter. This VCM represents the most important characteristics of travel demand in SCM.

3.2 Introduction of the reference area

Stuttgart City is the reference city of VCM. It is the sixth biggest city in Germany and the state capital of Baden-Württemberg. In terms of spatial structure and central place functionality, three tiers related to Stuttgart City are classified, as shown in a scaling-down sequence in Table 7. Stuttgart Metropolitan Region is one of the eleven metropolitan regions in Germany, defined by Ministerkonferenz für Raumordnung in Germany in 1995. This metropolitan region includes five regions, one of which is Stuttgart Region. Stuttgart Region is one of Europe's most important economic centres and is well-known for its high-tech industries. Stuttgart City includes 23 urban districts. As the core of Stuttgart Region, Stuttgart City is home of automobile companies (e.g. Daimler and Porsche).

Spatial level	Area [km²]	Population	Composition
Stuttgart Metropolitan Region	15,400	5.3 million	• **Stuttgart Region**, • Heilbronn-Franken Region, • Nordschwarzwald Region, • Neckar-Alb Region, • Ostwürttemberg Region.
Stuttgart Region (Reference area)	3,700	2.7 million	• **1 high-order central place (OZ) (Stuttgart City),** • 19 medium-order central places (MZ), • 40 low-order central places (GZ), • 119 communities (no central place function) (G).
Stuttgart City	207	0.6 million	• 5 urban districts in the inner city (IC), • 18 urban districts in the peripheral city (PC). (STATISTISCHES AMT STUTTGART, 2012)

Table 7: Characteristics of Stuttgart-related spatial units.

Among these three tiers, Stuttgart City is the primary focus of this work. The area of Stuttgart City is divided into 52% built-up area, 23% agricultural land and 24% forest (STATISTISCHES AMT STUTTGART, 2012). Activities are mostly concentrated in the built-up areas, which are eventually separated by forest, agricultural areas or the river Neckar. The biggest forest Rotwildpark covers a surface of 8 km² (4% of the total city area). The cauldron-shaped hilly landscape defines the layout of Stuttgart City. The elevation difference amounts to over 300 m between the highest and the lowest points in the city (STATISTISCHES AMT STUTTGART). This elevation difference sets constraints (e.g. for the use of the bicycle). These physical characteristics influence the layout of streets and distribution of settlements.

Stuttgart City is a multi-nodal city with a major city centre. A strong city centre is located in the densely inner city area (IC) and several sub-centres are located in the peripheral city (PC). The disaggregation of IC and PC enables to show the spatial difference of the characteristics in land use and composition of inhabitants in Table 8. Although IC covers only 16% of the total city area, it comprises 32% of all the inhabitants and 44% of all the work places. Although the residential density in the IC is 50% higher than in the PC, the shares of built-up area both in the IC and the PC are similar (around 50%). Compared to inhabitants in the PC, the IC has the following characteristics:

- Higher share of inhabitants in working age;
- Higher share of inhabitants with high income;
- Lower share of inhabitants with car ownership;
- Higher share of single households.

Category	Criteria		Stuttgart city	Inner city (IC)	Peripheral city (PC)
Land use	Area		207km² (100%)	16%	84%
	Share of the built-up area		51.5%	52%	51%
	Inhabitants		573,054 (100%)	32%	68%
	Residential density [inh./km²] (referring to the built-up area)		5,400 (100%)	7,400 (137%)	4,800 (89%)
	Work places		410,700 (100%)	44%	56%
Person structure	Share of inhabitants with the age of…	18-	16%	13%	17%
		18-65	66%	71%	63%
		65+	19%	16%	20%
	Share of employees with high income		30%	33%	28%
Household structure	Size of households [person]		1.9	1.7	2.0
	Share of single households		51%	59%	46%
	Share single parent households with children (<18)		18%	14%	20%
Income, car ownership	Income (2009)		100% (€24,500)	106%	99%
	Private car ownership [car/1000 inh.]		382	370	388

Table 8: Characteristics of Stuttgart City (based on the data of 2011 from STATISTISCHES AMT STUTTGART (2012)).

Another external factor that influences travel demand is transport supply. Stuttgart City has good accesses to motorways, to long distance and regional railway networks, to an airport and to inland waterways. Although there is no complete motorway ring around Stuttgart like in Munich or Berlin, 50 km motorways (Bundesautobahn) and 250 km federal highways (Bundesstraße) serve for long distance and regional trips. The network of main roads with a length of 500 km is the backbone of the city. Furthermore 2200 km secondary roads serve local accessibilities. Aside from road infrastructure, there are also manifold public transport services in Stuttgart City: 6 heavy rail lines, 15 light rail lines and 55 bus lines.

Given an overview of person-related factors, land use structure and transport supply of Stuttgart City, the characteristics of travel demand are introduced based on a one-week household interview survey in 2009/2010 (VRS, 2011). This survey includes 270,000 trips from 5,000 households and 13,000 persons. The report (VRS, 2011) analyses the characteristics of the travel behaviour in Stuttgart Region from recorded trips. Figure 24 displays these characteristics disaggregated by person groups. An average person in Stuttgart Region makes 3 trips and spends 75 min covering a distance of 35 km. Among all the inhabitants in Stuttgart Region, employees make most of the trips. These trips are the longest in time and distance followed by trips made by apprentices. Students make fewer trips with relatively long distance. The shortest trips in time and distance are completed by unemployed.

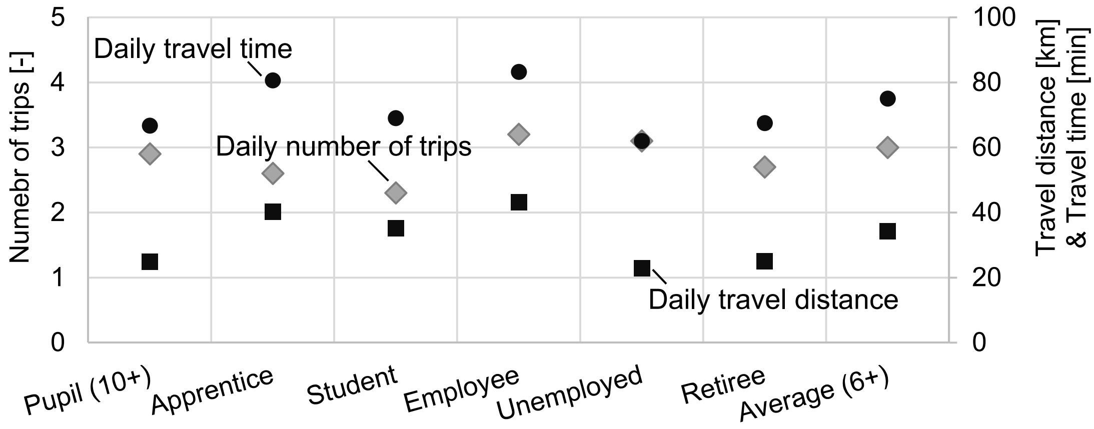


Figure 24: Characteristics of travel demand in Stuttgart Region (VRS, 2011).

Figure 25 shows the modal split of trips aggregated by different spatial units in the reference area. The aggregations of the IC and the PC are calculated based on the data from VRS (2011). In comparison to the PC, the IC has 5% more walk trips and 7% more PuT trips. This is a result of the comprehensive influences of the land use and the transport supply in the IC, such as high-quality PuT services, the restriction of parking places, and the higher density and diversity. Comparison between Stuttgart Region and Stuttgart City shows considerably fewer PuT trips and more car trips in Stuttgart Region than in Stuttgart City, as Stuttgart Region includes rural areas where PuT connections are poor and car use is dominant.

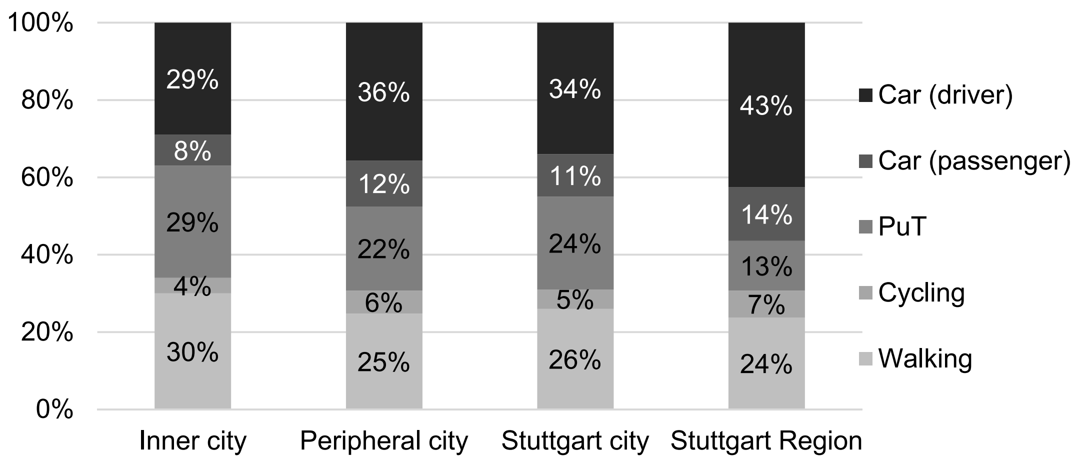


Figure 25: Modal split in Stuttgart-related spatial units (VRS, 2011).

These characteristics of travel demand in the reference area should be reproduced appropriately in VCM. More characteristics of travel demand with the comparison of SCM and VCM are introduced as a result of calibration and validation in chapter 4.5.

3.3 The network generator tool

A network generator tool, developed at the Chair of Transport Planning and Traffic Engineering, University of Stuttgart, is used to generate the network structure of VCM.

This network generator tool creates a city from a set of predefined tiles by assembling these tiles together according to a certain arrangement. A tile represents an area of 1 km² and it defines the most important elements of a network. Assuming that a city is composed of different typical areas, e.g. areas with low or high densities of roads or buildings. Each typical area corresponds to one or more tiles. After defining a set of typical tiles, these tiles can be arranged in a desired way to form a city. In this way the network generator tool supports the development of various city structures.

A first version of this tool was used to generate several city types (RODRIGUEZ, 2007). He compared the performances of three archetypes of cities, as shown in Figure 26. His work mainly proofed that it is possible to create virtual cities and to compute travel demand indicators of these cities. However, he used a rather aggregated and simple travel demand model without validating the resulted characteristics of trips.

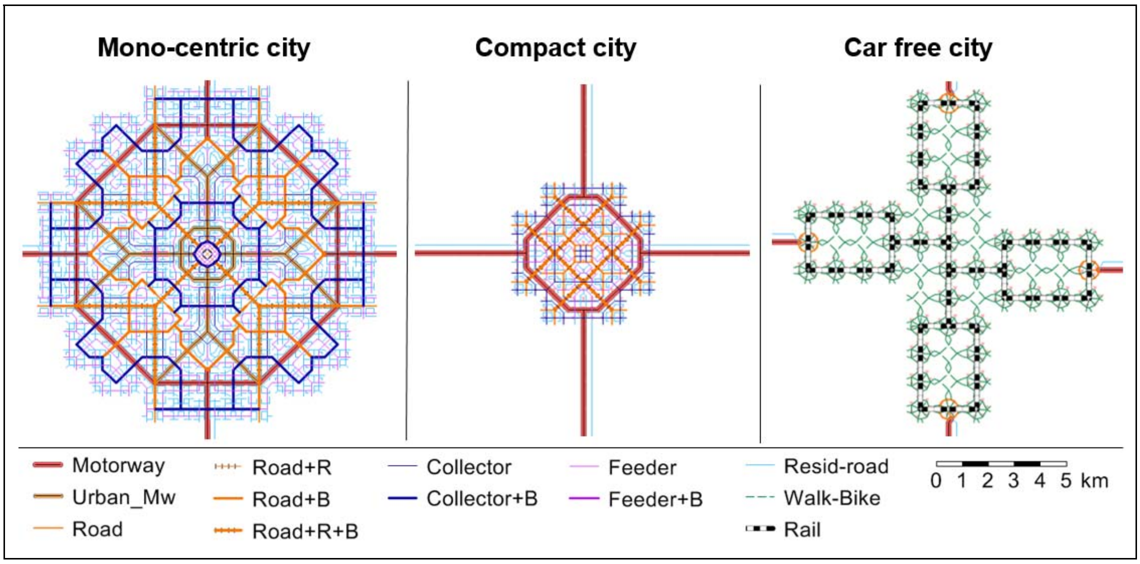


Figure 26: Networks generated by the first version of the network generator tool (RODRIGUEZ, 2007).

To fulfil the requirements of building VCM in this work, the first version of the network generator tool was further developed. It now has the following features:

- The maximum modelled area is 1000 km · 1000 km.

- The size of square-shaped zones in a tile can vary between 0.04 km² and 1 km².
- The spatial dimension of zones, i.e. zone polygons, can be defined in tiles and transferred to the output network.
- The symmetrical function is an option in the tool. With this option active, the whole network is automatically generated based on the first defined quadrant. This function saves manual symmetrical adjustments of tiles.
- Stops of public transport and their related objects (stop point, stop area) can also be defined in tiles.

All the tiles are based on the same square form. Figure 27 displays the scale and coordinate system of this form of each tile. It consists of 121 nodes with 100 m spacing. These nodes can serve as zone centroids, as FromNodes or ToNodes of links or as PuT stops. The minimum spacing between two links is 100 m. The edge of a tile is 1 km. A tile is connected with neighbouring tiles by 40 edge nodes. When creating a network, a unique number is assigned to each edge node based on the position of the tile in the city and the position of the node in the tile.

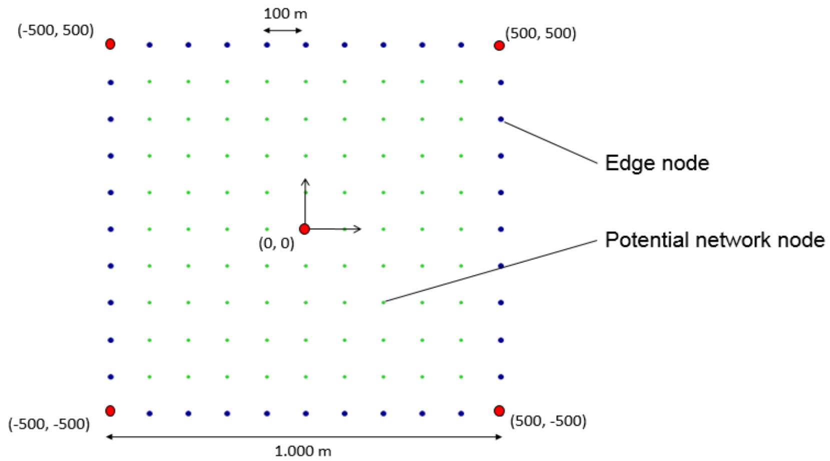


Figure 27: Characteristics of a tile.

Figure 28 shows how the network generator tool works using a simple example. Two main inputs are the predefined tiles and the table of distribution of these tiles. In this example three tiles are defined: mix-used central area (MC), mix-used area along the arterial road (MA), and residential area (R). Each tile includes the information of transport systems, link types, nodes, links, zones, connectors, stops and their attributes. The continuousness of links and the coordination of link types should be considered when designing neighbouring tiles. The tiles are represented by codes, which are used to fill the table of tile distribution. In this example the symmetrical function is active and it is sufficient to define only the tiles in the first quadrant, i.e. the North-Eastern quadrant of the city. Four equal quadrants in the network area are divided by two axes, over which the defined quadrant is mirrored to form the whole network. The network generator tool joints tiles by redefining the number of all the elements based on their original number and their relative locations. The output of this example is a network with 20 PuT stops, an urban ring road in the mixed-use central area, four arterial roads and the grid network in the residential area. 16 MC zones, 8 MA zones and 32 R zones are also generated in the output network out of only three original tiles.

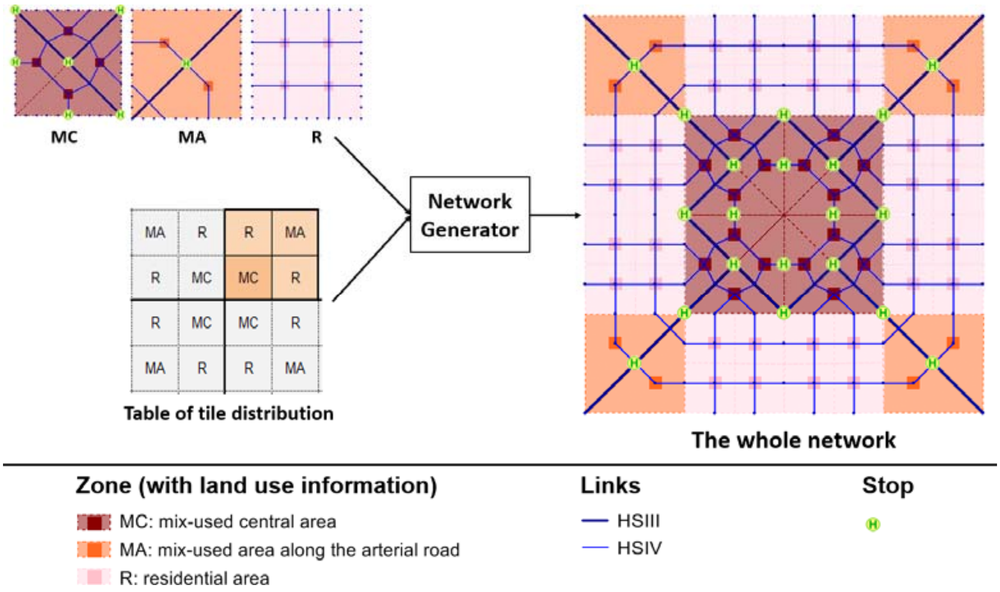


Figure 28: Workflow for constructing a network with the network generator tool.

Concerning VCM the network generator tool is used to build up a zoning system (see chapter 3.4) and a network model (see chapter 3.7). Figure 29 shows the spatial dimension and composition of tiles in VCM. Although settlements usually have irregular boundaries, the square shape is chosen for VCM considering the square form of tiles. Another important characteristic is the spatial dimension of VCM. The areas of the region and the city should be ideally the same as in SCM: 3,700 km² of the region and 207 km² of the city. Based on the conditions mentioned above, a virtual city of 14·14 tiles (196 km²) is most appropriate to model Stuttgart City; and a region with an area of 3400 km² is the most suitable variant to model the region area. The RoW area outside the main area in VCM is also generated by tiles at the four corners, as shown in Figure 29.

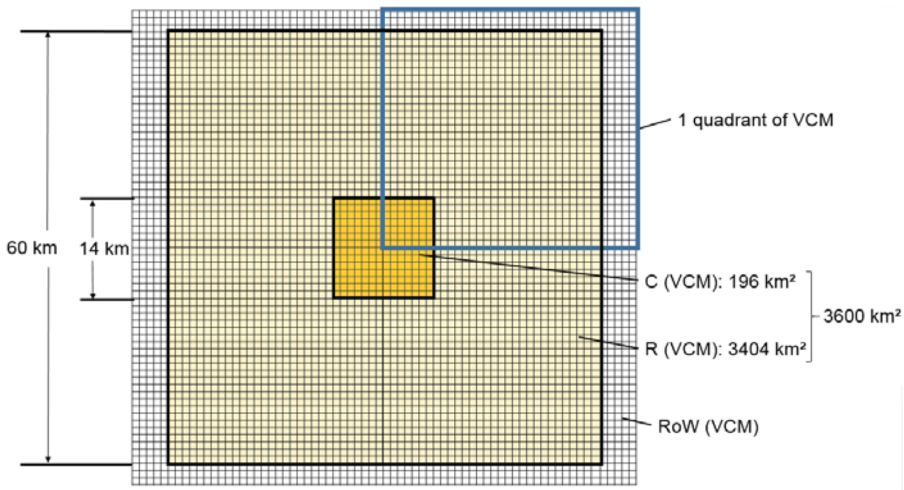


Figure 29: Tiles of VCM.

3.4 Spatial division

Two levels of spatial divisions are applied in the process of developing VCM. The first level is the division of the main area into spatial units. The second level is the division of the total modelling area into zones. The first spatial division results in the three spatial units in both the city and region areas, as listed in Table 9. These spatial units are applied to aggregate the characteristics such as the size of zones. The results of the characteristics of zones aggregated on the level of spatial units in both VCM and SCM are listed in Table 9. The methods of zoning in and outside the city in VCM are separately introduced in the following sub-chapters.

Spatial unit		Total area [km²]		Number (zone)		Average zone size [km²]	
		SCM	VCM	SCM	VCM	SCM	VCM
City	City Centre (CC)	5	4	43	40	0.1	0.1
	Inner city (IC) (except CC)	28	30	130	136	0.2	0.2
	Peripheral city (PC)	174	162	340	336	0.5	0.5
Region	Medium-order central place (MZ)	820	815	173	8	5	100
	Low-order central place (GZ)	1,110	1,100	138	16	8	70
	Rural area (RA)	1,520	1,500	188	8	8	185
Rest of the world (RoW)		27,500	-	162	4	170	-

VCM is simplified on purpose and these highlighted values in VCM are not comparable to those in SCM.

Table 9: Key features of zoning in SCM and VCM.

3.4.1 Zoning in the city

As listed in Table 9, there are three spatial units in the city, i.e. CC, IC (except CC), PC. The inner city includes the city centre. However, the inner city is divided into the CC and the IC (except CC) in order to distinguish the much more intensive land use in the city centre from the other areas in the inner city. Based on the total area of each spatial unit in SCM, the total area of the city in VCM is divided into the three spatial units. For example, the city centre in SCM covers an area of 5 km², in the network generator tool, the 4 tiles in the centre are referred to be the city centre with a total area of 4 km². The divisions of these three spatial units in SCM and VCM are shown in Figure 31.

The zoning system in the city of VCM is established based on the characteristics of SCM. An important characteristic of zoning in SCM is the cumulative frequency of the zone size in each spatial unit, as shown in Figure 30. 10% of the zones are located in the CC, most of which are smaller than 0.2 km². 20% of the zones are situated in the IC (except CC), most of which are smaller than 0.3 km². The remaining 70% of the zones are in the PC of SCM, half of which are also smaller than 0.3 km². Almost 90% of all zones in the city of SCM are smaller than 1 km². The remaining 10% of the zones includes usually a substantial amount of unbuilt space. These characteristics of the size of zones in SCM are considered in the zoning process in VCM.

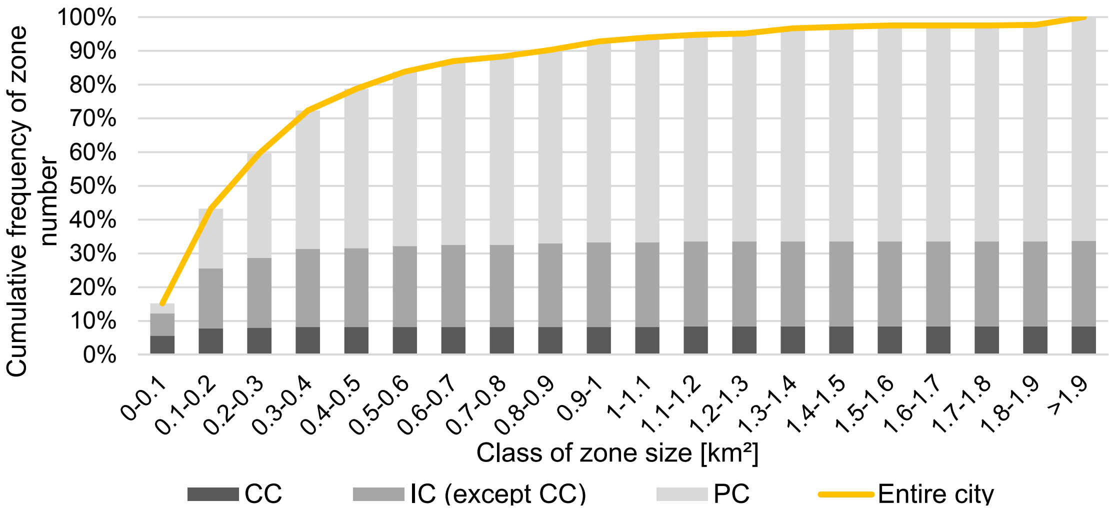


Figure 30: Cumulative frequency of zone size in SCM.

Based on the distribution of zone size in each spatial unit in SCM, 512 zones in VCM are generated with the network generator tool. With respect to the size of zones, five types of tiles are created: a 1 km² tile includes respectively 10, 6, 4, 2, 1 zones. Six types of zone size are distributed in the city of VCM as follows:

- The CC includes two types of zones: 0.06 km² and 0.13 km²;
- The IC (except CC) includes also two types of zones: 0.17 km² and 0.25 km²;
- The PC includes four types of zones: 0.17 km², 0.25 km², 0.5 km² and 1 km².

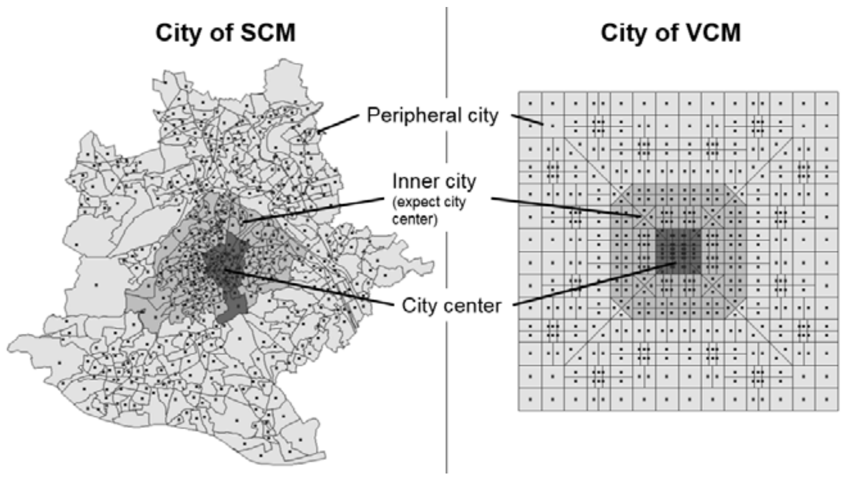


Figure 31: Zoning in cities of SCM and VCM.

The spatial distributions of zones in the city of SCM and VCM are shown in Figure 31. The 16 clusters of the smallest zones (0.17 km²) in the PC of VCM replicate sub-centres of the 16 city districts in SCM, whereas the 1 km² zones represent areas with a high share of unbuilt areas (e.g. forest). Unlike zones in SCM, zones in VCM have a regular form in both terms of zone size (six types) and zone centroid location (at the centre of zones). Due to the limitation of the network generator tool that the area of each tile is 1 km², 1 km² is the maximum zone size in VCM. The zones which are bigger than 1 km² in SCM are not represented in VCM.

In order to make sure that the location of zones in VCM matches the one in SCM, frequency distributions of the direct distance of all the od-pairs within the city are examined, as shown in Figure 32. Direct distance of od-pairs is determined by locations of zone centroids. Due to the regularity of VCM, the frequency curve of VCM goes with the fluctuation, and is not as continuously as SCM does. However, in general the frequency distribution of direct distance in VCM matches it in SCM. Thus zoning in the city of VCM is satisfactory.

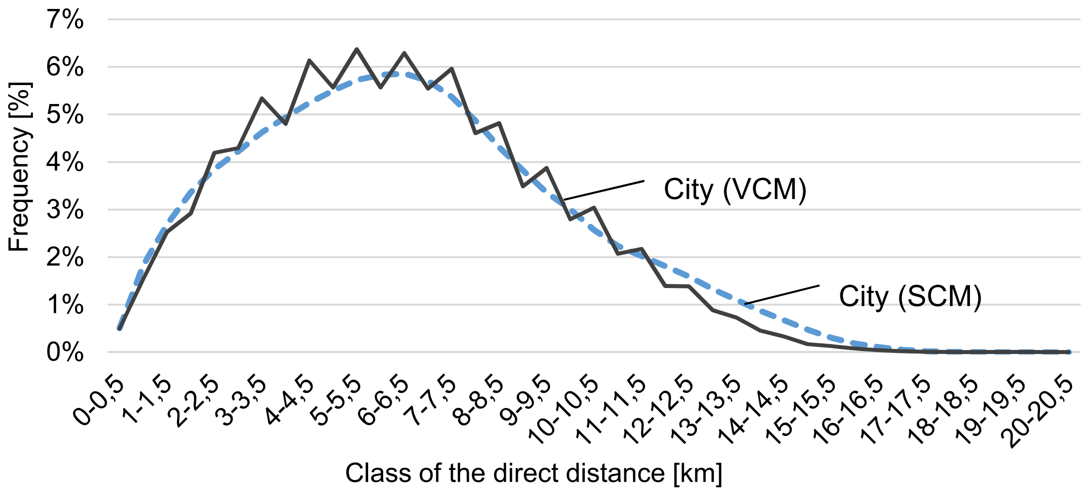


Figure 32: Frequency distribution of direct distance in SCM and VCM.

3.4.2 Zoning outside the city

As stated in chapter 3.2, Stuttgart Region has a poly-central structure. There are 19 medium-order central places (MZ), 40 low-order central places (GZ) and 119 communities without central place function in the region area. These communities without central place function are referred to be rural areas (RA).

Characteristics of zones outside the city in SCM are listed in Table 9. These are summarized in the following:

- The average size of zone in the region of SCM is much bigger than in the city.
- A community is represented by several zones. For example, a MZ zone is represented on average by nine zones, whereas a RA zone consists only by two zones.
- RoW is modelled with two types of areas: the surrounding area (136 zones) and the further area (26 zones). Their difference is discussed in detail in the calibration of trips.

Zones outside the city in VCM are developed on a higher aggregation level than those of SCM: R and RoW are represented respectively by 32 and 4 zones. The process to determine the number and the location of zones is conducted together with the development of the network in the region. It is assumed that the city is connected with the region by eight axes of arterial roads and railways. These eight axes are equally distributed from the city in horizontal, vertical and diagonal directions, as shown in VCM in Figure 33. The distribution of zones in the region is influenced by this structure of axes following the principle that MZ and GZ zones are located along these axes, whereas RA zones are situated in the broad areas between these axes. Two aspects from the central place theory from CHRISTALLER (1933) are applied to determine the distribution of zones in the region of VCM:

- The arrangement:
    - MZ zones surround OZ zones
    - Both MZ zones and OZ zones are surrounded by GZ zones;
- The sequence of number of zones from minority to majority: OZ, MZ, GZ.

The distribution of zones outside the city is shown in Figure 33. In VCM the city area is an OZ zone. Along the eight axes in the region area there are eight GZ zones near the city, eight MZ zones in the middle of the region area and eight GZ zones at the fringe of the region area. Eight RA zones are situated in the broad areas between these eight axes. The main area is connected by four motorway axes and four railway axes in diagonal direction to the four RoW zones. Figure 33 illustrates not only zone centroids, but also a variant of zone shape in VCM based on the average zone size of each spatial unit.

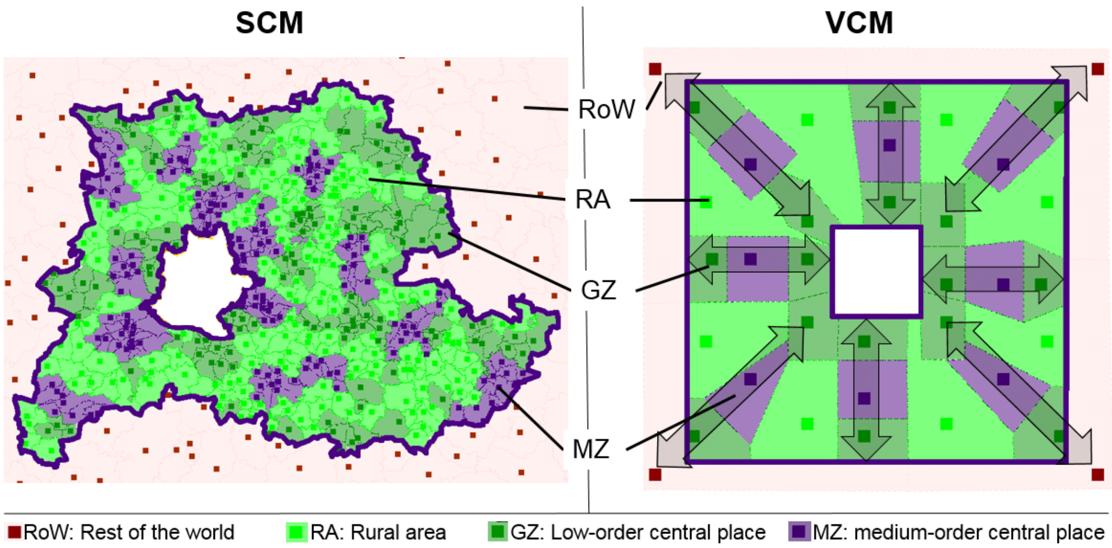


Figure 33: Zones outside the city of SCM and VCM.

To sum up for VCM, zones outside the city are approx. 100 times bigger than zones in the city. Since zones in the region of VCM are approx. 10 times bigger than zones in the region in SCM, the frequency distribution of the direct distance of od-pairs in these two models cannot be compared. A disadvantage of this type of zoning in VCM is the lack of variability in terms of distance of od-pairs, especially of those with short distances. Thus, those short-distant inter-zonal trips in the region of SCM can only be represented by intra-zonal trips in VCM.

3.5 Person groups and activities

VCM applies a high level of segmentation regarding 21 person groups and 17 activities, as in SCM (HEIDL and SCHLAICH, 2012). Table 10 lists these main person groups and activities in the model and how they are classified. In a first step the inhabitants are divided into 13 main person groups based primarily on the age and the main activities, and then on the level of education, incomes and types of work. In the second step 8 of these person groups are further categorized by car ownership. Exceptions are children, primary school pupils, secondary school pupils, apprentices and freelances. Children and pupils are not yet allowed driving. Behaviours of apprentices and freelances with or without car are aggregated due to their similarities. Activities are divided into 9 common activities for all the person groups and 10 individual activities of education or work only for corresponding person groups. Children under the age of 6 years do not carry on any kind of activities, the existence of this person group only ensures the total number of inhabitants.

<table>
<tr><th rowspan="3">Age</th><th rowspan="3">Main activity</th><th colspan="3">Person group</th><th colspan="2">Activity</th></tr>
<tr><th rowspan="2">Main category of person group</th><th colspan="2">With car?</th><th rowspan="2">Common</th><th rowspan="2">Individual</th></tr>
<tr><th>yes</th><th>no</th></tr>
<tr><td>0-6</td><td>-</td><td>Child</td><td>--</td><td>x</td><td colspan="2">No activities</td></tr>
<tr><td rowspan="4">6-25</td><td rowspan="4">Education</td><td>Primary school pupil</td><td>--</td><td>x</td><td rowspan="12">• Shopping (daily)
• Shopping (special)
• Personal business
• Visit
• Culture
• Sport
• Bringing/picking up
• Round trip walk
• Home</td><td>Primary school</td></tr>
<tr><td>Pupil</td><td>--</td><td>x</td><td>Secondary school</td></tr>
<tr><td>Apprentice</td><td>-</td><td>-</td><td>Vocational school</td></tr>
<tr><td>Student</td><td>x</td><td>x</td><td>University</td></tr>
<tr><td rowspan="6">25-65</td><td rowspan="4">Work</td><td>Employee (high income)</td><td>x</td><td>x</td><td>Work-high income</td></tr>
<tr><td>Employee (low income)</td><td>x</td><td>x</td><td>Work-low income</td></tr>
<tr><td>Freelance</td><td>-</td><td>-</td><td>Work-freelance</td></tr>
<tr><td>Part-time employee</td><td>x</td><td>x</td><td>Work-part-time</td></tr>
<tr><td rowspan="4">Leisure/ personal business</td><td>Unemployed</td><td>x</td><td>x</td><td>-</td></tr>
<tr><td>House person</td><td>x</td><td>x</td><td>-</td></tr>
<tr><td>65-75</td><td>Retired person<=75</td><td>x</td><td>x</td><td>-</td></tr>
<tr><td>75+</td><td>Retired person >75</td><td>x</td><td>x</td><td>-</td></tr>
</table>

--: impossible; -: no distinguish; x: true.

Table 10: Main person groups and activities in the main area of VCM.

In additional to the above introduced 21 main person groups, VCM includes also the other two person groups who commute between the main area and rest of the world. They are in- and out-commuters. In-commuters are those inhabitants who live in RoW zones but make trips in the main area. Out-commuters live in the main area, but their trip destinations are located in RoW zones. The activities of these two person groups are also modelled as in- and out-commuting activities.

Person groups and activities are relevant to both land use structure and behaviour modelling. The methods to determine the land use structure per person groups and activities are introduced in chapter 3.6. The parameters, which represent preferences of different person groups for different trip purposes, are described in chapter 3.8.

3.6 Land use structure

Land use structure is represented by the number of inhabitants per person group and the number of activity places per activity of each zone. The objective is to determine these quantities of VCM in such a way that they appropriately represent the characteristics of the land use structure in SCM. The overview of the methods to define the land use structure in VCM are listed in Table 11. Because of the different aggregation levels to model the city and the region area, different methods are applied to determine the main land use structure in the city and the region areas. In addition to the main land use structure, commuting land use structure in VCM is determined according to commuting trips in SCM due to the external commuting trip matrix. The listed three methods in Table 11 are introduced in the following sub-chapters.

Land use / **Location of zones**		**Main structure**		**Out-commuting**		**In-commuting**	
		Inhabitant	**Activity place**	**Inhabitant**	**Activity place**	**Inhabitant**	**Activity place**
The main area	City (C)	[1]		[3]	-	-	[3]
	Region (R)	[2]					
Rest of the world (RoW)		-		-	[3]	[3]	-

-: not related; [1], [2], [3]: index of methods to transfer land use data from SCM to VCM.

[1] Cross-classification of land use category, distance to the city centre and density;

[2] Average distribution separately for MZ, GZ and RA zones;

[3] Distribution based on the commuting trip table in SCM.

Table 11: Overview of different methods to define land uses in VCM.

3.6.1 Main structure in the city

The land use structure of the main person groups and activities in the city, i.e. 21 person groups and 17 activities, is the core of the land use structure in VCM, as the city area has the highest aggregation level among all areas. A procedure for transferring the land use structure of a real city to a virtual city is introduced in the following. The main indicator in this transferring process is the density, i.e. the density of inhabitants per person group and the density of activity places per activity.

The following assumptions are applied to this approach:

- The land use of a zone can be sufficiently described by means of a land use category which defines the main function of a zone, such as the residential zone.
- The location of certain land use categories in a radial city depends on the distance from the city centre.
- The distance from the city centre can be approximated through rings. A Ring comprises the area between two neighbouring concentric circles around the city centre with constantly increasing radiuses. The difference between radiuses of two neighbouring rings is the width of rings.
- The density of inhabitants per person group and the density of activity places per activity depends on the land use category and the ring number.

In summary these assumptions indicate that zones of the same land use category and in the same ring have the same density for each person group and activity. This approach cross-classifies the land use category, the land use density and distance to the city centre in the reference city. The results of this cross-classification are then assigned to VCM. In this way, the land use structure in VCM has similar characteristics to the one in SCM. The approach scheme of assigning the land use structure of a real city to a virtual city is shown in Figure 34. The process of this approach is generally described with the following steps:

- Corresponding to the land use indicators (densities of inhabitants and activity places) in SCM, a set of land use categories is defined.
- Each zone in SCM is assigned to a land use category.
- A number of rings with appropriated widths are defined for SCM and VCM.
- The appropriate ring number is assigned to each zone in SCM and in VCM.
- The share of each land use category in each ring is derived from SCM.
- Each zone in VCM is assigned to a land use category considering the share of this category in the particular ring from SCM.
- The average density of inhabitants per person group and of activity places per activity of a zone for each land use category in each ring is derived from SCM. The result is a table of density values for each combination of the land use category and the ring number.
- The resulting table of density values is assigned to each zone in VCM based on the land use category and the ring number. The absolute numbers of inhabitants and activity places for each zone are calculated based on the density and the area of each zone.

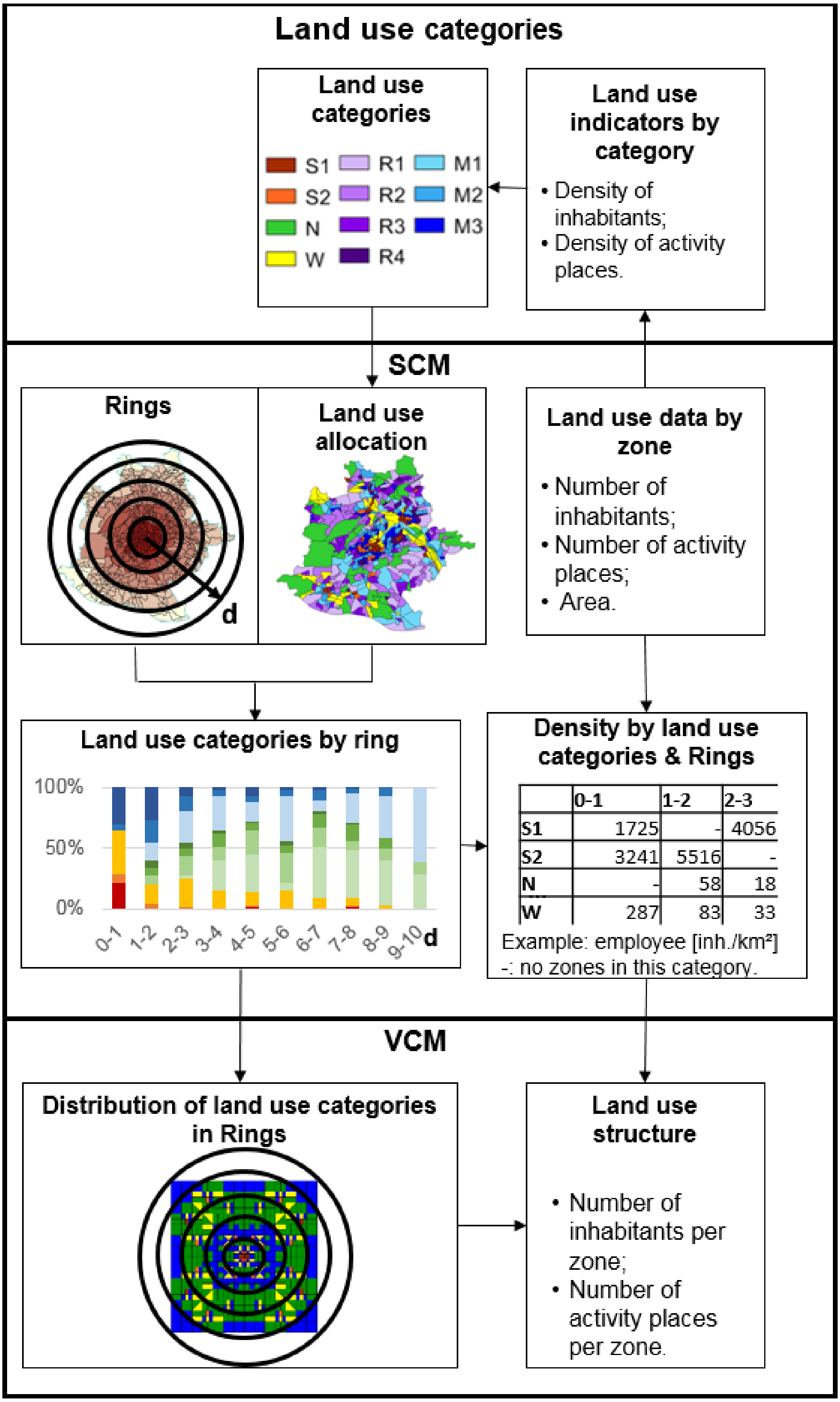


Figure 34: Approach scheme of assigning the main land use structure to VCM.

Land use categories

Land use categories are applied to represent land use characteristics. Land use categories in this work are urban activity oriented. They are different from those in geographic science. For example, woodland, agriculture and forest are not necessarily classified, as they make no difference concerning movements of travellers.

Figure 35 shows how the system of land use categories is developed. According to the dominant function, all zones in SCM can be seen as zones offering services, zones supplying work places, zones mainly for habitation, or zones without specific functions. Thus four main functions (including also no function) are distinguished. Based on this division of functions, five main categories of zones are distinguished with consideration of the relationship between work and residence. The indicators are densities of land uses representing these functions. Based on the five main categories and the further indicators distinguishing shopping arts and levels of densities, 11 detailed land use categories are developed.

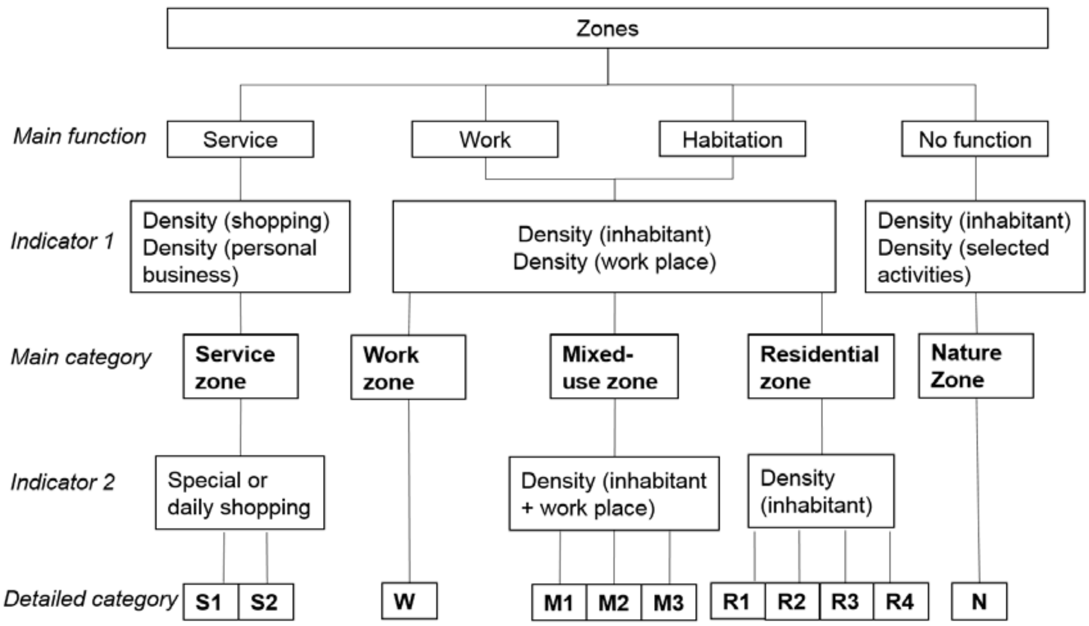


Figure 35: Development of land use categories.

The detailed criteria for these 11 land use categories are listed in Table 12. If special/daily shopping and personal business have an extremely high density, these zones are categorized as service zones. Shopping density describes the number of potentially attracted customers per unit area. This level of extremely high density is defined by criteria of density values, which are determined in a way that they represent only 10% of the highest density zones in SCM. Whether the special shopping or daily shopping is dominant determines a zone to be S1 or S2. A nature zone is defined by very low densities for selected land uses. After defining these two land use categories, the remaining zones are distinguished into work, residential and mixed-use zones based on the relation between the residential density and the density of work places. If the density of work places of a zone is much higher (i.e. at least five times) than the residential density, it is defined as a work zone. Oppositely if the residential density is much higher (i.e. at least five times) than the density of work places in a zone, this zone is defined as a residential zone. A fair relation between these two densities refers to the mixed-use. Residential and mixed-use zones are further divided based on different levels of density. These values of residential densities are inspired by the land use plan in Berlin (Senatsverwaltung für Stadtentwicklung Berlin, 2005). For mixed-use zones, the density of both work places and inhabitants is important and it is applied as the criterion.

Main category	**Detailed category**		**Criterion of indicator (D: density)**	
			Relation of density	**Density [unit/km²]**
Service zone	S1	Main service zone	-	• D (special shopping) > 9.000 • D (personal business) > 5.000
	S2	Sub-service zone	-	• D (special shopping) < 9.000 • D (daily shopping) > 19.000 • D (personal business) > 5.000
Nature zone	N	Nature zone	-	• D (inhabitant) ≤ 500 • D (work place) ≤ 500 • D (shopping) ≤ 500 • D (personal business) ≤ 500 • D (culture) ≤ 500
Work zone	W	Working zone	$\frac{\text{D (inhabitant)}}{\text{D (work place)}} < \frac{1}{5}$	-
Residential zone	R1	Very-low-density residential zone	$\frac{\text{D (inhabitant)}}{\text{D (work place)}} > 5$	D (inhabitant) ≤ 2.000
	R2	Low-density residential zone		• D (inhabitant) > 2.000 • D (inhabitant) ≤ 5.000
	R3	High-density residential zone		• D (inhabitant) > 5.000 • D (inhabitant) ≤ 10.000
	R4	Very-high-density residential zone		• D (inhabitant) > 10.000
Mixed-use zone	M1	Low-density mixed-use zone	$\frac{\text{D (inhabitant)}}{\text{D (work place)}} \geq \frac{1}{5}$ and $\frac{\text{D (inhabitant)}}{\text{D (work place)}} \leq 5$	D (inhabitant + work place) ≤ 5.000
	M2	High-density mixed-use zone		• D (inhabitant + work place) > 5.000 • D (inhabitant + work place) ≤ 12.000
	M3	Very-high-density mixed-use zone		D (inhabitant + work place) >=12.000

Table 12: Criteria of land use categories.

One notable feature of this system of land use categories is that there is no unique function for zones. These categories only reveal the relative dominance of functions. For example, there is also dwellings in service zones, but the function of services is dominant. In addition, this system of land use categories does not consider all 17 activities in SCM. For example, the distribution of sport facilities has no influence on the classification of land use categories. For land use categories in cities with different scales from Stuttgart City (e.g. mega-cities), the criteria of density values need to be redefined.

Cross-classification of land use categories and rings

The 11 land use categories are derived from SCM. Based on the criteria of land use categories, these categories are assigned to all the zones in the city of SCM. These land use categories have neither the same area nor the same number of zones in SCM. The distribution of land use categories in SCM is displayed in Figure 40 (b). Table 13 lists three characteristics of zones with different land use categories in SCM: the area, the number of zones, and the average size of zones of each land use category. The characteristics of zones with different land use categories are distinguished into the following three groups:

- For the high-density zones (S1, S2, W, R3, R4, M2, M3), the share of the number of zones is higher than the share of the area of zones. This leads to smaller size of zones (0.1-0.3 km²).
- For low-density zones (N, R1, M1), the share of the area is higher than the share of the number of zones. It causes larger size of zones (0.6-1.4 km²).
- R2 has the similar share of both the number and the area of zones with an average size of 0.4 km².

Land use category	Sum of area [km²]	Share of area	Number of zones [-]	Share of zones	Average size of zones [km²]
S1	4	2%	34	7%	0,1
S2	3	1%	20	4%	0,1
N	52	25%	36	7%	1,4
W	19	9%	59	12%	0,3
R1	28	14%	30	6%	0,9
R2	31	15%	74	14%	0,4
R3	17	8%	68	13%	0,3
R4	5	3%	32	6%	0,2
M1	27	13%	42	8%	0,6
M2	14	7%	61	12%	0,2
M3	8	4%	57	11%	0,1

Table 13: Characteristics of land use categories in SCM.

The distance from the city centre is classified by rings. Figure 36 shows how rings with a width of 1 km are defined in SCM. If the zone centroid of a zone is located in a ring, this zone is considered to be located in this ring. The number of rings for a city depends on the area of the city and the width of a ring, as shown in Figure 36. Rings with smaller width offer a less aggregated classification. However, a small width of rings does not necessarily deliver the best result, since it is possible that a ring does not include any zone due to its reduced width. For example in the case of the 0.1 km ring, zones in SCM are located in 91 rings but zones are located in only 49 rings in VCM due to the regular distribution of zones. In this work the ring with a width of 1 km is chosen for a moderate distribution of zones in VCM.

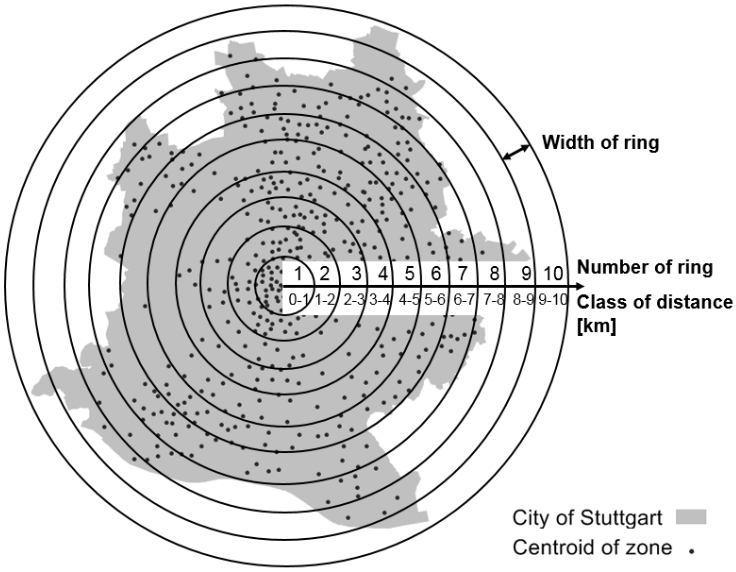


Figure 36: The scheme of rings with an example of SCM.

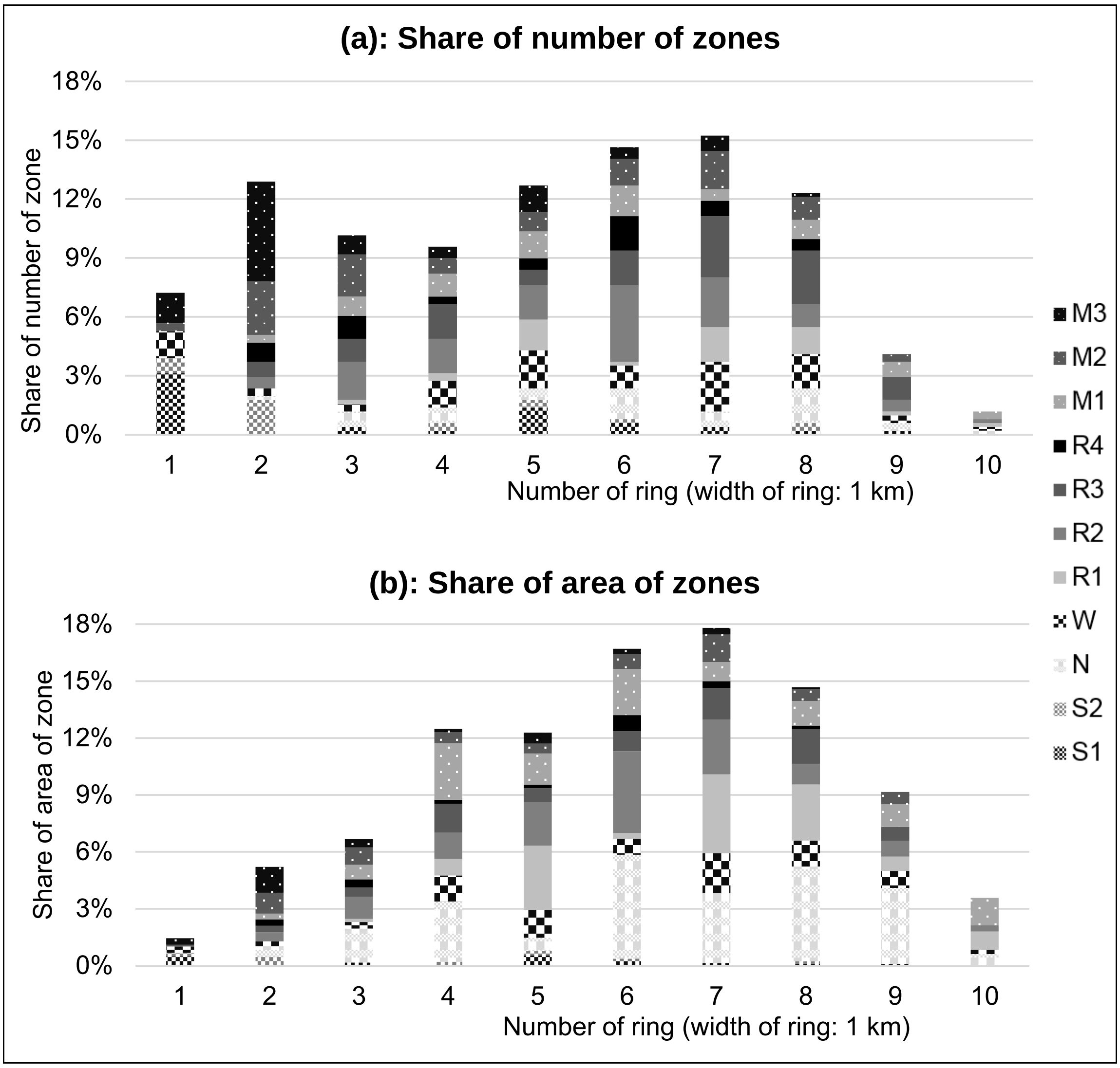


Figure 37: Distribution of land use categories in rings in SCM.

The share of zones with different land use categories in each ring in the city area of SCM has the following characteristics:

- Not all the land use categories are present in any ring. The allocation of 11 land use categories to each 1 km ring in SCM generates 92 classes, with additional 18 classes without zones. For example, there are no M3/R4 zones in the ring 10.
- The zones in SCM of these 92 classes are unevenly distributed in the city. High-density zones are located close to the city centre and fewer high-density zones are located in wider rings. For example, 5% of all zones are M3 zones in the ring 1-2 km whereas only 0.2% are M3 zones in the ring 7-8 km, as shown in Figure 37 (a).
- The total share of area increases from the ring 1 to 7 and decreases from the ring 7 to ring 10, as shown in Figure 37 (b). It is lead from the out-of-round share of Stuttgart City.

The distribution of land use categories in rings in SCM in terms of both the number and the area of zones in Figure 37 (a) and Figure 37 (b) serves as a reference for assigning land use categories to zones in VCM.

Cross-classification of land use categories, rings and densities

Land use categories are supposed to cluster similar land use structures. Aggregated densities per each land use category verify the significant differences of land use categories. Figure 38 (a) shows these aggregated densities of inhabitants and several activities in SCM. The shown densities per each land use category conform to defined criteria of these land use categories: Category S1 shows the extremely high density of special shopping and above-average high densities of other activities. The density of special shopping is much higher than the density of work places in this category. It does not mean number of shops are more than number of offices in a unit area, but represents that the number of potential customers attracted by shops for special shopping in the unit area is much higher than the number of attracted workers for working in the unit area. Category S2 is characterized by the high daily shopping density. Category N covers mainly low densities of all land uses. Category W offers dominantly high density of work places compared to other functions. From R1 to R4 the densities of all uses increase, especially the residential density and daily shopping density. From M1 to M3 the residential density, work place density and daily shopping density also increase.

Land uses in different rings also have different characteristics. Figure 38 (b) shows changes of the residential density and the work place density with rings. The average density in a ring is derived from the total number of uses and the total area of zones in this ring. In the city centre the work place density is extremely high. In the rings 1 and 2 the work place density decreases and the residential density increases. Only small deviations for both densities occur in the rings 2 to 10. In general the total deviation of the work place density is much higher than the deviation of the residential density.

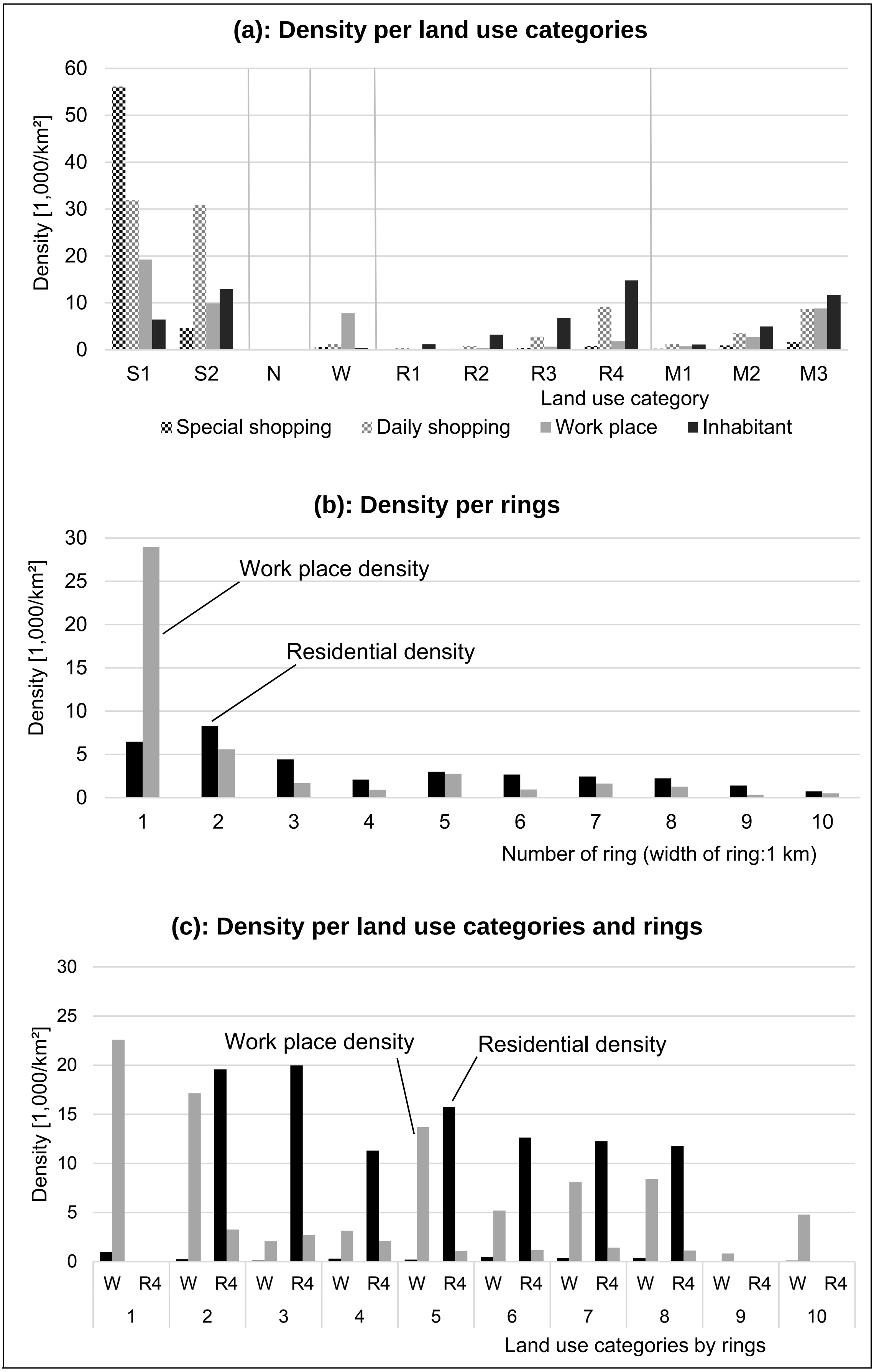


Figure 38: Examples of densities according to land use categories and rings.

The densities of each person group or activity for all the 92 classes of cross-classification of land use categories and rings are the key for transferring the land use structure from SCM to VCM. All the zones in the same class share the same density of land uses. The density of each class is calculated with the following equation:

$$D_{i,j,X} = \frac{\sum_{b=1}^{B} N_{X,b,i,j}}{\sum_{b=1}^{B} A_{b,i,j}} \qquad (3.1)$$

with	$D_{i,j,X,S}$	Density of person group/activity X per ring i and land use category j
	B	Sum of zones in the ring i and land use category j
	$A_{b,i,j}$	Area of the zone b in the ring i and land use category j
	$N_{X,b,i,j}$	Number of person group/activity X in zone b per ring i and land use category j

Figure 38 (c) shows the result from the above calculation with an example of the residential density and the work place density in the zones with categories W and R4. The distribution combines the characteristics from both Figure 38 (a) and Figure 38 (b). In general these densities of the cross-classification represent the land use characteristics in a more disaggregated way than only considering land use categories or rings. For example, according to the density of land use categories in Figure 38 (a), work place density in W zones is approx. 8,000 work places/km². Figure 38 (c) shows the increased variety of the work place density in W zones: The ring 1 has 23,000 work places/km², whereas the ring 3 has only 2,500 work places/km². Considering only densities in different rings as Figure 38 (b), the average work place density in the ring 5 is 3,000 work place/km². Figure 38 (c) shows that in the ring 5 the work place density in W zones is 14,000 work places/km², but in R4 zones is 2,000 work places/km². The residential density has the similar characteristics. There are no values of residential density in zones with the category R4 and the ring number 1, 9 and 10, as there is no R4 in these rings.

The cross-classification of densities, land use categories and rings generates 92 classes of densities. The method of cross-classification avoids the lack of variability of either only considering different densities per land use categories or only considering densities per rings. These generated 92 classes of densities are applied to transfer the land use structure from SCM to VCM.

Application to VCM

Based on the 92 classes of densities, the land use structure in VCM is calculated following the steps below:

- Exam the distribution of zones in rings in VCM;
- Classify zones in VCM into 11 land use categories;
- Assign the 92 classes of densities to zones in VCM and calculate quantities of land uses in VCM based on density values and areas of zones.

The first step is setting ring numbers to zones in VCM. Zoning in VCM determines directly the distribution of zones in rings. Two aspects of zones are exemplified in VCM with reference to SCM: the number of zones and the area of zones in each ring. The cumulative frequencies of these two aspects in SCM and VCM are shown in Figure 39. The cumulative area of zones is smaller than the cumulative number of zones, as the average size of zones increases with the number of ring. The distribution of zones in VCM for rings from 1 to 4 matches the distributions in SCM in an outstanding way. However, for rings from 5 to 10, the cumulative frequency of both the number and the area of zones in VCM is slightly higher than in SCM. It is lead from the smaller average size of zones in these rings in VCM than in SCM. Figure 40 (a) shows the comparison of the distribution of zones in rings in SCM and VCM. The irregularity of SCM and regularity of VCM are obvious: zones in VCM are regularly square-shaped, thus, the boundary of each ring is also angular.

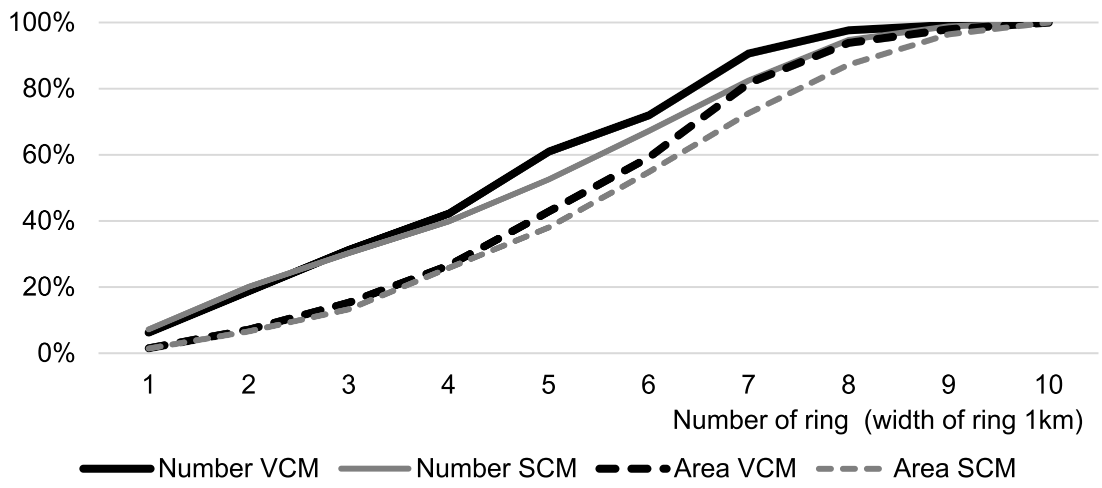


Figure 39: Cumulative frequency of zones in rings in SCM and VCM.

The second step is the determination of land use categories for all the zones in VCM. These 11 land use categories are manually defined in each zone with the network generator tool. The distribution of these land use categories is mainly based on frequencies of the number of zones and the area of zones of each land use category in each ring (Figure 37) and the neighbouring zones in terms of their land use categories (Figure 40 (b): SCM). Figure 40 (b) compares the distribution of land use categories in SCM and VCM. The following characteristics of the land use structure in both SCM and VCM can be addressed:

- In both models high-density areas and low-density areas are mixed.
- In the central area of the city zones have generally a high density of diverse activities (S1, S2, W, and M3).
- Service zones, which are distributed widely from the centre, are surrounded by high-density zones (R3, R4, M2, and M3).

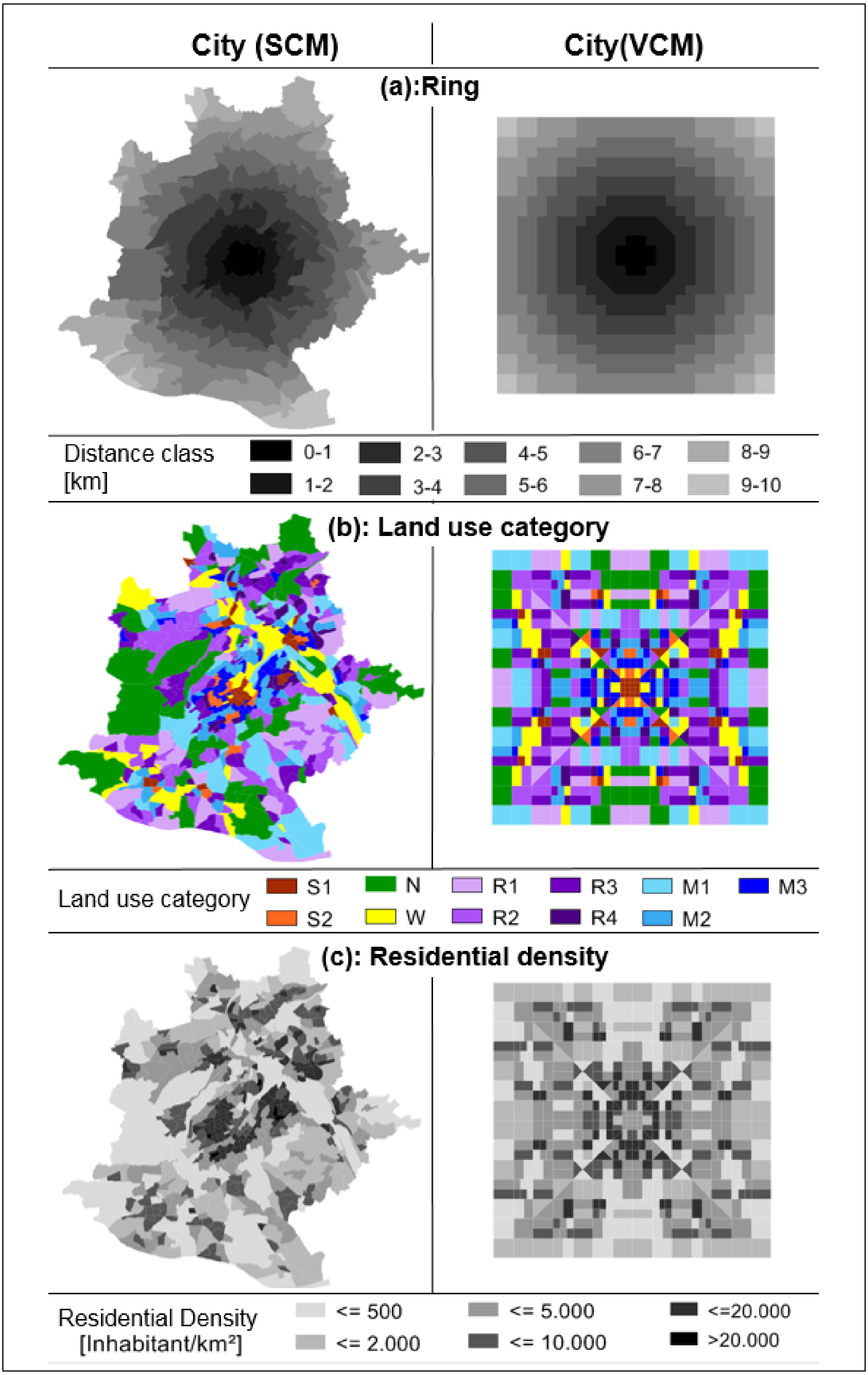


Figure 40: Ring, land use category, and residential density in SCM and VCM.

- The inner city is characterized by a higher share of mixed-use than the peripheral city: For zones with high densities, most of the M3 are located in the inner city while most of the R4 are located in the peripheral city.
- The low-density zones (N, R1, R2, and M1) are mainly located in the peripheral city.

The third step is assigning the densities of 92 classes to each zone in VCM. Figure 40 (c) shows the distribution of residential densities in SCM and VCM. Given the density and the area of each zone in VCM, the number of inhabitants per person group and activity places per activity is calculated for each zone in VCM. To ensure the same total number of inhabitants and activity places in VCM and in SCM, the calculated quantities in VCM are adjusted. The adjusted land use data in the city of VCM represents the land use structure in the city of SCM.

The following requirements or shortcomings of this approach should be considered for further applications.

- Due to the influence of the distance from the city centre (the rings), this approach is most suitable to represent land use structure in monocentric cities.
- To apply this approach, the aggregation level of zoning (size of zones) in a VCM should be similar to the reference model.
- For cities of a comparable size to Stuttgart City, these land use categories can be directly applied. However, for cities with different spatial scales (e.g. mega-cities like Paris) the density values for each land use category should be redefined.

3.6.2 Main structure in the region

Due to different aggregation levels of zones in the region area of SCM and VCM, the approach of applying densities based on land use categories and rings is not suitable for the transfer of the land use structure from SCM to VCM.

The land use structure in the region area of VCM is generated by categorizing types of zones (MZ, GZ, and RA) and distributing the quantities of land uses of each type of zones in SCM equally to the same type of zones in VCM. For example, 0.8 million inhabitants in 173 MZ zones in SCM are equally distributed in 8 MZ zones in VCM.

This method of transferring the land use structure on a very high aggregation level leads to a high amount of inhabitants and activity locations in the same zone. It results then to plenty of intra-zonal trips. In this method the difference within the same type of zones is ignored, for example GZ zones near the OZ (the city) may have different number of inhabitants than GZ zones at the edge of the region. This difference is emphasized in the process of calibration of the land use structure (see chapter 4.3).

3.6.3 In- and out-commuters

The distribution of in- and out-commuters and their activity locations are the basis for modelling trips between the main area and RoW. Commuting trips in SCM are modelled with the two methods:

- 40% of the trips (350,000) are generated by a trip generation model with 219,000 in- and out-commuters and a trip rate of 1.6;
- Another 60% (530,000) of the trips are modelled by two external trip tables respectively for car and PuT.

Thus, the total amount of 880,000 commuting trips are generated by 550,000 commuters in VCM with an assumed trip rate of 1.6, the same as in SCM. Because the number of trips made by in-commuters is 2.5 times of the number of trips from out-commuters in SCM, it is assumed that number of in-commuters is 2.5 times of out-commuters in VCM.

Quantities of commuters and activity places in each zone of VCM are determined based on the distribution of trips made by out- and in-commuters in SCM. The distribution of out-commuters and destinations for in-commuters in the main area of VCM is based on proportions taken from commuting trips in SCM. For example, in MZ zones there are 33% of out-commuter and 42% destinations for in-commuter in VCM, because accordingly 33% trips of out-commuters are from MZ zones, and 42% of trips made by in-commuters have the destinations in MZ zones in SCM.

Land uses of commuters in the city of VCM should be coordinated with land use categories of zones in the city. For example, no out-commuters should live in a work zone. The following principles show a simple way of coordination:

- Out-commuters live only in residential and mixed-use zones in the city.
- Destinations of in-commuters are only located in service and work zones in the city.

The land use structure of commuters is further calibrated to reach proper characteristics of commuting trips, as introduced in chapter 4.3.

3.7 Transport supply

3.7.1 General network settings

Transport supply is described by means of a network model. The general settings of the VCM network model with respect to transport systems and modes, link types and connectors are introduced in the following.

Transport systems and modes

Table 14 lists the modelled transport systems and modes in VCM with reference to SCM. VCM considers eight transport systems and five modes for person transport. PuT is an aggregated mode from two sorts of tickets (single or season ticket). PuT walk represents access/egress paths between stops and origin/destination or a transfer path between stops. Based on the abstracted representation of RoW areas in VCM, the long distance train covering a length up to 350 km in SCM is excluded in VCM. Because of the difficulties to design a realistic bus network in the city of VCM, the transport system bus is not considered in the city area of VCM. However, bus lines are designed in the region area providing PuT connections for the rural areas.

<table>
<tr><th rowspan="2">Type</th><th rowspan="2">Transport system</th><th rowspan="2">Mode</th><th rowspan="2">Mode Interchangeable</th><th colspan="2">Included in…</th></tr>
<tr><th>SCM</th><th>VCM</th></tr>
<tr><td rowspan="5">PrT</td><td>Walk</td><td>Walk</td><td>yes</td><td rowspan="10">yes</td><td rowspan="7">yes</td></tr>
<tr><td>Bike</td><td>Bike</td><td>no</td></tr>
<tr><td rowspan="2">Car</td><td>Car-driver (Car-D)</td><td>no</td></tr>
<tr><td>Car-passenger (Car-P)</td><td>yes</td></tr>
<tr><td>Truck</td><td>Truck</td><td>yes</td></tr>
<tr><td>PuTWalk</td><td>PuT walk</td><td rowspan="4">PuT (including PuT-single ticket and PuT – season ticket)</td><td rowspan="4">yes</td></tr>
<tr><td rowspan="3">PuT</td><td>Heavy, light rail, regional train</td></tr>
<tr><td>Bus</td><td>yes (only in region)</td></tr>
<tr><td>Long-distance train</td><td>no</td></tr>
</table>

Table 14: Transport systems and modes in SCM and VCM.

The networks of these PrT and PuT transport systems are introduced in chapter 3.7.2 and chapter 3.7.3.

Link types

Links in network models are classified into link types. Link types in VCM are derived from RIN (Richtlinien für integrierte Netzgestaltung) by Forschungsgesellschaft für Staßen- und Verkehrswesen (2008) (see Table 4 in chapter 2.4.2). Continental and vicinity connections do not match the spatial scale of VCM, thus they are excluded. 9 road categories for car from AS I to HS IV are considered in VCM. In case of PuT, SB III, UB II/NB II, NB I represent respectively light rail, heavy rail and regional train in VCM. Heavy rail is operated in both built-up areas (UB II) and open areas (NB II). For the two slow modes, i.e. bike and walk, only categories on the local level are chosen for VCM.

More than 90 link types in SCM are aggregated to 10 link types in VCM. These 10 link types in VCM with their characteristics in speeds and capacities are listed in Table 15. The following assumptions are made:

- Walk, bike and PuT walk are allowed on all the roads (except on motorways and railways), i.e. these roads may consist of a sidewalk, a lane for bicycle and a lane for car respectively. Speeds of walk and bike are defined to be 5 km/h and 15 km/h.
- Different to special tracks of light rails on roads in the city, heavy rails and regional trains have independent tracks. Values of speed for these three PuT systems in Table 15 result from the calibration of the PuT supply in VCM.
- Values of free flow speed by car in VCM are generally higher than target speeds from RIN (2008), as target speeds consider the delay time due to the congestion and the waiting time at turns. Free-flow speed values in Table 15 result from the calibration of the free-flow travel time of od-pairs.
- Values of capacity (car) of link types in VCM are determined so that the congested travel time of od-pairs in VCM is comparable to SCM. According to CR-functions, the congested travel time depends on the calibrated trips, calibrated free-flow time and capacities of links. Capacities outside the city are significantly higher than those in the city due to the high aggregation level of links in the region area.

Link type		**Permitted transport system**	**Target speed [km/h] RIN (2008)**		**Free flow speed (v_0) [km/h]**		**Capacity (car) [vehicle/day]**
Outside the city	AS I	Car, truck	100-120 (car)		120 (car)		98,000
	AS II	Car, truck			120 (car)		55,000
	LS II	Car, bus, walk, bike, PuT walk, truck	70-80 (car)		70 (bus)	85 (car)	48,000
	LSIII		60-70 (car)			70 (car)	38,000
Outside the city / In the City	Rail	Heavy rail, regional train	30-100 (heavy rail) 40-100 (regional train)		38 (heavy rail) 85 (regional train)		-
In the City	VS II	Car, walk, bike, PuT walk, light rail, truck	15-35 (light rail)	40-60 (car)	30 (light rail)	90 (car)	36,000
	VS III			30-50 (car)		70 (car)	14,000
	HS III			20-30 (car)		50 (car)	9,000
	HS IV			15-25 (car)		18 (car)	2,000
	ES IV			-		15 (car)	1,900

Table 15: Link types and their characteristics in VCM.

ORTÚZAR and WILLUMSEN (2011) state that the lowest level of road hierarchy is modelled with the biggest errors based on the study from JANSEN and BOVY (1982). The lowest hierarchies in VCM are ESIV/HSIV. These links serve the purpose of connecting zone centroids and therefore have a big tolerance of errors.

Link types are applied to aggregate indicators of links. For example, the indicator “length of links by each link type” is applied to represent characteristics of a network and to evaluate the network of VCM with the reference to SCM, as shown in chapter 3.7.2.

Connectors

A connector represents the access or egress path between settlements and the network. It describes the first or the last trip leg of a journey, and it assigns the demand to the network by connecting zone centroids with nodes in the network. Similar to zoning, it is of importance in the process of connector generation to determine the number and location of nodes with which zones are connected (ORTÚZAR and WILLUMSEN, 2011). These nodes are the points where travel demand is loaded onto the network.

Connectors in SCM are defined in a detailed way. Each zone in SCM is connected to more than one node in the network: a zone is connected on average by 12 connectors. Figure 41 shows how connectors are modelled in SCM with an example of connectors of two 0.1 km² inner city zones. The PuT connectors are distinguished from the PrT connectors in terms of connected nodes: a PuT connector assigns travel demand only to PuT stops, whereas a PrT connector can locate on any nodes. The connected nodes can be located inside, outside, or at the edge of zones.

Each connector carries a certain share of the travel demand. These shares are shown on each connector with the corresponding percentages in Figure 41. Modelling connectors with absolute shares can represent the real world in a more accurate way, as this method allows to consider the specific distribution of inhabitants or activity locations in a zone. This approach however requires detailed input data and more computing time. For these reasons this approach is not applied to model connectors in VCM.

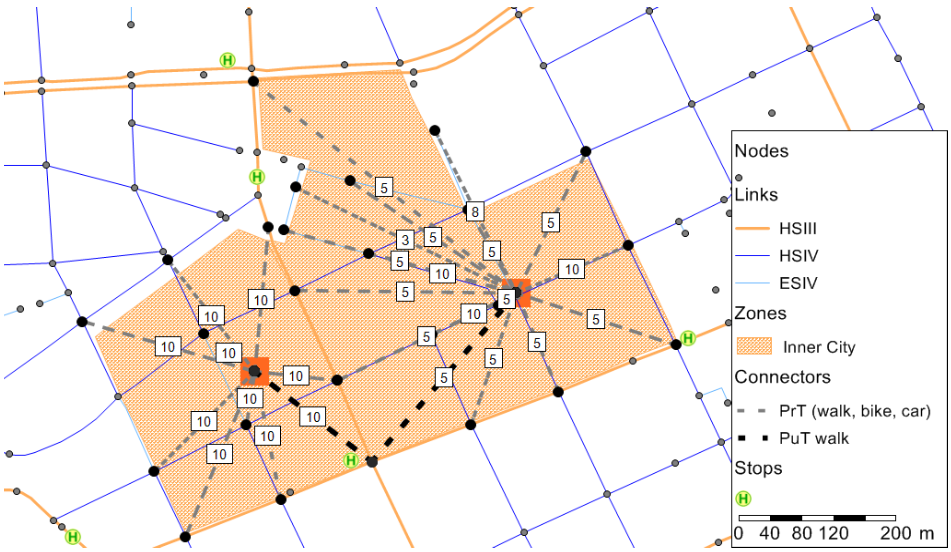


Figure 41: Example of connectors of two zones in SCM.

Since the approach of modelling connectors in SCM cannot be applied to model connectors in VCM, further research on modelling connectors is examined. GALSTER (2009) compares three methods of connector generation in his dissertation.

In these three methods by GALSTER (2009) each zone is connected:

- to one node (the zone centroid) in the middle of the zone,
- to all nodes in the zone,
- to several randomly chosen nodes in the zone.

According to his analysis, the method with only one connector per zone generates the same travel time as a more accurate microscopic model. This method however produces unrealistic flows in the feeder road network. The other two methods do not lead to realistic travel times (GALSTER, 2009).

Since the one-connector method leads to accurate travel times and it is based on an uncomplicated procedure, this method is applied to VCM. In order to apply this method, the following two requirements should be satisfied:

- Zone centroids are located preferably in the middle (zoning see chapter 3.4.1).
- Links should go through zone centroids, so that travel demand can be assigned to these nodes in the network (network layout see chapter 3.7.2).

No difference between PrT and PuT connectors is distinguished in VCM. Instead of connecting travel demand to PuT stops as in SCM, PuT connectors are also located at zone centroids in VCM. Thus, walking time to PuT stops is calculated based on the network instead of being defined by the modeller for each connector. This method also avoids the necessity of selecting stops, with which each zone should be connected. Connectors in the region area of VCM follow a different principle: PuT stops and zone centroids share the same node, thus, PuT trips are directly loaded at PuT stops.

The time of connectors is normally supposed to represent the access and egress time, start waiting time (PuT), parking search time (car), and possible travel time in the feeder road network. However, the length of connectors in VCM is 0 km, and the time of connectors (except PuT connector in the region) in VCM is also 0 min. The time of PuT connectors in the region area is applied to model travel time in the subordinated network, as the size of zones in the region area is large. The above-stated supposed times are not defined on connectors, but either calculated based on the network (e.g. PuT access and egress time) or manually defined based on influencing factors (e.g. car access time and parking search time). These relevant times are introduced in chapter 4.2.2.

The different methods to generate connectors in VCM and SCM might lead to different characteristics in these two models. For example, if two neighbouring zones share a common connector node in SCM, travel times between these two neighbouring zones is extremely short. This phenomenon does not exist in VCM because each zone is connected to the one node in the middle.

3.7.2 Private transport supply

The road network provides the physical basis for the road transport. It determines characteristics such as travel distance and travel time between two places. The road network represents both the private transport supply and also road-based public transport supply. Based on the defined link types, the road network of VCM is developed with the help of the network generator tool considering the integration of networks for different modes and the characteristics of SCM (e.g. density of links per link type). Two further factors of the network, i.e. CR-functions and time penalties at turns, are also introduced in the following, as they have an important influence on travel times and hence also on the quality of the private transport supply.

Road network of the city

As a result of a long history of the city development, the pattern of the road network in the most of European cities, including Stuttgart City, cannot be classified consistently. The present network form depends largely on the topography and the distribution of settlements in the city. A mixture of radial-ring system and grid system can be extracted from the irregularity of SCM. In addition to the pattern of the road network, the characteristic of the road network in Stuttgart City, which is represented by the indicator the length of links per link types and urban areas, serve also as an important reference for designing the road network in VCM.

Figure 42 (a) shows the irregularly distributed road network in the city of SCM and the symmetrically distributed road network in the city of VCM. The network is classified by link types: major roads include VSII/III and HSIII links, and networks of HSIV and ESIV links describe minor roads in VCM. These networks have the following characteristics:

- The VSII/III network offers fast connections within the city or between the city and the areas outside the city. The VSII/III network in VCM is designed as a radial-ring-system with eight axes and two rings based on the pattern in SCM. However, the ring around the inner city in SCM is incomplete, and not all eight VSII axes in SCM go through the city centre.
- The HSIII network provides the main connections within the city, especially between sub-centres of urban districts. The HSIII network in VCM follows a grid form which distributes equally in the entire city with a spacing of 1 km.
- The HSIV/ESIV network represents minor roads and fulfil the feeder function. The HSIV/ESIV network in VCM follows the grid form. Intersections within the HSIV/ESIV network in VCM are possible locations of zone centroids.

The total length of each link type in both SCM and VCM should be similar. Figure 42 (b) displays the densities of links distinguished by link types and urban areas, as an evaluation of the road network in the city of VCM. Since the lengths of links in VCM are adjusted in the calibration of travel distance (see chapter 4.2.1), the shown densities of links are conducted after this adjustment. As shown in Figure 42 (b), link densities have the following characteristics in different areas of the city:

- The peripheral city (PC) has the lowest density of both major and minor roads;
- The density of major roads in the city centre (CC) is the highest;
- The highest density of minor roads lies in the inner city (except the city centre).

Figure 42 (b) shows the similarities and difference of the link densities in VCM and SCM. Densities of minor roads in the two models are in general comparable. However, the density of VSII links in IC (except CC) of VCM is much higher than the one in SCM due to the incomplete radial-ring-system in SCM. The density of HSIII links in all the urban areas of VCM shares the similar values due to the equally distributed grid form, whereas the density of HSIII links in different urban areas of SCM shows differences: PC has lower density than IC.

The road network in VCM, especially of HSIII/HSIV/ESIV links, is not only regularly distributed in the urban area, but also abstracted on a higher level than in SCM. Two exemplary intersections in both models are shown in Figure 43. In SCM links of big intersections in opposite directions are modelled with spatially separated links, whereas in VCM these are modelled by two links sharing the same two nodes. Furthermore there are no extra non-motorized links in VCM like in SCM. As stated in the definition of link types, non-motorized modes share the same network with motorized modes (except on motorways). This way of definition deteriorates the attractiveness of slow modes by ignoring the existence of shorter walk paths. This disadvantage is compensated with the calibration of walking distance in chapter 4.2.1.

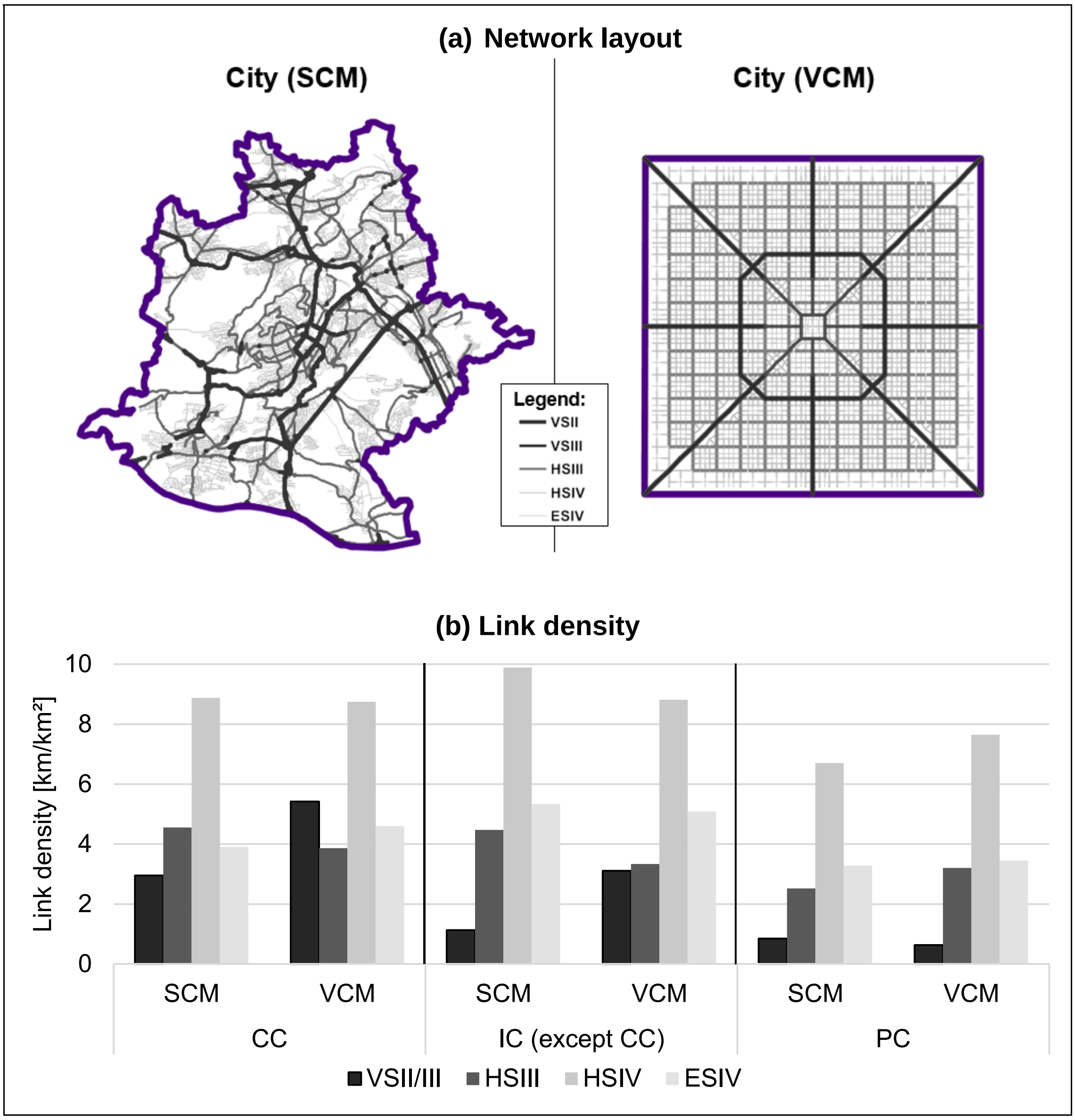


Figure 42: Comparison of private networks in the city of SCM and VCM.

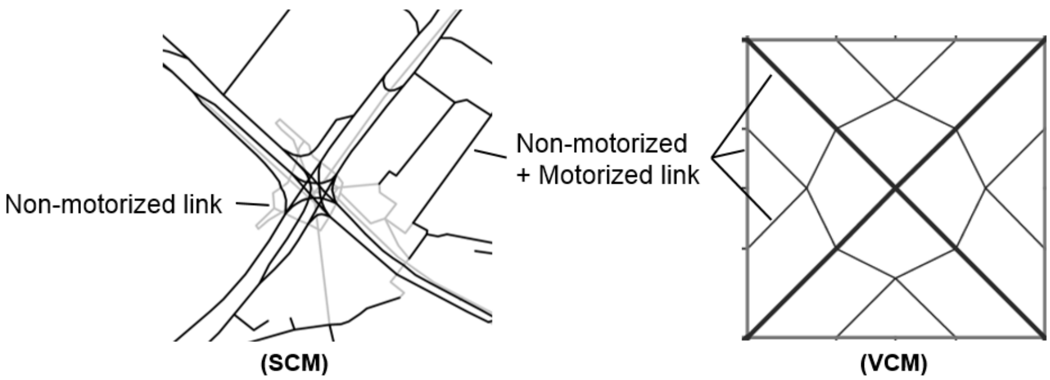


Figure 43: An exemplary intersection in the city of SCM and VCM.

Road network outside the city

The road network outside the city in VCM offers not only the connections between the city area and the area outside the city, but also connections within the area outside the city. However, like different aggregation levels of zoning in the region and the city areas, the area outside the city has a higher aggregation level of the road network than the city area. The different aggregation levels in and outside the city area in VCM require also different designing concepts.

Connecting zones with different central place functions with links on the appropriate connection levels is the main concept of the road network design outside the city in VCM. It is different from the network design in the city with reference to the length of links in SCM. The main links types in the region area are ASI/II (motorway) and LSII/III (rural road). The network structure of these link types should be designed based on the distribution of zones with different central place functions. Locations of zones and the network form are developed in consideration of each other, as stated in chapter 3.4 of zoning outside the city. Similar to the network in the city, all the links except motorways are shared by both motorized and non-motorized transport modes.

Figure 44 shows the road network outside the city disaggregated by link types in VCM. The design principles and characteristics of the road network outside the city are listed in the following:

- The motorway network (ASI/II) connects the modelled area with RoW zones. The motorway network consists of a ring in the region and four axes up to RoW. The spacing between the motorway ring and the city centre is 14 km.
- The network of rural roads with the link type LSII offers connections between the core city (OZ) and MZ zones in the region, and also between MZ zones in the region area. LSII network extends the eight axes from the city and leads to eight MZ zones in the region. The spacing between the LSII ring and the city centre is 20 km.
- The network of rural roads with the link type LSIII is applied to connect GZ or RA zones to the network of LSII/ASI. LSIII links are mainly distributed in the fringe area of the region with spacing of approx. 8 km.
- Zone centroids of GZ and MZ zones in the region area are directly located at PuT stops along PuT axes, which are introduced in chapter 3.7.3. The eight axes of ASI/II and LSII links are distributed within a certain distance to these zones. This arrangement emphasizes the good PuT connections of MZ and GZ zones.
- Four RoW zones are connected by motorways outside the region area.

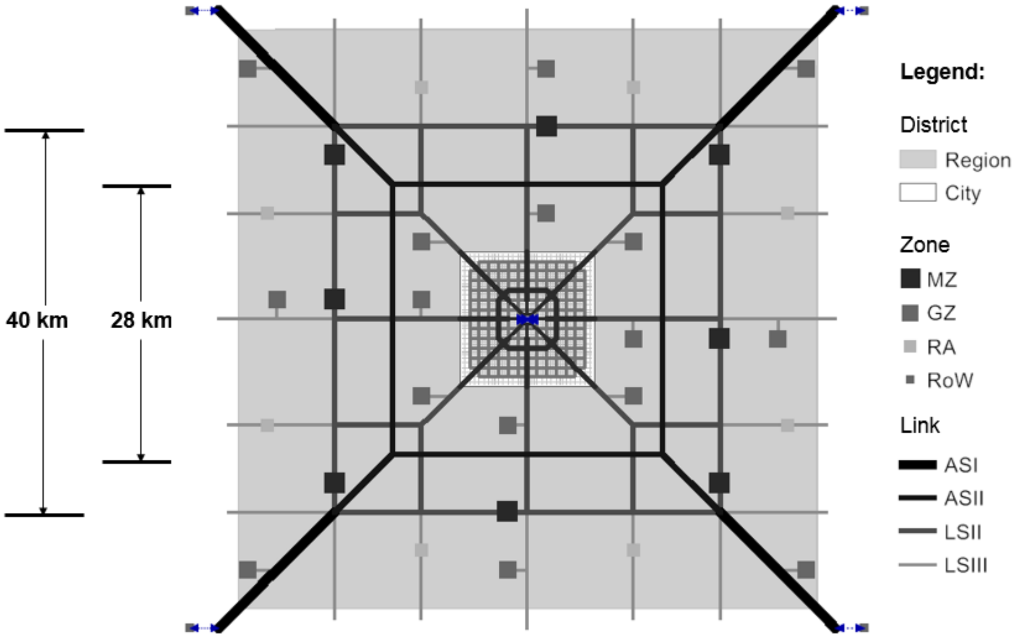


Figure 44: Road network outside the city in VCM.

Compared to the completely modelled road network outside the city area in SCM, only major roads are modelled in VCM. The total length and the density of links in VCM lie below the length and the density in SCM: The road network with a length of 5,800 km in the region of SCM is contrasted by only 1,700 km in VCM. Among all the links for car, LSIII links display the biggest difference: SCM has 4,300 km LSIII links, which is seven times longer than it in VCM (530 km). The motorway displays the opposite characteristics: ASI/II in VCM (520 km) has almost twice the length in SCM (280 km) because of a complete motorway ring around the city in VCM. The motorway outside the region area in SCM is much longer than in VCM, as the modelled area outside the region area in SCM is much larger than the counterpart in VCM.

The calibration of the network in terms of lengths of links outside the city in VCM is described in chapter 4.2.1.

CR-functions

SCM applies a CR-function introduced by Lohse (LOHSE, 1997). The applied form of Lohse CR-functions in SCM is shown in equation 3.2. This form is developed from the basic from of CR-function issued by Bureau of Public Roads (NATIONAL RESEARCH COUNCIL (U.S.), 1985). The advantage of the Lohse CR-function is that the delaying time caused by oversaturation is more realistic, compared to other forms of CR-functions (PTV, 2014).

As shown in equation 3.2, in the case of oversaturation (q/C>1), travel time in the congested network rises linearly with the saturation (q/C) of links. In VCM car travel times in the congested network are calculated with the same Lohse CR-functions as SCM.

$$t_{Con} = \begin{cases} t_0\left(1 + a \cdot (\frac{q}{C})^b\right), & \frac{q}{C} \leq 1 \\ t_0(1+a) + a \cdot b \cdot t_0 \cdot \left(\frac{q}{C} - 1\right), & \frac{q}{C} > 1 \end{cases} \tag{3.2}$$

with $t_{con}, t_0,$ Travel time in congested / free-flow network

$\frac{q}{C}$ Saturation of link: volume (q) divided by capacity (C)

a, b Parameters

The parameters of CR-functions for different link types in VCM are defined according to those in SCM. Since SCM has more link types than VCM, parameters of CR-functions in VCM need to be aggregated from several parameters in SCM. Figure 45 shows the relations between congestion levels and the saturations on links for different link types in VCM, attached with values of parameters for each link type. Based on Figure 45 the following conclusions can be drawn:

- If the volume does not exceed the capacity of a link, the delay times of the link types do not differ considerably.
- In case of the oversaturation, the change of congestion level on rural roads is higher than on urban roads. Among urban roads, the change on major roads is higher than on minor roads. The smallest change occurs on ASI/II links.

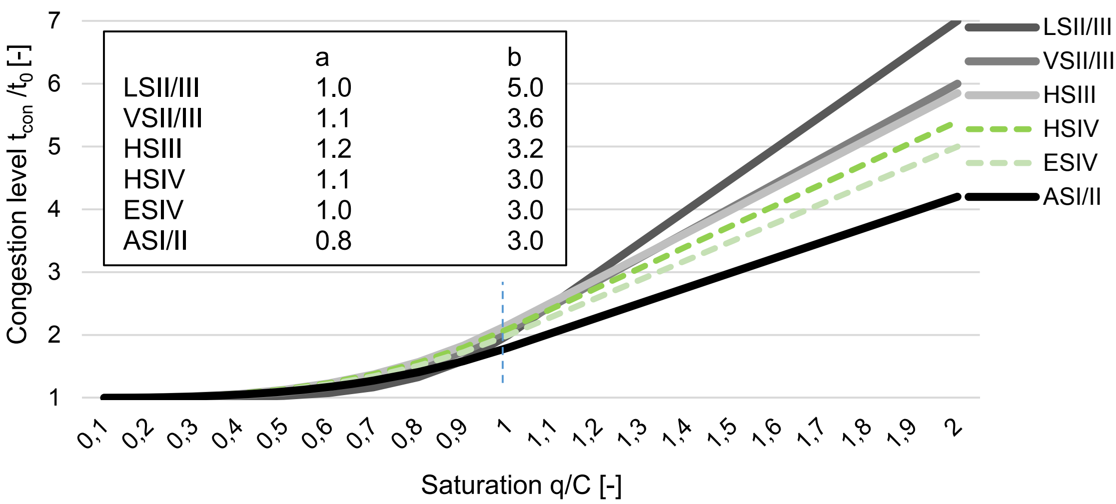


Figure 45: The curves of CR-functions of link types in VCM.

Time penalty of turns

Time loss at intersections is an important factor influencing the travel time, especially in urban traffic. In a network model this time loss is represented by time penalties of turns. Without considering average waiting time at turns in Stuttgart City, the travel time of internal car trips within the city decreases by more than 35%; and in the inner city even by 50%. Given the importance of the average waiting time at turns for car travel time, it is also modelled in VCM.

Average waiting time at turns depends on the basic type of turns (signalized or unsignalized), the type of direction (right, straight, left, U-turn), and the priority rules (from main stream to minor/main stream, etc.). Average waiting time of each lane depends on the volume of this lane and the characteristics of turns and signals. To defined the average waiting time at turns the following principles are considered:

- There is no waiting time at non-turn nodes. The network generated by the network generator tool includes non-turn nodes, especially edge nodes of tiles. These nodes are excluded from the consideration of time penalties at turns.
- There are no signals and thus no waiting time on motorways.
- Waiting time at turns in the region is defined in a way that the share of the total waiting time at turns of the total travel time in the region of VCM matches the one in SCM. The lack of minor roads in the region of VCM is compensated by longer average waiting times at turns of LSII/III links.
- All turns of VSII/HSIII links are signalized.
- All turns in the city of VCM except VSII/HSIII links are unsignalized. Waiting time on major/minor roads differs according to the priority rules: Vehicles from minor directions wait for a relatively longer time than those from major directions. In order to avoid choosing minor roads in the case of time penalties on major roads, a small amount of waiting time is set for all the minor roads in VCM.

Based on the above considerations, turns in VCM are categorized and the following average waiting times are assigned to each category of turns in VCM:

- U-turns: 25 s;
- turns in the region:
  - of ASI/II links: 0 s;
  - of LSII/III links: 60 s;
- turns in the city:
  - of HSIV/ESIV links: 5 s;
  - of VSII/HSIII/HSIV/ESIV links: 20 s (from minor direction), 8 s (from major direction);
  - of VSII/HSIII links: signalized turns (based on equation 3.3, results see Table 16).

Average waiting time at signalized turns of VSII/HSIII links in the city of VCM is calculated following the equation 3.3 based on Handbuch für die Bemessung von Straßenverkehrsanlagen (FORSCHUNGSGESELLSCHAFT FÜR STAßEN- UND VERKEHRSWESEN, 2001). Originally average waiting time at signalized intersections includes both basic waiting time and waiting time of remaining congestion. Only the basic waiting time is considered in VCM pursuing the principle of simplification, as shown in equation 3.3.

$$w = \frac{t_C (1-f)^2}{2\,(1 - q/q_s)} \tag{3.3}$$

with w Average waiting time at an intersection [s]

t_C Cycle time [s]

f Share of green time (green time of a lane/ cycle time at intersection)

q Hourly traffic volume on the referring lane [car/h]

q_s Saturated hourly traffic volume of the referring lane [car/h]

The calculation and evaluation of average waiting times at signalized turns of VSII/HSIII links are shown in Table 16. This calculation is based on the assumed volumes of each stream at a simplified signalized intersection with 4 phases in a cycle time of 90 s and 20 s inter green time.

<table>
<tr><th colspan="2">Type of turn</th><th>q [veh/h]</th><th>q_s [veh/h]</th><th>q/q_s</th><th>Green time [s]</th><th>Cycle time [s]</th><th>f</th><th>w [s] (waiting time)</th><th>LOS</th></tr>
<tr><td rowspan="3">Main stream</td><td>Turn right</td><td>100</td><td rowspan="6">1800</td><td>0.06</td><td rowspan="2">27</td><td rowspan="6">90</td><td rowspan="2">0.30</td><td>23</td><td>A</td></tr>
<tr><td>Straight</td><td>200</td><td>0.11</td><td>25</td><td>A</td></tr>
<tr><td>Turn left</td><td>30</td><td>0.02</td><td>13</td><td>0.14</td><td>33</td><td>C</td></tr>
<tr><td rowspan="3">Minor stream</td><td>Turn right</td><td>30</td><td>0.02</td><td rowspan="2">22</td><td rowspan="2">0.24</td><td>26</td><td>B</td></tr>
<tr><td>Straight</td><td>200</td><td>0.11</td><td>29</td><td>B</td></tr>
<tr><td>Turn left</td><td>30</td><td>0.03</td><td>8</td><td>0.09</td><td>38</td><td>C</td></tr>
</table>

Table 16: Calculation of average waiting time at signalized intersections.

The above introduced values of average waiting times at turns are the results of the calibration of travel time by car in VCM and validation series of “modified car speed”.

3.7.3 Public transport

Design of public transport in VCM does not only require the spatial distribution of stops and lines of PuT transport systems but also the temporal distribution of line services, i.e. the timetable or headway. PuT lines of VCM cannot be defined with the network generator tool, as the continuousness of PuT lines cannot be reached by separate tiles. Therefore PuT lines are developed additionally in the road network. Similar to the PrT network, the PuT network in VCM is also divided into the urban area and the area outside the city with different levels of abstraction.

The PuT network in the city of VCM is designed based on the characteristics of SCM. As stated in the introduction of transport systems in chapter 3.7.1, only heavy rail and light rail are considered in the city of VCM. Figure 46 (a) displays the distribution of stops and PuT lines. Similar to SCM, 12 light rail lines and 6 heavy rail lines are generated in VCM. Following the pattern of PuT lines in Stuttgart City, the light rail network in VCM is a mixture of radial and tangential structures; and all the heavy rail lines in VCM traverse the central area of the city. The length of PuT lines in VCM is determined by the corresponding length in SCM. Compared to SCM, PuT lines in VCM serve large areas due to the symmetric and widely spaced structure. Stops of heavy and light rail systems are located at the edge of zones in VCM. The average distances between stops of heavy rail and between stops of light rail in the inner city are 1 km and 0.5 km respectively; in the peripheral city are 1.5 km and 1 km respectively.

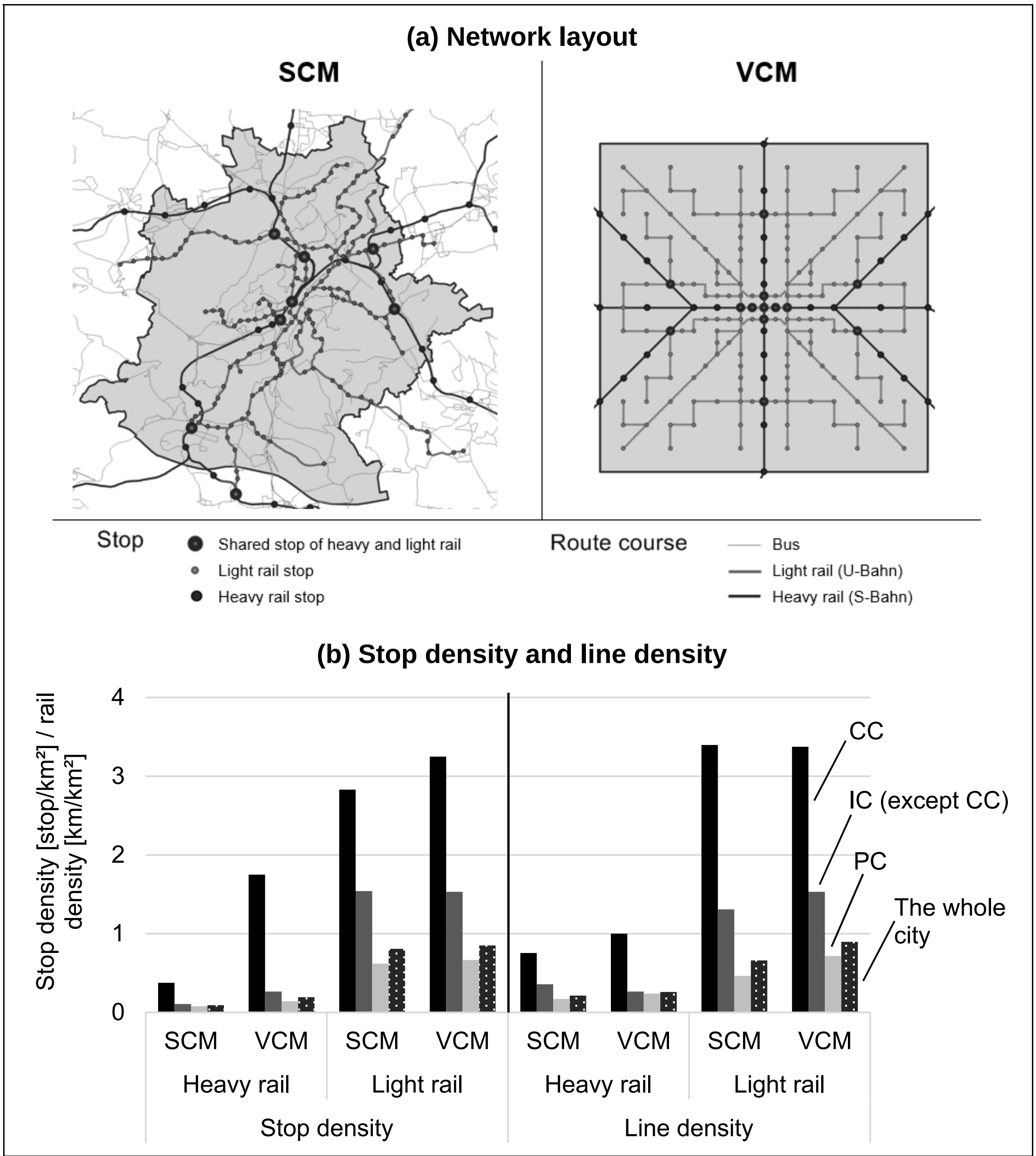


Figure 46: Comparison of PuT networks inside the city of SCM and VCM.

The generated PuT network in the city of VCM is evaluated by two aggregated indicators: stop density and line density. These two densities represent the average number of stops and the length of lines per PuT transport system in an area of 1 km². Figure 46 (b) shows the comparison of stop density and line density for all the three city areas in SCM and

VCM. Both stop density and line density in VCM are comparable to those in SCM. From the city centre to the peripheral city, stop density and line density decrease in both models. However, the density of stops for both heavy rail and light rail systems in the inner city of VCM is higher than it is in SCM. It intends to compensate the lack of densely distributed bus stops in these areas and to provide comparably good PuT service in VCM, as in SCM.

The public transport network outside the city in VCM has a higher level of abstraction than in SCM. Similar to the road network outside the city in VCM, the PuT network outside the city is designed based on connection levels between zones with different central place functions. For example, OZ and MZ zones should be well connected by PuT lines and relatively poor PuT connections are supplied for RA zones.

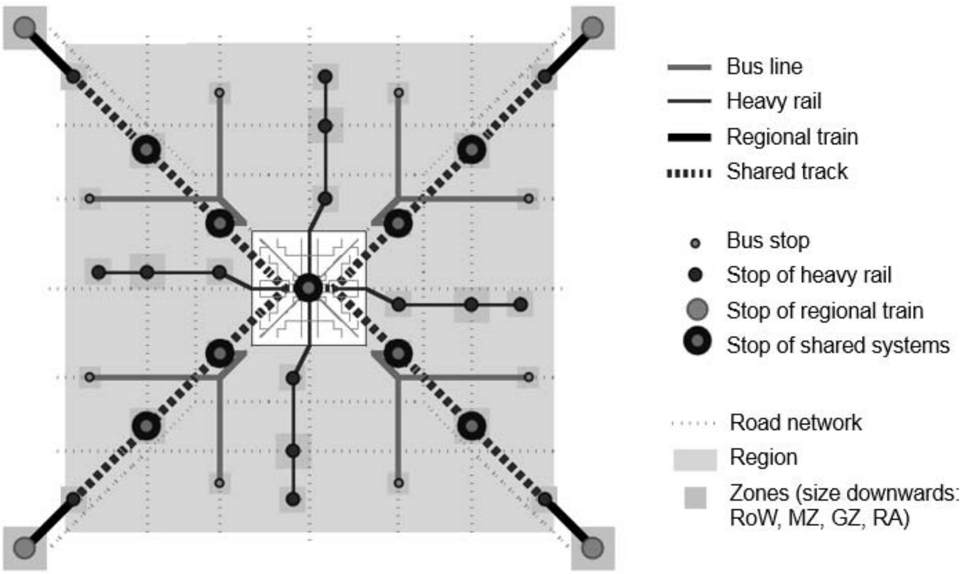


Figure 47: PuT network outside the city in VCM.

The layout of PuT stops and lines outside the city in VCM, together with zones with different central place functions in the region area, is shown in Figure 47. The following characteristics are addressed:

- Stops outside the city are directly located at zone centroids. They provide direct PuT connections.
- Rail-based PuT lines (heavy rail and regional train) run parallel to roads.
- Two regional train lines in the diametrical form connect RoW zones to the main area.
- Six heavy rail lines offer connections between MZ/GZ zones in the region and the city.
  - Four lines in the radial form share rails with regional trains (in the 45° direction),
  - Two lines in the diametrical form run in rectangular directions (horizontal and vertical).
- Eight bus lines supplement rail-based PuT systems and connect RA zones to other areas. Each of these bus lines runs between RA zones and GZ zones near the city.

The comparison of characteristics of heavy and light rail lines in SCM and VCM shows both similarities and differences. These characteristics are listed in Table 17.There are 6 heavy rail lines and 12 light rail lines with more than 200 stops in both SCM and VCM. The following identifications can be extracted from Table 17:

- There are more stops for heavy rail lines in the city of VCM than in the city of SCM, which leads to more widely distributed heavy rail lines. The better PuT quality should compensate the lack of bus lines.
- Due to the higher level of abstraction VCM displays fewer stops in the region than SCM.
- The relation between the length of lines and the length of rails shows the share of the common track. Although the total length of lines in the two models is comparable, the total length of rails in VCM is considerably higher than it in SCM. The share of the common track in VCM is much smaller than in SCM. This shows the more widely distributed lines in VCM than in SCM. The widely distributed services in VCM should compensate the lack of bus lines.

Object	Indicator			SCM		VCM	
Stop	Number of stops…	in the city with the type of…	shared stop	7		13	
			stop for heavy rail	12		25	
			stop of light rail	159		154	
		in the region		77		29	
Heavy rail line	Number of lines			6		6	
	Total length of rails… [km]		in the city	90	380	100	510
			in the region	290		410	
	Total length of lines [km]			530		540	
	Share of the common track			28%		5%	
Light rail line	Number of lines			12		12	
	Total length of rails… [km]		in the city	210	240	350	350
			in the region	30		0	
	Total length of lines [km]			410		460	
	Share of the common track			40%		24%	

Table 17: Profiles of heavy and light rail networks in SCM and VCM.

The public transport includes both spatial distribution (lines routes) and temporal distribution (schedules). Following the principle of simplicity, headways of PuT lines are used to describe the temporal distribution of PuT lines in VCM. Characteristics of timetables in SCM are applied to determine headways in the course of a day in VCM. Table 18 lists these headways for different PuT systems in different time periods. Headways for heavy rail, light rail and regional train during peak hours are shorter than those during off-peak hours. Since bus lines provide PuT connection for RA zones in the region area, their headways are adjusted according to the PuT quality of RA zones, and the difference between peak hours and off-peak hours is inconsiderable.

PuT system	5:00-6:30	6:30-8:30	8:30-16:00	16:00-18:30	18:30-21:00	21:00-5:00
Heavy rail [min]	30	20	30	20	30	(not considered)
Light rail [min]	15	10	15	10	15	
Regional train [min]	60	30	60	30	60	
Bus [min]	30	30	30	30	30	

Table 18: Headways of PuT systems in VCM.

The PuT network of VCM is supposed to represent the PuT network of SCM. However, some different characteristics may lead to significant influences. For example, every heavy rail stop in SCM is connected with at least one bus line. But bus lines is not considered in the city of VCM, thus all accesses and egresses by bus are conducted by PuT walk. As a consequence, VCM may have fewer transfers, shorter ride time, but longer access time than SCM. This effect should be alleviated by the process of calibration. These time-related attributes of PuT network are introduced in chapter 4.2.2.

3.8 Modelling travel behaviour

Modelling travel behaviour is based on the mobility behavioural data of each person group. Travel behavioural data describes trip frequencies, the willingness to spend travel time for certain trip purposes and modal preference. Most of these data in VCM are directly adopted from SCM. The data in SCM are extracted from the database of a household interview survey in Stuttgart Region in 2009/2010 (VRS, 2011). This database is used as inputs for modelling trip generation, for calibrating parameters in SCM. The core components of travel behaviour modelling in VCM are introduced in the following chapters.

3.8.1 Trip generation

Travel behaviour in VCM is built in a tour-based model due to the advantage that it reproduces the daily routine based on activity sequences. The formation of an activity chain and its frequency rate for each person group in VCM are the same as those in SCM. Activity chains with more than three activities are not considered because of implausibility. It is assumed that all the activities are equally important, for example, work has no modelling priority compared to sport.

The total number of generated trips is determined by the number of inhabitants per person groups and the frequency of activity chains. Different person groups perform different characteristics in terms of activity chains. For example, more than 60% of employees with high income perform the activity chain home-work-home, but only 6% of those perform the activity chain home-shopping-home. The same person group in different areas, i.e. inner city, peripheral city and region, also shows different behaviour, especially with respect to mobility rates. Thus, three series of activity chain frequencies in the trip generation model are applied to represent the difference among inner city, peripheral city and region area.

Figure 48 displays mobility rates for selected person groups in VCM. These mobility rates of aggregated activities are summed up from activity chain frequencies. Some characteristics can be addressed, for example, unemployed with car in IC make four trips per day on average whereas unemployed without car in IC make two trips per day on average. Besides, person groups who make work and education trips perform much fewer shopping and service trips, compared to unemployed and retiree. Furthermore, home trips cover fewer than 50% of all the trips due to the home-based activity chain structure and the existence of activity chains with three activities.

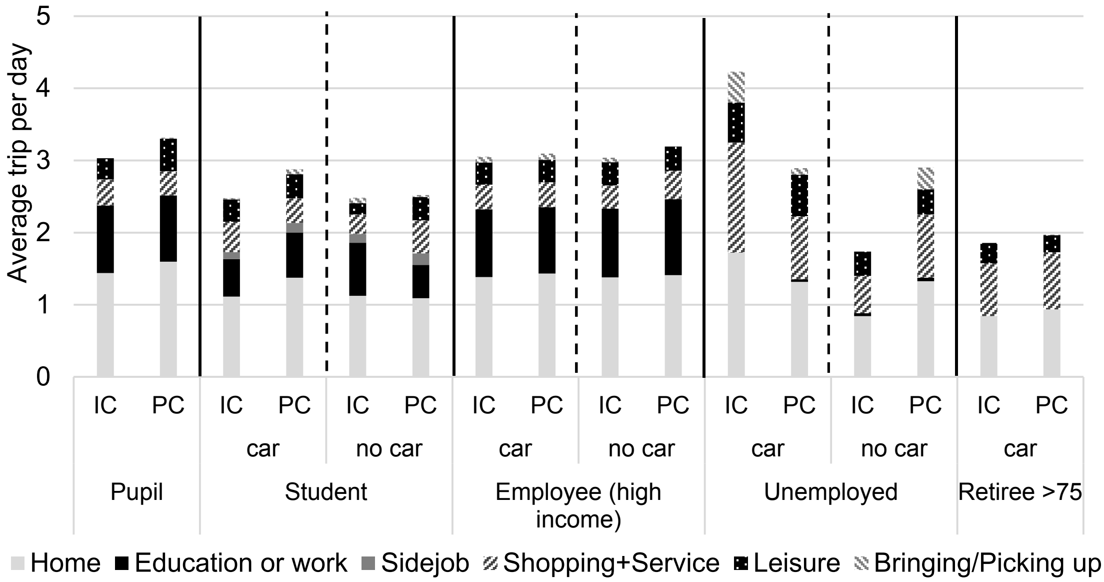


Figure 48: Generated trips of selected person groups by trip purpose.

Since travel demand is distributed not equally over 24 hours, the temporal segmentation of activity pairs is addressed to replicate choice of departure time for each activity. Based on the characteristics from the household interview survey in Stuttgart Region, temporal segmentation is modelled by time series for each activity pair with percentages of hourly travel demand. For example, 85% of home-work (full time) trips perform between 5 and 9 in the mornings. In contract there are only 1% of home-culture trips in this period, while 64% of home-culture trips perform between 5 and 9 in the evening. In total 232 time series for 342 activity pairs (19 activities) are defined in SCM. These time series in SCM are directly applied to VCM.

3.8.2 Destination choice and mode choice

Destination choice and mode choice are modelled simultaneously in VCM. Both choices are modelled with a Logit-Model, as shown in chapter 2.4.4. The equations 3.4-3.7 in SCM (Heidl and Schlaich, 2012) are applied to model destination choice and mode choice in VCM. Their variables and parameters are discussed in the following.

Destination choice

$$F_{g,a,i,j} = O_{g,a,i} \frac{D_{g,a,j} \cdot f_{g,a}(\mathrm{w}_{ij})}{\sum_{z=1}^{Z}(D_{g,a,z} \cdot f_{g,a}(\mathrm{w}_{iz}))} \tag{3.4}$$

$$f_{g,a}(\mathrm{w}_{ij}) = \exp\left(\beta_{g,a}\left(-\ln \sum\nolimits_{m} \exp(U_{m,g,a,i,j})\right)\right) \tag{3.5}$$

Mode choice

$$U_{m,g,a,i,j} = -C_{m,g,a} - p_{1,m} \cdot JT_{m,i,j} - p_{2,m} \cdot \mathrm{AET}_{m,i,j} - p_{3,m,g,a} \cdot TC_{m,i,j} - p_{4,g,a} \cdot \mathrm{PC}_{i,j} - p_5 \cdot \mathrm{WT}_{i,j} - p_6 \cdot \mathrm{NoT}_{i,j} - p_7 \cdot \ln(DD_{i,j}) \tag{3.6}$$

$$F_{g,a,i,j,m} = F_{g,a,i,j} \frac{\exp(\alpha \cdot U_{m,g,a,i,j})}{\sum_{m=1}^{M}(\exp(\alpha \cdot U_{m,g,a,i,j}))} \tag{3.7}$$

with		
Index	i, j	Indices of origin zone i and destination zone j
	g, a	Indices of main person group g (excluding child) and activity a
	z, Z	Indices of traffic zone, Total number of zones.
	m, M	Indices of modes, Total number of modes.
Parameter	$\beta_{g,a}$	Parameter of the destination choice function
	$p_1 \dots p_7$	Parameters of mode choice utility function
	$C_{m,g,a}$	Parameter (Constant) of mode choice utility function
	α	Parameter of mode choice
Variable of transport supply	$JT_{m,i,j}$	(Walk, ride, in-vehicle) time of mode m
	$\mathrm{AET}_{m,i,j}$	Access and egress time of mode m
	$TC_{m,i,j}$	Travel cost of mode m (gasoline cost or PuT ticket)
	$\mathrm{PC}_{i,j}$	Parking cost of car (for both work and other purposes)
	$\mathrm{WT}_{i,j}$	Waiting time of PuT (start waiting time, transfer walk and waiting time)
	$\mathrm{NoT}_{i,j}$	Number of transfer of PuT
	$DD_{i,j}$	Direct distance between i and j
Impedance	$f_{g,a}(\mathrm{w}_{ij})$	Impedance function
	$U_{m,g,a,i,j}$	Utility value of mode m
Travel demand	$F_{g,a,i,j}$	Trips
	$F_{g,a,i,j,m}$	Trips of mode m
	$O_{g,a,i}$	Produced trips in origin zone i
	$D_{g,a,j}$	Attracted trips in destination zone j

The two variables of travel demand for destination choice modelling, i.e. $O_{g,a,i}$ and $D_{g,a,j}$, result from the trip generation model. The impedance function of the destination choice model uses the logsum of all modes, i.e. it considers the sum of evaluated utilities overall models. In this way destination and mode choices are modelled simultaneously considering the interdependencies between the two steps. It offers the comprehensive consideration of influences of all the modes on the destination choice for each od-pair (HEIDL and SCHLAICH, 2012). The only parameter β in the impedance function describes the influence of utility values on the destination choice and is estimated based on the survey data of Stuttgart Region. The result of the destination choice model is a trip table, which can be disaggregated by trip purpose or person group. Destination choice model determines travel distances and travel times of od-pairs by establishing locations of trip destinations.

The mode choice is based on the trip table resulting from the destination choice model, the parameter α and utility functions of each mode. Similar to β in destination choice modelling, α describes how the utility of each mode influences mode choice. Utility functions have seven transport supply variables and eight parameters. Not all the variables in the utility function are applied to every mode. For example, cost-related variables are only relevant for car and PuT. The variables are aggregated values of all routes for an od-pair. All these variables in VCM are calculated and calibrated in reference to SCM so that VCM can reach reasonable results in the mode choice. The calibration of these distance-, time- and cost-related variables is introduced in chapter 4.2.

Parameters in utility functions determine the degree of importance for variables of the mode choice. The estimation of parameters in SCM is based on the observed travel behaviour data from the household interview survey in Stuttgart region with the maximum-likelihood-estimation method (HEIDL and SCHLAICH, 2012). Parameters in SCM are directly applied to VCM. Table 19 lists all the parameters in the utility function (in equation 3.6) of mode choice.

<table>
<tr><th>Parameter for</th><th>Walk</th><th>Bike</th><th>Car driver</th><th>Car passenger</th><th>PuT_single</th><th>PuT_season</th></tr>
<tr><td>Constant</td><td>7.9-10.8</td><td>1.2 – 4.0</td><td>0.04 – 3.0</td><td>0.6 – 10.4</td><td>7.9 – 10.8</td><td>7.2 – 11.2</td></tr>
<tr><td>JT</td><td>0,13</td><td>0,13</td><td colspan="2">0.06</td><td colspan="2">0.07</td></tr>
<tr><td>AET</td><td rowspan="6">-</td><td>0.13</td><td colspan="2">0.13</td><td colspan="2">0.08</td></tr>
<tr><td>TC</td><td rowspan="5">-</td><td colspan="2">0 – 1.04</td><td>0 – 1.19</td><td>0 – 0.59</td></tr>
<tr><td>PC</td><td colspan="2">0 – 5.61</td><td colspan="2">-</td></tr>
<tr><td>WT</td><td colspan="2" rowspan="3">-</td><td colspan="2">0.11</td></tr>
<tr><td>NoT</td><td colspan="2">0.12</td></tr>
<tr><td>DD</td><td colspan="2">-0.99</td></tr>
</table>

-: not related (variable not for the according mode).

Table 19: (Range of) parameters in the utility functions of mode choice.

The parameters in utility functions have the following characteristics:

- Parameters for time- and distance-related variables are equal over all person groups and activities.
- Parameters for cost-related variables differ between activities and person groups.
- Cost parameter and the constant are used to differentiate PuT with single ticket and PuT with season ticket.
- The constant parameters model the preferences of different person groups for choosing various modes for different trip purposes. For example, car (driver) is more preferred to PuT, as the constant of car (driver) is much smaller than of PuT.
- The parameter values show the influence of variables on utility. For example, given an increase of 1 min for JT or AET of car, the influence of AET on utility is more significant (+0.07) than of JT.
- Some variables are only relevant for PuT, i.e. WT (waiting time), NoT (number of transfers) and DD (direct distance). DD does not describe PuT characteristics, however, the negative parameter for the natural logarithm of DD represents the preference to use PuT for longer-distance trips.

3.8.3 Route choice

As stated in route choice sub-model (see chapter 2.4.4), private transport and public transport apply different route choice models. VCM applies the same assignment method for private transport, but different method for public transport, compared to SCM. These methods are introduced in the following.

It is assumed that travellers in VCM have complete information about their alternatives. Thus, deterministic user equilibrium assignment based on Wardrop's first principle is applied in VCM for modelling route choices. It indicates a stable state that all the chosen routes have equal and minimum impedance. The impedance is represented by the impedance function in the route choice model. Different from calibration of parameters in the impedance function of model choice with statistic data, parameters in impedance functions are estimated based on empirical values, as the observation of route choice in reality is generally unavailable (FRIEDRICH, 2013).

Impedance functions of route choice model in SCM are applied in VCM, as shown in equation 3.8. The following impedance function is applied to all the PrT transport systems and to all the relevant network objects links, turns and connectors. The single variable t_{con} is calculated based on CR-functions (see chapter 3.7.2). The volume on each link, which influences t_{con}, is a result of an iterative process of the equilibrium (Lohse) assignment. This assignment method replicates the learning process of travellers in a way that the next route search considers the former knowledge gained by using roads (PTV, 2014).

$$W_{PrT,a} = 100 \cdot \mathrm{t}_{con} \tag{3.8}$$

with $W_{PrT,a}$ Impedance of route a (PrT)

t_{con} Ride time in the congested network of route a

Route choice for PuT in VCM searches connections, i.e. route and departure time, per headway assignment, and then the PuT demands are distributed by the Logit-Model with the definition of an impedance function. PuT trips in SCM are assigned to the network with a timetable-based assignment. Headway-based assignment in VCM shortens the calculation time at the cost that the start waiting time and transfer time cannot be calculated rightly and comparably as in SCM.

Temporal segmentation of PuT trips is considered for assigning PuT trips to the network, as PuT travel demand varies in the course of a day. In SCM, PuT travel demand in peak hours is calculated from the travel demand model and the rest of PuT travel demand is determined based on the percentages, as shown in Table 20. The time intervals of PuT demand are identical to those for headways of PuT supply. The results of the generated PuT trips for each time interval in SCM are directly applied to VCM with a form of percentage values, as shown in Table 20. This method of temporal segmentation in VCM ensures the requirement of simple structure of VCM.

Time interval	**SCM (matrices)**		**VCM (percentage)**
	1st step	**2nd step**	
5:00-6:30		Rest of trips*10%	6%
6:30-8:30	Calculated from travel demand model		17%
8:30-16:00		Rest of trips*70%	44%
16:00-18:30	Calculated from travel demand model		20%
18:30-21:00		Rest of trips*20%	13%

Table 20: Temporal segmentation of PuT trips in both models.

The impedance for PuT is the perceived journey time and it is calculated with equation 3.9. Parameters in the impedance function represent passengers' preference. For example, the tolerance of one minute waiting time is higher than a transfer, as one min waiting time equals two minutes journey time whereas a transfer represents eight minutes journey time for a passenger using PuT systems.

$$W_{PuT,a} = JT_a + 2 \cdot \mathrm{AET}_a + 2 \cdot \mathrm{WT}_a + 8 \cdot \mathrm{NoT}_a \tag{3.9}$$

with $W_{PuT,a}$ Impedance of route a (PuT)

JT_a In-vehicle time of route a

AET_a Access and egress time of route a

WT_a Waiting time of PuT (start waiting time, transfer walk and waiting time) of route a

NoT_a Number of transfer of PuT of route a

4 Calibration and Validation of VCM

4.1 Overview

The VCM resulting from chapter 3 is developed with the reference to the characteristics of SCM in terms of zones, person groups and activities, the land use structure, the transport supply and the travel behaviour. Nonetheless VCM has still different characteristics compared to SCM, such as average travel distances and times on the level of od-pairs. Such differences are corrected in the calibration process. The calibrated VCM should then reproduce the characteristics of the reference model in the current state of the transport supply and the land use. The subsequent validation process evaluates the capability of VCM to represent SCM under different conditions. These two processes ensure VCM to generate reasonable results and to be applied for the further research.

Calibration of a model in a usual way is a process of adjusting model parameters in a way that the modelled results are close to the measured values of reality. The parameters of VCM are introduced in chapter 3.8. The modelled results are represented by indicators such as the total distance and time travelled. However, the calibration process of VCM is different from the usual calibration. Firstly, the characteristics of VCM are not compared with measured values but with the modelled values in SCM. Secondly, variables in VCM instead of parameters should be calibrated. Because all the parameters in VCM are directly reproduced from SCM representing behavioural preferences and choices, variables of land use structure and transport supply should be calibrated in order to generate the same travel demand indicators in VCM as in SCM.

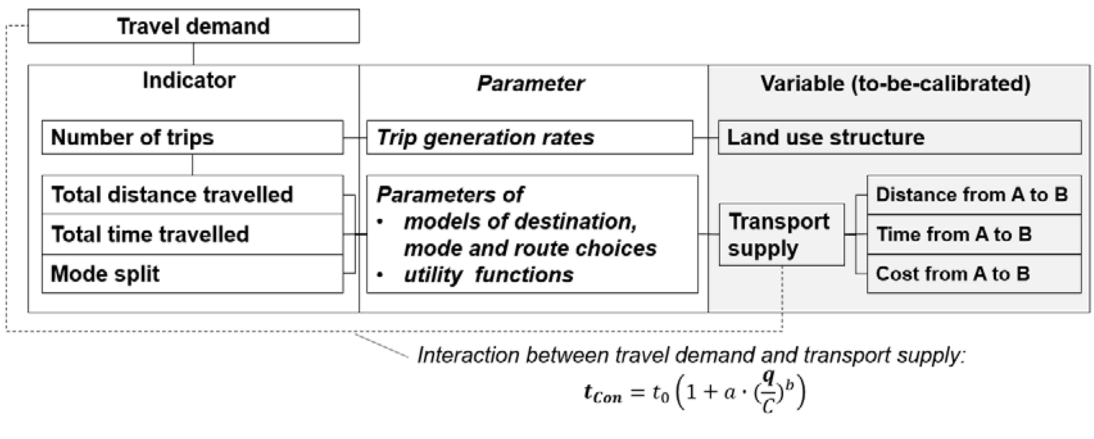


Figure 49: Travel demand indicators, parameters and to-be-calibrated variables in VCM.

The relation between main indicators of travel demand, fixed parameters and the variables that should be calibrated in VCM are shown in Figure 49. All the variables in VCM are subject to calibration. Variables of transport supply are classified further into distance-, time- and cost-related variables. They are examined on the level of od-pairs and represented by skim values (see chapter 2.4.2). Congested travel time by car is a variable in utility functions and influences travel demand indicators. The travel demand on the network influence the congested travel time. This interdependence is described by CR-functions, as indicated in Figure 49.

Not all these variables in VCM are similar to those in SCM due to different aggregation levels of zoning and network modelling in the region area. Hence, not all the indicators of travel demand in VCM can be calibrated, such as the travel distance in the region area. Table 21 lists the indicators of calibration disaggregated by type of od-pairs. Six types of od-pairs are addressed based on the spatial division, as stated in chapter 3.1. Based on whether the trip destination and the origin are located in the same zone, intra-zonal and inter-zonal od-pairs are classified. The most important indicators include number of trips, modal split, and arithmetic mean skim values. The arithmetic mean skim value (also: average value) weighted with the demand of od-pairs is an important aggregated indicator. These indicators should be calibrated for all types of trips except RoW-RoW trips, as RoW-RoW trips in VCM serve only the purpose to provide the appropriate congestion level of the network in the main area. The frequency distribution of skim values in both models can only be compared for internal trips in the city, as only the city area in both models has the comparable aggregation level of zoning.

Type of od-pair	**Number of trips**	**Modal split**	**Average skim values of…od-pair**			**Frequency distribution of skim values (trip-weighted)**
			all	**intra-zonal**	**inter-zonal**	
C-C	yes	yes	yes	yes	yes	yes
C-R	yes	yes	yes	-	yes	no
R-R	yes	yes	yes	no	no	no
R-RoW	yes	yes	yes	-	yes	no
C-RoW	yes	yes	yes	-	yes	no
RoW-RoW	no	no	no	no	no	no

yes: necessary for the calibration; no: not necessary for the calibration; -: not relevant.

Table 21: Indicators of calibration in VCM.

The calibration process for inter- and intra-zonal od-pairs is different. Variables of inter-zonal od-pairs are calculated based on characteristics of the network. Thus, the calibration of inter-zonal od-pairs requires adjustments of the network, for example, length, speed and capacity of links, as well as stop time of stops. Different from inter-zonal od-pairs, variables of intra-zonal od-pairs are determined by the modeller according to the characteristics of zones. Intra-zonal variables in the city of VCM are determined with the reference to intra-zonal variables in the city of SCM; and intra-zonal variables in the region of VCM are determined in a way that the average skim values of all R-R od-pairs in VCM are comparable to those in SCM.

The calibration follows the spatial sequence “city-region-RoW” as well as the skim sequence “distance-time-cost”. Frequency distribution of skim values for C-C od-pairs is evaluated as the first step. The network in the city is adjusted for C-C od-pairs. Further adjustments of the network and of land use structure in the region area are mainly responsible for C-R and R-R trips. For these trips, only the average skim values are evaluated. Characteristics of motorways and commuting trips are the main determinant for both C-RoW and R-RoW od-pairs. For all the od-pairs, distance-related skim values are calibrated at first by adjusting length of links, followed by travel time, which depends on not only distance but also other variables, such as speeds and waiting time for PuT. The cost for car is also distance-dependent, whereas the cost for PuT is defined in a tariff model.

The characteristics of transport supply are evaluated by frequency distribution of skim values not weighted with trips; whereas the evaluation of travel demand is conducted by the frequency distribution of skim values weighted with C-C trips, and the average skim values weighted with trips of different od-pairs. The calibration of transport supply are introduced in chapter 4.2, and the calibration of trips is introduced in chapter 4.3.

Validation serves for identifying fundamental errors with methods such as comparison of model results with unused measured values, plausibility tests or sensitivity tests. VCM is validated with series of sensitivity tests that examine how a model reacts to a specific change. In these sensitivity tests, the same change in transport supply or land use structure is applied to both VCM and SCM. The reaction results of VCM are then compared to the reaction results of SCM. If the results of both models are similar, VCM is successfully validated. Otherwise VCM need to be corrected in an iteration process up to the similarity of results. Two sensitivity tests in both transport supply and land use structure with their final results are introduced in chapter 4.4. GEH values are applied to evaluate differences of modelled values and target values in the validation process. It is calculated according to equation 4.1. The smaller a GEH value is, the closer the pair of comparing values is. In this work, values in VCM are M and values in SCM are C.

$$GEH = \sqrt{\frac{2 \cdot (M - C)^2}{M + C}} \tag{4.1}$$

with M Modelled value

C Real-world value

The characteristics of the calibrated and validated VCM are summarized in chapter 4.5.

4.2 Calibration of transport supply

4.2.1 Travel distance

Distance on the level of od-pairs is a basic characteristic of transport supply. It directly influences the travel time of od-pairs, and accordingly destination and mode choices. It determines the total distance travelled in combination with travel demand. The distance of inter-zonal od-pairs and distance of intra-zonal od-pairs are introduced in the following.

Distance of inter-zonal od-pairs

Distance of inter-zonal C-C od-pairs in VCM should be calibrated to have the comparable frequency distribution as in SCM. An appropriate frequency distribution of direct distance of inter-zonal od-pairs is the prerequisite of a correct frequency distribution of distance. As shown in the evaluation of zoning of the city in chapter 3.4, the frequency distribution of direct distance in the city of VCM is comparable to that of SCM. Based on the appropriate direct distance, distance of inter-zonal od-pairs depends on the configuration of the networks, such as the lengths of links.

The relation between direct distance and distance is defined by the indicator detour factor of od-pairs. The detour factor on the level of od-pairs is defined as the ratio of distance and direct distance of od-pairs. The frequency distribution of the detour factor for C-C od-pairs in VCM does not match to the one in SCM. As shown with the dashed curve in Figure 50, urban network in VCM offers more direct od-pairs than SCM. Detour factor values of od-pairs in SCM range from 1.1 to 2.4 and are distributed in an average way, whereas those in VCM are between 1.0 and 1.6 with a peak of 35% in detour factor class 1.1-1.2. This difference of distance distribution is calibrated by adjusting the length of links of the network model. The distribution of detour factor of od-pairs in VCM after calibration matches it in SCM, as shown in Figure 50.

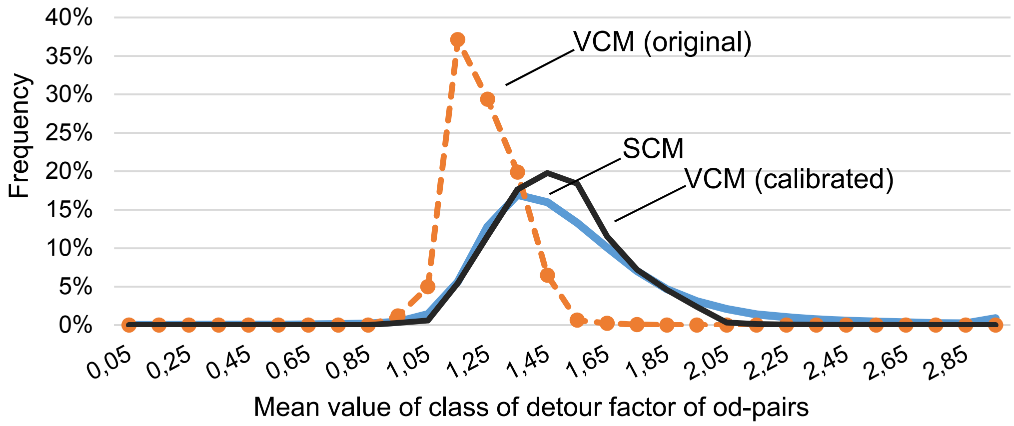


Figure 50: Frequency distribution of detour factor of od-pairs within the city.

With the help of a schematic representation of an od-pair in SCM and VCM, as illustrated in Figure 51, the reason why the distance of od-pairs in VCM is different from it in SCM can be addressed. The network form of SCM leads to high detour factors because of the topography and irregularly distributed land uses. Roads have to be adjusted to the distribution of built-up or natural barriers such as factories, parks, rivers and forests. VCM has neither irregular topography nor big land uses, thus VCM generates relatively direct connections with straight links. In order to increase the travel distance of od-pairs without changing the network structure of VCM, the detour factor of links is adjusted.

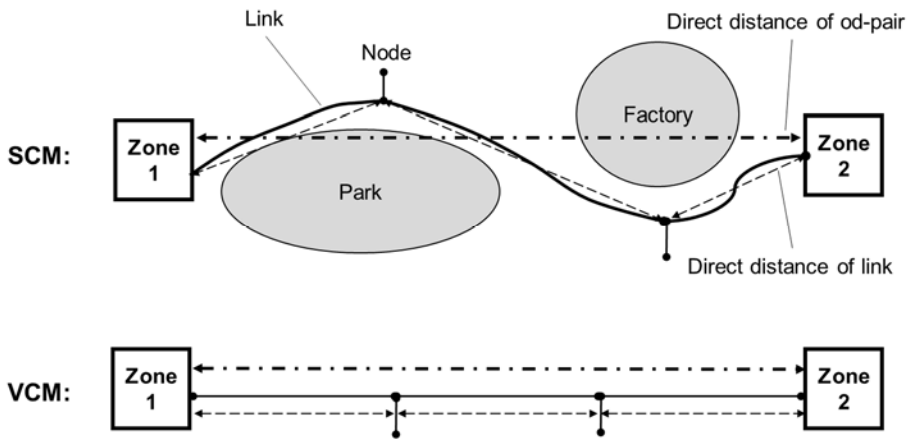


Figure 51: Schematic representation of an od-pair in SCM and VCM.

Similar to the detour factor of od-pairs, the detour factor of links describes the relation between the length and the direct length of a link. Detour factor values of most links in SCM are smaller than 1.1, as illustrated in Figure 51. The concept of applying the detour factor of links in VCM is that it represents the natural curve of roads and compensates the regular network structure. Based on this concept a detour factor value is assigned to each link. The following methods are tested to the links in the city area of VCM:

- Assigning a constant detour factor value to all links.
- Assigning a random detour factor value between 1.1 and 1.4 to all links.
- Assigning four different detour factor to the links in each of the four square quarters.

The above three methods of assigning detour factor values to links lead to different frequency distributions of distance of od-pairs:

- A constant detour factor for all the links leads to poor results, as it shifts the curve of the original detour factor in Figure 50 parallel to the right. However, the distribution still has the same low standard deviation.
- Randomly generated detour factors are able to generate a good distribution of distance of od-pairs. Nonetheless, it is impossible to reproduce the same calibrated result because of the randomness. Thus, this method is not applied in VCM.
- Quarter-based detour factors decrease the regularity of the urban structure in VCM by differentiating four quarters. They lead to the similar frequency distribution of distance in VCM as in SCM.

The quarter-based detour factors are applied to VCM, as this method is able to model the diversity of urban structures. For example, a quarter with a high link detour factor represents a network structure with many large building blocks or natural barriers. The detour factor values in square quarters of the city are shown in Figure 52: clockwise from the quarter at the top left, the quarter-based detour factors are 1.0, 1.1, 1.3, and 1.4. The calibrated curve of VCM in Figure 50 is generated applying these values.

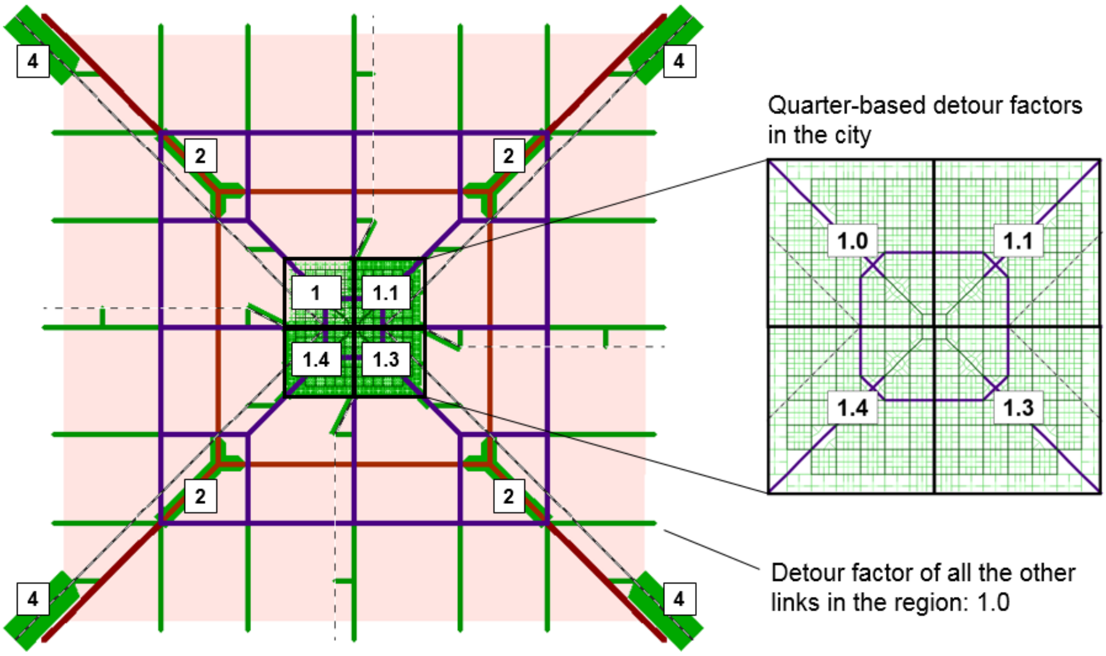


Figure 52: Detour factors of links in VCM.

The frequency distribution of distance for other od-pairs except C-C in VCM is not comparable to the one in SCM due to different zoning aggregation levels. For other od-pairs, only the average distance weighted with trips is applied for evaluation. Figure 53 shows the average distances both by car and PuT for four od-pair types in SCM, VCM before calibration and VCM after calibration. These resulted distances are weighted with the number of trips which result from the calibration of land use structure.

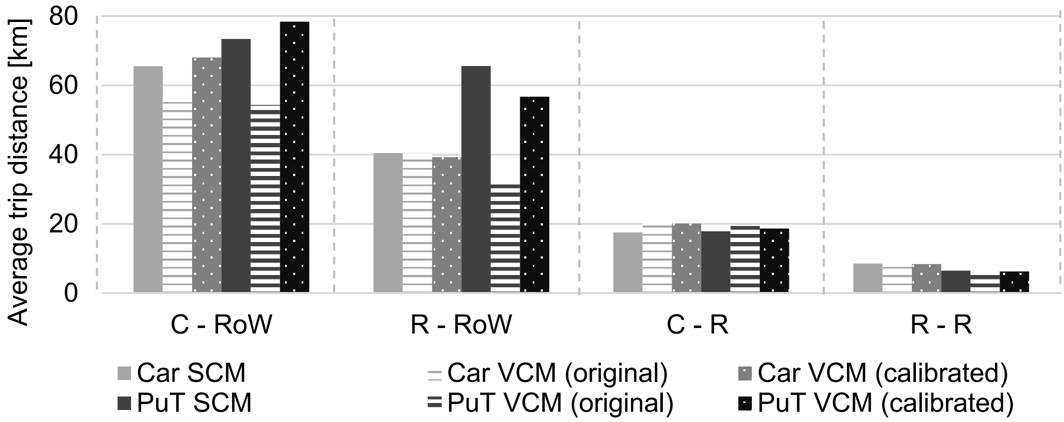


Figure 53: Average trip distances per mode of od-pairs except C-C.

As shown in Figure 53 VCM has shorter distance for car C-RoW trips, and shorter distance for PuT C-RoW and R-RoW trips. Adjusting the detour factors of selected links solves this problem of shorter distances in VCM. The principle of adjusting detour factors for car trips is that the distance for C-RoW trips should be extended without R-RoW trips being stretched. Thus, the motorway in the middle of the region is assigned with the detour factor of two, as shown in Figure 52. The principle of adjusting detour factors for PuT trips is that the distance for C-RoW and R-RoW trips should be both extended without influencing C-R trips. Hence, railway near RoW has the detour factor of four, as shown in Figure 52. The results of this calibration are shown in Figure 53. The calibrated average distances for these four types of trips in VCM are comparable with those in SCM.

Frequency distribution of walk distance between the two models is still different due to differences of network: a separated network for walking is modelled in SCM, whereas all the PrT modes share the same network in VCM. Thus car trips have the same length as non-motorized trips in VCM; whereas the length of motorized trips differs considerably from the one of non-motorized trips in SCM. In SCM the average distance of walk trips within the city is 300 m, whereas it is 500 m in VCM. Figure 54 shows the frequency distribution of walk distance for C-C od-pairs: 1% of od-pairs in VCM have a walk distance smaller than 1 km, whereas there are 3% in SCM. Walk distance should be calibrated, as walk distance influences walking time and share of walk trips. Instead of rebuilding a walk network in VCM, the skim matrix of walk distance is directly modified. To simulate od-pairs whose walk distance is shorter than car distance in VCM, walk distance for C-C od-pairs is shortened in the following two ways:

- For the od-pairs with walk distance shorter than 1 km, walk distance is set to be 25% of the car distance;
- For the od-pairs with walk distance longer than 1 km, walk distance is set to be 0.45 km shorter than the car distance.

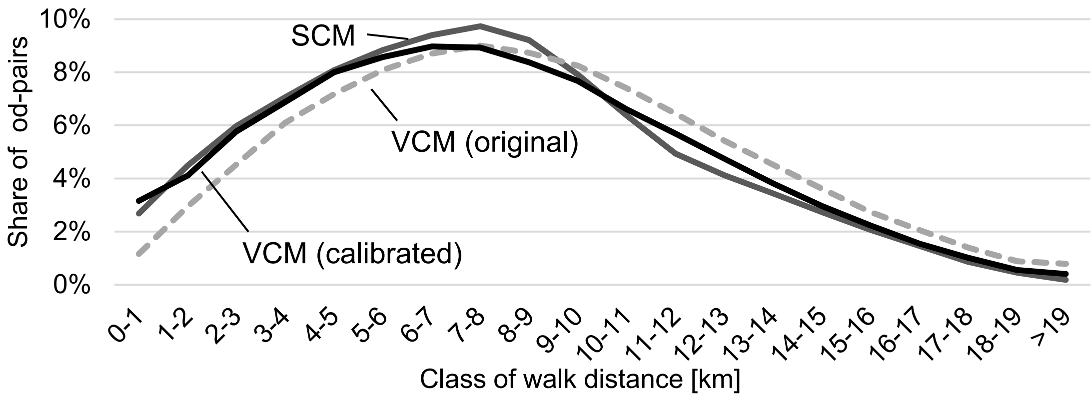


Figure 54: Distribution of walk distance of od-pairs within the city.

With the above two adjustments, walk distance for C-C od-pairs in VCM matches it in SCM, especially for short distance (0-2 km), as shown with the curve of VCM (calibrated) in Figure 54. Inter-zonal distance within the region in VCM is too long to be walked due to the big size of zones in the region. Thus, walk distance in the region is determined by the intra-zonal distance, introduced in the following sub-chapter.

Distance of intra-zonal od-pair

Intra-zonal distance represents the distance of trips within a zone. The characteristics of zones (e.g. size of zones) are considered in determining the distance of intra-zonal od-pairs. For the region area the relationship between intra-zonal distances and inter-zonal distances are also considered.

Intra-zonal distance in the city of VCM mainly depends on the size of zones. Figure 55 (a) shows the intra-zonal distance of all the modes in relation to the area of zones in the city of SCM with continuous grey points. Small-scale zones (<0.3 km²) have a constant average distance of 50 m, as differences are so insignificant that they can be ignored. For bigger zones (>0.3 km²), the intra-zonal distance increases with the area of zone according to the equation in Figure 55 (a). This equation is based on the assumption that each zone is looked upon as a form of circle and the average trip distance is one third of the radius of a zone. These equations are applied in the city of VCM. In contrast to the high diversity of zone size in SCM, the city of VCM has only six sizes of zones. The corresponding intra-zonal distances of these zones are shown in Figure 55 (a) with the six black points.

The intra-zonal distance in the region of VCM is different from the one in the city area. The aggregation levels of areas outside the city in VCM and SCM are different. Due to this aspect the intra-zonal distances in SCM and VCM cannot be compared. For example in SCM 40% of R-R car trips are shorter than 5 km and 98% of R-R walk trips are within 2 km distance. However, the minimum distance of inter-zonal od-pairs in the region of VCM is 5 km because of the large size of zones. The design of the region area in VCM fails to replicate short-distant inter-zonal od-pairs. Thus, these short-distance trips in SCM should be modelled as intra-zonal trips in VCM. Almost all walk and bike R-R trips should be modelled as intra-zonal trips in the region area.

The following aspects are considered in adjusting the distance values:

- The average distance for all R-R trips (both inter- and intra-zonal trips in the region);
- The share of both walk and bike trips for all R-R trips;
- The relationship of R-R trips and C-R trips.

Intra-zonal distance values in the region area result from the calibration considering the above aspects. These values for each mode in each type of zones are shown in Figure 55 (b) with the following characteristics:

- In general zones with higher central place function have shorter trip distances, as zones with higher central place function are assumed to provide more mixed land uses with a higher density.
- Car distance are identical to PuT distances, and car/PuT distance is much longer than the one of non-motorized modes.
- Bike distances are 1.8 times longer than walk distances.

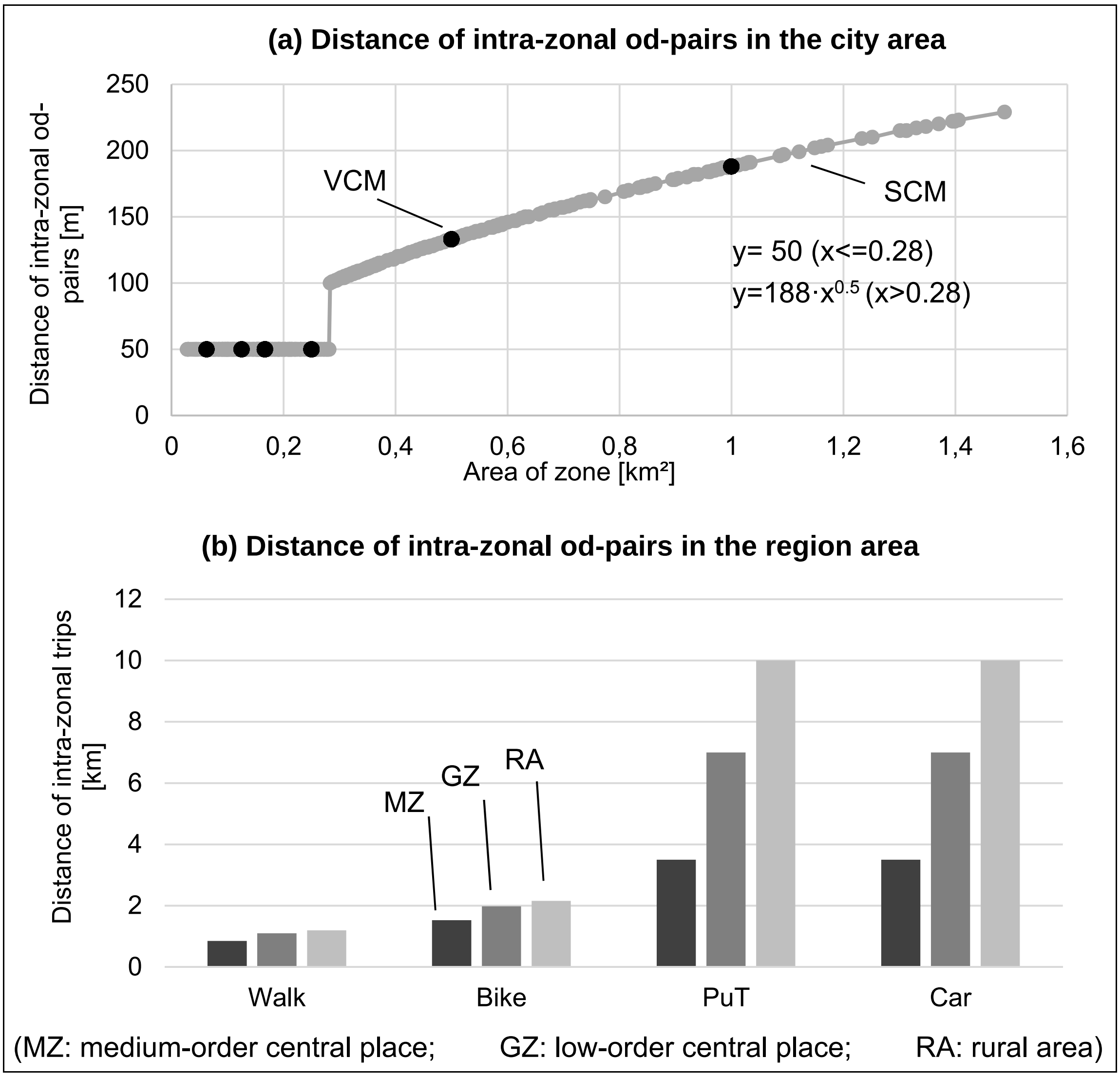


Figure 55: Distances for intra-zonal od-pairs in VCM.

4.2.2 Travel time

Travel time of od-pairs determines travel time expenditure (veh·h) together with the travel demand. Travel time is composed of the following relevant time components for different modes:

- Walking time (for walk) or ride time (for bike, car and PuT),
- Access/egress time (for bike, car and PuT),
- Waiting time (only for PuT).

As a main part of travel time, walk or ride time of inter-zonal od-pairs is calculated by summing up times on all network elements (links, connectors, and turns) of routes for od-pairs. Walk or ride time of each link depends on the adjusted length of links and speed of each transport system. In contrast to the network-based time of inter-zonal od-pairs, walk or ride time of intra-zonal od-pairs is determined by the adjusted intra-zonal distance and the defined speed.

The above listed time components are calibrated, so that travel time of od-pairs in VCM replicates the one in SCM. The procedures and methods of travel time calibration of walking, biking, by car and of PuT are introduced in the following paragraphs.

Walking time

Walking time is calculated from the adjusted walk distance values of od-pairs and walk speed (5 km/h). The frequency distribution of walking time for C-C od-pairs indicates that VCM has fewer od-pairs with relatively long walking time compared to SCM.

To calibrate this difference, walking time values of selected od-pairs are multiplied with a parameter. This calibration method is also applied in SCM. Walking time for C-C od-pairs from or to the inner city is prolonged, as these od-pairs offer the best opportunity to be covered by walking. This prolongation simulates waiting times caused by traffic lights at intersections in the inner city. After doubling all the walking times of od-pairs from or to the inner city, walking time in the city of VCM has similar characteristics as the one of SCM. The frequency distribution of the calibrated walking time of C-C od-pairs, together with travel times of other modes, is shown at the end of chapter 4.2.2.

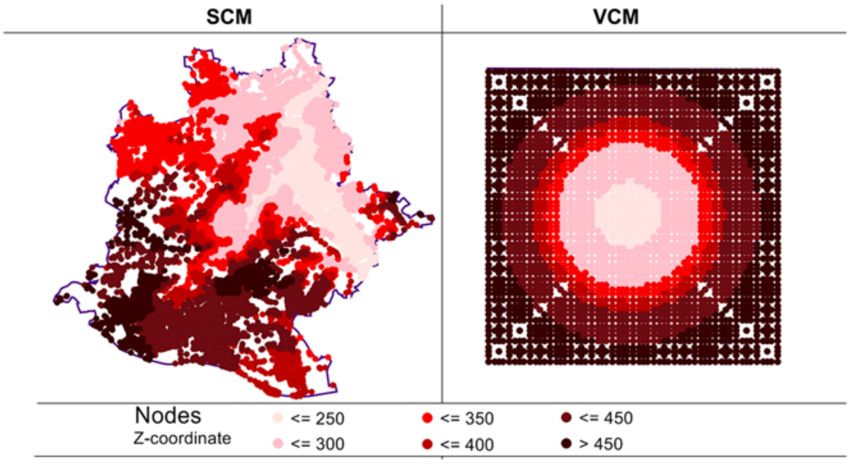
Bike time

Bike time consists of access time, ride time, and egress time. Given the adjusted bike distance, bike speed needs to be determined. A constant bike speed fails to model the proper bike time, as bike time in SCM depends on topography. In order to model comparable bike time in VCM as in SCM, topography is also considered in VCM by means of defining the height of nodes and the according slope of links.

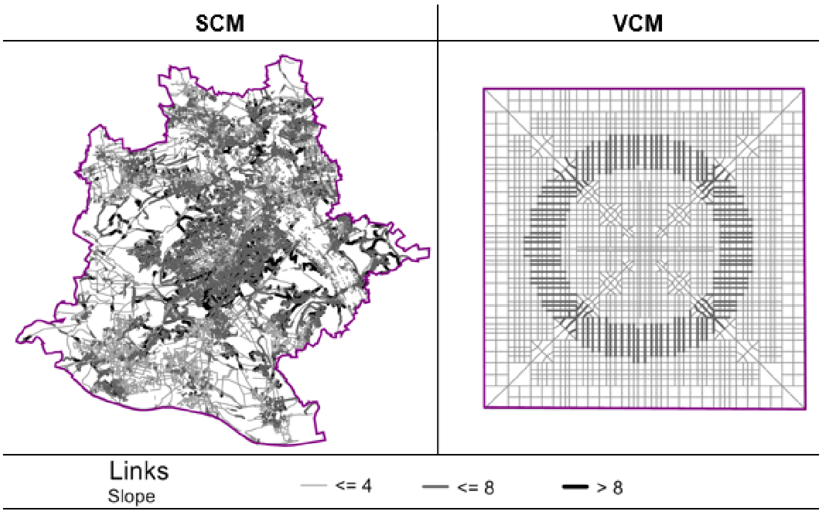
For a real city topography of a network model is taken from a digital elevation model (DEM), which is created from the terrain elevation data. The design of topography in VCM considers the cauldron-shaped topography of Stuttgart City. The distribution of height of nodes (z-coordinate) in VCM is designed based on the following assumptions:

- Height of nodes is distributed symmetrically.
- There is a caldera in the inner city, and highland in the peripheral area.
- The nodes with the same distance to the city centre have the same heights.
- The steepest slope is located at the edge of IC/PC at a distance of 3.5-5 km from the centre of city.
- The region area (with a distance further than 7 km from the centre of city) is flat.

$$Z_{Node} = \begin{cases} 27 * D_{Node} + 207, & 0 < D_{Node} \leq 3.5 \\ 83 * D_{Node} + 11, & 3.5 < D_{Node} \leq 5 \\ 38 * D_{Node} + 234, & 5 < D_{Node} \leq 7 \\ 500, & D_{Node} > 7 \end{cases} \tag{4.2}$$



$$S_{Link} = \frac{Z_{ToNode} - Z_{FromNode}}{L_{Link} * 1000} * 100 \tag{4.3}$$



$$V_{Bike,Link} = \begin{cases} 20, & S_{Link} \leq -5 \\ 13.6 - S_{Link}, & -5 < S_{Link} < 10 \\ 4, & S_{Link} \geq 10 \end{cases} \tag{4.4}$$

with	Z_{Node}	Z coordinate of Node
	D_{Node}	Distance from Node to the centre of city [km]
	S_{Link}	Slope of Link [-]
	L_{Link}	Length of Link [m]
	$V_{Bike,,Link}$	Bike speed on Link [km/h]

Bike speed depends on the slope that is relevant to z-coordinates. Their relations are listed in the above equations, together with figures of calculated z-coordinates and slopes in SCM and VCM. The parameters in equation 4.2 are optimized in order to reach a comparable distribution of slopes in VCM and SCM. Although the designed topography of VCM is different from the one of SCM, their distributions of slopes are comparable. The parameters in equation 4.4 are optimized to achieve a comparable distribution of bike times in VCM and in SCM. With this method, ride time for C-C od-pairs of VCM is calibrated. Since the region area is flat, according to equation 4.4, bike speed of links in the region area is 13.6 km/h. The speed of intra-zonal bike trips in the region and the city is 14 km/h and 17 km/h respectively.

A further adjustment is applied to compensate the influence of different design of connectors in VCM and SCM on bike times. Connectors of neighbouring zones in SCM generate bike time as short as intra-zonal bike trips. Connectors in VCM fail to generate those inter-zonal od-pairs with short bike time. This is adjusted by multiplying 0.5 with the bike time for all inter-zonal od-pairs whose travel distance is within 2 km. As a result there are more od-pairs with short bike time, and ride time is successfully calibrated.

Access and egress time (AET) are the second part of bike time. With the assumption that bikes are kept close to places of activities, 2 min AET for bike of od-pairs is modelled both in VCM and in SCM.

In the region area, since travellers are not supposed to ride a bike for inter-zonal trips which cover a long distance, AET is set to be extremely long for those inter-zonal od-pairs from and to the region area. Thus, the large impedance for travelling by bike avoids inter-zonal bike trips.

Time of car

Travel time of car is composed of access time, ride time, and egress time. Table 22 gives an overview of indicators related to travel time of car with resulted values disaggregated by type of zones. Travel times of inter-zonal and intra-zonal od-pairs are introduced in sequence in the following.

<table>
<tr><th colspan="2">Indicator [min]</th><th>CC</th><th>IC (no CC)</th><th>PC</th><th>MZ</th><th>GZ</th><th>RA</th><th>RoW</th></tr>
<tr><td rowspan="3">Inter-zonal od-pairs</td><td>Ride time</td><td colspan="7">Calculated by distance, speed (link), waiting time (turn), volume & capacity (link, turn)</td></tr>
<tr><td>Parking search time</td><td>15</td><td>11</td><td>7</td><td>5</td><td>4</td><td>3</td><td>0</td></tr>
<tr><td>Time in sub-ordinated network</td><td colspan="3">0</td><td>8</td><td>0</td><td>8</td><td>15</td></tr>
<tr><td rowspan="2">Intra-zonal od-pairs</td><td>Ride time</td><td colspan="7">Calculated by distance, speed (45 km/h), congestion level (1.17)</td></tr>
<tr><td>Access & egress time</td><td colspan="3">14</td><td>6</td><td>4</td><td>2</td><td>0</td></tr>
</table>

Table 22: Indicators related to travel time of car in VCM.

Ride time of car is differentiated into free-flow time and congested time according to the network status. Free-flow time depends on the calibrated distance (chapter 4.2.1), car speed and time penalty at turns (chapter 3.7.2). Car speed of each link type (chapter 3.7.1) is calibrated to achieve a comparable distribution of free-flow times of od-pairs. Congested time considers both free-flow time and delay time caused by traffic loads on the network. The relationship between congested time and volume of links is determined by CR-functions (chapter 3.7.2). The appropriate congestion level is calibrated through capacity of each link type (chapter 3.7.1), number of trips, such as commuting trips and freight transports (chapter 4.3).

AET of inter-zonal trips depends on time to access to or egress from car (2 min for each), parking search time of origin zone and destination zone, and time in sub-ordinated network, as shown in equation 4.5.

$$AET_{ij} = \mathbf{2} + \mathbf{2} + 0.5 \cdot PST_i + 0.5 \cdot PST_j + 0.5 \cdot SOT_i + 0.5 \cdot SOT_j + 0.5 \qquad (4.5)$$

with AET_{ij} Access and egress time of od-pair ij (form i to j) [min]

$PST_{i/j}$ Parking search time in the zone i or j [min]

$SOT_{i/j}$ Time in sub-ordinated network in the zone i or j [min]

Parking search time depends on both quality of parking facilities and demand of parking. Space is a scarce resource in dense areas. Thus, it takes longer to search for a parking place in such areas as the inner city. This explains the different values of parking search time in different types of zones, as shown in Table 22.

The indicator time in the sub-ordinated network is unconsidered in SCM but is included in VCM in order to compensate for the reduction of car travel time caused by the lack of minor roads outside the city. As shown in Table 22, there is no extra time for GZ. It is a result of the calibration of C-R and RoW-R trips. There are eight GZ zones close to the city and eight GZ zones near RoW. No extra time in the sub-ordinated network in GZ zones improves the attractiveness of C-R and R-RoW trips, and therefore counterbalances the disadvantage of the high level of aggregation in the region area. Together with the calibrated ride time, the calculated AET leads to good car travel time for inter-zonal od-pairs.

For intra-zonal trips, free-flow time is calculated by the calibrated distance and speed. Intra-zonal ride speed is optimized as 45 km/h. For zones with small size (e.g. zones in the city), the difference between congested and free-flow time is too small to be distinguished. For large-size zones in the region, since 60% of all the car trips generated from the region of VCM are intra-zonal trips, the congestion level of intra-zonal trips is important for the total congestion level. A congestion level (congested time divided by the free-flow time) of intra-zonal trips in the region is optimized to be 1.17, and the congested time is calculated from the free-flow time and this congestion level. AET of intra-zonal trips is defined according to the characteristics of each type of zone. In order to decrease intra-zonal car trips in the city, a relatively long AET in the city is determined. AET of intra-zonal trips in the region is defined with reference to parking search times. As intra-zonal trips in RoW are not considered, AET for this type of trips is not calculated.

Figure 56 shows an example comparing the accessibility to the city centre by car in both SCM and VCM. Because of the quarter-based distance calibration in VCM, the accessibility by car in the city of VCM is not symmetric any longer. The city centre can be reached from all zones in the inner city within 30 min car travel time. The centre can be reached within 60 min by car from most of zones in the region in SCM, whereas all zones are within 60 min accessibility in VCM. RoW in SCM shows more variability, as the further modelled areas in SCM are bigger than in VCM. The frequency distribution of the calibrated car time is shown at the end of chapter 4.2.2.

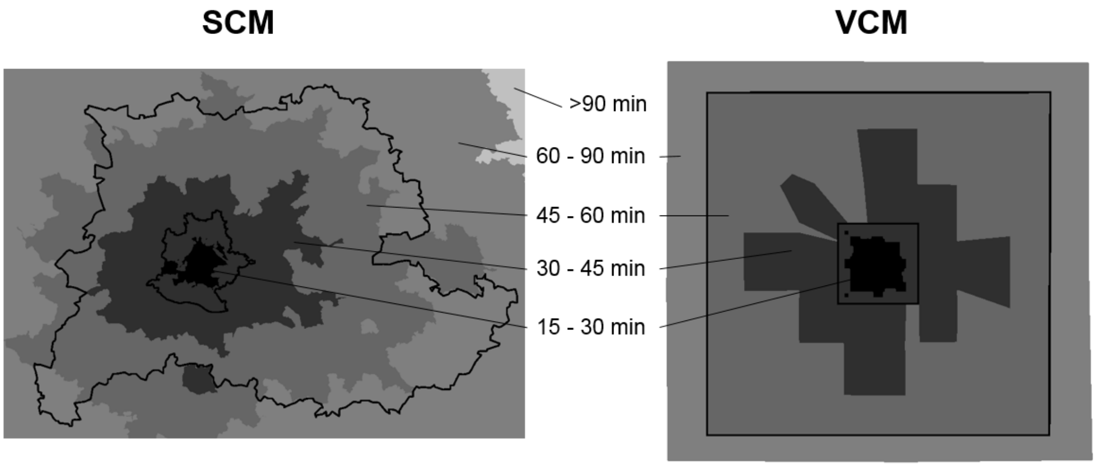


Figure 56: Accessibility to the centre of city (travel time by car).

Time of PuT

Travel time of PuT includes access time, waiting time, ride time, and egress time. The differences between the two networks in SCM and in VCM, such as the structure of connectors, influence PuT travel time. Figure 57 compares an exemplary PuT trip of SCM and VCM in both temporal and spatial dimensions. In SCM bus is an access/egress means of transport for light/heavy rail lines. For each transfer, walking time is necessary, as stops for each transport system in SCM are defined separately. With connectors directly at stops, access/egress time representing walking time to/from stops in SCM is marginal. The access and egress times are defined on connectors. Different from SCM, bus does not serve as an access/egress means of transport in the city of VCM, thus light/heavy rail stops are accessible only through walking. As shown in Figure 57, compared to access and egress time in SCM, access and egress time in VCM is longer. In order to compensate the lack of bus system, lines and stops in VCM are distributed more widely. However ride time is shorter and transfers are fewer in VCM than in SCM due to the lack of bus lines. Furthermore, transfer waiting time and walking time in VCM are accordingly incomparable to those in SCM. Given the above differences, travel time of PuT in VCM is calibrated as follows.

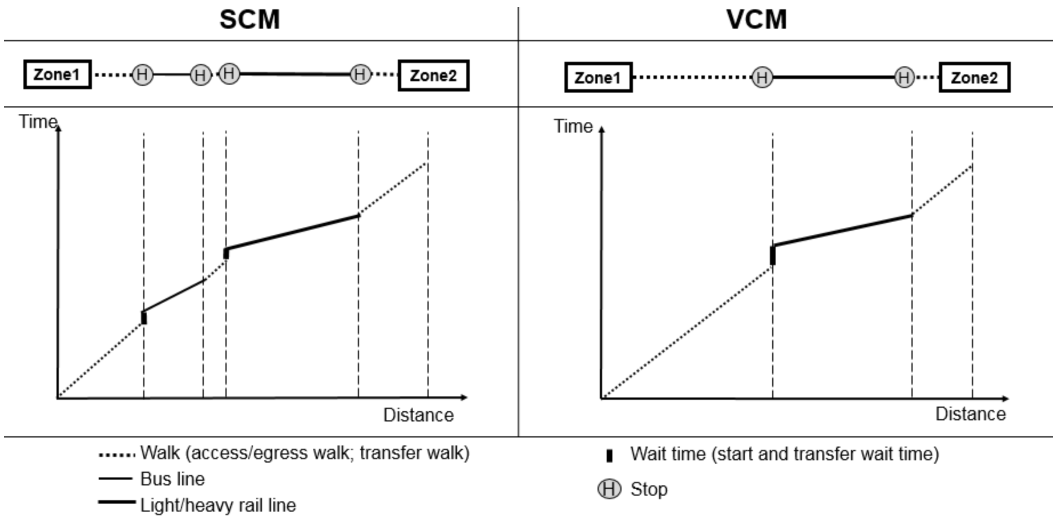


Figure 57: An exemplary PuT trip in SCM and VCM.

Table 23 shows the results of calibration of PuT travel time: values or calculations of PuT time components for both intra-zonal and inter-zonal od-pairs in VCM. Ride time, access/egress time and waiting time are introduced in the following.

Indicator [min]		CC	IC (no CC)	PC	MZ	GZ	RA	RoW
Inter-zonal od-pair	Ride time	Calculated based on PuT network						
	Access/egress time	PuT walking time			2	5	6	5
	Waiting time	Calculated based on PuT network and headway						
Intra-zonal od-pair	Ride time	Calculated by distance and speed (35 km/h city; 30 km/h region)						
	Access & egress time	14						
	Waiting time	5			8	16	20	0

Table 23: Indicators related to travel time of PuT in VCM.

PuT ride time of inter-zonal od-pairs depends on the calibrated length of network (chapter 4.2.1) and speed of each PuT transport system (chapter 3.7.1). PuT ride time of intra-zonal od-pairs is related to intra-zonal distance (chapter 4.2.1) and intra-zonal PuT speeds: 35 km/h for zones in the city and 30 km/h for zones in the region area. Stop time is also included in ride time of inter-zonal od-pairs. According to LEIBBRAND (1980), stop time of heavy rail should be between 15 s and 60 s, while stop time of light rail is shorter: between 5 s and 30 s. Stop time in VCM for all PuT lines is set to be 30 s.

Access and egress time (AET) in the city is calculated based on the network length and PuT walk speed on links between stop and zone centroid. AET in the region depends on the type of zones: the higher the central place function a zone has, the shorter the AET of this zone is. AET for intra-zonal od-pairs is defined to be 14 min, as PuT intra-zonal trips should not be preferred.

Waiting time in VCM sums up the start waiting time and the transfer waiting time. Waiting time of intra-zonal od-pairs depends on the corresponding PuT quality in each type of zone: intra-zonal waiting time in the city area is the shortest, whereas in the rural area the waiting time is assumed to be extremely long up to 20 min. Intra-zonal od-pairs in RoW are not considered. The start waiting time in SCM depends on the service frequency: the more frequent service leads to the shorter start waiting time. This relationship is represented in two different ways in Figure 58. The dashed curve is based on the simple assumption that start waiting time is 50% of the corresponding headway. It shows an unrealistically long start waiting time in case of the less frequent service. This disadvantage is overcome by the other way of modelling with two equations represented by the continuous curve in Figure 58. It is remarkable that start waiting time has negative values in case of a high level of service frequency. This modelling method is unrealistic and inelegant, however, these negative values enhance the advantages of PuT for those od-pairs with high frequent PuT services. These two equations of start waiting time addressed from SCM are applied to VCM. Based on the similar distribution of service frequency in VCM and SCM, the start waiting times in both models are also comparable.

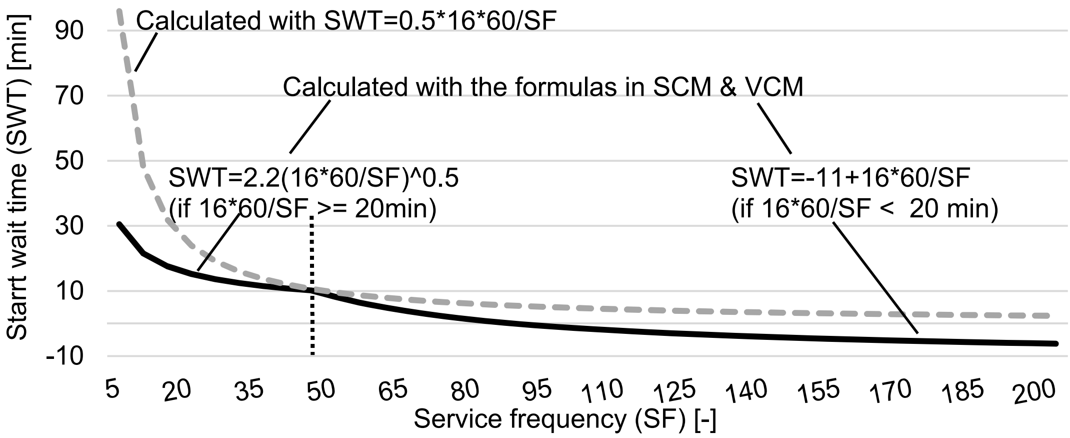


Figure 58: Calculations of start waiting time from service frequency (SF).

Cumulative frequencies of the above-discussed indicators of PuT travel time in SCM and VCM are compared in Figure 59. All waiting times, access/egress times and ride times of VCM are different from the corresponding times of SCM:

- Access/egress time has the largest difference between two models. Access/egress time in VCM partly represents in-vehicle time of bus lines in SCM. Given the grid structure of the network in VCM and the location of the zone centroids in the middle of zones, access/egress time in VCM is much longer than in SCM.
- The difference in waiting time can also be observed. Compared to SCM, VCM has shorter transfer walk and waiting time due to fewer number of transfers.
- VCM has higher frequency of slightly shorter in-vehicle time than SCM because of the lack of bus lines in VCM.

Although these three elements of PuT travel time in VCM are respectively incomparable to those in SCM, the sum of travel time can be still comparable, i.e. the longer access/egress time in VCM compensates the shorter waiting time and ride time.

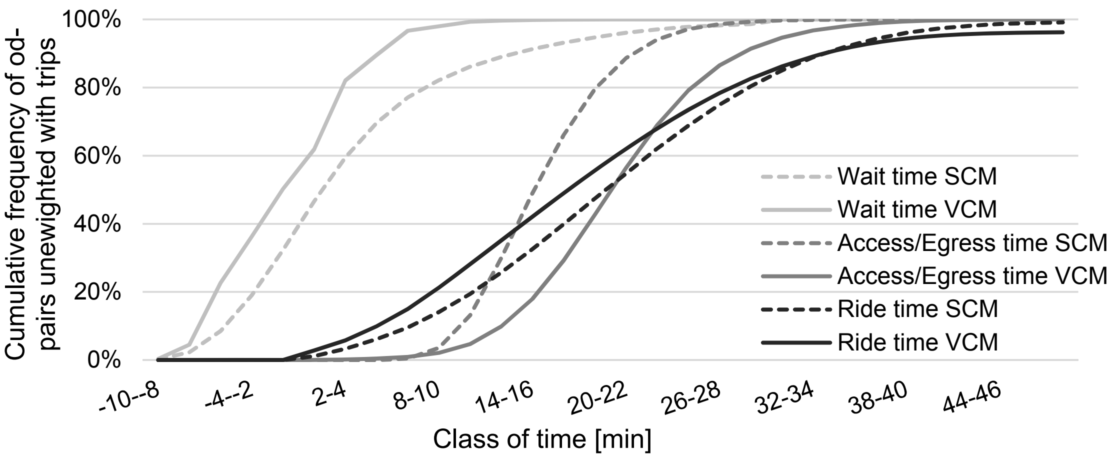


Figure 59: Cumulative frequencies of temporal indicators for PuT.

Result

As a result of the above calibrations of travel times for walk, bike, PuT and car, frequency distributions of od-pairs within the city for all the modes in both models are compared. Figure 60 shows these frequency distributions of travel times with a class width of 10 min.

These travel times are not weighted with the number of trips, so that the transport supply quality can be evaluated. The frequency distributions of travel time in VCM match roughly with the ones in SCM, though differences exist. For example, transport supply of PuT in VCM is slightly better than in SCM, as VCM displays 5% more od-pairs with travel time of 20-40 min but 5% fewer od-pairs with travel time of 60-80 min.

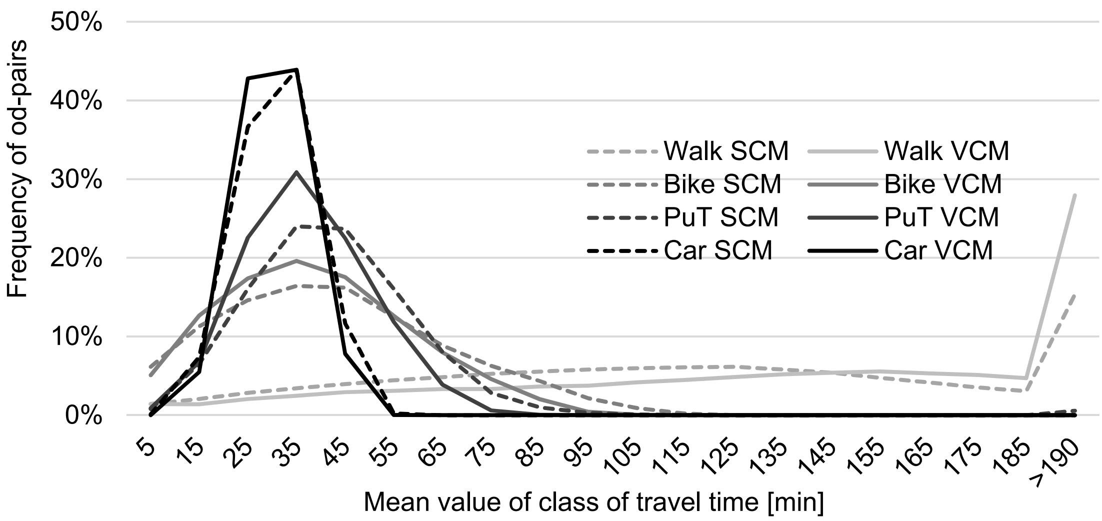


Figure 60: Frequency distribution of travel time of od-pairs in the city.

4.2.3 Travel cost

The price of transport supply plays an important role in decision-making processes. Travel cost can be looked upon from two sides: the operator side and the traveller side. Focusing on the influence of costs on the travel demand for travellers, this work concentrates only on costs for travellers. Since walk and bike are free of charge, only costs for car use and PuT are considered. Travel costs are modelled in VCM with the methods stated below.

Cost of car use

There are two monetary costs for car use in VCM: the cost for driving and for parking. Further costs can also be modelled as measures in VCM, such as a congestion fee. The methods and relevant values for modelling these two basic costs of car use for both intra-zonal and inter-zonal od-pairs from SCM are applied to VCM.

Driving costs result mainly from the energy consumption of vehicles. Given the certain unit price of energy and the unit consumption of energy, driving costs are directly proportional to driving distances, as shown in the following equation.

$$DC_{ij} = \frac{C \cdot SP}{1000 * 100} \cdot D_{ij} \tag{4.6}$$

with DC_{ij} Driving cost of car from zone i to zone j [€]

D_{ij} Travel distance from zone i to zone j [m]

C Unit consumption of fuel [Litre/100km] (=7.0 in VCM)

SP Unit fuel price [€/Litre] (=1.5 in VCM)

Increasing parking cost is an effective transport planning measure especially in the inner city. Parking cost is calculated with the parking price and the share of paid parking. These location-dependent attributes are defined in zones according to the type of zones in VCM with reference to the corresponding attributes in SCM, as shown in Table 24. Parking in the city centre has the highest cost, and parking costs in other areas are half the costs in the city centre. Parking costs in RoW is not defined, as costs do not influence the utility value and then the travel behaviour of commuters. The share of paid parking for activities other than working is in general higher than the share of paid parking to work, as parking at work places is more frequently free of charge.

Attribute of zones	CC	IC (no CC)	PC	MZ	GZ	RA
Parking cost	1.4	0.7	0.6	0.6	0.7	0.6
Share of paid parking (to work)	16%	16%	4%	4%	2%	2%
Share of paid parking (others)	50%	50%	20%	20%	16%	8%

Table 24: Location-dependent attributes of the parking cost calculation.

PuT cost

PuT costs refer to the cost of tickets for using PuT systems. The fare model in SCM includes seven fare systems. Two of these seven fare systems have a zone-based fare structure, the other two systems have a short-distance fare structure and the remaining three systems have a from-to-zone-based fare structure mainly for longer trips. The main fare system in Stuttgart Region depends on fare zones. 60 fare zones are located in the main area of SCM and the other 90 fare zones are distributed in RoW zones of SCM.

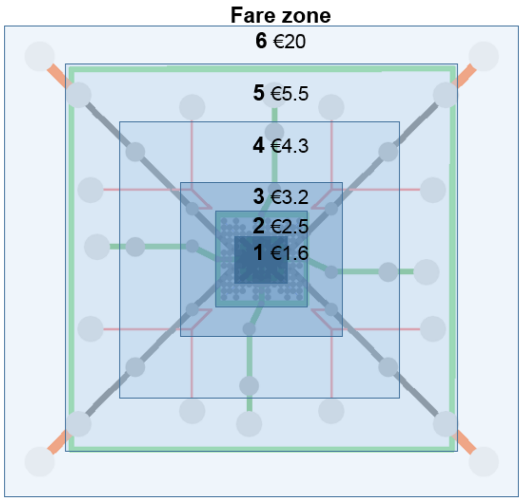


Figure 61: Fare system with fare zones and fares in VCM.

Following the principle of simplification in VCM, a fare system with six fare zones is modelled, as shown in Figure 61. Two fare zones are located in the city area, three fare zones in the region area and the other one fare zone outside the main area. These six fare zones in VCM are defined with reference to the form in SCM. A fare zone number is assigned to all stops in a fare zone. For example, 81 stops in the inner city and 116 stops in the peripheral city of VCM are assigned to the fare zone 1 and 2 respectively. The fare costs depend on how many fare zones a PuT trip crosses. For example, a PuT trip between two stops in the same fare zone without intersecting other fare zones costs €1.6. This fare system in VCM is able to generate the similar PuT costs as in SCM. PuT cost for intra-zonal trips is defined to be €1 in VCM as in SCM.

4.3 Calibration of trips

Not all the trips in VCM are modelled in the same way as in SCM. Table 25 shows the differences in modelling and the numbers of generated trips per type of trips. Internal trips of the main area (C-C, C-R, R-R) in both models are modelled with a trip generation model (TGM) based on the land use structure introduced in chapter 3.6. Trips between the main area and RoW in VCM are also modelled with a TGM, whereas in SCM 60% of these trips are imported from external sources (trip tables for car and PuT), and the other

40% are modelled with a TGM. RoW-RoW trips in SCM are also modelled with external sources and they are responsible for 6% of the total distance travelled in the network of the main area in SCM. RoW-RoW trips traversing the main area are also modelled with a matrix in VCM for a moderate congestion level in the main area. In SCM truck trips take up 20% of total distance travelled on motorways in the main area. Thus, freight transport in the main area is modelled with a TGM in VCM serving the same purpose as RoW-RoW trips for a moderate congestion level in the network. Modelling with a TGM rather than a fixed matrix has the advantage that freight transport is accordingly adjusted to the rearrangement of the land use structure.

<table>
<tr><th colspan="2" rowspan="2">Type of trips</th><th colspan="2">Art of modelling</th><th colspan="2">Number of trips (·1000)</th></tr>
<tr><th>SCM</th><th>VCM</th><th>SCM</th><th>VCM</th></tr>
<tr><td colspan="2">Internal trip of the main area</td><td colspan="2">TGM (of main person groups)</td><td>7,690</td><td>7,690</td></tr>
<tr><td rowspan="2">Trip between main area and RoW of…</td><td>extended area</td><td colspan="2">TGM (of in-/out-commuters)</td><td>350</td><td rowspan="2">880</td></tr>
<tr><td>further area</td><td rowspan="3">External matrices (car & PuT)</td><td></td><td>530</td></tr>
<tr><td rowspan="2">RoW-RoW*…</td><td>through main area</td><td>Matrix (car)</td><td rowspan="2">2,050</td><td>8</td></tr>
<tr><td>outside main area</td><td>no</td><td>0</td></tr>
<tr><td rowspan="2">Freight transport*</td><td>Internal, original, destination trips of main area</td><td rowspan="2">External matrix</td><td>TGM</td><td>190</td><td>100</td></tr>
<tr><td>Internal trips of RoW</td><td>no</td><td>460</td><td>0</td></tr>
</table>

TGM: Travel Generation Model.

*: Trips are modelled in VCM for the purpose of the appropriate congestion level in the network.

: VCM is simplified on purpose and these highlighted values in VCM are not comparable to SCM.

Table 25: Differences of modelled trips in SCM and VCM.

The numbers of internal trips in the main area and trips between the main area and RoW in Table 25 result from TGM. Calibration of these trips is conducted by adjusting land use structures. VCM has the identical number of trips as SCM. Numbers of trips for RoW-RoW and freight transport in Table 25 result from the calibration of through traffic and land use structure of freight transport. These numbers in VCM are different from the ones in SCM, however, the caused congestion levels in the network are comparable in both models. Calibration methods of these trips are introduced in the following paragraphs.

4.3.1 Person transport

Land use in the region

Land uses in the region are generated assuming no differences in each type of zones (MZ, GZ and RA), as stated in chapter 3.6.2. This distribution of land uses draws 50% fewer but 10% longer C-R trips in VCM than the counterpart in SCM. This results from the small amount of zones in the region area within the 15 km travel distance radius from the city in VCM. The value of 15 km is the average travel distance of C-R trips.

In order to decrease the impact of the high aggregation level of zoning on trip destination choice, land uses in the region of VCM are adjusted. Because the number of activity places is of importance for defining the central place function of zones in the region, it is not adjusted as much as the number of inhabitants. Eight GZ zones are located within the 15 km travel distance radius in VCM. More inhabitants should be assigned to these GZ zones, so that more trips can be generated from these zones and accordingly it leads to more short C-R trips. The following three adjustments are conducted to amend the land use in the region:

- 20% inhabitants and 10% activity places in eight MZ zones are moved to GZ zones,
- 50% inhabitants and 30% activity places in eight RA zones are moved to GZ zones,
- 80% inhabitants and 70% activity places in all the GZ zones are assigned to the eight GZ zones close to the city; whereas the other 20% inhabitants and 30% activity places are distributed to the other eight GZ zones at the edge of the region.

This process doubles the residential density of the eight GZ zones close to the city, i.e. the residential density in these GZ zones is changed from 500 inhabitants/km² to 1,000 inhabitants/km². After the calibration, the number of C-R trips in VCM increases by 20%, and the length of C-R trips decreases by 10%, compared to those in VCM before the calibration. The number of C-R trips in VCM is still not as many as in SCM, but the values in VCM after the calibration and in SCM come closer.

Land use of commuters

In- and out-commuters and their corresponding activity locations in VCM are distributed according to trip tables in SCM (see chapter 3.6.3). Commuting trips in VCM have longer travel time and fewer PuT trips than in SCM.

Because RA zones in VCM refer to the areas with poor accessibility to other zones, out-commuters and activity locations of in-commuters in RA zones should be relocated to other areas in the region of VCM. The following adjustment is conducted: 30% of out-commuters and activity locations of in-commuters in RA zones are relocated to MZ zones. This relocation of land uses results from the following two reasons: On the one hand, MZ zones are connected with RoW zones well both by car and PuT. On the other hand, MZ zones have a higher central place function, it is a realistic scenario for MZ zones to attract more commuting trips. With this adjustment of land use structure for commuters, characteristics of commuting trips in VCM are similar to those in SCM.

Through traffic matrix

A large share of the through traffic (80%) in SCM is located on motorways. The through traffic plays an important role in congestion level of C-RoW, R-RoW trips. Modelling through traffic in VCM ensures the right extent to which changes of land use structure in the main area influence the congestion levels and accordingly congested travel time. Thus the calibration of the through traffic matrix is a prerequisite to obtain proper validation results (chapter 4.4.2).

Through traffic in VCM is simply defined based on the assumption that a specific number of trips are made from each RoW zone to its neighbouring RoW zones in horizontal or vertical directions. In this way, through traffic is located on motorways and contributes to higher congestion levels on motorways. According to the above assumption, each RoW zone generates through traffic to the other two RoW zones, and there are totally eight od-pairs of through traffic. Assigning 1,000 car trips to each od-pair results in appropriate congestion levels for C-RoW and R-RoW trips. This sums up to 8,000 RoW-RoW trips in VCM.

4.3.2 Freight transport

VCM focuses on person transport. However, on-road freight transport influences the travel time in the congested network of individual motorized person transport. Freight transport in VCM refers to movements of trucks on roads and it is modelled by a transport system truck with a maximal speed of 80 km/h. Freight transport is usually modelled in a different way from person transport. In VCM it is modelled as specific demand groups in the demand model.[1] Similar to person groups that aggregate inhabitants, demand groups of freight transport represent trucks. As shown in Table 26, different demand groups and their corresponding activities are defined in order to distinguish internal truck trips from commuting truck trips. For example, outgoing trucks (located in the main area) deliver goods only to RoW zones. Similar to home-based activity chains of person transport, activity chains of freight transport are storage-based, i.e. delivery trips are made from storage site and back to storage site afterwards. As listed in Table 26, the simplest activity chains for delivery trips are considered in VCM.

Demand group (location)	Activity (location)	Activity chain
Outgoing truck (C)	Outgoing delivery (RoW)	Storage – outgoing delivery – storage
Internal truck (C,R)	Internal delivery (C,R)	Storage– internal delivery – storage
Incoming truck (RoW)	Incoming delivery (C)	Storage – incoming delivery – storage

Table 26: Demand group, activity and activity chain of freight transport in VCM.

Not all zones in the city of VCM are involved to freight transport. The determination of storage sites and delivery destinations in the city considers land use categories. Locations of storage site (trip origin) and delivery site (trip destination) are distributed based on the following assumptions:

[1] The software version PTV VISUM 15 should be able to model freight transport directly. The work applied PTV VISUM 14 and freight transport is modeled in the same way with person transport.

- Natural zones (N) and residential zones (R1, R2, R3, and R4) are not involved.
- Storage sites are located in work zones (W) and low-density mixed-use zones (M1)
- Delivery destinations are distributed in service zones (S1, S2) and high/very high-density mixed-use zones (M2, M3).

Considering the above assumptions, the distribution of land uses for freight transport in VCM applies the same method as defining land uses for commuters with the help of generated and attracted trips per zone. All truck trips in SCM are divided into three categories: out-commuting, in-commuting and internal trips referring to the main area. The results of produced and attracted delivery trips are listed in Table 27. The number of produced delivery trips of a zone type in VCM is determined by total trips generated from this zone type in SCM and the number of zones of this zone type in VCM. Similarly the number of attracted delivery trips of a zone type in VCM is calculated by dividing trips attracted to this zone type in SCM by the number of zones of this zone type in VCM.

Zone type	Land use category	Number of produced delivery trips from …trucks per zone			Number of attracted delivery trips from …trucks per zone		
		Outgoing	Internal	Incoming	Outgoing	Internal	Incoming
CC	W	30	470	-	-		
	S1, S2, M3	-			-	110	10
IC	W, M1	40	80	-	-		
	S1, S2, M2, M3	-			-	80	10
PC	W, M1	50	270	-	-		
	S1, S2, M2, M3	0			-	270	60
MZ	-	0	3,980	-	-	4,000	0
GZ	-	0	1,010	-	-	1,000	0
RA	-	0	2,140	-	-	2,130	0
RoW	-	-	-	1,270	1,260	-	-

-: not relevant

Table 27: Number of produced and attracted delivery trips per zone in VCM.

The destination choice is modelled with a Logit-Model and the congested travel time of truck is the only variable in the utility function of destination choice model. Parameters in the utility function are determined to reach the proper results of destination choice: the parameter for internal trips is set to be -0.02, whereas for commuting trips it is -0.01. In order to avoid the high share of intra-zonal truck trips in the region area due to the high aggregation level of zoning, average intra-zonal distance of trucks is defined as 10 km, which is longer than travel distance to neighbouring zones. Since truck is the only mode for freight transport, a modal choice model is unnecessary for freight transport.

The modelled freight transport in VCM produces more than 3 million vehicle kilometre and 0.05 million vehicle hours on the network, which are at the same level as in SCM. The influence of freight transport is shown in the result of the calibrated congestion level in chapter 4.5.

4.4 Validation

An important requirement of a model is its sensitivity towards measures. The process of validation examines whether a VCM is able to replicate influences of the same changes of input on travel demand as the reference model. Two series of validation tests are undertaken applying the same changes in transport supply and land use structure in both VCM and SCM. Then the characteristics of caused changes are extracted and compared. This chapter introduces the two implemented validation tests. The tests should furnish answers to the following questions:

- What changes are supposed to be caused by the changes in tests?
- Do the characteristics in VCM change in a similar way as these in SCM do?
- If results in VCM and SCM are different, what causes the difference?

4.4.1 Tests of "modified car speed"

In the first series of validation tests, the input of transport supply, i.e. free-flow car speed, is modified. It is assumed that cars on all roads can drive at a modified speed under the uncongested condition. As a direct result of this alteration, travel time on roads is accordingly altered to the specific degree. The above assumption is implemented in the two models by modifying free-flow car speed (v_0) on the level of links in a way that free-flow travel time of links is changed at the same rate. These five tests of "modified car speed" in a sequence from slowness to fastness are:

- t_0 +20%: an increase of car travel time of links of 20% by decreasing speed by 17%;
- t_0 +10%: an increase of car travel time of links of 10% by decreasing speed by 9%;
- t_0 0%: no change of car travel time of links (the reference case);
- t_0 -10%: a decrease of car travel time of links of 10% by increasing speed by 11%;
- t_0 -20%: a decrease of car travel time of links of 20% by increasing speed by 25%.

As stated in the above definitions of these tests, change rates of car travel time are not equal to change rates of speed. An example of the test "t_0 -20%" shows that in order to get $\frac{4}{5}$ (80%) of car travel time of links, the speed should be $\frac{5}{4}$ times of the original speed, which means the speed should be increased by $\frac{1}{4}$ (25%). In this way, five tests with a sequence of 10% gradient free-flow time change are generated.

Intra-zonal car speeds are altered accordingly to link speeds. This is important for zones in the region area of VCM due to the large zone size. For example, 80% of internal trips in the region of VCM are intra-zonal trips. However, car speeds for intra-zonal trips are not modified to the same extent as for links, because not only ride time on links, but also waiting time at turns influences travel time. Assuming that 50% car travel time of intra-zonal trips is caused by waiting time at turns and 50% by ride time on links, free-flow speed of intra-zonal trips are modified by the following rates: -8%, -5%, 0%, +6%, +13% in the tests "t_0 +20%", "t_0 +10%", "t_0 0%", "t_0 -10%", "t_0 -20%".

The modification of car speed does not influence the trip generation. Thus, the total generated trips are constant for all these tests. The supposed changes according to the modification of car speed are the car ride time of od-pairs, and then destination choice and mode choice. Theoretically an increase of free-flow speed is supposed to induce more car trips with shorter time but longer distance.

The directly changed characteristic of the network is car travel times of od-pairs without being weighted with trips. Figure 62 shows cumulative frequencies in the tests "t_0 +20%", "t_0 0%", "t_0 -20%". Free-flow time (t_0) is exhibited with continuous curves and congested time (t_c) with dashed curves. Both free-flow and congested times generate the same reaction to the change of speed on links: increased speed on links leads to shorter time of od-pairs, but to a smaller extent due to the contribution of the constant waiting time at turns. The change made by the test "t_0 +20%" is slightly smaller than the change in the test "t_0 -20%" with the reference to the test "t_0 0%". Besides, the distribution of congested time in the reference case"t_0 0%" is similar to the free-flow time in the test "t_0 +20%".

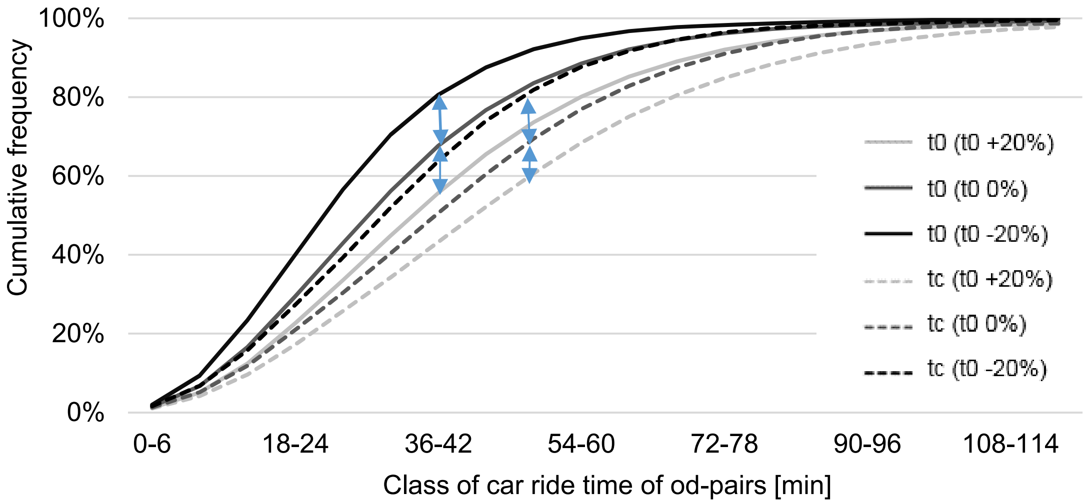


Figure 62: Cumulative frequency of t_0 and t_c of C-C od-pairs in SCM.

In order to simulate the same sensitivity to the modified speed in VCM as in SCM, the relationship between waiting time at turns and car travel time on links is a key feature to be adjusted. Without considering waiting time at turns, car travel time of od-pairs changes at the same rate as ride time of links. The appropriate proportion of waiting time at turns attenuates the change of travel time. Waiting time at turns is introduced in chapter 3.7.2 and those values are the result of experiments to search for the appropriate proportion of waiting time at turns. Based on this adjustment, VCM reacts in the same way as SCM in these tests.

In addition to the direct influence on travel time of od-pairs, travel demand indicators in each validation test are analysed, and the changes of indicators in both SCM and VCM are compared. The change rates of selected macroscopic indicators of both SCM and VCM in all of the five validation tests are shown in Figure 63. These change rates are based on the reference case and the change rate of the reference case is assumed to be 100% for all the indicators. In order to clearly show the relationship between the change rate of free-flow travel time on links and change rates of the macroscopic indicators, the five tests are illustrated with the change rates of free-flow travel time on links by their definitions. The result indicates that the decrease of travel time leads to more car trips with shorter time but longer distance. As shown in Figure 63, a change of 20% car travel time on links leads to 7% change of travel expenditure (congested), 7% contra-change of travel performance and 4% contra-change of car trips. Free-flow travel expenditure (10%) has the biggest sensitivity, whereas number of both car and PuT trips (4%) has the smallest sensitivity to the modified speed. The competition between modes is clearly shown by the same decrease rate of car trips and increase rate of PuT trips. Overall, the sensitivities of indicators in VCM have similar trends as those in SCM. The unmatched position locates at travel expenditure in the tests of "t_0 +20%": change rate in VCM is slightly smaller than in SCM.

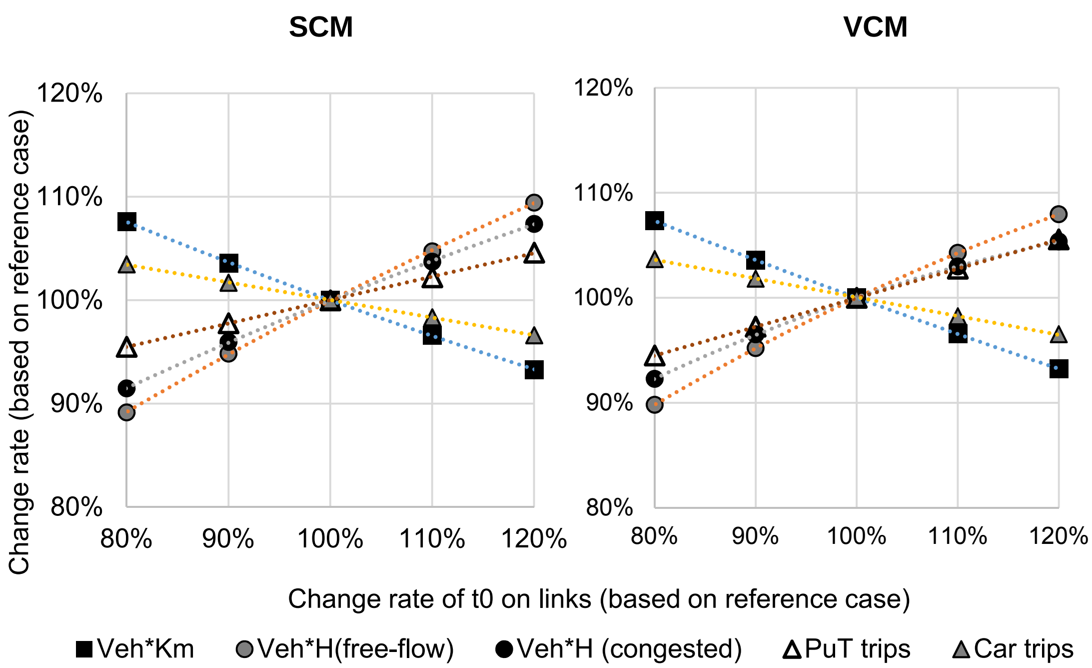


Figure 63: Elasticity of indicators in the tests of "modified car speed".

In addition to the influence of the above indicators of travel demand, the influence on the congestion levels aggregated of all the trips is also investigated. VCM shares the same changes of congestion levels as SCM. The aggregated congestion level in the reference case "t_0 0%" is 1.21. In the tests with increased travel times in the network, congestion levels decrease, i.e. in "t_0 +10%" 1.20 and in "t_0 +20%" 1.19, because of the reduced number of car trips on the network. In contrast in the tests with reduced travel times in the network, congestion levels increase, i.e. in "t_0 -10%" 1.23 and in "t_0 -20%" 1.25. The change rates in the tests with reduced time are bigger than those with increased time.

This results from the form of CR-functions, i.e. the power function of congested times from volumes on links.

Disaggregation of trips in the tests shows more differences between SCM and VCM. Figure 64 shows the comparison of average car travel time disaggregated by type of trips in SCM and VCM. The general trend reveals that average travel increases with the decrease of speed on links. However, travel time changes for C-RoW and R-RoW trips are much more than those for C-C, C-R and R-R trips. The differences are possibly caused by the proportion of waiting time at turns: many turns in the city area and no turns on motorways. Comparing VCM with SCM, the average travel times are located close to the y=x line, especially the aggregation of all trips. However, travel time changes for R-Row and C-Row trips in VCM are more significant than in SCM. It results from that all the trips from/to RoW are located on motorways in VCM and there is no turns on motorways. In SCM these trips do not necessarily use motorways. The GEH value is applied to evaluate the deviation of modelled average travel time in VCM from that in SCM. As shown in Figure 64, all the points are located within GEH=1 area.

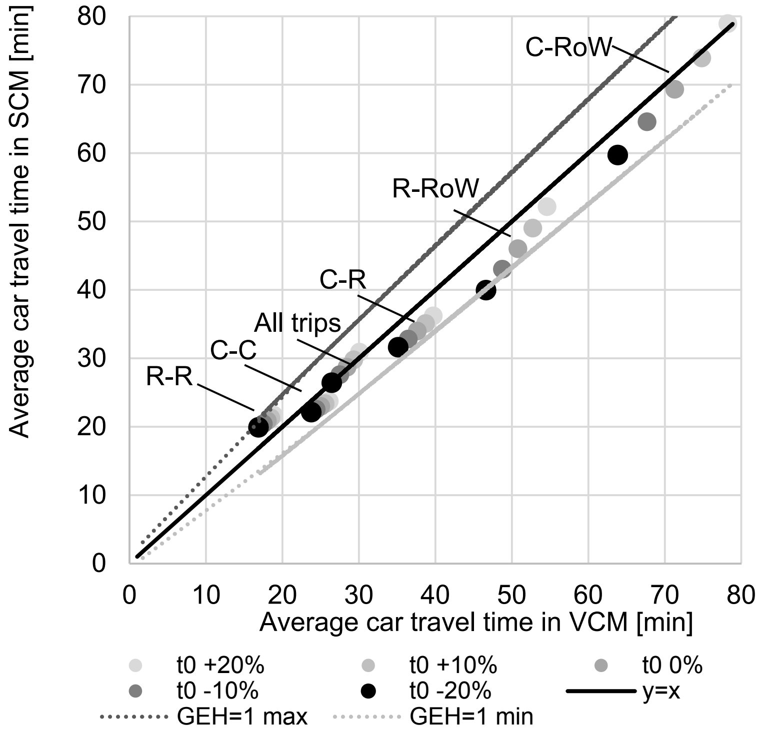


Figure 64: Average travel time by car in the validation test “modified car speed”.

To summarize the tests of “modified car speed”, after adjusting the characteristics of the network (e.g. waiting time at turns) and the number of trips (e.g. through traffic and truck trips), the aggregated indicators in VCM have comparable sensitivities as the counterpart in SCM. However, the disaggregation of trips shows slight differences between SCM and VCM, especially for R-RoW, C-RoW and C-R trips. It is based on the modelling difference in the region area. These validation tests have ensured the robustness of the network model in VCM.

4.4.2 Tests of “modified residential density”

The second series of validation tests examine “modified residential density”. In these tests, it is assumed that residential densities are changed to a specific degree without change of any other inputs. These tests of “modified residential density” are realized in models by modifying the number of inhabitants of each zone. Not all the person groups are modified: In- and out-commuters are excluded due to the impossibility of comparison between SCM and VCM, as commuting trips are partly modelled in SCM by an external source. Given this condition, trips between the main area and RoW are constant in these tests. The five tests of “modified residential density” are listed as follows:

- D -20%: residential density decreases by 20%;
- D -10%: residential density decreases by 10%;
- D 0%: residential density does not change (the reference case);
- D +10%: residential density increases by 10%;
- D +20%: residential density increases by 20%.

The only changed input in these validation tests is the residential density. However in reality some other characteristics react to changes of residential density as well, such as land uses (e.g. new shopping locations in dense residential areas) and transport supply (e.g. new PuT stops and longer parking search time in dense residential areas). These interactions are not considered in these validation tests.

Transport supply does not change in the tests of “modified residential density” except for congested car travel time, which depends on changed trips on the network. Congestion levels of intra-zonal od-pairs in the region are altered according to changed congested travel time on links, as there is a large number of intra-zonal trips in the region of VCM. Without this according alternation, sensitivity in VCM would be smaller than in SCM. In the reference case of “D 0%” the congestion level for intra-zonal trips is 1.17. Congestion levels for intra-zonal trips are modified as: 1.140, 1.155, 1.185, and 1.20 respectively in the tests “D -20%”, “D -10%”, “D +10%”, and “D +20%”. This method models the influence of residential density on congested travel time of intra-zonal trips in a simple way.

Modified residential density alters directly the generated trips. The sensitivity of total generated trips to the residential density in VCM is the same as in SCM. Destinations, modes and routes are chosen according to the changed impedance of each alternative, due to the changed congested travel time on links.

The expected changes caused by the increased density are more trips and a lower share of car trips. The result of these tests shows that the number of trips changes to the same extent as the residential density and modal split changes to a small extent. For example, increasing of residential density by 20% leads to a 1.4% decrease in share of car trips, a 0.1% increase in PuT share and a 1.1% increase in share of walk trips. This indicates that a higher residential density leads to the substitution of car trips by walk trips.

The key feature for VCM to generate the same travel demand characteristics as SCM with the changed residential density is the relationship of the generated trips from changed land use structure, uninfluenced trips, and capacities on links. Commuting trips, through trips and freight transport are constant in these tests. Both changed and constant trips determine volumes on links. Volume and capacity on links influence the saturation and then the congested travel time on links. For example, an appropriate saturation based on the large number of constant trips and the large capacity on links results in smaller sensitivity of congested travel time to changed residential density. Adjustments of constant trips (chapter 4.3) and capacities on links (chapter 3.7.1) enable VCM to react in the same way as SCM in these tests.

Change rates of macroscopic travel demand indicators based on the reference case in both SCM and VCM are shown in Figure 65. The sensitivity of indicators in VCM shows similar trends as in SCM. The following characteristics are addressed from Figure 65.

- Increased density leads to a decrease in both average travel distance and average travel time. The travel distance has a higher sensitivity than the travel time. It indicates a contra-change of average speed to residential density.
- Increased density leads to an increase in both PuT and car trips. PuT trips have higher sensitivity than car trips. It results from the relation between residential density, congested travel time and car trips. In case of a higher density, more cars on links leads to higher saturation on links which induces fewer car trips, thus the sensitivity of car trips towards residential density is smaller.
- Increased density leads to an increase in travel expenditure and performance: a change of 20% in residential density leads to 12% change in travel expenditure and 8% change in total distance travelled.

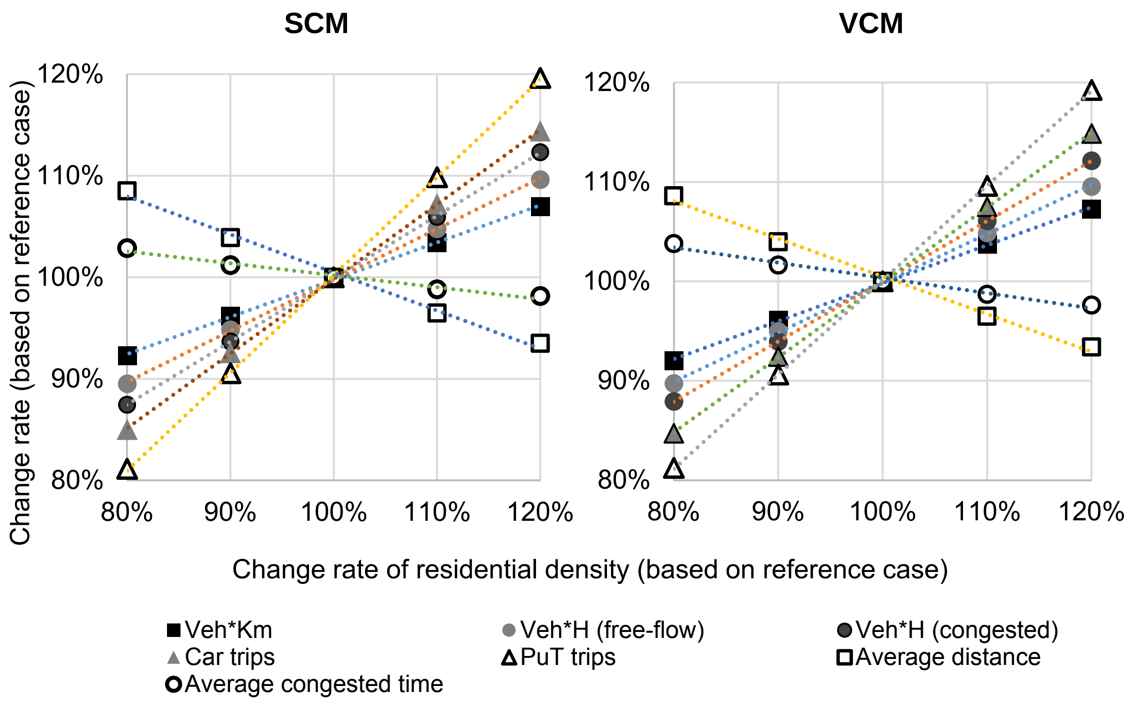


Figure 65: Elasticity of SCM and VCM in the tests of “modified residential density”.

The total number of trips and the residential density change at the same rate in these validation tests. However, not all types of trips have the same change rate: disaggregation by type of trips shows differences, as illustrated in Figure 66. The following aspects are characterized:

- C-RoW and R-Row trips do not change as significant as other types of trips, as no changes have performed to commuters in these tests.
- For the remaining trip types, i.e. C-C, C-R and R-R trips, an increase of residential density leads also to an increase in the number trips.
- The reaction of C-R trips to the increase of residential density in VCM differs from the one in SCM: VCM does not increase as much as SCM. It results from the differences in the network characteristics in the region area: zones in the region area of VCM are located not as close to the city as the ones in SCM. The less increased C-R trips in VCM with increased density have become C-C and R-R trips, as shown in Figure 66.

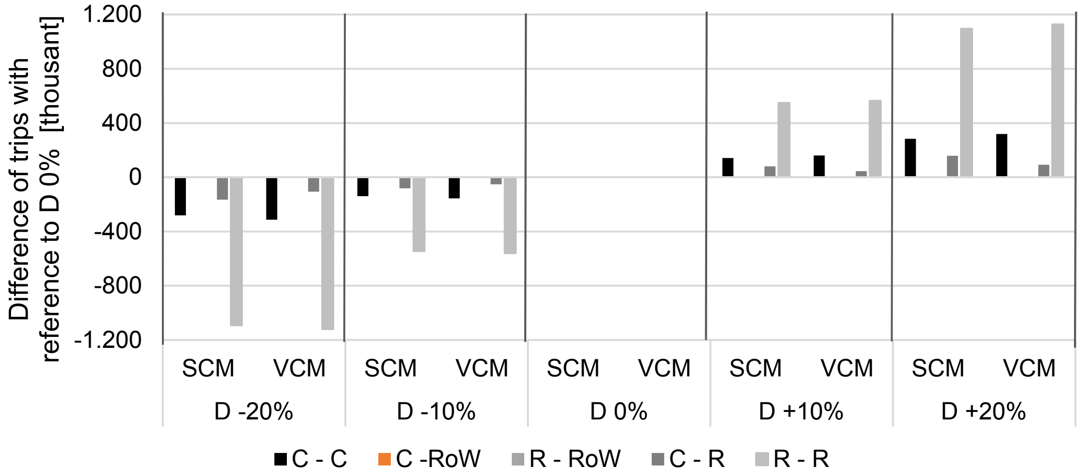


Figure 66: Change of trips in the tests of “modified residential density”.

In these tests of “modified residential density” the original calibrated VCM performs different degrees of changes from SCM. After iteratively adjusting the transport supply (e.g. improving C-R connections by increasing capacity of links) and land use structure (e.g. distributing more land uses in regional zones near the city), the aggregated indicators in VCM have the comparable sensitivity as the counterpart in SCM, as shown in Figure 65. These validation tests examine the robustness of the network reacting to changes of trips.

4.5 Results

After both processes of calibration and validation, VCM can represent characteristics of travel demand in SCM under various conditions. An inhabitant in the main area makes on average 3 trips. The generated trips in VCM are completely identical to the ones in SCM.

A good model should be able to achieve the same output given the same input, for example to generate the proper mode share according to the characteristics of modes (e.g. travel time) for each od-pair. Figure 67 shows how the car share or PuT share changes with the relation of car and PuT travel times (trip time ratio) for selected od-pairs. Trip time ratio is calculated by dividing PuT travel time by car travel time. A trip time ratio smaller than 1 indicates the better accessibility by PuT than by car; whereas a trip time ratio higher than 1 indicates the opposite. The C-C od-pairs are chosen to be shown in Figure 67, if they meet the following two criteria: either the car or PuT share is higher than 50%, and the share of both PuT and car trips is higher than 90%. With these criteria, those od-pairs that are dominant by slow modes are excluded and the relation between car and PuT is clearly observed. VCM is able to generate the same trip share from the trip time ratio as SCM. However, VCM provides fewer od-pairs whose trip time ratio is smaller than 1 or bigger than 2.

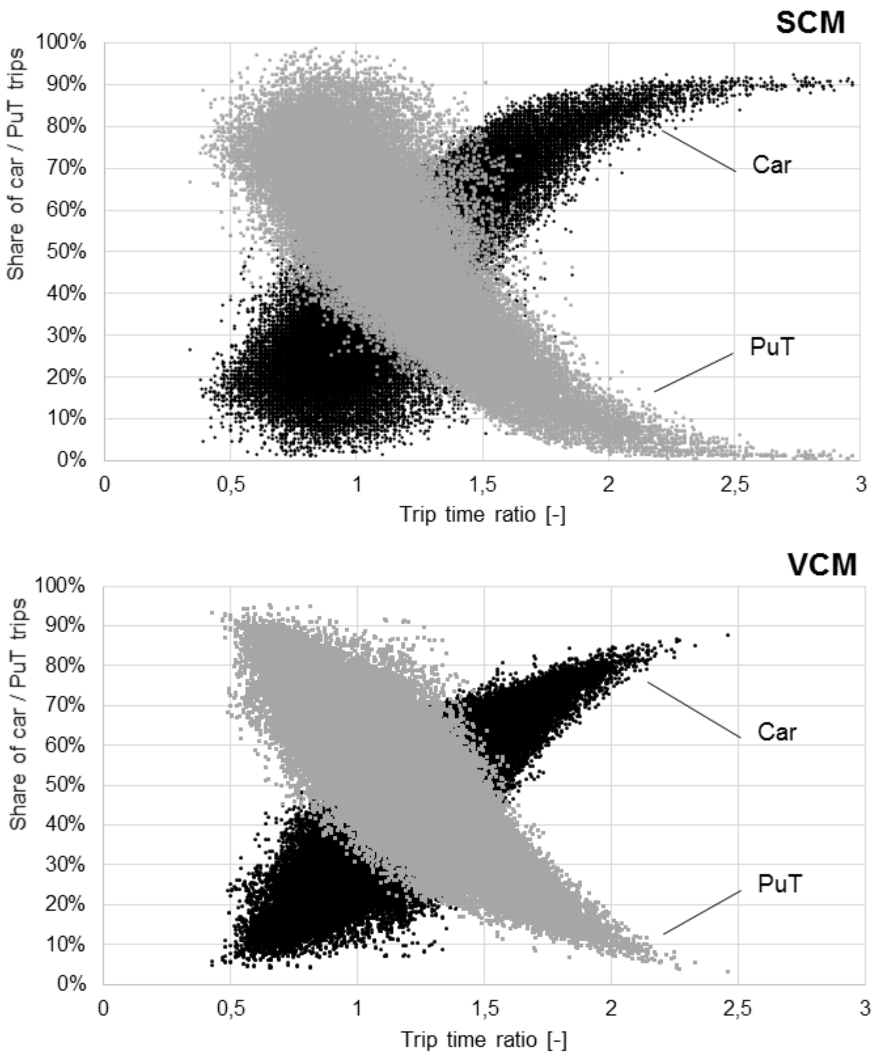
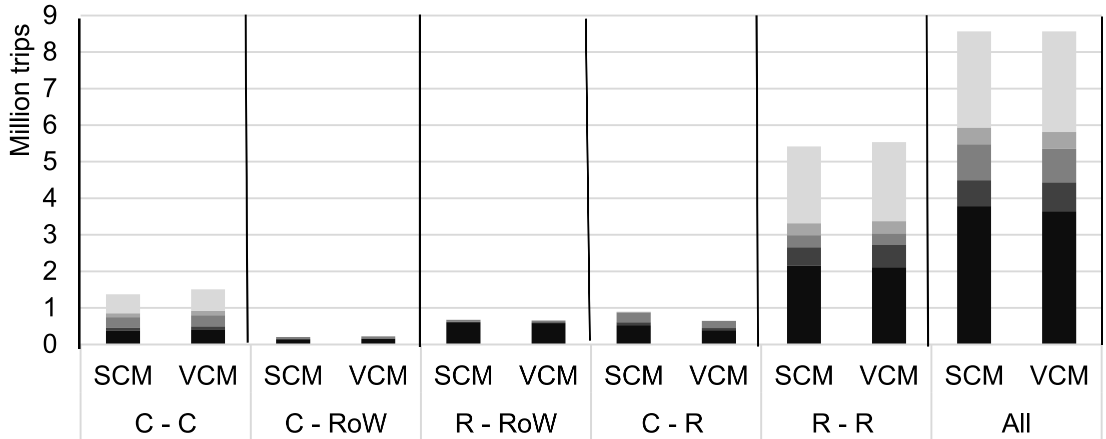


Figure 67: Mode share and trip time ratio for C-C od-pairs.

VCM should be able to model person trips as SCM. The first part in Figure 68 shows the number of trips per mode and type of trips. In total more than eight million person trips are generated. More than five million trips (60%) are R-R trips due to the large number of inhabitants who live in the region area. Besides, there are more than one million C-C trips, approx. one million C-R trips and approx. one million commuting trips (C-RoW and R-RoW trips). On average 40% of the total trips are made by car-driver and only 11% of trips are PuT trips. Commuting trips are motorized-mode-dominant with the share of car trips of 70% for C-RoW trips and 90% for R-RoW trips. Walk and bike are mainly used for C-C and R-R trips. Approx. 50% of all C-C or R-R trips are performed by slow modes.

The second part of Figure 68 illustrates the total distance travelled: from approx. 90 million total kilometres travelled, 1/3 are R-RoW trips due to the long distance, 1/3 are R-R trips because of the large number of trips, and the other 1/3 are C-RoW, C-R and C-C trips. Compared to SCM, VCM has fewer C-R trips and shorter distances travelled for C-R trips. However, calibrations of transport supply and land use distribution have already increased C-R trips in VCM. Without changing zone centroids in the region area of VCM, C-R trips in VCM cannot be the same as the ones in SCM. Approx. 70% of the total distance travelled are performed by car trips, from which 10% are by car-passenger. Although 30% of trips are made by slow modes, they perform only 4% distance travelled.



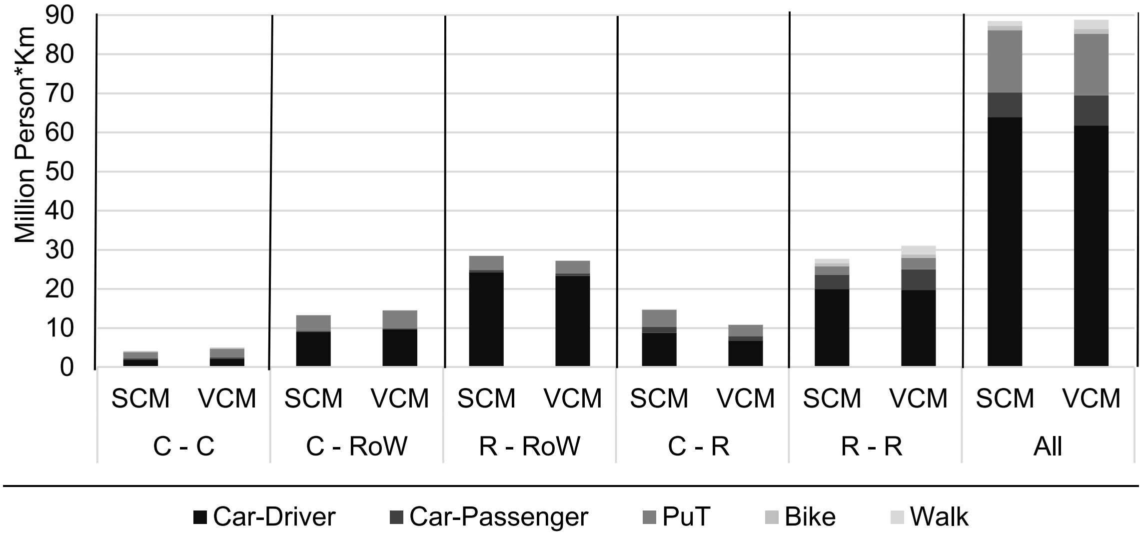


Figure 68: Person trips and total distance travelled per mode and type of trips.

VCM generates the same aggregated indicators as SCM. These arithmetic mean indicators are listed in Table 28. Internal trips in the city area are shortest in distance, but due to a high share of walk trips, the average speed is the lowest. Internal trips in the region area take the shortest time, and influenced by large rural areas, motorized modes are applied. C-R trips are double as long as R-R trips in both travel distance and travel time. Commuting trips (C-RoW and R-RoW trips) are characterized by the longest travel distance, longest travel time and the fastest travel speed, which implies the dominant use of motorized modes.

Arithmetic mean indicator	C-C trips	R-R trips	C-R trips	C-RoW trips	R-RoW trips
Average travel distance [km]	5	9	17	62	40
Average travel time [min]	24	20	35	70	48
Average travel speed [km/h]	13	27	29	53	50

Table 28: Arithmetic mean indicators weighted with demand per type of trips.

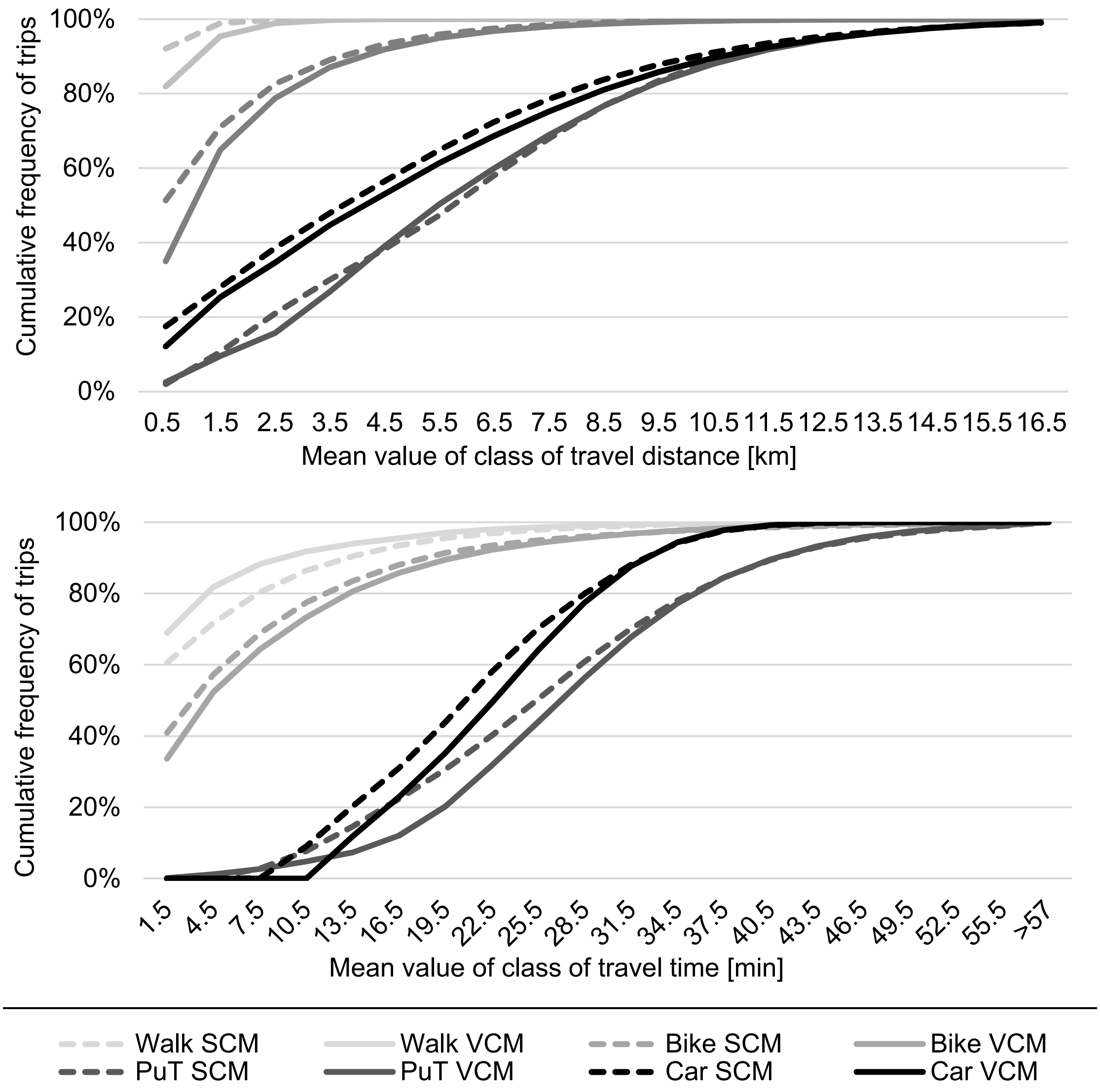


Figure 69: Cumulative frequencies of travel distance and travel time for C-C trips.

In addition to the aggregated indicators, the distribution skim values provides a disaggregated aspect. As the comparison of frequency distribution of skim values requires the same aggregation level of zoning, only C-C od-pairs are applied for the disaggregated evaluation. The distribution of skim values weighted with the number of trips describes the characteristics of travel demand.

Figure 69 shows the cumulative frequencies of travel distance and travel time for C-C trips. The characteristics of travel distance for different modes in VCM match those in SCM. For example, 100% of the walk trips, 80% of the bike trips, 40% of the car trips and 20% of the PuT trips are shorter than 3 km in both SCM and VCM. Despite the calibration of shortening walk and bike distance in VCM, trips shorter than 1 km in VCM are still approx. 10% fewer than in SCM. There are slight differences of distribution of travel time between SCM and VCM. For example, VCM has 5% fewer car trips and 10% fewer PuT trips that are shorter than 21 min than SCM.

Travel distance can be disaggregated by trip purposes and trip types. The first part of Figure 70 shows the difference of average distance for different trip purpose between SCM and VCM, assuming that all the trips are made by car. The average distance for different trip purposes in VCM ranges from 5 km (daily shopping trip) to 14 km (university trip), whereas in SCM it is between 2 km (primary school trip) and 16 km (university trip). For most trip purposes VCM has a longer distance than SCM, such as school trips, shopping trips and leisure trips. However for some trip purposes VCM has a shorter distance than SCM, such as university trips.

The difference of distances by trip purposes between SCM and VCM is analysed by disaggregating trips per purpose by trip types, as shown in the second part of Figure 70. Commuting trips are excluded from these trip purposes. For all the selected trip purposes, the average distance for C-C trips in VCM and SCM is comparable. The average distance for C-R and R-R trips in VCM is slightly longer than in SCM. An exception is the purpose for work (high-income): the average distance in both models is comparable for all three types of trips. Nevertheless, for short trips such as gong to primary school or daily shopping, the average distance for R-R trips in VCM is much longer than in SCM. It results from the high intra-zonal distance in the region area. Because of the high abstraction level of the region area in VCM, intra-zonal distance represents the average level by means of sacrificing those short trips to ensure the proper destination choice, especially the balance between C-R and R-R trips.

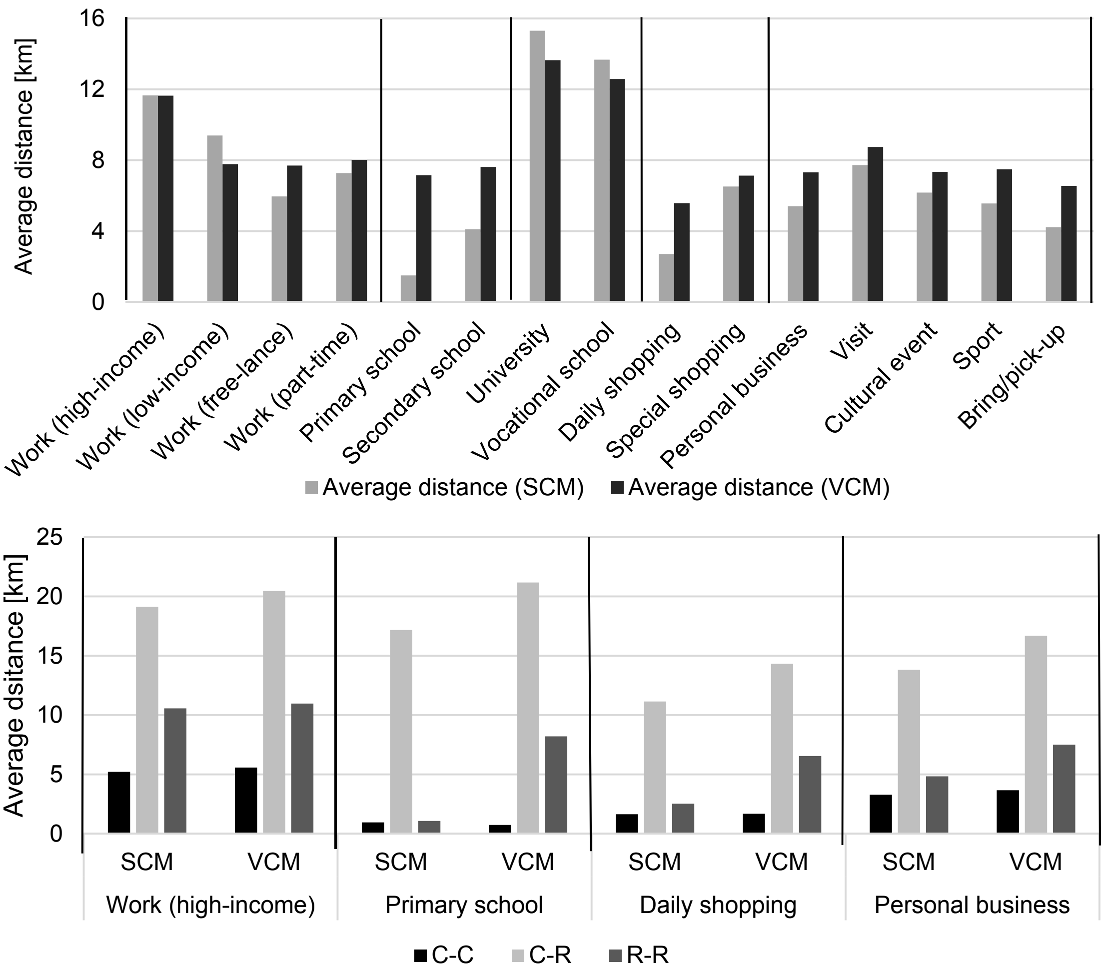


Figure 70: Average travel distance per trip purposes and types of trips.

The city area in VCM has the complete network, thus the total distance travelled on links in both SCM and VCM is comparable. There are approx. 7 million vehicle kilometres of both car and truck in the network within the city area of both models. 2 million vehicle kilometres are of type C-C trips. Origin/destination trips are responsible for the remaining 4-5 million vehicle kilometres in the network of the city area. Freight transport is responsible for approx. 0.5 million vehicle kilometres. Nevertheless, VCM has no through traffic on the network in the city area, whereas 0.5 million vehicle kilometres on the urban network in SCM are lead from through traffic. This difference results from the external bypass of motorway in VCM.

Congestion level is an indicator for car traffic. The aggregated congestion level of a trip type is calculated by dividing the sum of travel expenditure (congested) by the sum of travel expenditure (free-flow). The comparison of congestion levels of SCM and VCM is shown in Figure 71. Characteristics of congestion levels and the calibration methods of congestion levels for the following trip types are addressed:

- Aggregating all the trips, VCM and SCM have the same congestion level of 1.21.

- C-C trips have the lowest congestion level of 1.12 in both VCM and SCM. This value in VCM is calibrated by adjusting characteristics of the network and trips in the network.
- The congestion level of R-R trips in VCM is the same as in SCM amounting to 1.17. This value in VCM can only be obtained by defining the congestion level of intra-zonal trips to be 1.17 in VCM.
- The congestion level of C-R trips is slightly higher than the average congestion level of total trips.
- VCM has different congestion levels for commuting trips (C-RoW and R-RoW) from SCM. Both C-RoW trips and R-RoW trips share the same motorway to/from RoW in VCM, whereas SCM offers different routes for commuting trips. Thus, congestion levels of both commuting trips in VCM are influenced largely by the motorways and they are close to each other (1.27 and 1.29). However, congestion level of C-RoW trips in SCM is much higher than that of R-RoW trips. However, differences of congestion levels in SCM and VCM are within the GEH value of 0.05, as shown in Figure 71.

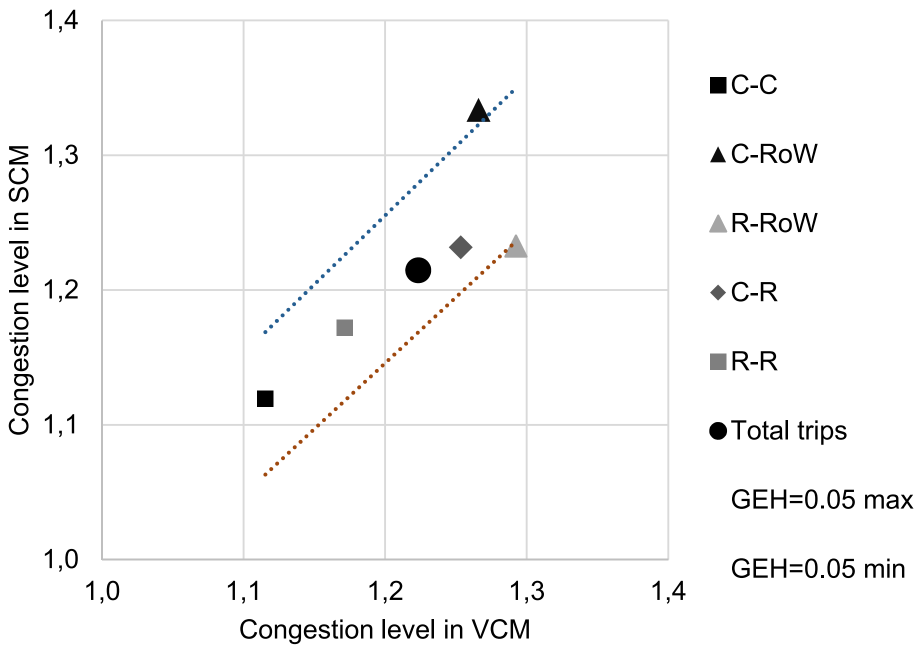


Figure 71: Congestion levels per type of trips.

After calibration and validation VCM is able to model travel demand on an aggregation level in a reasonable way. VCM can be applied to analyse influences of macroscopic measures on travel demand, especially in the city area.

5 Applications

5.1 Influence of land use structure

Two main characteristics of land use structure are density and degree of mixture. Validation tests with “modified residential density” indicate that higher residential density leads to a lower share of car trips and a shorter average travel distance by car. The influence of different degrees of mixture on travel demand is under investigation with the help of VCM in this chapter. Furthermore, metropolitan areas are in a continuous process of development and locating new developments is a core question of land use planning. In this chapter, different scenarios of locating increased population are presented and the influences of these different locations on travel demand are examined.

5.1.1 Degree of mixture

Generation of scenarios

Two scenarios with different degrees of land use mixture are developed in the city of VCM. These two scenarios are shown with concepts borrowed from BERTAUD (2002) in Figure 72. The total number of inhabitants in all scenarios remains constant. S_0 is the reference scenario of VCM representing the current degree of mixture in Stuttgart City; S_1 tests the influence of the separation of land uses with a strong centre; and S_2 explores the influence of a high degree of mixture represented by the poly-centric form in the city.

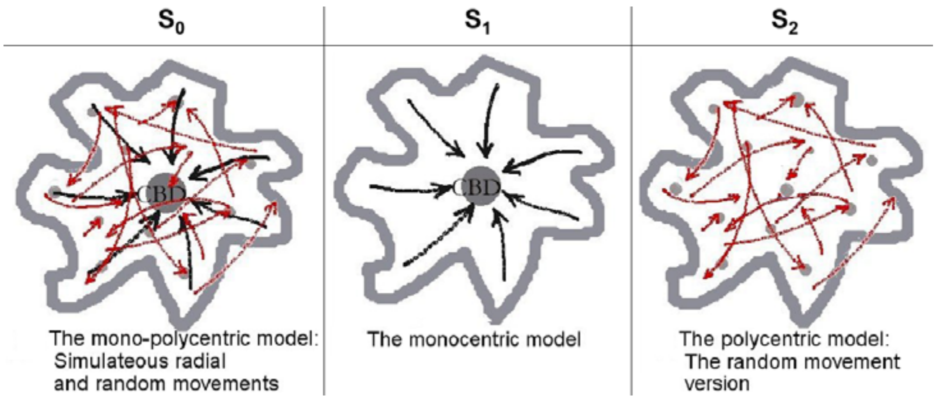


Figure 72: Scenarios with degree of mixture.

Scenario S_1 decreases the degree of mixture, and assumes a strong separation of functions: all activity locations are assigned to the inner city, whereas residential areas are located in the peripheral city. Radial trips are generated from this land use structure. Compared to S0, an increase of trip distance and fewer non-motorized trips are expected as a result of S1. The 11 land use categories (see chapter 3.6.1) are used to distinguish the functions of a city. However, there is no absolute separation of different functions, according to the definition of land use categories. For example residential zones always contain some shopping and service facilities.

The distributions of zones with different land use categories in the two scenarios of S_0 and S_1 are compared in Figure 73. The distribution of land use categories in S_1 is based on the following principles:

- Distribution of land use categories is symmetrical within the city;
- The total area of each land use category in S_1 is the same as in S_0;
- All service zones are located in the city centre;
- All main- and sub-service zones, work zones and very-high-density mixed-use zones are located in the inner city;
- Mixed-use zones are distributed between inner and peripheral city;
- Residential zones are distributed in the peripheral city and the residential density decreases with the increase of distance to the centre;
- Nature zones are located at the edge of the city.
- Out-commuters live only in residential zones, and activity locations for in-commuters are in main, sub-service zones and work zones.
- Storage and delivery of freight transport are adjusted in accordance with land use categories following the same principles as S_0.

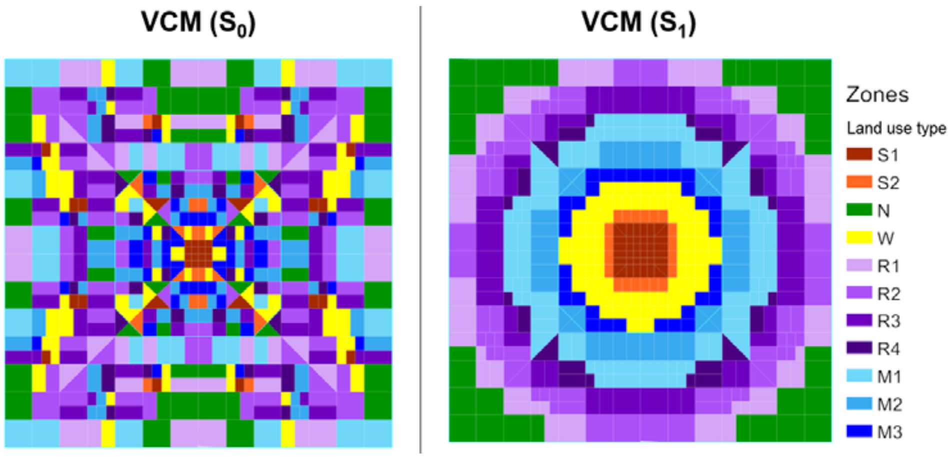


Figure 73: Distribution of land use categories in the city of VCM (S_0 & S_1).

After assigning land use categories to each zone in the city of S_1, land use data are determined according to the average density of each person group or activity of land use category in S_0 and the area of each zone. Some minor adjustments are made to ensure the same total number of land uses as in S_0.

In contrast to S_1, S_2 increases the degree of land use mixture up to an ideal condition. In this scenario all land uses are distributed equally in the city without distinguishing any land use category, i.e. all of the zones in S_2 have the same density for all person groups and activities. Land uses for commuting trips and freight transport are also evenly distributed. Given this ideal mixture in the city, shorter travel distance and more walk trips are expected. However, it is notable that this ideal mixture is associated with a relatively low intensity of land use, whereas S_1 offers zones with both high and low intensities of land use. For example, fewer trips are generated from a zone in S_2 than from a high-density-mixed-use zone in S_1.

Results of scenarios

The changes in land use structure influences the travel demand. Table 29 gives an overview of key indicators of travel demand with both changed values and change rates in S_1 and S_2 in comparison to S_0, disaggregated by trip types. Since the land use structure in the city area has been changed, changes of city-related trip types are listed. The following characteristics are addressed from Table 29.

- Compared to S_0, the number of C-C trips in S_1 decreases by 1% while C-R trips increase by 2% due to the closeness of residential areas (city) to activity locations (region) in S_1. S_2 makes no significant difference from S_0 in terms of trip numbers.
- The total distance travelled in S_1 increases whereas the distance in S_2 decreases from S_0. It fulfils the expectation that the separation of land uses leads to longer trips and the mixture of land uses results in shorter trips.
- However, the total distance travelled by car in S_2 increases as a result of more frequent car trips with longer distance (see Figure 76). The total distance travelled by car for C-RoW trips in S_1 decreases by 12% mainly due to 10% shift from car trips to PuT trips, which is promoted by relocating activity locations for in-commuters in the inner city with the good accessibility to regional trains.
- The changes of travel time expenditure by car in S_1 and S_2 have the similar characteristics as travel distance by car.

Travel demand indicator		**S_0**	**S_1**		**S_2**	
		Value (reference)	**Changed value**	**Change rate**	**Changed value**	**Change rate**
Total number of trips	C-C trips	1,500,000	-13,000	-1%	+1,300	0%
	C-R trips	640,000	+12,000	+2%	-1,600	0%
	C-RoW trips	220,000	0	0%	0	0%
Total distance travelled	C-C trips	5,100,000	+270,000	+5%	-210,000	-4%
	C-R trips	10,900,000	+400,000	+4%	-20,000	0%
	C-RoW trips	14,600,000	+340,000	+2%	-160,000	-1%
Total distance travelled (car)	C-C trips	2,200,000	+87,000	+4%	+350,000	+16%
	C-R trips	6,800,000	+280,000	+4%	+660,000	+10%
	C-RoW trips	9,700,000	-1,200,000	-12%	+,840,000	+9%
Travel time expenditure (car)	C-C trips	80,000	+4,000	+5%	+12,200	+15%
	C-R trips	170,000	+1,700	+1%	+18,000	+11%
	C-RoW trips	140,000	-20,000	-14%	+11,200	+8%

Table 29: Key features of city-related trips in scenarios with degrees of mixture.

In order to observe the influence of a maximization of land use mixture in a better way, S_2 is compared to S_1. Assuming that all numbers of trips per mode in S_1 are 100%, the ratios (numbers of trips per mode in S_2 divided by numbers of trips per mode in S_1) are shown in Figure 74. Maximization of land uses leads to more walk trips and more car trips, but much fewer PuT trips for C-C trips. Reduced PuT trips in S_2 result from the uncoordinated PuT network with the distribution of land uses, in which case cars are widely used for zones with poor PuT service. Equally distributed out-commuters and activity locations for in-commuters in S_2 lead to more car commuting trips and fewer PuT trips for C-RoW trips. The increase of PuT R-RoW trips in S_2 can be explained by the increased congestion level on the network which is lead from more car trips using the network in the region. Longer travel time by car in the congested network leads to fewer car trips and more PuT trips. Aggregating all the trips, there are on average more car trips and fewer PuT trips.

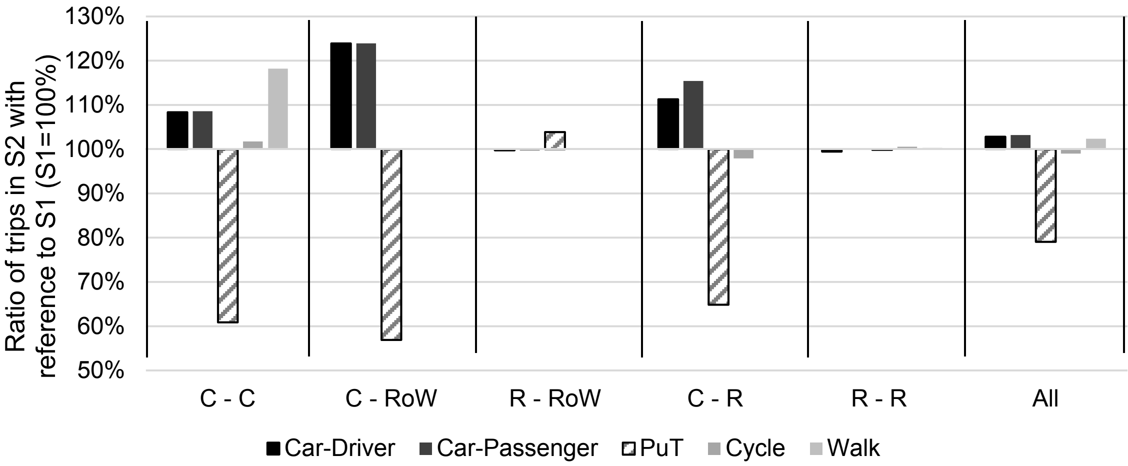


Figure 74: Comparison of number of trips by mode and type of trips in S_1 and S_2.

The separation of land uses in S_1 generates longer trips, whereas the good mixture of land uses in S_2 results in shorter trips, compared to S_0. The disaggregation of trip distances per purposes for C-C trips is evaluated and shows not all the trip purposes fulfil the above characteristic, as shown in Figure 75. Comparing S_1 and S_0, some trips have approx. 1 km longer distance such as work trips (low-income, free-lance, and part-time); whereas some are only slightly longer such as shopping trips; some activities have even shorter distance in S_1 such as university trips. S_2 leads to shorter trips for the purposes of work, school, shopping and service than both S_0 and S_1. However, for purposes such as work (high-income), university and visit, travel distances in S_2 are even longer than in S_1. This difference can be explained by different values of parameter β in the destination choice function of each trip purpose (see chapter 3.8.2), as shown in Figure 75. For example, the value of β for secondary school trips is 5, but the value of β for university trips is 1. This indicates that secondary school trips are more preferred to be distributed to od-pairs with smaller utilities than university trips. It is observed in Figure 75 that for trip purposes with a β value above the line of 1.7, the distance in S_1 is the longer than in S_2. In contrast, for trip purposes with a β value below this line, the distance in S_2 is longer than in S_1. For these trip purposes the advantage of mixture is not utilized.

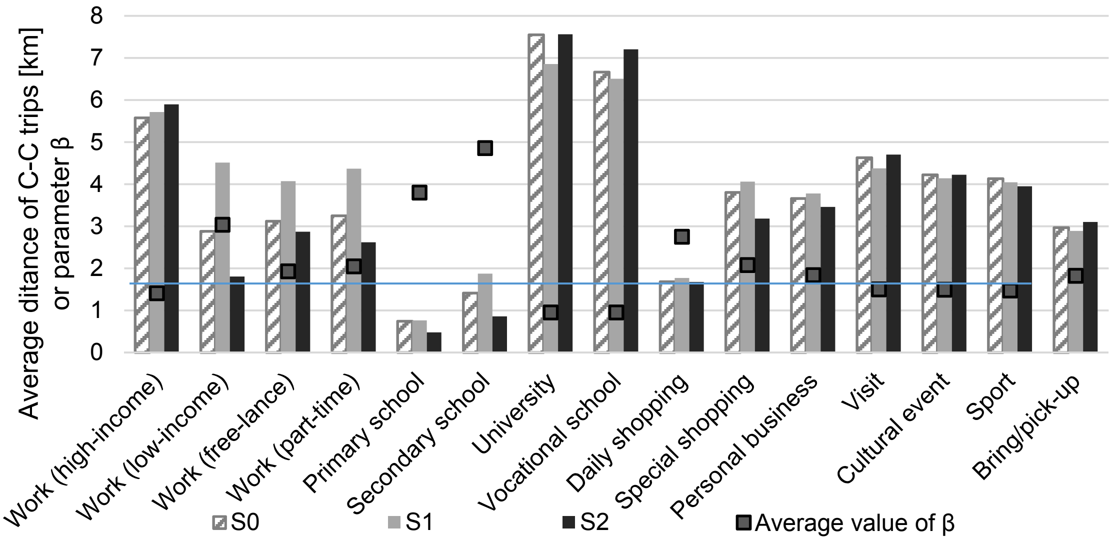


Figure 75: Average distance of C-C trips in scenarios with degrees of mixture.

Figure 76 displays the different frequency distributions of the car travel distance for C-C trips. Comparing S_2 with S_1, the mixture of land uses (S_2) does not lead to more trips with short distance and fewer trips with longer distance than the separation of land uses (S_1), but results in more trips shorter than 3 km or longer than 11 km. In addition to car travel distance, PuT travel distance and travel time have the similar structure of the frequency distribution. There are more car trips with travel time shorter than 8 min or longer than 24 min in S_2, compared to S_1. This phenomenon can be explained by the different distribution of land uses: equally distributed land uses in S_2 lead to more od-pairs with short distance; in contrast S_1 provides fewer opportunities for trips with extremely short or long distances. S_2 enable trips with long distance for those trip purposes for which distance is unimportant to destination choices, as shown in Figure 75.

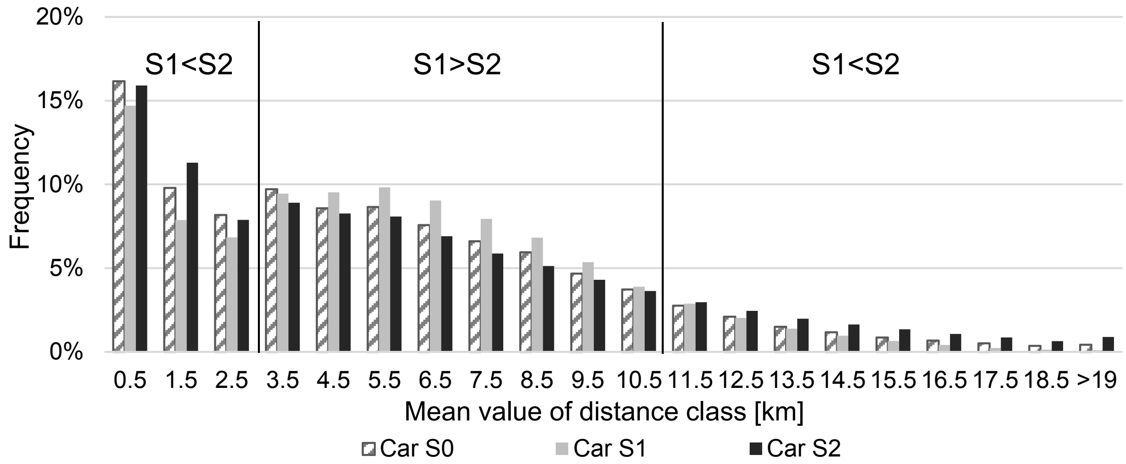


Figure 76: Frequency distribution of car travel distance for C-C trips in scenarios with degrees of mixture.

Differences in the land use structure lead also to different results of assigning travel demand to the network. Figure 77 shows the distribution of both car and PuT volumes in the network. Low volumes on minor roads are not shown, however, it does not mean that the network is incomplete. Compared to volumes in S_1, volumes in S_2 are distributed more equally in the urban space. For example, there are higher volumes on tangential roads (e.g. on the HSIII network in the peripheral city), and lower volumes in the radial direction of both car and PuT. The trips in the radial direction in S_1 result from the separation of land uses. Because of more car trips and fewer PuT for the types of C-RoW and C-R trips in S_2, higher car volumes on VSII roads but lower PuT volumes on heavy rails are characterized in S_2.

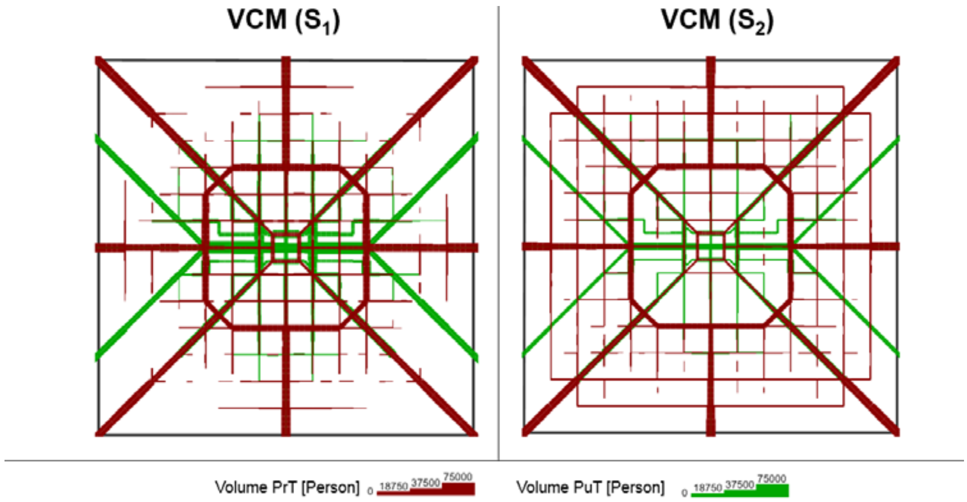


Figure 77: Comparison of PrT and PuT volumes in the city of S_1 and S_2.

5.1.2 New developments

Development of scenarios

VCM can be applied to predict possible changes of travel demand caused by different solutions for locating new developments. Both changes of activity locations and of populations can be referred to new developments. In this work different solutions of locating increased population are developed and their influences on travel demand are investigated with the help of VCM. It is assumed that 50,000 new migrants will be located in Stuttgart Region. This number of new migrants amounts as 50% of the total registered refugees in 2015 in Baden-Württemberg, Germany (BUNDESAMT FÜR MIGRATION UND FLÜCHTLINGE, 2016). We also assume that these new inhabitants are completely integrated and they make similar activities and behave similarly as current inhabitants.

The composition of new inhabitants is listed in Table 30. The age structure is estimated by applying the composition of registered refugees in January 2016 (BUNDESAMT FÜR MIGRATION UND FLÜCHTLINGE, 2016). The further estimated share per person group is based on the assumptions of low motorization rate (50 motorized vehicles per 1000 inhabitants), low share of employees with high income, and higher share of apprentices than students.

<table>
<tr><th rowspan="2">Age</th><th rowspan="2">Share (BUNDESAMT FÜR MIGRATION UND FLÜCHTLINGE, 2016)</th><th colspan="2">Person group</th><th rowspan="2">Further share (estimated)</th><th rowspan="2">Number of inhabitants</th></tr>
<tr><th>Main category</th><th>With car?</th></tr>
<tr><td>0-6</td><td>12%</td><td>Child</td><td>no</td><td>12%</td><td>6,000</td></tr>
<tr><td rowspan="2">6-18</td><td rowspan="2">18%</td><td>Primary school pupil</td><td>no</td><td>9%</td><td>4,500</td></tr>
<tr><td>Pupil</td><td>no</td><td>9%</td><td>4,500</td></tr>
<tr><td rowspan="2">18-25</td><td rowspan="2">26%</td><td>Apprentice</td><td>no</td><td>16%</td><td>8,000</td></tr>
<tr><td>Student</td><td>no</td><td>10%</td><td>5,000</td></tr>
<tr><td rowspan="7">25-60</td><td rowspan="7">42%</td><td>Employee (high income)</td><td>yes</td><td>3%</td><td>1,500</td></tr>
<tr><td rowspan="2">Employee (low income)</td><td>yes</td><td>2%</td><td>1,000</td></tr>
<tr><td>no</td><td>10%</td><td>5,000</td></tr>
<tr><td>Freelance</td><td>no</td><td>-</td><td>-</td></tr>
<tr><td>Part-time employee</td><td>no</td><td>10%</td><td>5,000</td></tr>
<tr><td>Unemployed</td><td>no</td><td>7%</td><td>3,500</td></tr>
<tr><td>House person</td><td>no</td><td>10%</td><td>5,000</td></tr>
<tr><td>60+</td><td>2%</td><td>Retired person<=75</td><td>no</td><td>2%</td><td>1,000</td></tr>
<tr><td>Sum</td><td>100%</td><td colspan="2"></td><td>100%</td><td>50,000</td></tr>
</table>

Table 30: Composition of new inhabitants in VCM.

In order to provide residence places to these 50,000 new inhabitants, the development by either increasing building concentration in the existing settlements or building on undeveloped lands can be chosen. In city areas with limited space, only development by increasing building concentration can be applied. The following three scenarios of locating new inhabitants are generated:

- S_3: Locate all of the new inhabitants equally in residential zones and mixed-use zones in the city area;
- S_4: Locate all of the new inhabitants in MZ zones in the region area;
- S_5: Locate all of the new inhabitants in RA zones in the region area.

The assumed 95% of the new inhabitants who do not own a car are captive riders. The city area provides a high concentration of service facilities and offers good PuT services. MZ has a medium-order central place function and is well connected to other areas. RA offers available lands for the new development but has no central place function and offers insufficient PuT services. It is expected that PuT share in all scenarios will increase, but the increase of PuT trips in S_3 will be more than in S_5. Besides, the average trip length in S_3 will be shorter than in S_5.

Results of scenarios

Changed values of aggregated travel demand indicators in the three scenarios with reference to S_0 are listed in Table 31. 50,000 new inhabitants generate 130,000 new trips in all three scenarios. S_3 promotes PuT trips the most: S_3 generates the highest number of PuT trips, the highest total distance travelled and time expenditure of PuT trips. In contrast, S_4 and S_5 restrict PuT trips: S_5 leads to the lowest number of PuT trips but the highest total distance travelled and time expenditure of car trips, and S_4 results in the lowest total distance travelled and time expenditure for PuT trips. Taken the total distance travelled as a criterion for negative impacts of traffic, S_4 is the optimal solution that S_4 results in the least total distance travelled.

Travel demand indicator	S_0	S_3	S_4	S_5
Total number of trips	8,570,000	+130,000	+130,000	+130,000
Number of PuT trips	920,000	+46,000	+11,100	+10,800
Total distance travelled (car)	61,750,000	+130,000	+80,000	+370,000
Total distance travelled (PuT)	15,700,000	+500,000	+100,000	+200,000
Travel time expenditure (car)	1,720,000	+10,000	+10,000	+20,000
Travel time expenditure (PuT)	720,000	+30,000	+8,000	+12,000

Table 31: Key features of scenarios of new development.

The average travel distance by car is 17 km in all scenarios S_0, S_3, S_4 and S_5. New inhabitants have little influence on commuting trips (C-RoW and R-RoW). For most of the trip purposes there are no measurable differences in these scenarios. Trip purposes with different distances are shown in Figure 78. It is remarkable that S_3 has the longest distance for C-R trips, especially trips to primary school. It results from the limited number of school places in the city and new pupils need to travel to the region area for school. S_4 leads to relatively shorter distances for all trips. This results from the plenty of activity locations in MZ zones and the relatively short distance of intra-zonal trips in MZ zones. S_5 has generally longer distance than S_4 for most trip purposes for both C-R and R-R trips. This indicates that RA zones without central place function are unfavourable locations of new inhabitants.

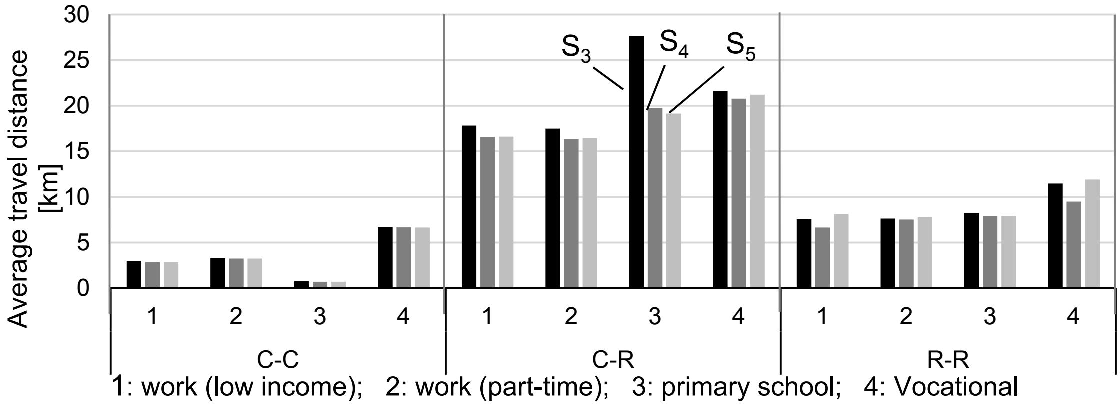


Figure 78: Average travel distance in scenarios of new development.

Additional trips that are performed by new inhabitants have different characteristics in the three scenarios. Numbers of additional trips per mode disaggregated by C-C trips, C-R trips and R-R trips are shown in Figure 79. Commuting trips are excluded, as they have no significant changes. The most significant changes in additional C-C trips occur in S_3; and in additional R-R trips in S_4 and S_5. C-R trips show no significant changes for all three scenarios. In S_3 there are around 40,000 more PuT C-C trips and even more walk C-C trips, but only a slight increase in C-R and R-R trips. S_4 influences C-C and C-R trips to a minor degree, but it generates around 70,000 more walk R-R trips. Although MZ zones are connected by good PuT services, walk intra-zonal trips are more attractive for new inhabitants due to their short walking times. S_5 has also little impact on C-C and C-R trips, but induces around 50,000 more walk R-R trips. S_5 has the most car-driver and car-passenger R-R trips among all these scenarios. The extremely high number of walk R-R trips in S_4 and S_5 shows a limitation of mobility as a reaction to a low level of transport supply. The high number of additional car-passenger trips in S_5 is unrealistic as it is impossible for new inhabitants to be car-passenger with car-driver from existing inhabitants. In case of more new inhabitants with the car availability, much more car trips can be generated in S_5 as new developments are located in the areas with insufficient PuT supply.

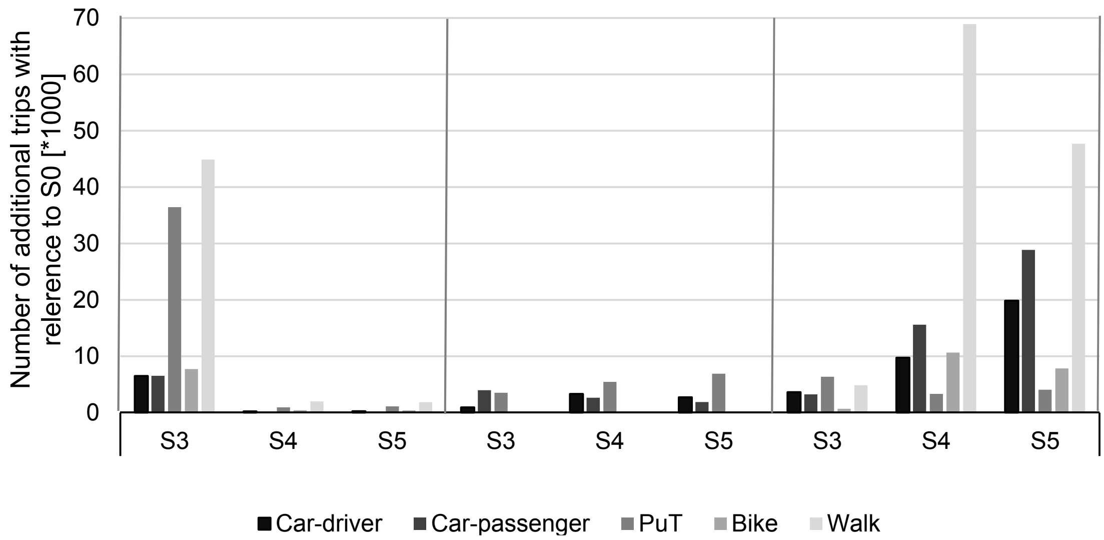


Figure 79: Number of additional trips in scenarios with new developments.

In conclusion, S_3 can satisfy necessities of movement for new inhabitants to the highest degree due to its good PuT services. However, locating new development in the city area requires an extension of relevant facilities such as primary schools. S_4 has the advantage of the lowest total distance travelled. An unrealistic increase of walk trips in S_4 and S_5 results from the high level of aggregation in the region area. In order to precisely model regional planning measures and developments, the level of detail in the region area should be improved for VCM.

5.2 Influence of transport supply

Transport measures are most often applied to solve problems caused by traffic. Validation tests “modified car speed” have indicated that higher car speed leads to more car trips and more total distance travelled. In addition to driving speeds, many other indicators influence the transport supply through travel times and costs. Two application examples of VCM with changed transport supply, i.e. one example with an improved road supply for cars and one example with a better PuT supply are examined in the following. Their characteristics of travel demand are compared to those in S_0.

5.2.1 No congestion in the city

The scenario S_6 excludes congestion from the urban network by setting capacities of all the links in the city to a maximum value. According to the CR-function, maximizing capacity of links leads to the equality of travel times by car in both congested and free-flow network. It is obtained in models by setting capacities of all link types in the city to be unlimited. In reality this measure would require the extension of all roads, even if it is unfeasible to be implemented due to space and finance limitations, and possible induction of more car traffic. This improvement of private transport supply is applied to VCM and its impacts are analysed. Reduced car travel time and more induced car traffic on the network in the city area are expected in S_6.

The maximization of capacity on all links in the city area avoids congestions and decreases congested travel time by car for those trips using the urban network. The degree to which travel time decreases depends on delay time caused by congestion on the urban network in S_0. It is also related to the share of urban network that a type of trip uses. The aggregated congestion level of each type of trip, as introduced in chapter 4.5 on page 146, is applied to evaluate effects of maximization of capacity on all links. Changes in the congestion levels are listed in the following:

- Travellers of C-C trips only travel on the urban network and S_6 has a congestion level of 1.0, which is changed from 1.12 in S_0.
- C-R trips use both the urban network and the LSII and LSIII networks in the region. Given the constant characteristics of the LSII and LSIII networks, the congestion level of those trips decreases from 1.25 in S_0 to 1.13 in S_6.
- C-RoW trips depend mainly on motorways in the region and the urban network. The congestion level of C-RoW changes from 1.27 in S_0 to 1.20 in S_6. Compared to C-C and C-R trips, C-RoW trips have a smaller change of congestion level because capacity on motorways remains constant in S_6.
- Congestion levels for R-RoW and R-R trips have no significant change in S_6, compared to S_0.

Table 32 lists the change rates of key aggregated indicators in S_6 with reference to S_0. The total number of all modelled trips is constant, but there are more car trips with shorter travel time and longer travel distance. No congestion on the urban network leads to more C-C, C-R and C-RoW trips, and shorter travel time for these city-related trips. C-R trips benefit the most from the maximization of capacity as they increase to the largest degree among all types of trips. It results from the fact that the delay time on the VSII network is responsible for congestion of C-R trips and the improved urban road supply solves this problem. More C-R and C-RoW car trips lead to a higher saturation on the network in the region area. It results in 0.4% longer travel time for R-R and R-RoW trips and 0.5% fewer R-R trips.

Indicator	C-C	C-RoW	R-RoW	C-R	R-R	All trips
Congestion level	-10,3%	-5,3%	+0,2%	-9,7%	+0,2%	-2,8%
Average travel time by car	-3,9%	-3,7%	+0,4%	-5,5%	+0,4%	-0,7%
Average travel distance by car	+5,1%	-0,2%	0,0%	+2,2%	-0,1%	+0,8%
Number of car trips	+3,0%	+3,9%	0,0%	+11,4%	-0,7%	+1,3%
Number of total trips	-1,1%	0,0%	0,0%	+7,1%	-0,5%	0,0%

Table 32: Change rates of key indicators in S_6 compared to S_0.

As a conclusion, the maximization of capacity on links in the city induces more car C-C trips with longer distance and shorter time. It leads also to more car C-R and C-RoW trips with shorter time. The total distance travelled increases from 62 million in S_0 to 63 million person kilometres in S_6.

5.2.2 Improvement of urban PuT supply

The seventh scenario S_7 improves urban PuT quality by means of increasing frequency of light rails and decreasing PuT walking time:

- Frequency of light rails in S_0 is described by headways of 15 min and 10 min respectively for off-peak and peak hours. In S_7 both headways are set to be 5 min. In reality, such an assumption would increase operating costs in both personal and vehicular aspects, this assumption would also exceed the capacity of the rail network.
- At the same time, the speed of walking between PuT stops and zones in the city is raised from 6 km/h to 20 km/h. It is based on the assumption that slower walking trip legs are replaced by faster means of transport, which serve to connect home or activity location to PuT stops. They can be public bikes, electric cars or mini-buses.

Expected changes of the combination of shorter headway and higher PuT access speed are more PuT trips and shorter travel time of PuT. To which extent these measures influence the travel demand is examined in the following.

Shorter headways decrease both start waiting time and transfer waiting time. Increase of PuT access speed decreases access and egress time. Thus, the total travel time of PuT decreases in S_7 compared to S_0.

The comparison of PuT travel time between S_7 and S_0 is shown in Figure 80. The PuT travel time aggregated by all the modelled trips decreases from 47 min in S_0 to 32 min in S_7 with a strong decrease in waiting time and a slight decrease in access and egress time in S_7. Changes disaggregated by types of trips are listed as follows:

- Characteristics for C-C trips are influenced the most: travel time decreases from 26 min in S_0 to 12 min in S_7. Access and egress time of C-C trips is 40% shorter. Waiting time changes from -2 to -8. These negative values result from the equation to calculate the start waiting time in Figure 58 (chapter 4.2.2). Negative values emphasize the advantage of short headways in the mode choice process.
- PuT trips of types C-RoW and C-R are mainly undertaken by heavy rail and regional train which have the unchanged characteristics in S_7 when compared to S_0. Thus, the waiting time, access and egress time for C-RoW and C-R trips are only slightly changed. The slight decrease of travel time of PuT C-RoW and C-R trips is caused by the use of light rail as a part of a PuT trip especially for those travellers who travel from or to places far away from stops of heavy rail and regional train.
- PuT R-RoW trips are mainly relevant to regional train. Ride time for R-RoW trips in S_7 is slightly longer than in S_0.
- No measures are taken in the region area. There is no change of characteristics of PuT supply for R-R trips in S_7 compared to S_0.

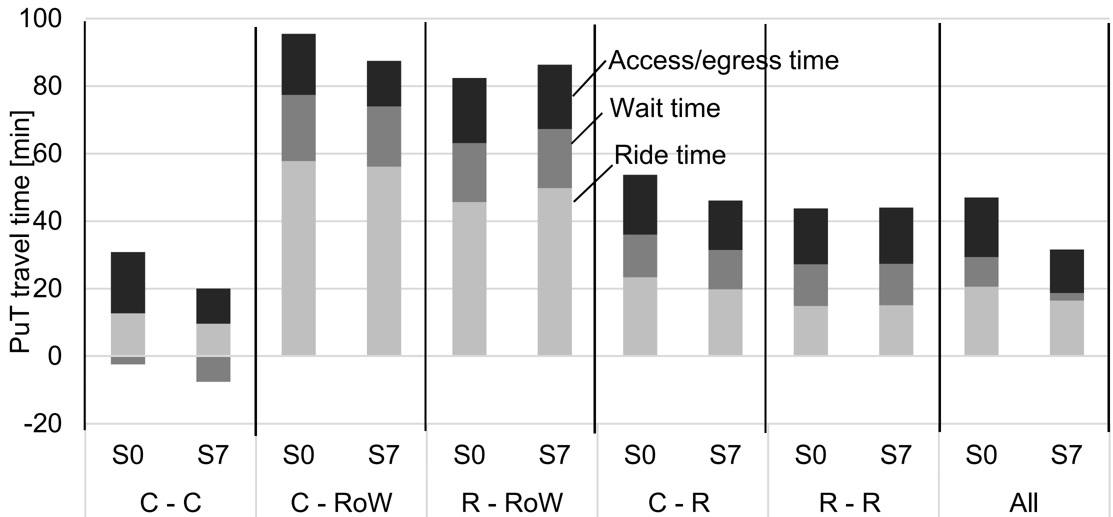


Figure 80: PuT travel time components in S_7 and S_0.

The mean travel distance for PuT trips of all the types is increased in S_7. However, the mean travel time for PuT trips of types which are city-related (C-C, C-R, C-RoW trips) in S_7 decreases. It results from the increased PuT access speed in S_7.

The improvement of PuT service in S_7 influences modal split significantly, as illustrated in Figure 81. The PuT share for the total modelled trips increases by 80% in S_7 in comparison to S_0. Reducing PuT time by 50% for C-C trips leads to an increase of the PuT share from 21% in S_0 to 60% in S_7. Both PuT shares for C-RoW and C-R trips increase by approx. 60%. There are no significant changes of modal split for R-R and R-Row trips.

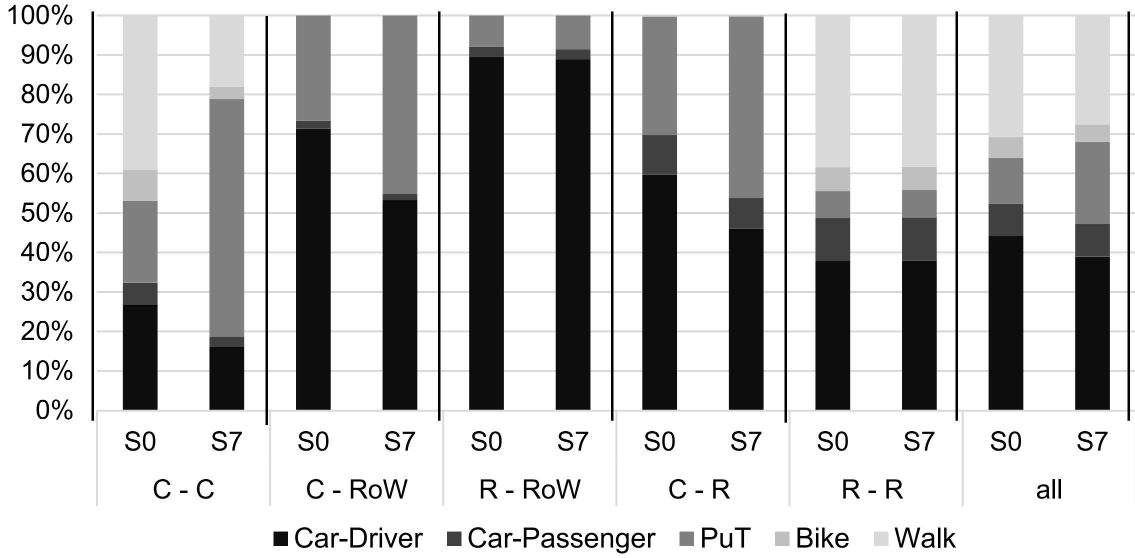


Figure 81: Comparison of modal split in S_0 and S_7.

More PuT trips and fewer car trips in S_7 result in shorter total distance travelled of 58 million in S_7 instead of 62 million person kilometres in S_0. Because of the reduced C-C, C-RoW and C-R trips by car, the saturation on the network in both city and region areas in S_7 are smaller than those in S_0. As a result, the congestion levels of all types of trips decrease, especially for C-RoW and C-R trips. The reduction of congestion levels induces more car trips. However, this effect of inducing more car trips due to a lower congestion level is not as significant as the effect of inducing more PuT trips by the improvement of PuT supply. Thus, the improvement of PuT supply leads to more PuT trips and fewer car trips.

6 Conclusion

"Essentially, all models are wrong but some are useful" –George Box

In this dissertation a macroscopic travel demand model of a virtual city including land use data, a network model and behavioural data is developed with reference to the model of a real city – SCM (Stuttgart City Model). Furthermore, this virtual city model, especially the network model, is calibrated to ensure that the characteristics in VCM can represent the ones in SCM to a certain degree. Before applying VCM for further studies, sensitivity tests are performed in terms of both land use structure and transport supply in the process of validation. At the end of this dissertation, some examples of applying VCM to study influences of measures in both land use planning and transport planning are given. The methodological accomplishment of VCM, major findings from application examples, potential improvements of VCM, and further possible applications are summarized as conclusion.

The virtual city model in this dissertation is different from existing virtual city models, as it emphasizes the modelling of travel demand, rather than real buildings and city structure. Furthermore the virtual city model in this dissertation is also different from other travel demand models of real cities due to its unreal regularity and simplicity. Methodological contributions of this work are listed below:

- Eleven land use categories can be applied to represent the land use structure in a city. These land use categories are based on both the density values of each activity and the relation of densities for different activities. These values of density are only suitable for middle-sized cities as Stuttgart. For larger cities the values of density in criteria should be adjusted accordingly.
- The cross-classification of land use categories, distance to the city centre and densities of land uses is applied to transfer the land use structure in a real city to a virtual city.
- The network generator tool can be applied to develop a large modelling area with a limited number of pre-defined 1 km² tiles, where most of network elements, and even land use categories of zones are defined.
- Aggregated indicators such as road density per link type, stop density per PuT transport system are applied to compare VCM with the reference model in the process of developing VCM.
- Different from calibration of a real city model where survey data are available for determining parameters in behaviour functions, calibration of VCM focuses on the adjustments of travel time, distance and cost of od-pairs. Trips in the network are also calibrated due to the influence on travel time in the congested network.
- VCM is validated by a series of sensitivity tests in terms of both land use and transport supply. Given the same modification of density or car speed, the comparable change of travel demand in VCM and in the reference model shows robustness of VCM, otherwise relevant modules in VCM are adjusted till the comparable result is reached.

Influences of developments and measures can be studied by applying VCM. Seven scenarios are generated in this work with five in land use planning and two in transport planning. The following findings from these application examples can be concluded:

- The separation of land uses, i.e. work places in the centre and residence in the periphery area, leads to more PuT trips. It confirms the findings in literature such as from LECK (2006). Compared to separation of land uses, the ideal mixture of land uses leads to more car trips.
- Locating the new development in the city area rather than in the region area induces more PuT trips due to good PuT services in the city area. However, relevant facilities such as schools in the city area should be provided accordingly for the increased population.
- Ideal improvement of capacity on roads, i.e. no congestion in the network, induces more car trips with longer distance but slightly shorter time. It also conforms to the research in the literature such as from MOKHTARIAN and CHEN (2004).
- Ideal improvement of the PuT service increases the PuT share significantly. However, this conclusion is only suitable for cities with a relative high density.

These application examples are on the basis of “other things remaining equal”, which ignores the possible interaction between the changed measure and other elements in the model. VCM is applied to model the influence of land use structure and transport supply on travel demand. However, it is not able to model the interaction between land use structure and transport supply. For example, changes in the land use structure would also cause changes in the transport infrastructure, especially the arrangement of public transport lines. Another example of disadvantage of this basis “other things remaining equal” lies in the first scenario (S_1), where all work places are located in the central area of a city. In this scenario the increase of parking search time due to limited parking places is not modelled, otherwise it results in even more PuT trips. Therefore, the modelling result of VCM can be interpreted as the moment that one change happens and other changes have not yet reacted to this change.

A VCM is able to represent travel demand of the reference area with a certain validity. However, different aspects of VCM can be improved in further studies, for example:

- The land use structure in a polycentric city can be transferred by the cross-classification of land use categories, densities and rings referring to not only the city centre, but also to sub-centres. In the current version of VCM, only rings referring to the city centre are considered.
- A database of tile structures with typical network forms and components of zones can be created for the network generator tool. Different concepts of cities can be generated with corresponding tile structures in the database.
- The region area can be modelled on a lower aggregation level with more zones, so that regional planning measures can also be studied applying VCM. For example, the

unrealistically high number of walk trips can be avoided in scenarios S_4 and S_5 of locating new development in the region area.

- New version of VISUM 15.0 introduces also modelling of freight transport with different structure from person transport by means of generating real tours and trip tables of freight transport. Applying this version of VISUM should be able to model freight transport in a better way than the current VCM does.

More development scenarios and measures in land use and transport planning than scenarios in chapter 5 can be modelled and analysed in VCM. As a potential further application of VCM, a combination of the PuT improvement in S_7 and the limitation of car use can be tested. Besides, as it is suggested to adopt an integrative approach for transport planning and land use planning in the literature, the influence of combing measures in land use planning and transport planning can be studied. A measure that can be tested is the high density with mixed-use and restricted car use policies, as suggested by CERVERO and KOCKELMAN (1997).

Another interesting potential further research applying VCM is the comparison of VCMs with different land use structure and transport supply. The methodological processes can be applied to develop new virtual city models, such as with another network form or with a new reference model. An example is the comparison between Detroit Region in the USA and Stuttgart Region, as these two regions have similar characteristics of population and size. Land use data in Detroit Region can be transferred with the methods of cross classification into a new VCM. Similarly a new network model based on the network structure in Detroit Region can also be generated with the network generator tool. For a precise forecast, this network model should be calibrated and validated with the existing data from the Detroit Region. Assuming that all of the residents in Stuttgart Region are living in Detroit Region in the USA, i.e. behaviour data in Stuttgart Region are applied, travel demand of these travellers in the new VCM can be investigated. Comparing travel demand of these two VCMs, although they share the same behavioural data, the land use and network structure in the U.S.A are supposed to produce more and longer car trips, as shown in differences between surveys in the USA and Germany.

This version of VCM is available for more applications, and other versions of VCM can be generated following the same methods.

Bibliography

AXHAUSEN, K. W. and M. FRICK (2005): B1 Nutzung-Strukturen-Verkehr. In: Steierwald, G., H. D. Künne and W. Vogt (Eds.): Stadtverkehrsplanung. Grundlagen, Methoden, Ziele. Springer, Berlin.

BADOE, D. A. and E. J. MILLER (2000): Transportation–land-use interaction. Empirical findings in North America, and their implications for modeling. In: Transportation Research Part D: Transport and Environment 5 (4): 235–263.

BERTAUD, A. (2002): Transportation and Urban Spatial Structure. In: Washington ABCDE Conference.

BONZ, M., W. ARNOLD and K.-D. LOHRMANN (2005): C6 Öffentlicher Verkehr. In: Steierwald, G., H. D. Künne and W. Vogt (Eds.): Stadtverkehrsplanung. Grundlagen, Methoden, Ziele. Springer, Berlin.

BROTCHIE, J. F. (1984): Technological Change and Urban Form. In: Environment and Planning A 16 (5): 583–596.

BUEHLER, R. (2009): Determinants of Automobile Use. A comparison of Germand and the US. In: Transportation Research Record: Journal of the Transportation Research Board 2139: 161–171.

BUNDESAMT FÜR MIGRATION UND FLÜCHTLINGE (2016): Aktuelle Zahlen zu Asyl.

CERVERO, R. (1996): Mixed land-uses and commuting. Evidence from the American Housing Survey. In: Transport research Vol.30 (Nr.5): 361–377.

CERVERO, R. and K. KOCKELMAN (1997): Travel demand and the 3Ds. Density, diversity, and design. In: Transportation Research Part D: Transport and Environment 2 (3): 199–219.

CERVERO, R. and J. MURAKAMI (2010): Effects of built environments on vehicle miles traveled. Evidence from 370 US urbanized areas. In: Environment and Planning 42 (2): 400–418.

CHRISTALLER, W. (1933): Die zentralen Orte in Süddeutschland. Eine ökonomisch-geographische Untersuchung über die Gesetzmäßigkeiten der Verbreitung und Entwicklung der Siedlungen mit städtischen Funktionen. A. Fischer Verlag, Jena.

CURTIS, C. and T. PERKINS (2006): Travel Behaviour: A review of recent literature. Department of Urban and Regional Planning, Curtin University.

DEPARTMENT FOR TRANSPORT IN UK (2015): National Travel Survey: England 2014.

DEPARTMENT OF TRANSPORT IN SOUTH AFRICA (2005): Key results of the national household travel survey. The first South African national household Travel Survey 2003.

DIELEMAN, F., M. DIJST and G. BURGHOUWT (2002): Urban Form and Travel Behaviour. Micro-level Household Attributes and Residential Context. In: Urban Studies 39 (3): 507–527.

EWING, R. and R. CERVERO (2010): Travel and the Built Environment. In: Journal of the American Planning Association (76 (3)): 265–294.

FELLENDORF, M., T. HAUPT, U. HEIL and W. SCHERR (1997): VISEM - an activity chain based traffic demand.

FORSCHUNGSGESELLSCHAFT FÜR STAßEN- UND VERKEHRSWESEN (1995): Empfehlung für die Anlage von Erschließungsstraßen. EAE 85/95.

FORSCHUNGSGESELLSCHAFT FÜR STAßEN- UND VERKEHRSWESEN (2001): Handbuch für die Bemessung von Straßenverkehrsanlagen (HBS). FGSV Verlag, Köln.

FORSCHUNGSGESELLSCHAFT FÜR STAßEN- UND VERKEHRSWESEN (2008): Richtlinien für integrierte Netzgestaltung (RIN). FGSV, Issue 121. FGSV Verlag, Köln.

FRIEDRICH, M. (2010): Route Choice in Road Networks. Observing and Modelling Route Choice. In: Proceedings of the 5th International Symposium "Networks for Mobility" (FOVUS) Stuttgart.

FRIEDRICH, M. (2011): Wie viele? Wohin? Womit? Was können uns Verkehrsnachfragemodelle wirklich sagen? In: Tagungsbericht Heureka 11.

FRIEDRICH, M. (2013): Verkehrsplanung und Verkehrsmodelle. (Skript zur Vorlesung im Wintersemester 2013/2014). Institue für Straßen- und Verkehrswesen, Lehrstuhl für Verkehrsplanung und Verkehrsleittechnik, Universität Stuttgart.

FRIEDRICH, M. (2016): 4.2 Travel Demand Models. In: Gentile, G. and K. Noekel (Eds.): Modelling Public Transport Passenger Flows in the Era of Intelligent Transport Systems. COST Action TU1004 (TransITS). Springer: 159–179.

FRIEDRICH, M. and C. RITZ (2014): Was bringt wie viel? Alte und neue Verkehrs- und Mobilitätskonzepte für Städte. In: Tagungsbericht Heureka 14.

GALSTER, M. (2009): Modellierung von Anbindungen in Verkehrsplanungsmodellen. Schriftenreihe des Instituts für Verkehrswesen der Universität Stuttgart, Heft 40.

GATHER, M., A. KAGERMEIER and M. LANZENDORF (2008): Geographische Mobilitäts- und Verkehrsforschung. Studienbücher der Geographie. Borntraeger, Berlin [u.a.].

GEA (2012): Chapter 18 Urban energy systems. In: GEA (Ed.): Global Energy Assessment - Toward a Sustainable Future. Key findings, summary for policymakers, technical summary. International Institute for Applied Systems Analysis, Vienna, Austria and Cambridge University Press, Cambridge, UK and New York, NY, USA.

GRÜBLER, A. (1990): The rise and fall of infrastructures. Dynamics of evolution and technological change in transport. Contributions to economics. Physica-Verlag, Heidelberg.

HANDY, S., X. CAO and P. MOKHTARIAN (2005): Correlation or causality between the built environment and travel behavior? Evidence from Northern California. In: Transportation Research Part D: Transport and Environment 10 (6): 427–444.

HEIDL, U. and J. SCHLAICH (2012): State of the art of multimodal macroscopic transport modelling. In: Proceedings of the 5th International Symposium "Networks for Mobility" (FOVUS) Stuttgart.

HEINZE, G. W. and H. H. KILL (1995): Das Auto von morgen in unseren Städten von morgen. In: Appel, H. (Ed.): Stadtauto. Mobilität, Ökologie, Ökonomie, Sicherheit, Issue 13. Vieweg, Braunschweig [u.a.].

HOLTZCLAW, J. (1994): Using residential patterns and transit to decrease auto dependence and costs. San Francisco, USA.

HOWARD, E. (1902): Garden Cities for Tomorrow. Swan Sonnenschein & Co., Ltd., London.

INFAS and DLR (2010): Mobilität in Deutschland 2008. Ergebnisbericht Sturktur-Aufkommen-Emissionen-Trends.

KIM, J. and D. BROWNSTONE (2010): The impact of residential density on vehicle usage and fuel consumption.

KIRCHHOFF, P. (2002): Städtische Verkehrsplanung. Konzepte, Verfahren, Massnahmen. Teubner, Stuttgart, Leipzig, Wiesbaden.

KUPPAM, A. R. and R. M. PENDYALA (2001): A structural equations analysis of commuters' activity and travel patterns. In: Transportation 28 (1): 33–54.

KUTTER, E. and A. STEIN (1998): Minderung des Regionalverkehrs. Chancen von Städtebau und Raumordnung in Ostdeutschland. Forschungsberichte des Bundesamtes für Bauwesen und Raumordnung Heft 87. Bonn.

LE NÉCHET, F. (2012): Urban spatial structure, daily mobility and energy consumption: a study of 34 European cities. In: Cybergeo : European Journal of Geography.

LECK, E. (2006): The Impact of Urban Form on Travel Behavior: A Meta-Analysis. In: Berkeley Planning Journal (19 (1)).

LEIBBRAND, K. (1980): Stadt und Verkehr. Theorie und Praxis der städtischen Verkehrsplanung. Birkhäuser, Stuttgart.

LILL, E. (1889): Die Grundgesetze des Personenverkehrs : eine Studie. In: Zeitschrift für Eisenbahnen und Dampfschiffahrt: 697.

LOHSE, D. (1997): Grundlagen der Straßenverkehrstechnik und der Verkehrsplanung: Band 2-Verkehrsplanung, Issue 2. Verlag für Bauwesen Berlin.

LU, Y., K. KAWAMURA and M. ZELLNER (2008): Exploring the Influence of Urban Form on Work Travel Behavior with Agent-Based Modeling. In: Transportation Research Record: Journal of the Transportation Research Board 2082: 132–140.

MAO, H. (2005): Research of trip characteristics of Chinese urban citizens. Translated from 中国城市居民出行特征研究 (毛海虓). Dissertation. Beijing Industry University, Beijing, China.

MILLER, E. J. and R. M. SOBERMAN (2003): Travel Demand and Urban Form.

MOKHTARIAN, P. L. and C. CHEN (2004): TTB or not TTB, that is the question. A review and analysis of the empirical literature on travel time (and money) budgets. In: Transportation Research Part A: Policy and Practice 38 (9-10): 643–675.

MORTON, P. J., R. C. DALTON and E. M. THOMPSON: Virtual City Models: A Global Perspective in the development and distribution of VCMs.

NAESS, P. (2000): Urban structures and travel behavior. Experiences from empirical research in Norway and Denmark. Paper for the International Conference “Land Use and Travel Behaviour”, Amsterdam.

NATIONAL RESEARCH COUNCIL (U.S.) (1985): Highway Capacity Manual. In: Transport Research Board (Special Report 209).

NEWBOLD, K. B., D. M. SCOTT, J. E. SPINNEY, P. KANAROGLOU and A. PÁEZ (2005): Travel behavior within Canada’s older population: a cohort analysis. In: Journal of Transport Geography 13 (4): 340–351.

NEWMAN, P. W. G. and J. R. KENWORTHY (1989): Gasoline Consumption and Cities: A Comparison of U.S. Cities with a Global Survey. In: Journal of the American Planning Association 55: 24–37.

NEWMAN, P. W. G. and J. R. KENWORTHY (1996): The land use—transport connection. An overview. In: Land Use Policy 13 (1): 1–22.

NEWMAN, P. W. G. and J. R. KENWORTHY (2006): Urban Design to Reduce Automobile Dependence. In: Opolis 2 (1): 35–52.

NOBIS, C. and B. LENZ (2005): Gender Differences in Travel Patterns: Role of Employment Status and Household Structure. In: Transportation Reserach Board Conference Proceedings 35: 114–123.

ORTÚZAR, J. D. D. and L. G. WILLUMSEN (2011): Modelling transport. Wiley-Blackwell, Oxford.

POLK, M. (2004): The influence of gender on daily car use and on willingness to reduce car use in Sweden. In: Journal of Transport Geography 12 (3): 185–195.

PTV (2014): PTV Visum 14 – Manual 2014.

RODRIGUE, J.-P., C. COMTOIS and B. SLACK (2006): The geography of transport systems. Routledge, London and New York.

RODRIGUEZ, A. (2007): City Structure and Sustainability. Master thesis. Master of infrastructure planing, University of Stuttgart, Stuttgart.

ROTH, G. J. and Y. ZAHAVI (1981): Travel time “budgets” in developing countries. In: Transportation Research Part A: General 15 (1): 87–95.

RYLEY, T. (2006): Use of non-motorised modes and life stage in Edinburgh. In: Journal of Transport Geography 14 (5): 367–375.

SCHAFER, A. and D. G. VICTOR (2000): The future mobility of the world population. In: Transportation Research Part A: Policy and Practice 34 (3): 171–205.

SCHMIEDEL (1984): Bestimmung verhaltensähnlicher Personenkreise für die Verkehrsplanung. University of Karlsruhe.

SCHOTT, V. (2014): Junge Leute - Abwendung vom Auto? In: Internationales Verkehrswesen 66 (3): 68–70.

SCHWANEN, T., F. M. DIELEMAN and M. DIJST (2001): Travel behaviour in Dutch monocentric and policentric urban systems. In: Journal of Transport Geography 3 (9): 173–186.

SCOTT, D. M. and P. S. KANAROGLOU (2002): An activity-episode generation model that captures interactions between household heads: development and empirical analysis. In: Transportation Research Part B: Methodological 36 (10): 875–896.

SENATSVERWALTUNG FÜR STADTENTWICKLUNG BERLIN (2005): Flächennutzungsplan Berlin (FNP). Erläuterung der Darstellung.

SIEBER, N. (2000): Durch Raumplanung Verkehr vermeiden. in Verkehr in Stadt und Region : Leitbilder, Konzepte und Instrumente. Forschungs- und Sitzungsberichte der ARL. Verl. der ARL, Hannover.

STATISTISCHES AMT STUTTGART: Lage und Größe der Landeshauptstadt Stuttgart. In: http://statistik1.stuttgart.de/statistiken/tabellen/7552/jb7552.php. Call: 15.9.2015.

STATISTISCHES AMT STUTTGART (2012): Datenkompass Stadtbezirke Stuttgart. Statistik und Informationsmanagement Themenhefte. Stuttgart.

THE WORLD BANK: 3.12 World Development Indicators: Urbanization. In: http://wdi.worldbank.org/table/3.12#. Call: 22.2.2016.

U.S. DEPARTMENT OF TRANSPORTATION (2011): Summary of travel trends. 2009 National household travel survey.

UDRY, J. R. (1994): The nature of gender. In: Demography 31 (4): 561–573.

VAN ACKER, V. and F. WITLOX (2010): Car ownership as a mediating variable in car travel behaviour research using a structural equation modelling approach to identify its dual relationship. In: Journal of Transport Geography 18 (1): 65–74.

VERBAND DEUTSCHER VERKEHRSUNTERNEHMEN (1997): Zukunftsfähige Mobilität: Menschen bewegen; ÖPNV in Deutschland. Düsseldorf.

VOGT, W. (2005): C1 Historische Entwicklung von Verkehrsnetzen. In: Steierwald, G., H. D. Künne and W. Vogt (Eds.): Stadtverkehrsplanung. Grundlagen, Methoden, Ziele. Springer, Berlin.

VOS, J. de, B. DERUDDER, V. VAN ACKER and F. WITLOX (2012): Reducing car use: changing attitudes or relocating? The influence of residential dissonance on travel behavior. In: Journal of Transport Geography 22.

VRS (2011): Mobilität und Verkehr in der Region Stuttgart 2009/2010. Regionale Haushaltsbefragung zum Verkehrsverhalten. No. 29.

WARDROP, J. G. (1952): Some theoretical aspects of road traffic research. In: Proceedings of the Inst. of Civil Engineering, London.

WEGENER, M. (1994): Die Stadt der kurzen Wege - müssen wir unsere Städte umbauen? No. 136.

WEGENER, M. and F. FÜRST (1999): Land-Use Transport Interaction. Technische Universität Dortmund.

WEIGELE, S. (2014): Urbane Mobilität im Umbruch? Verkehrliche und ökonomische Bedeutung des Free-Floating-Carsharing.

WERMUTH, M. (2005): B5 Modellvorstellungen zur Prognose. In: Steierwald, G., H. D. Künne and W. Vogt (Eds.): Stadtverkehrsplanung. Grundlagen, Methoden, Ziele. Springer, Berlin.

ZAHAVI, Y. and J. M. RYAN (1980): Stability of travel components over time. In: Transportation Research Record (750).

Glossary und Abbreviations

Change rate	The change rate is applied to compare the same indicator in two scenarios. It is defined as the ratio (of dividing the value in the examined scenario by the value in the reference scenario) minus 1 resulting in an increased rate in case of a positive value, or a decreased rate in case of a negative value.
Congestion level	Congestion level is defined as t_{con} /$t_{0.}$ It is an indicator describing the difference of car travel times in both congested and free-flow networks. It can be referred to a link, an od-pair, a type of od-pairs.
NHTS	National household transport survey is a survey where all the information on travel behaviour on the level of households is gathered. This abbreviation is applied in English-speaking countries.
PrT	Private transport, includes both motorized individual mode (car) and non-motorized modes (also slow modes: walk and bike).
PuT	Public transport
od-pair	Od-pair (also: relation) is an object and units for matrix in transport model. It is defined with an origin zone and a destination zone.
RIN	Richtlinien für integrierte Netzgestaltung = Guidelines for an Integrated Network Planning issued by the Research Association for Roads and Traffic.
Saturation	Saturation is derived by dividing the actual volume by the capacity of a link. It is also called volume-capacity-ratio.
SCM	Stuttgart city model is the reference model of the virtual city model.
Demand group	Travel demand class in respect to both person groups and trip purposes
Time series	Time series offer information on how the generated trips are distributed temporally along a one-day period.
Utility	Utility is the evaluation of an alternative of choices. The higher the utility of an alternative, the higher the possibility that this alternative will be selected. A utility function in a transport demand model is applied to model the utility of an alternative.
VCM	Virtual city model, a travel demand model of a virtual city
VMT	Vehicle miles of travel is a commonly used indicator mainly in the USA to represent the total distance travelled.

(Road categories)

AF	Walk lane outside build-up areas (Fußweg außerhalb bebauter Gebiete)
AR	Bike road outside build-up areas (Radweg außerhalb bebauter Gebiete)

AS	Federal motorways (Autobahn)
ES	Collector road (Erschließungsstraße)
FB	Long-distance heavy rail track (Fernverkehrsbahn)
HS	Arterial road with buildings (angebaute Hauptverkehrsstraße)
IF	Walk lane inside build-up areas (Fußweg innerhalb bebauter Gebiete)
IR	Bike lane inside build-up areas (Radweg innerhalb bebauter Gebiete)
LS	Rural roads (Landstraßen)
NB	Regional heavy rail track (Nahverkehrsbahn)
RB	Regional bus (Regionalbus)
SB	Partly independent light rail track (Stadtbahn)
TB	Tram/urban bus (Tram/Bus)
UB	Independent rail track (Unabhängige Bahn)
VS	Arterial road without buildings (anbaufreie Hauptverkehrsstraße)

(Spatial division)

CBD	Central business district, usually located in the central area of a city.
CC	City centre is a central part of inner city.
G	Community without central place function (Gemeinde)
GZ	Low-order central place (Grundzentren)
Hinterland	Hinterland refers to the surrounding area of a city. It is important in an urban model to generate commuting trips of the corresponding city.
IC	Inner city includes also the city centre. The remaining area of the inner city aside from the city centre is “IC (except CC)”.
MR	Metropolitan region (Metropolregion)
MZ	Medium-order central place (Mittelzentrum)
OZ	High-order central place (Oberzentrum)
PC	Peripheral city is the rest area of the city outside the inner city.
RA	Rural area in VCM, representing the areas without central place function in the region area.
RoW	Rest of the world represents the rest of the world in reference to the modelled city and region.

Schriftenreihe des Instituts für Straßen- und Verkehrswesen

Heft 1	1. Fachkolloquium Straße und Verkehr - Stuttgart 1986	9/1987
Heft 2	2. Fachkolloquium Straße und Verkehr - Stuttgart 1988	4/1989
Heft 3	Arbeiten aus dem Institut für Straßen-und Verkehrswesen	7/1989
Heft 4	Beiträge zum Ruhenden Verkehr	8/1989
Heft 5	Festkolloquium anlässlich der Vollendung des 60.Lebensjahres von Prof. Dr.-Ing. Gerd Steierwald	5/1990
Heft 6	3. Fachkolloquium Straße und Verkehr - Stuttgart 1990	4/1991
Heft 7	Wolfgang Hertkorn Veränderungen des Kraftstoffverbrauchs und der Abgasbelastungen durch Geschwindigkeitsreduktion in untergeordneten städtischen Straßennetzen	2/1992
Heft 8	City Stuttgart - attraktive Innenstadt im Zentrum einer Agglomeration (Autofreie Innenstadt = Attraktive City?)	3/1992
Heft 9	Arbeiten aus dem Institut für Straßen-und Verkehrswesen	4/1992
Heft 10	Reinhard Unkhoff Der Einfluß des Schwerverkehrs auf Geschwindigkeitsverhalten und Pulkbildung auf Autobahnen	6/1992
Heft 11	Stefanos Bazis Interaktiver Straßenentwurf mit Hilfe der EDV	7/1992
Heft 12	Jiann-Sheng Wu Stochastische Simulation des Überholverhaltens auf zweistreifigen Landstraßen	7/1992

Heft 13	4. Fachkolloquium Straße und Verkehr - Stuttgart 1992	5/1993
Heft 14	Stephan Herkt Abstimmung der Leistungsfähigkeit von Knotenpunkten mit Lichtsignalanlage und knotenpunktfreien Strecken an innerörtlichen Hauptverkehrsstraßen	4/1994
Heft 15	Von den Anfängen bis zur Gegenwart -Straßen- und Verkehrswesen an der Universität Stuttgart	9/1994
Heft 16	Ashraf Hamed Abwicklung des Lieferverkehrs innerörtlichen Hauptstraßen	10/1994
Heft 17	5. Fachkolloquium Straße und Verkehr - Stuttgart 1994	3/1995
Heft 18	Chronik und Retrospektive - Gerd Steierwald und das Institut für Straßen- und Verkehrswesen	10/1995
Heft 19	Heiko Tempel Zusammenhänge zwischen Verkehrsablauf, Kraftstoffverbrauch und Schadstoffemissionen im städtischen Busverkehr	11/1995
Heft 20	Volker Mörgenthaler Strategien zur Verminderung der Emissionen von Ozonvorläufersubstanzen des Nutzfahrzeugverkehrs in Ballungsgebieten	2/1996
Heft 21	Martin Schmid Auswirkungen der Kraftstoffbesteuerung auf die Pkw-Fahrleistungen im Freizeitverkehr	11/1996
Heft 22	Burkhard Flasche Fahrraumbewirtschaftung mit Sonderfahrstreifen für ausgewählte Stadtverkehre	2/1998
Heft 23	Szabolcs Törgyekes Ableitung spezifischer Abgas-Emissionsfaktoren für Kraftfahrzeugkollektive anhand von Konzentrationsmessungen in einem städtischen Straßentunnel	3/1998

Heft 36	Volker Schmid Reaktivierte Nebenbahnen und alternative Buskonzepte Vergleich von ökologischen Wirkungen	7/2003
Heft 37	8. Fachkolloquium Straße und Verkehr - Stuttgart 2003	3/2009
Heft 38	Matthias Lenz Auswirkungen des Ausbaus der verkehrlichen Infrastruktur auf das regionale Fernpendleraufkommen	2/2005
Heft 39	Steffen R. Herrmann Simulationsmodell zum Wasserabfluss- und Aquaplaningverhalten auf Fahrbahnoberflächen	2/2008
Heft 40	Manuel Galster Modellierung von Anbindungen in Verkehrsplanungsmodellen	8/2009
Heft 41	10. Fachkolloquium Straße und Verkehr - Stuttgart 2008	8/2009
Heft 42	Johannes Schlaich Nutzung von Mobilfunkdaten für die Analyse der Routenwahl	6/2010
Heft 43	Florian Bitzer Mikroskopische Modellierung und Simulation des Fußgängerverkehrs	9/2010
Heft 44	Eileen Mandir Potential of Traffic Information to optimize Route and Departure Time Choice	7/2012
Heft 45	Anne Wolff Simulation of Pavement Surface Runoff using the Depth-Averaged Shallow Water Equations	3/2013
Heft 46	Stefan Alber Veränderung des Schallabsorptionsverhaltens von offenporigen Asphalten durch Verschmutzung	3/2013

Heft 47	Thomas Otterstätter Methoden zur Erfassung von Verkehrsströmen und Fahrzeiten mit stationären fahrzeugwiedererkennenden Detektoren	8/2013
Heft 48	Bruno Arbter Numerische Bestimmung der akustischen Eigenschaften offenporiger Fahrbahnbeläge auf Basis ihrer rekonstruierten Geometrie	5/2014
Heft 49	Juliane Pillat Methoden zur Analyse und Prognose des Verkehrsaufkommens unter Berücksichtigung des Wetters auf Autobahnen	7/2014
Heft 50	Jochen Lohmiller Qualität des Verkehrsablaufs auf Netzabschnitten von Autobahnen - Bewertung unter Berücksichtigung der Zuverlässigkeit und Analyse von Einflussfaktoren	7/2014
Heft 51	Katrin Keller Modellierung und Optimierung des Verkehrsablaufs in Evakuierungssituationen	9/2014
Heft 52	Yaohua Xiong A Framework for Traffic Assignment with Explicit Route Generation	9/2014
Heft 53	Markus Weise Einflüsse der mikroskaligen Oberflächen-geometrie von Asphaltdeckschichten auf das Tribosystem Reifen-Fahrbahn	11/2015
Heft 54	Benjamin Rabenstein Öffentliche Fahrradverleihsysteme - Wirkungen und Potenziale	12/2015
Heft 55	Lu Liu Development of a Virtual City Model for Urban Land Use and Transport Planning	8/2016