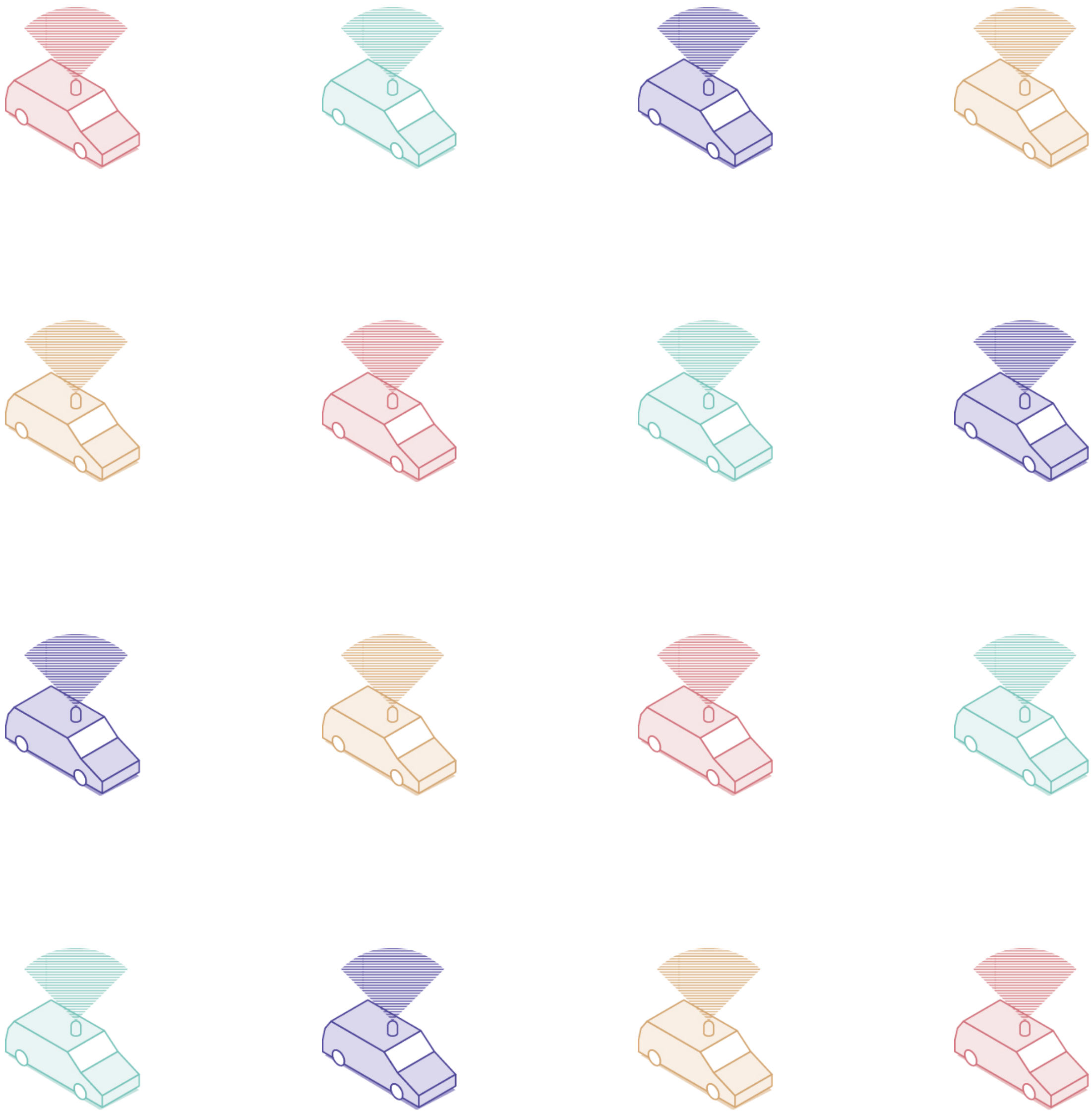

AUTOMATED DRIVING:
DRIVING URBAN DEVELOPMENT?

AN INTEGRATED RESEARCH-BY-DESIGN COMPUTATIONAL MODELLING APPROACH IN URBAN PLANNING PROBLEMS

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Track Urbanism

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BY

MARTIJN LEENDERT HOLLESTELLE

In partial fulfilments of the requirements for the degree of

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PREFACE

A recognisable event among fellow students is for sure that a final version of a design, report or any document happens to be not the final version. After altering the changes, versions like 'final_2', 'final-of-the-final' or 'finally-the-final' will be created. It is worth stating that this report is fore sure a 'final' version but not actually the 'final-of-the-final'. This research, is in which this report is established, is part of the graduation process for both the master of Urbanism at the faculty of Architecture and the master of Transport & Planning at the faculty of Civil Engineering. This report is submitted for the partial fulfilment of the Urbanism exam. Some steps within the research are not executed for time constraints and will be further evaluated for the fulfilment of the Transport & Planning exam. I would like to attend readers of this report that a 'final-of-the-final' version is on its way or already exists (depending on when one reads this).

This research started from the motivation to employ both my Civil Engineering and my Urbanism perspective to problems in the built environment as I am convinced that this will lead to better understandings and solutions. Although this research bears the topic of automated driving, my primary motivation lies in attempt to bring the two disciplines together. Combining two master theses in one research is very challenging and feels like doing three researches. One must elaborate on both perspectives plus the integration of these both perspectives. This was at times very tough, but reflecting on what it has taught me very rewarding.

Reader interested in the aspects of using an integrated research approach in urban planning problems can read on this aspect in chapter 2. Chapter 3 elaborates on computational urban models as a mean to study the dynamic processes in the built environment. Reader particularly interested in the case of automated driving can find all aspects in chapter 4 to chapter 10. Chapter 11 concludes on the research approach.

I would like to express my gratitude towards the teachers supervising this research, Egbert Stolk and Akkelies van Nes. Egbert, you have been of great support. Our discussions about methodologies has helped me to obtain a self-conscious attitude within this research and made me explore topics I would have not grasped on by myself. The insights these gave me, are more valuable to me than all knowledge I obtained about self-driving cars during this research together. Akkie, your positive and collaborative attitude towards this project has supported me greatly in persevering in this research. Additionally, I want to thank the members of my Civil Engineering committee. Bart van Arem, Gonçalo Correia and Dimitris Milakis have provided important input on the case of automated driving and all practical aspects related to formalising the methodology. Special thanks go out to Justin Hogenberg of the Province of Utrecht and Arnout Kwant of Goudappel Coffeng for their support regarding the transport modelling. It was great fun to brainstorm together how to use VRU to study automated driving effects.

Furthermore, I would like to thank everyone else who has been part of my graduation process. My fellow students of the graduation office (goes by the name of 'Hok') provided a very nice working environment. Thank you, paps and mams for all the unconditional support, not only during my graduation but during my entire study career. Kiitos, Lotta for your patience and your support in all the high and low moments.

Martijn Leendert Hollestelle
Delft, October 2018

SUMMARY

Complex urban planning problems comprise socio-spatial conditions, human behaviour and external factors (e.g. technological developments). The perspective of urban planners and designers is crucial to comprehend these problems from a holistic point of view but does not possess the skills to grapple the full problem. Cities bear characteristics of complex systems in which the interaction between decision makers is an important factor in the manifestation of urban change. Quantitative and computational methods are becoming increasingly capable at evaluating this aspect of urban planning problems. Computational models, although a simplification of reality, can help to evaluate many data and therefore extend the thinking capacity. Design thinking can interpret model outcomes in the broader socio-spatial context. But integration between these engineering-based methods on the one hand and the conventional urban planning and design methods proves challenging. This research investigates how an integrated methodology can lead to better understanding of urban planning problems. Models that comprehend built environment dynamics, can be used as design evaluation tool.

The uncertainty around the spatial impacts of automated driving is used as case study for a complex urban planning problem. How automated driving will affect cities depends on the development and the deployment of the technology but also on how human agents adapt their behaviour. Mobility aspects (and therefore automated driving) relate to the built environment through the concept of accessibility and by the integration of the transportation system in space.

An important condition to employ computational models within a research process is to explicitly define the system one evaluates. This research narrows down to households and their location choice behaviour as important behavioural aspect in urban development. The residential location choice depends on characteristics of the households itself and on dwelling, environment and location attributes. Automated vehicles are propagated to be more efficient in terms of infrastructure demands and travel efficiency compared to conventional vehicles. Therefore, this technology relates to the decision factors of households through spatial quality and accessibility effects.

A scenario approach is employed to grapple the uncertainty around automated driving. In four scenarios, different development paths of automated driving are assumed. The province of Utrecht in the Netherlands is used as case study to provide for context and data. This research employs a residential location choice model to examine the changes in moving behaviour of households in space caused by the development of automated driving. The

accessibility effects are studied with a transport model and the spatial quality effects are obtained by research and design. The residential location choice model evaluates these factors. The result is a change in urban development pattern. The results are interpreted in an urban strategy where the results of previous research steps are synthesised and assessed, to provide for interpretation of the research outcome from a holistic socio-spatial perspective.

Automated driving has a positive effect on accessibility although induced travel demand reduces some of these benefits. The relative change in accessibility is around the same magnitude for each place. Despite potential infrastructure capacity gains, arterial roads within cities are prone to congestion if public transport will be assigned to the road network or by induced travel caused by new user groups or alternative parking solutions. The spatial quality effects are examined on two scale levels based on the infrastructure requirements assumed in the scenarios and on the network loads from the transportation model. On neighbourhood scale, the transformation potential is examined by indicating possibilities for new urban function. On street level, new street profiles are designed. The spatial quality has similar magnitude over all urban areas under the assumption of a system wide shared autonomous system. Under the assumption that automated driving develops as private mobility system with valet-parking services in dense urban areas, the benefits are primarily observed in the concerning areas. Under other scenarios, the spatial quality effects are limited. The spatial quality effects are considered modest as many roads and streets in all scenarios still need to facilitate significant numbers of traffic, or the road section by itself allows for little improvement. By evaluating the accessibility and spatial quality effects in a residential location choice model, an increase in housing preference from the areas in the west of the province to the east can be observed. Under a scenario showings spatial quality effects primarily within the denser urban areas, an increase in preference of such areas is observed concurrent to the prior development.

For the development of the urban strategy, the research focusses on the City of Utrecht as this is where the largest assignment for automated driving arises. Automated driving has the potential to enhance spatial quality and accessibility to some extent but comes with the consequence of potentially higher congestion on the urban road network and housing demand. The city of Utrecht generates such large numbers of travel demand that mass transit is considered crucial to facilitate this demand. Therefore, the strategy proposes an urban development strategy of dense mixed-use urban areas around the central railway station and around access nodes along strategic positions along the ring road. This allows to steer the traffic through the city network and anticipate on the uncertainties regarding the development of automated driving by reserving space for remote parking solution and transfer hubs. A follow-up research step would be to evaluate the strategy in the same methodologic framework. However, due to time constraints, this step has not been executed.

Computational models ask for explicit data which complicates the compatibility between various research steps. This research shows that it is possible to implement qualitative design methods within the data collection process. Design-based research methods are easier to apply and therefore relate directly towards the context of the problem. For using a computational model, this requires often for an operational model before one can comprehend the context. This makes for a more complicated research process. Therefore, employing an integrated methodology in urban planning research proves challenging but helps to approach the urban planning problem from a holistic perspective.

An integrated approach broadens both perspectives to consider and combine the most important variables. By explicitly defining the problem, core principles reveal and computational models help to explain the dynamics between these core principles. Interpretation of the results in the socio-spatial context allows to account for the values that are inherent to urban planning problems. The method is labour intensive and does not guarantee more inspiring and detailed plans or designs. But the outcomes for proposed actions relate better to the factors that are significant to the system and elaborate more accurately on the uncertainty and dynamics the urban planning problem encompass.

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1 INTRODUCTION

Figure 1-1: This research starts from the conviction that an integrated approach between engineering and design thinking can lead to better understanding of urban planning problems (image courtesy of BIG).

This research is conducted from an integrated perspective; an engineering-based and design-based approach combined. Reason for this integrated approach is the conception that an integrated methodology can lead to better understanding of urban planning problems (Figure 1-1) - where this research uses the cause of automated driving. The role of external developments related to e.g. technology, economy, climate or society on cities are a contemporary research topic for disciplines occupied with aspects related to the built environment. Cities are physical manifestation of human behaviour and interaction and comprises therefore two realms: the buildings, streets and space that provide for urban life on the one hand and the system of dynamic interaction between agents in the city on the other hand.

The modern world is becoming increasingly digital and globalised. The physical and social domains of cities are stronger connected to external developments than ever before. This makes the urban planning problems where urban planners and designers deal with more complex and asks for both a broader perspective and stronger specialisation. These requirements seem contradictory at first, but are vital for adequately solving future urban planning problems. This research attempts to bring these requirements together by an integrated engineering and research-by-design approach.

1.1 RESEARCH BACKGROUND

Automated driving is propagated as a potentially disruptive technology that can have great impact on cities. Advances in communication and sensory technology enable driving without intervention of the human driver needed. The effects of automated vehicles are expected to be numerous and the potentially disruptive character is stated in an increasing number of both scientific publications and popular media. Increase in research suggests that knowledge on vehicle automation is rapidly growing. However, whereas most studies examine traffic effects, spatial effects are underexposed within scientific literature (Fagnant & Kockelman, 2015; Milakis, van Arem, & van Wee, 2015) even though spatial changes triggered by automated vehicles are plausible. The notion that land-use and transportation are two very interrelated domains reveals in Figure 1-2 and is widely recognised by all researchers that are occupied with built environment related topics. Advances in transportation technology in the past effected the built environment and drove changes in spatial development.

Figure 1-2: All roads of the Netherlands in one map. By mapping of the road network, also the cities and landscape structure reveal (source data: Kadaster (2016b).

The spatial impacts of automated driving are two-sided: it has potential to improve accessibility on the one hand and spatial quality on the other hand. These two aspects both influence urban development differently. Accessibility relates to performance of the transportation network. Changes in spatial quality are the result of integration of the transportation network within the built environment.

1.2 PROBLEM ANALYSIS

Technological development and urban change are very different processes with their own dynamics and time dimensions (Wegener, Gnad, & Vannahme, 1986). Automated driving is a technology under development which emerges on vehicle level but is propagated to impact beyond the urban scale both by spatial quality and accessibility effects. Many plans and ideas exist how automated driving can improve cities. However, much of this research focuses on single aspects related to traffic effects or street design. These studies do often not comprehend the full scope the urban planning problem really comprises.

Problem factors

To understand the case of automated driving as an urban planning problem, it needs interpretation in the broader context of external development and time factors, human factors and socio-spatial conditions (Figure 1-3). Today, it is unclear how automated driving will develop as a technology and can be implement within the transportation system. This is bound by the spatiotemporal conditions set by cities. Not every urban area allows or asks for similar mobility solutions. However, another important aspect is the role human behaviour has in this problem. Microscopic interaction between decision makers in the built environment generates patterns on a macroscopic level (Figure 1-4), which in turn affects microscopic behaviour. Automated driving can affect the travel behaviour of people and therefore not only impacts the built environment solely as a technology, but also through the human behaviour that is influenced by this technology.

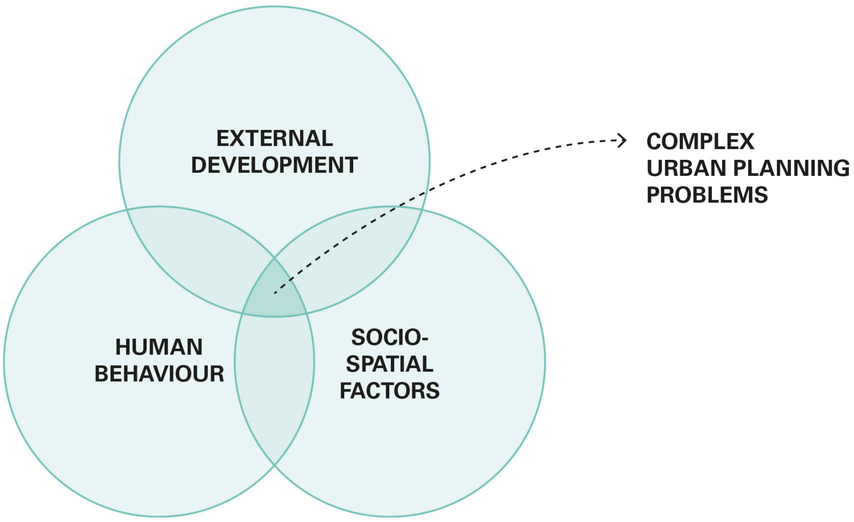


Figure 1-3: Factors that make the impact of automated driving a complex urban planning problem.

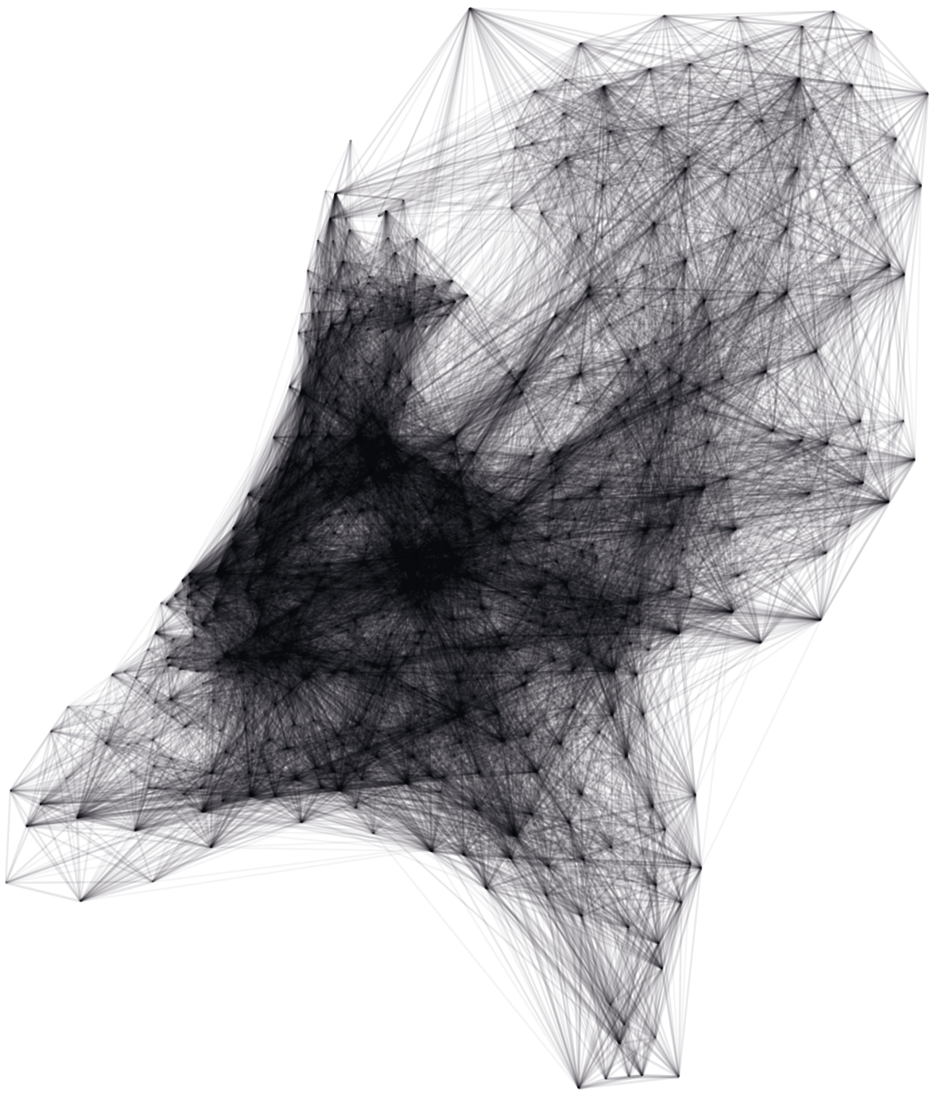


Figure 1-4: All flows in the Netherlands evaluated by the transport model for the province of Utrecht (VRU). The travel behaviour of individual people generates mobility patterns.

Knowledge gap

Based on consideration that human behaviour is a core factor in the urban planning problem, it allows to clarify the main question of the spatial impacts of automated driving, and this question involves human behaviour as a driving force of urban development. Vehicle automation as a technology is on the one hand expected to make cities more attractive by making cities safer and greener. However, considering the benefits on the transportation system, it can make distance less a factor of consideration in any spatial decision by any decision maker. This can lead to dispersion of urban settlements just as that the rise of the automobile as consumer product has facilitated urban sprawl (Ewing, Pendall, & Chen, 2002). It is unclear how vehicle automation technology will establish within the transportation system and within space. Therefore, it is uncertain which changes automated driving will trigger in urban development and travel behaviour.

Perspective on the problem

Understanding the spatial impacts of vehicle automation as a process driven by human behaviour asks for a specific perspective. The built environment is no static object but classifies as a ***complex system***. Cities manifest phenomena such as self-organisation, nonlinearity and emergent properties (Portugali, 2011, p. 12). This can be better explained through the example of a swarm of birds (Figure 1-5). When birds fly in a swarm, their behaviour can be explained through a certain set of rules as e.g. not colliding with nearby neighbours and aligning direction based on surrounding birds (Reynolds, 1987). Based on these rules on microscopic level, complex patterns on macroscopic level be studied and explained.

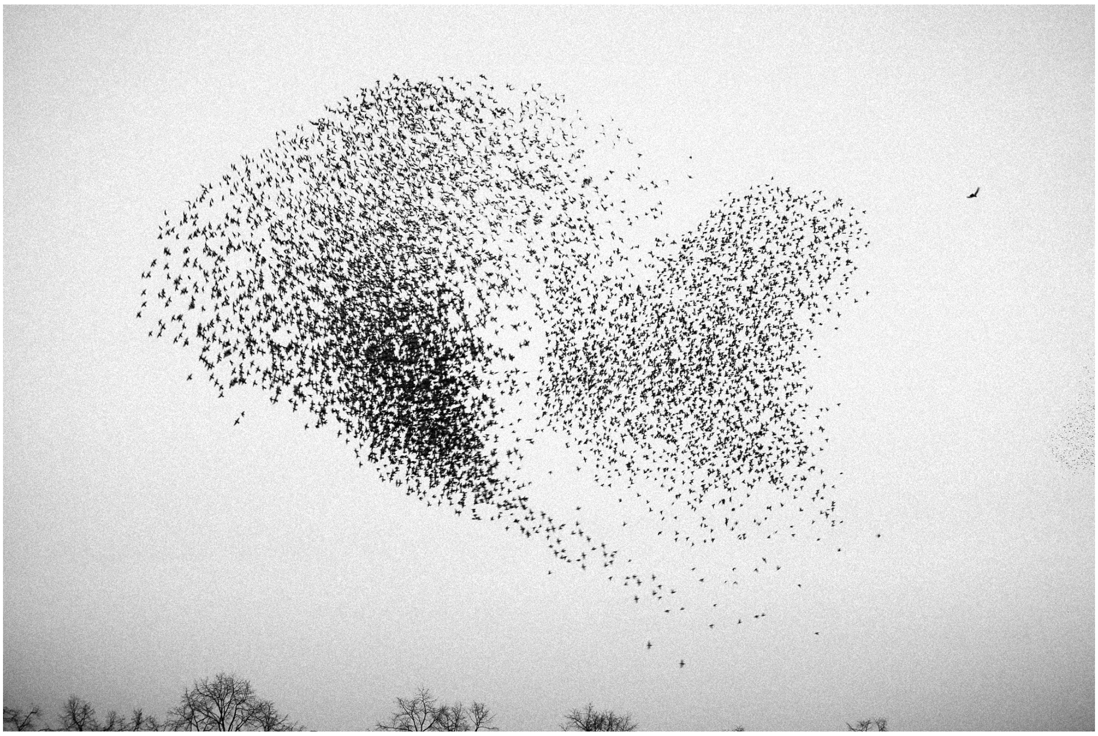


Figure 1-5: A swarm of birds generates a complex pattern based on behavioural rules from individual birds (Image courtesy of Heleen Klop, contrast and colour changes by the author).

To comprehend human behaviour adequately, this research takes on a similar perspective to the problem as to in the example of the swarm of birds. Decision makers in cities can move through space by a certain behaviour. This behaviour is influenced by who the decision maker is and by characteristics of the environment. The behaviour of the decision maker and the characteristics of the environment are subject of change by automated driving. Taking on this perspective to the urban planning problem allows to incorporate the human behaviour, socio-spatial conditions and the technology of automated driving.

1.3 PROBLEM STATEMENT

This research takes on the spatial impacts of automated driving as an urban planning from a holistic point of view. Based on prior problem analysis, two problem statements can be identified. The first problem relates to the case of automated driving itself. The second problem statement relates to the larger context of urban planning problems

The case of automated driving

First problem statement relates to the case of automated driving itself: There is no substantiated image how automated driving will integrate within the transportation system and within space. It is unclear what urban development patterns will be generated under the emergence of vehicle automation.

Urban development patterns emerge from the perspective of this research by the location choices of urban decision makers. From a societal point of view, it is of importance to examine to spatial effects of automated driving to utilise the potentials of automated driving to improve cities. Even though automated driving is still under development and there is no full certainty that automated driving will establish itself as a technology, it is also of importance that strategic frameworks are conducted that cope with the uncertainty around vehicle automation deployment and set the conditions for sustainable urban development. Just as any technological advancement, automated driving is subject to the Collingridge dilemma, after Collingridge (1982):

> "On the one hand, it is often not possible to predict the consequences of new technologies already in the early phase of technological development. On the other hand, once the (negative) consequences materialize it of the become very difficult to change the direction of technological development." - van de Poel and Royakkers (2011, p. 79)

The reason why it is not easy to predict the consequences of automated driving lies in the first place in the fact that it is unclear how (and if) vehicle automation will establish itself. Even if all technological, legal and ethical challenges are overcome, the behavioural aspects regarding mobility will still pose challenges.

Domain of urban planning research

The beginning of this chapter explains how urban planning problems are increasingly becoming more complex. Many variables must be taken into consideration and processed. Current methods and models for solving urban planning problems are so dispersed that different cultures can be identified. In this research two perspective on urban planning problems are examined; an engineering-based and a design-based perspective. Both perspectives take on a different planning approach. Engineers employ methods to understand the urban context as a complex system which is driven by rules and is considered complex by the wide range in decision makers both in numbers and heterogeneity. Designers, are primarily occupied by a specific urban context in which the complexity is found the complexity of the urban spaces and the unique social processes and values which coincide with these spaces. Both perspectives are important and essential in adequately addressing the challenges urban areas face, and the case of automated driving is only one example of this.

1.4 RESEARCH GOALS AND QUESTIONS

The goal of this research is to use the case of spatial impacts of automated driving, to establish a methodology in which both perspectives in an integrated way contribute to the understanding of urban planning problems (Figure 1-6).

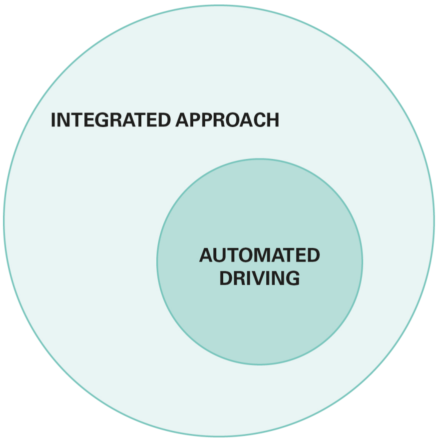


Figure 1-6: This research investigates the spatial impacts of automate driving in the bigger context of integrated research approaches.

Methodological goal

From a methodological perspective, the main research goals are to find out what an integrated methodology contributes to the understanding of built environment related questions and how such method can be formalised. The primary goal of this research is go through such a process and reveal the challenges, opportunities and considerations needed to employ an integrated methodology.

Goal regarding vehicle automation

Besides the goal to provide a proof-of-concept for an integrated methodology, the methodology itself also driven by a specific goal. This goal has two-sides:

1. Knowledge is lacking on the accessibility effects of automated driving and therefore the first goal is to obtain insights how the variables of the environment and the behaviour of the decision makers changes under the case of automated driving
2. Since urban planning problems generate value-related questions, it must also be assessed in such context. Emergent urban development patterns ask for interventions, which in turn will again influence the development of this pattern. Therefore, the goal is not only to obtain knowledge regarding vehicle automation aspects, but also assess how the potentials of automated driving can be employed towards more sustainable and liveable urban areas.

Research questions

The main research question is:

How can an integrated engineering-based and design-based research lead to better understanding of urban planning problems and what are the consequences of an integrated approach for the research process?

The first sub question further elaborates on the methodological and integrated aspect:

1. ***What are the fundamental differences between engineering-based research and design-based research in urban planning problems and how can both approaches be integrated into one methodology?***

As this research considers urban development the result of human behaviour in a complex system, the second sub question is:

2. ***By which methods and models can cities be evaluated as complex systems and what are the main processes to elaborate on?***

With the help of the third research question, the research connects to the case of automated driving:

3. ***By which variables does vehicle automation as a technology relate to urban development?***

1.5 SCOPE AND APPROACH

The urban environment houses a wide variety of decision makers. In this research, we identify the households as most determining agent in relation to urban development and automated driving. Housing takes on the largest share of space in the built environment and empirical research finds that jobs follow people instead of the other way around. Therefore, the most important indicator for urban development is (the transformation of) household density. Since context is an important factor in urban planning problems, this research uses a real-world case study to provide for context and corresponding data. The region considered for this study is the region of Utrecht.

Although this research applies an integrated approach, the primary focus lies in using engineering methods in design-based research processes. This distinction is made because the research takes on a holistic attitude towards the case of automated driving. However, within the application of the methodology, the both perspectives are as much as possible considered as equal (Figure 1-7).

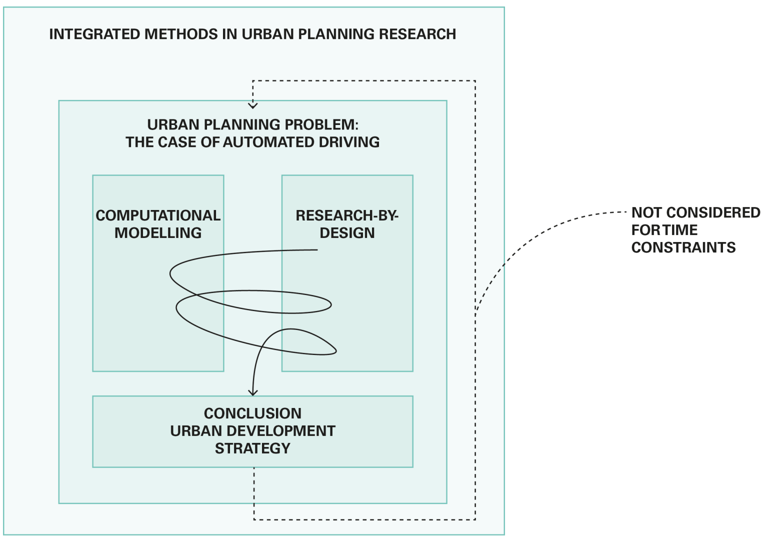


Figure 1-7: The case of automated driving investigated through an integrated methodology in the bigger context of integrated research methods in urban planning research.

To consider cities as complex system, computational models are an important tool to comprehend this system. Therefore, this research is characterised using computational urban models within the research process. Computational models are very explicit models and therefore dictate to a certain extend which factors are required to take into consideration to further develop and employ the methodology. Nevertheless, the process should not be solely dominated by computational models. Such models are often very specific and therefore cannot provide answers to all questions posed within this research. By combining both perspectives, a stronger research process is envisioned.

1.6 THESIS OUTLINE

This report is comprised of three parts (Figure 1-8). The first part of the research is providing for the background information required to adequately design and execute the integrated methodology.

Chapter 2 elaborates and urban planning problems from and engineering and design perspective. Important concepts and notions within the urban planning domain on engineering and design perspective are explained in this chapter based. This chapter examines the models, values and goals designers and engineers in research processes. With the insights obtained, a general understanding of integrated methods with concurrent opportunities and challenges is derived.

Chapter 3 explains how computational models can help to obtain understanding of the built environment. For assessing cities as complex systems, these models are essential to support the research act. These models are not primarily explained from a practical perspective, but are explained for their underlying principles. This chapter provides for insights how cities and the dynamic processes within cities can be explained through explicit quantitative models. The goal of this chapter is therefore to understand how to formalise a model which evaluates the behaviour of households in relation to urban development.

Chapter 4 examines the relevant aspects of automated driving and connects these aspects to the scope of the research. This chapter provides for insights in the state of the art research and the context in which the technology establishes itself.

The second part elaborates solely on the case of automated driving and covers the largest share of the integrated research approach.

In chapter 5, the set-up of the integrated research approach is presented. Based on the insights in chapter 2, the most important fields of interaction between engineering and design approach are found. Based on the insights of chapter 3 and 4, the problem entity of derived of the system how automated driving relates to urban development. Besides providing an explanation of the research set-up, this chapter gives answer to the sub questions of this research.

Because of the uncertainty around automated driving, a scenario approach is employed. The scenarios are conducted in chapter 6. The scenarios are a mean to make coherent assumptions and specify these. With the help of a mapping exercise, the scenarios are connected to the study area.

Chapter 7 evaluates the effects of automated driving with the help of a transport model to grasp the changes in the mobility behaviour. Based on this modelled behaviour, the accessibility effects and travel implications are obtained. These results are then assessed through a design exercise in chapter 8 to obtain insights in the spatial quality effects of automated driving.

Based on the insights in the first part of the research, it reveals that residential choice behaviour is for a large part driven by location attributes and neighbourhood characteristics. These factors together are evaluated with the help of a residential location choice model.

The third part of this report comprises the synopsis. In this part, the conclusions of the research are presented in two different chapters. The first chapter concludes on the spatial impacts of automated driving. However, the results are not presented in a listed manner. This research identifies that the spatial impacts of automated driving not only relate to the changes automated driving triggers within the built environment, but also how urban planners, designers and policy makers act on these changes. Therefore, the conclusions are presented in the form of an urban development strategy to elaborate on the urban context and the desirability of the automated driving effects. This strategy focus on the city of Utrecht.

The final chapter, chapter 11 steps away from the case of automated driving and concludes and reflects on the integrated research approach by answering the research question.

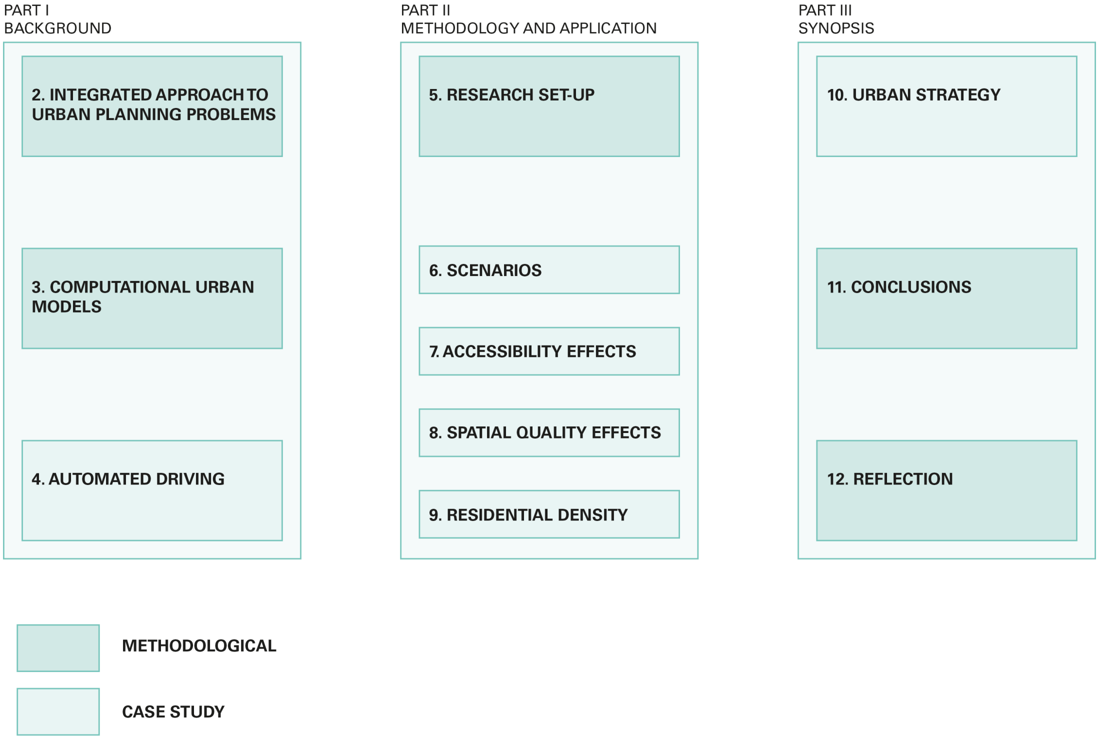


Figure 1-8: Report structure

PART I. BACKGROUND

2 RESEARCH IN URBAN PLANNING FROM AN ENGINEERING AND DESIGN PERSPECTIVE

Engineering, design and models are concepts that have different meanings in different contexts and domains. Urban planning problems are one of the many problems engineers and designers deal with. For this research, it is important to clarify the definitions used within this research as well as the context in which this research is conducted.

This chapter examines the complications and differences between engineering and design-based perspectives on urban planning problems and previews towards a methodology in which both perspectives can be combined for better understanding of these problems. The first section explains the most important concepts and definitions to specify the fundamental differences between engineering-based research and design-based research. The second section introduces the thesis of two cultures to explain the intellectual divide between engineering and design in the domain of research. In the third section, the fundamental differences between engineering and design models and their relationship with the researcher are explained. The last part of this section previews towards an integrated methodology.

2.1 CONCEPTS AND DEFINITIONS

The introduction of this chapter already reveals some complications within terminologies. The need for clear definitions within this research reveals also from the most cited statement on design in the field of design research, by Herbert Simon (1969/1996, p. 111):

> "Engineers are not the only professional designers. Everyone designs who devises courses of action aimed at changing existing situations into preferred ones"

His work can be seen an attempt to merge various scientific disciplines with the goal of problem-solving in the domain of the artificial (Huppatz, 2015). This quote reveals that - according to Simon (1969/1996) - engineers are apparently designers. Everybody who is occupied with the act of problem-solving within the artificial domain designs. Therefore, it is important to clarify the difference between what engineering and what design is. This is explained in the context of research instead of the context of blueprinting artefacts i.e. design processes.

2.1.1 ENGINEERING AND DESIGN IN DESIGN PROCESSES

Solving urban planning problems is not always the primary occupation for engineers and designers. Engineering and design practices are in the first place occupied by the creation of artefacts (confusingly this is often called a design process in which both designers and engineers are involved). Within such processes, the role between these two practitioners is considered relatively clear. Designers are primarily occupied with the qualitative aspects and the relation between user and artefact. Engineers are occupied by the functional and technological aspects of the artefact. Within such processes, these engineering and design methods can be complementary - being with a healthy dose of friction between their different goals and values. This benefits the process and brings both perspectives closer together. Literature on engineering and design processes is often established within this specific context, particularly in the field of industrial design engineering or to a lesser extent the field of architecture. Within the realm of urban planning problems, this specific point of view is not satisfactory.

2.1.2 RESEARCH IN URBAN PLANNING PROBLEMS

Urban planning processes ask for problem-solving in the artificial domain without the explicit goal of raising an artefact, but with the goal of setting boundaries and depicting the context in which later interventions can steer towards a desired goal (George, 1997). Consequence is that processes, goals and methods to some extent differ from design processes, of which one speaks when the goal is to specifically blueprint an artefact. But if the goal is to obtain understanding how interventions and developments can or will shape the built environment, this is a research processes instead and research has the aim of filling knowledge gaps. Therefore, research in urban planning problems is considered a process in which the effects of developments, policies or interventions on aspects related to the urban environment are examined. It is within such research processes that a complementary relationship between engineering and design perspectives is harder to establish compared to design processes. To some extent that is surprising. Because what distinguishes engineering and design from other occupations (e.g. policy makers, geographers, lawyers or politicians) is the perspective on the city as physical object serving social processes and their task to improve urban life through spatial interventions, hence a common objective exists.

The aim for spatial interventions has a consequence on the composition of the research process. The research is not only aimed at obtaining insights through observation but also on the process of experimentation is equally important to examine and assess the impact of external trends or interventions on the urban development. What characterises urban planning research is that events in the urban environment are non-recurrent (Klaasen, 2007, p. 472), which complicates deriving of general understanding. And because of the scale of cities, and the amount of researches needed for intervention, it is of importance to have a model through which hypothesis can be tested and evaluated.

The complex nature of the built environment is widely recognised but often not fully understood nor explicitly stated. Most often one alludes to the wide range of stakeholders, interests and the limited space available to fit all urban functions. This is the contextual component of urban complexity and urban planners are often occupied with this side of the problem. The complex nature of the urban environment ***as a system*** is often neglected and harder to comprehend: the urban environment bears unpredictable developments triggered by interaction between independent decision makers. Local interactions generate emergent patterns which are hard to predict (Portugali, 2011).

2.1.3 ENGINEERING-BASED AND DESIGN-BASED RESEARCH

To understand the different perspectives in urban planning problems, an abstract view to research provides a good starting point. The most primary form of research relates obtaining the following goal (Dorst, 2010, p. 132):

$$what + how \ \rightarrow result$$

In the context of most research, either the how or $result$ are unknown:

$$what + how \ \rightarrow x$$

$$what + x \ \rightarrow result$$

Therefore, the purpose of the research process is to find x. These research problems above, ask respectively for deductive or inductive reasoning (Dorst, 2010, p. 132). Essentially all scientific research comprises one or both of these reasoning patterns (Freedman, 1949; Haig & Evers, 2015). The built environment is no product of a natural phenomenon alone, but can be considered a socio-technical system consisting of both a physical system and a human system (Hillier, 2012). Consequence is that urban planning problems are not free of values (Wachs, 1985, p. xv). To take aspects related to social conditions or other democratic factors into consideration, a different reasoning pattern is required in which making choices plays a larger role. These choices relate to defining the desired path of action and the means by which this can be obtained. Dorst (2010, p. 132) describes the pattern of abductive reasoning, which reasons towards an aspired goal to solve:

$$what + how \ \rightarrow (aspired)value$$

where either $what = x$ and/or $how = x$, and even the $(aspired)value$ can be subject of debate. Within urban planning research, both aspects of research are essential to comprehend the complexity of the urban environment.

Based on these reasoning patterns, the principle difference between engineering-based and design-based research is defined. Engineering-based research strongly relates to the scientific domain. This field of research is therefore occupied by obtaining understanding of the built environment through deductive and inductive reasoning, often by quantitative methods. The goal of this field of research is to obtain insights in general rules behind urban phenomena. The choice to use the terminology engineering-based research comes from the conception that this field of research is – although scientific – an applied research act.

The act of design-based research is associated by the reasoning pattern of abduction. Design-based research explicitly allows for value judgment from the perspective of the designer. Through this perspective, the question how goals can be obtained plays an important role. For strong focus on the how-question the design act itself has a prominent role within the research process (Breen, 2002, p. 137) and actually is a research method itself.

This distinction between engineering-based research and design-based research (Figure 2-1) forms the basis for the differences in methods, models, goals and values between design and engineering practices when the goal is not about creating artefact primarily.

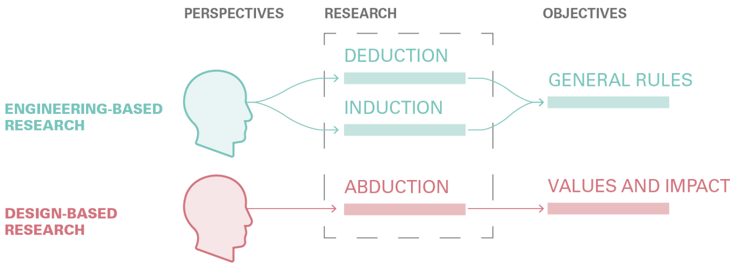


Figure 2-1: Engineering-based research and design-based research distinguish themselves in reasoning patterns within their research processes as well as the objectives the researches bear. This has consequences for the methods, modals, goals and values.

2.2 TWO CULTURES

The different perspectives in engineering-based research and design-based research have the potential to be complementary. Unfortunately, engineering and design practices have very different norms and values and could therefore be classified as the two opposite cultures of intellectual divide as introduced by Snow (1959/1965). Snow, himself a physical chemist and a novelist introduced the famous thesis of two opposite camps in the academic world: a culture of science and scientists and an opposing culture of arts and humanities (Portugali, 2011, p. 9). Design practices nowadays relate stronger towards humanities and arts, whereas engineering can be considered a form of natural science. The analogy of cultures drawn by Snow (1959/1965) is particularly striking because from the perspective of cultures, one culture emphasises (often exaggerated) common elements of one group "as well as the difference between them and other groups" (Portugali, 2011, p. 9). This accepted notion of two cultures leads to misunderstanding, ignorance and false biases between the engineering and design practitioners about methods and skills.

In the past, there was place for deductive methods in urban planning and design. Hence, quantitative methods to study the built environment are no novelty: Theories by e.g. von Thünen (1826), Christaller (1933) or the gravity-based equilibrium model by Lowry (1964) have been applied in planning practice. However, from the 1970s, these theories - and the methods they have inspired in planning - got in discredit by many planners and designers under influence of the works of Jacobs (1961) and Rittel and Webber (1973) stating respectively the qualitative and wicked aspects of urban planning problems. Models from that era presumed that an optimal solution exists for urban problems. This is not necessarily aligned with the vision urban designers obtained nor with the paradigm of cities as complex systems. Most mentioned point of criticism towards the engineering approaches is that the methodologies lack the ability to answer holistic questions, while urban planning problems often ask for a holistic approach. The criticism states that the solutions posed are of technocratic character as their (often quantitative models) presume some sort of optimum solution. However, also design practices receives criticism: Various scholars in the domain of design research state the friction that an academic context gives to design (Cross, 2007; Hillier, Musgrove, & O'Sullivan, 1972/1984). One could state that urban design and regional planning practices have insufficiently developed a scientific foundation (Klaasen, 2007) and clearly defined itself as a distinguished act from the scientific activity (Bonsiepe, 2007, p. 28). In the scientific world, design methods can be considered speculative and unproved. And therefore, the design practice always had a unique relation towards science, also because its relationship with the arts for instance.

Design is often proclaimed to be aimed at creativity and the signature of an individual (Stolk, 2015). Hillier et al. (1972/1984, pp. 246, 250) assign the necessity of creativity to the fact that designers synthesise solutions based on a large frame of factual data, rather than creating new knowledge (the analysis-synthesis thesis (Hillier et al., 1972/1984, p. 245)). Creative thinking by designers opposed to the rational reasoning by engineers is a popular yet false conception to describe differences between two professions. Creative thinking is not exclusive to designers since engineers must synthesise a lot of data sources too. Engineers can obtain important innovations by non-linear creative thinking (Peters, 1998, p. 48). Even Einstein and Infeld (1938, p. 33) state the importance of the human mind in the creation of physical concepts. The physics theories, which Einstein is famous for, are merely an explanation and bridge between our mental perception and the environment. With that notion in mind, the thinking processes between e.g. Einstein and Le Corbusier - both distinct geniuses in their profession - reveal similarities despite the different models and corresponding language of representation (Figure 2-2). Within practice, the existence of the two cultures cannot be denied as it really exists. This divide is, as explained, partly based on fundamental differences, but also on mutual misunderstandings. To allow for an integrated methodology, it is important to obtain better insights in the two cultures. Mutual understanding is fundamental to bridge differences. An important nuance to made is that not all differences are as black and white as sometimes put forward. Any research can be considered a cognitive activity and is therefore subject to the concept of bounded rationality (Simon, 1991). This means that any researcher can shift from strategy either consciously or unconsciously. However, this is often not manifested in the reporting of the research process.

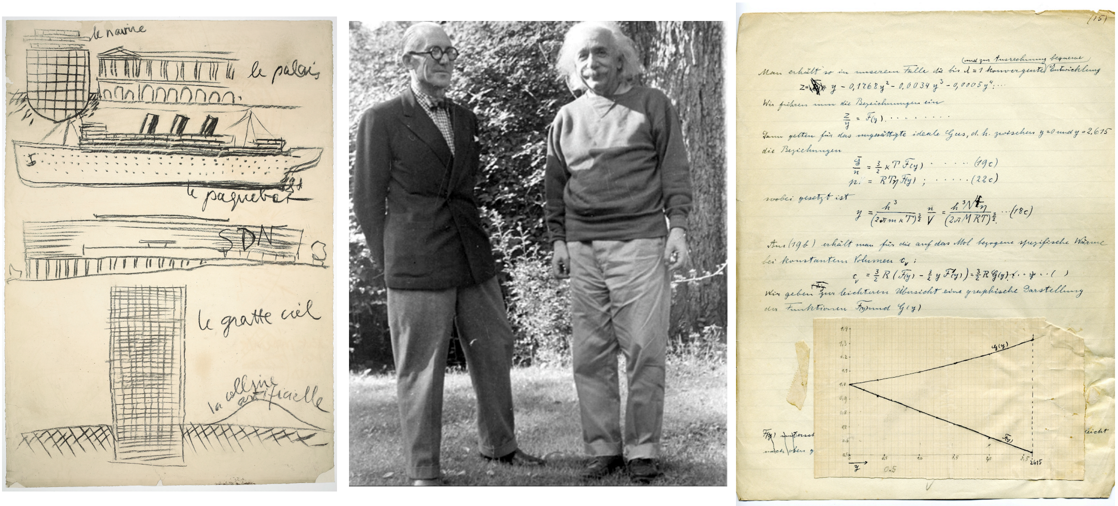


Figure 2-2: Left: manuscript by Le Corbusier (image courtesy of foundation Le Corbusier), centre: meeting between Einstein and Le Corbusier (image courtesy of Busalto, 2011) and right: manuscript by Einstein (image courtesy of Instituut Lorentz, Leiden University)

2.3 MODELS IN ENGINEERING AND DESIGN-BASED RESEARCH

Because of the scale, magnitude and complexity of urban planning problems, models are crucial to support the thinking process (Simon, 1969/1996, p. 153). Models can be either internal models of the mind or external models - ranging from simple sketches to complex mathematical models. By examining the different models engineers and designers employ and how insights are obtained through these models, the fundamental difference between engineering and design practitioners reveals. Models are tools to support cognitive processes within the brain, and any research can be considered a cognitive activity. But the relation between the model and the mind is a fundamental difference between engineering and design practices just as the kinds of models and processes, goals and values. A distinct difference between engineering and design manifests in the processes and the role reproducibility of the process and outcome itself has. This will be further explained with the help of Figure 2-3, in which the research processes are graphically depicted.

Within engineering practices, the mainstream tools of research are increasingly becoming models of computational character (Figure 2-2, right). These models are about reduction (deriving rules of the seemingly complex, e.g. an equation stating explicitly what is taken into consideration). The complexity is thereafter evaluated with the help of computers processing data and events, followed up by the critical assessment of the researcher. Engineers establish a bridge between the computerised model and the mind; engineering research models are often of computational nature and provide a mathematical laboratory to test hypothesis. One of the most important values within scientific research is the possibility to reproduce the results from a specific research. This asks for two requirements. The researcher must explicitly state the aspects or variables which are considered and how. The models engineers employ force to make the implicit explicit (Epstein, 2008). Secondly, engineering-based researches are presented very sequentially. An important condition for a sequential process, is the compatibility of the outcome between various models/parts of the models employed. Because of lot of efforts is put in the formulation of the system, there are moments in the process that all gathered information must be channelled and processed in one model. The models that engineers employ – especially in a computational environment – extent the human cognitive capabilities, and therefore elaborate on the complex aspects of the environment in terms of heterogeneity and magnitude of processes and decision makers. Such processes cannot be comprehended solely by the human brain, the engineer at some point hands out some aspects of the thinking process to the model he or she prior defined.

The act of modelling is often associated to scientists or engineers. But everybody models (Epstein, 2008). For designers, models are more often implicit and therefore take on a more unconscious role within the research process. Design-based research models manifest either as visual or physical, e.g. drawings or scale models (Figure 2-2, left). Design models are more of associative nature. Rather than that all information is channelled, connections are made between a wide variety of aspects. Therefore, design is a very associative process and the models bear more implicit components – or components or aspects are later added within the process. Where engineering models evaluate specific variables in a way the human brain is not capable of, design models have a role of constantly stimulating the brain. Instead of a sequential process, a constant interaction between model and researcher occurs. For this reason, design models must work intuitively and are often obtained through low-tech or direct techniques such as sketching, mapping or drawing.

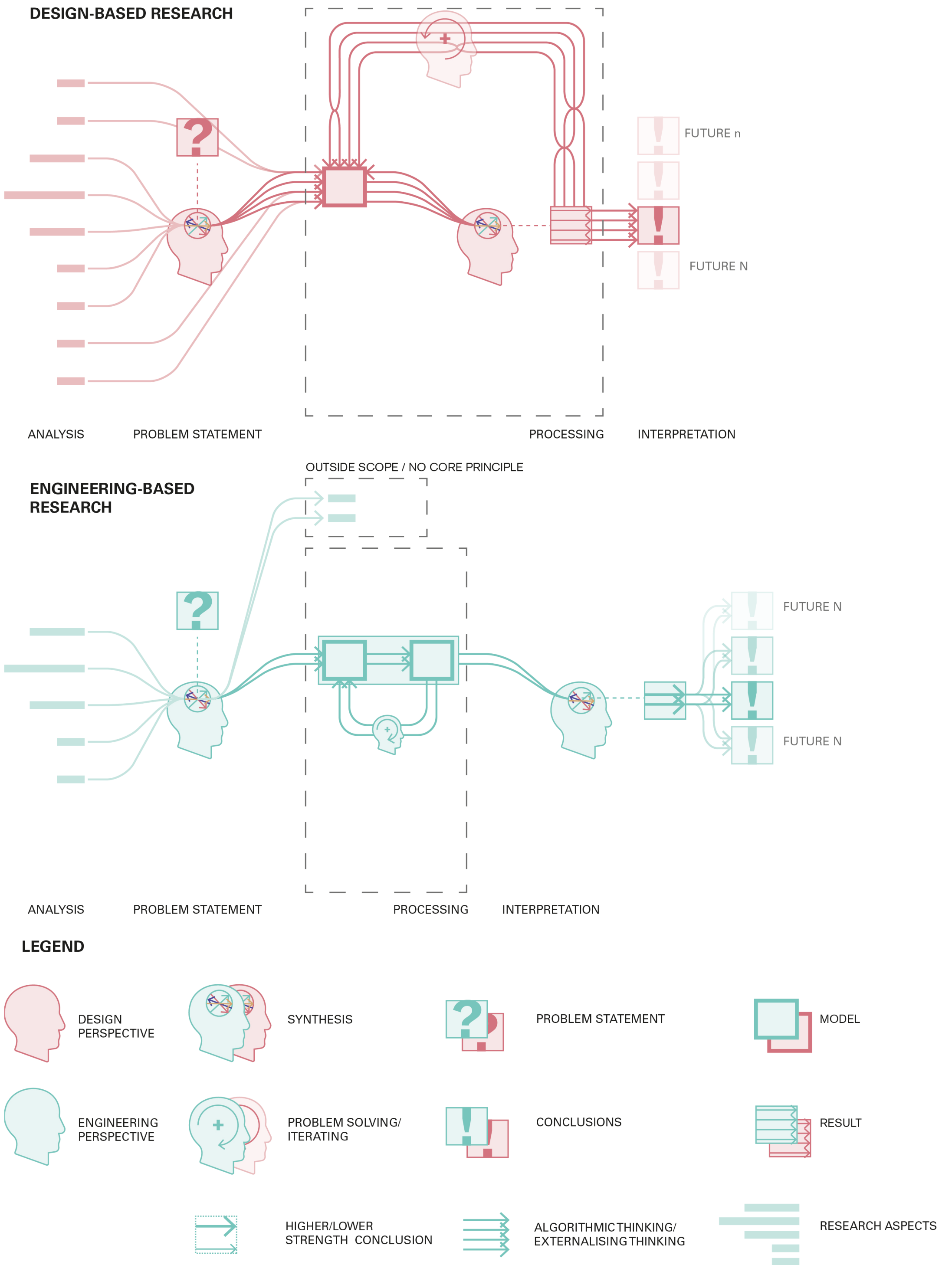


Figure 2-3: Graphical representation of a design-based research process and an engineering-based research process with the relationship between the researcher and the model.

The place and role of the results within the research process is another important difference between engineering-based and design-based research for two reasons, namely:

1. The criterion for which a result is accepted;
2. The place of the result within the process.

At some point within a research process, a model will provide for a (final) outcome. Designers follow their intuition and rely on a strong narrative. This makes assessment based on informal – hence personal – judgment (Lawson, 1979, p. 59). Engineers express the unpredictability and uncertainty around events through stochasticity. By doing multiple reproduction within the modelling environment or through sample testing, statistical tests provide insight in the level of certainty the result has. The outcome is therefore a result to which a certain level of accuracy can be assigned. Design practitioners often do not possess the skills to grapple with uncertainty or do not think that it is possible. And it is often not the primary purpose of the design research. Final images of design-based research often characterise as impressions of how a location could look like. These images are primarily aimed at revealing the potentials and inspire for action. These images are maybe not fully realistic or likely to be achieved, but help to initiate further research steps and provide for an important basis to enable attractive urban environments. By depicting potentials and trying to obtain quality on multiple aspects and scales benefits might reveal that cannot be found through engineering-based researches.

The place of the result within the process is the other stated distinct difference. Within a design-based research, the result is indisputable part of the iterative research process. Design-based research constantly bears characteristics of prototyping. A principle or intervention is evaluated within the (often graphical) model and thereafter either rejected or accepted. Within an engineering-based research, when a computerised model is employed, the result is not part of the iterative process. Engineering processes comprise prototyping as well, but the distinct difference from designing is that not the result is prototyped, but the model or method itself. Within a design-based research, trial-and-error is within the solution. In engineering-based research, the trial-and-error is within the model. Reflecting to the quote of Simon (1969/1996) in section 2.1, one could consider the process of constructing a model, a design process.

2.4 CONCLUSION: TOWARDS AN INTEGRATED METHODOLOGY

The cultural divide is still present within the contemporary urban planning and research domain. Based on the elaboration of the previous sections, the most fundamental differences between engineering-based and design-based research are listed in Table 2-1. Respected scholars among Snow (1959/1965) and Simon (1969/1996) propagate communication between the two cultures crucial for “solving the world’s problems” (Portugali, 2011, p. 9-on the thesis of Snow (1959/1965)). Also, new wave of scholars as e.g. Portugali (2011, pp. 252-253) and Batty (2000, pp. 483-484) promote the role quantitative models can play within planning practices. The built environment asks for values and qualitative statements to steer towards a desired path in the future, but also bears the characteristics of a complex system. Properties of such system cannot be comprehended from a design-based research perspective only, but ask for state-of-the-art computational models to study urban phenomena. Additionally, the built environment is of such complex magnitude that urban models can be of help in providing for a evaluation environment in which interventions can be prototyped more accurately.

Table 2-1: Fundamental differences between engineering and design-based research

Fundaments	Engineering-based research	Design-based research
Goals	Derive general rules Objective interpretation Reproducible research	Elaborate on values and have impact Individual signature Creative approach/outcome
Domain	Scientific	Humanities and arts
Reported process	Sequential	Iterative
Models	Mathematical formulation	Visual representations of context
Variables	Quantitative	Qualitative
Scope	Narrowed down	Holistic

Figure 2-4 provides a graphical representation of how an integrated research process can be shaped. This scheme shows how engineering thinking can be integrated within design thinking. The reason for this order and not the other way around is that urban planning problems always comprises many variables and should therefore be considered from a holistic perspective. It is important that the problem statement supports this. With the help of a computerised (in this case urban) model, the complex and non-recurrent factors are evaluated. When this model generates results, these allow for value-based interpretation and new design principles. These can then in turn be re-evaluated with the urban model, eventually leading to better understanding of the urban planning problem and better policy and design solutions.

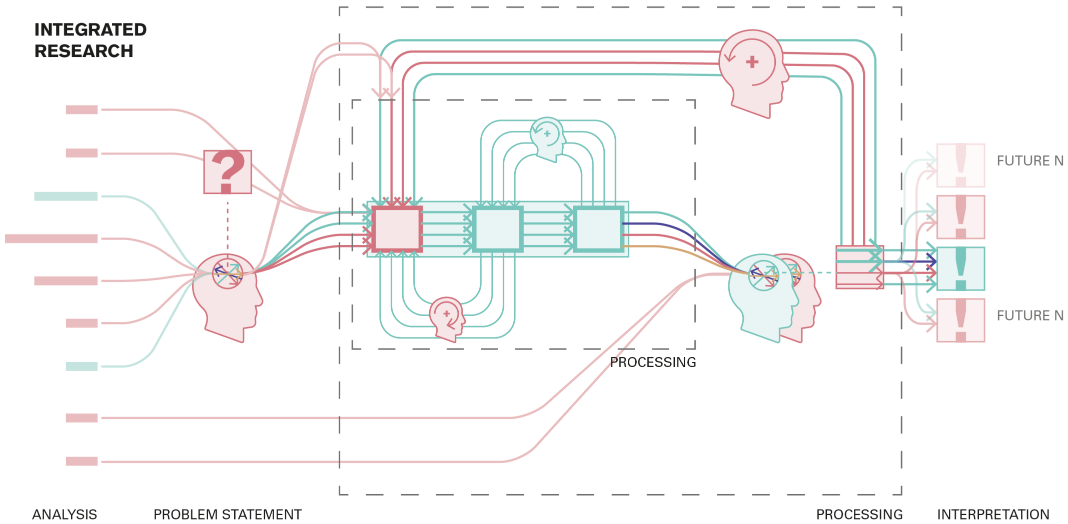


Figure 2-4: Graphical representation of an integrated design and engineering based research process (for legend see Figure 2-3)

From this elaboration, the potential of an integrated method reveals. Yet, there are some challenges within an integrated methodology. These challenges are hard to tackle and might provide for an explanation of why the cultural divide sustains. The primary challenge related to the formalisation of the method emerges from the need of compatible steps. Within an engineering-based research, the system is explicitly defined. To establish a bridge within other research steps that are more characterised by design-thinking the compatibility between the research steps is an issue of concern. Model outcomes do not often directly translate into a design exercise and design solutions do not directly provide for input within a computational model.

The second challenge arises with the interpretation of the results. The outcomes of an engineering-based research are predictive but do not always relate fully to the context or allow for interpretation about the desirability and how this can change. The main conclusion of the research is often already drawn before that stage and the core principles are explained. It is thereafter the task of design thinking to assess the desirability of the results and see how this knowledge on the core principles can be employed to steer towards a specific future. One must realise, that this knowledge can lead primarily to more realistic results and not to more inspiring future projections as a computational model can also illuminate on which factors one can have influence.

An integrated methodology can lead to a better understanding of urban planning problems as it allows to comprehend both the complexity of the urban environment as a system as well as its complex context. However, the most important challenges arise in the formalisation of an integrated research process and in the interpretation of the results. Altogether, an integrated method will make research in urban planning problems more data driven, comprehensive and accurate.

3 COMPUTATIONAL URBAN MODELLING AND LAND-USE TRANSPORT INTERACTION

The previous chapter revealed that it is essential to explicitly define urban development as a system to understand urban development from a computational model. With such model, assumptions are revealed and the cognitive capacities of the researcher are extended. This chapter explains how urban development can be explained from a systematic point of view and by which methods the dynamics in cities can be evaluated in a model environment.

How cities and urban areas can be expressed in metrics is explained in the first section of this chapter. In chapter two, conceptual models for urban development are explained, elaborating on the relationship between various functions and spatial entities. Additionally, the section elaborates on computational urban modelling methods to evaluate these relationships. Since this research is scoped towards residential location function, more elaborate explanation of to residential location choice behaviour is provided in the third section of this chapter.

3.1 QUALITATIVE SPATIAL REPRESENTATION

Any model is a simplification of reality, whether the model is physical, digital or mental. Models of urban environments are often spatial and have therefore also a spatial abstraction. In this abstracted representation, data can be stored that tells something about specific places. Images of cities arise by the differences between local data values. These data can have many forms, ranging from a basic description of the main land-use function in an area to a more specific description based on one or a combination of different urban form parameters. Awareness of what data and parameters can be used, how it is structured and what one derives from it is important to adequately employ models in urban studies.

3.1.1 SPATIAL DATA STRUCTURES AND SCALES

Expressing cities in metrics asks for a data structure to store these metrics. The data needs to be structured in such a way that it can give a graphical spatial representation of the urban area. Figure 3-1 gives an overview of the most common spatial representations.

An important aspect when studying urban form parameters is on what scale you apply your indicators to derive conclusions from. Cervero and Gorham (1995) illustrate the difficulty of this matter by stating that there is no consensus what a neighbourhood is. One of the main question in this field of research is therefore which scale levels provide the most useful and

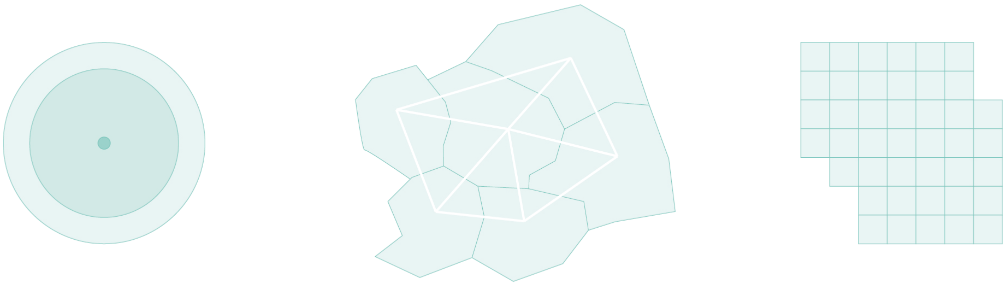


Figure 3-1: Various data structures to spatially represent space by means of urban metrics.

adequate indicators (Milakis, Cervero, & van Wee, 2015). Both Næss (2011) and Milakis, Cervero, et al. (2015) state that large scale variables exert stronger influences on travel behaviour than smaller, neighbourhood scale characteristics.

3.1.2 URBAN METRICS

Urban form is a concept used both in urban planning and design practices as well as in field as e.g. transport engineering or urban geography. The reason not to use the terminology of urban form is because it is often confused for urban morphology, which is a popular conception among urban designers. Typo-morphological or spatial-morphological studies are attempting to explain the shape of the urban fabric through space and time (Moudon, 1992, pp. 374-377). This means that urban morphological studies are not necessarily quantitative although they can bear quantitative characteristics. A stronger emphasis lies on patterns and structures rather than on explicit values. For this reason, the term urban metrics is used throughout this study as a quantitative unit expressing the appearance of the built environment.

Basic and hybrid urban metrics

An urban metric describes space on a more elaborate level than merely describing the function that covers the concerning area (the land-use description). Urban metrics know many expressions, ranging from straightforward density values to advanced indices which do not necessarily elaborate on the physical or functional character of cities only. Bases on the '3Ds' of urban form and travel demand by Cervero and Kockelman (1997) (Density, Diversity and (network) Design), a classification of three groups of basic urban metrics is distinguished:

- Metrics describing the physical appearance of urban places (e.g. parameters related to the building stock);
- Metrics describing the functional appearance of urban places (e.g. sociodemographic parameters);
- Metrics describing the relation between urban places (e.g. distance to closest train station).

By combining various metrics regarding the urban environment it becomes possible to interpret the data to obtain more insights (Figure 3-2). Some examples are:

- Indicators for healthy urban environments based on household composition, dwelling characteristics and employment status (Pacione, 2003);
- Indicators for economic competitiveness based on employment, population composition, education (Florida, 2004);
- Indicators of fuel consumption for transportation per household based on urban density (Figure 3-3) (Kirby, 2008).

Some of these hybrid metrics and indicators are important for this research. These metrics relate to accessibility and typological indicators. Therefore, this are explained in further detail.

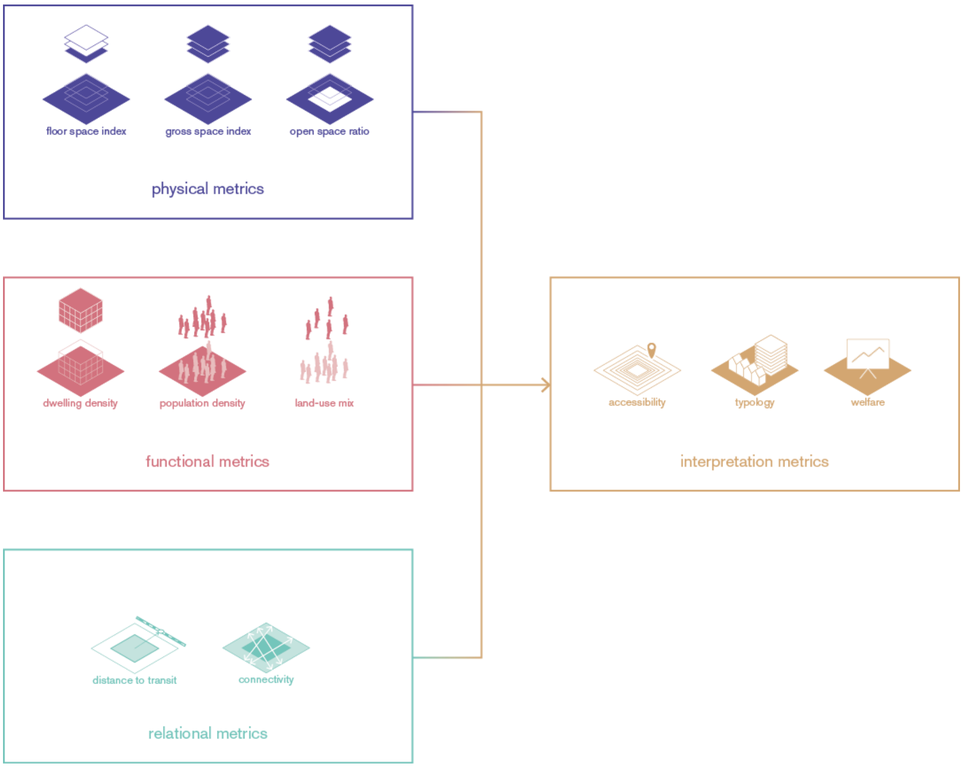


Figure 3-2: Classification of urban metrics in different groups. Diagrams within the boxes are examples.

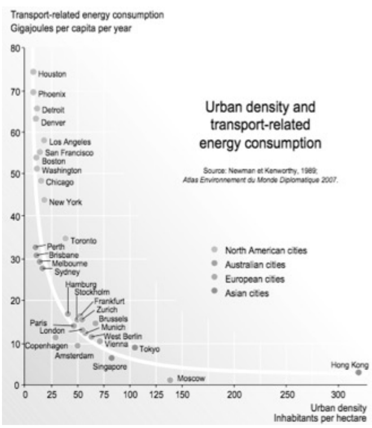


Figure 3-3: Urban density and transport-related energy consumption for cities in North America, Australia, Europe and Asia (Kirby, 2008, p. 158).

Accessibility

From a land-use transportation perspective, accessibility is a key concept. Various ways exist to express accessibility. Early models similar to the model by von Thünen (1826) use the concept of 'distance to urban core or CBD'. Today, more advanced and heterogeneous expressions for accessibility are applied which comprise more variables than just distance to urban centre. Geurs and van Wee (2004, p. 128) provide an overview of the various components of accessibility (see Table 3-1). This means that advanced accessibility indicators not only express the relation between places in terms of network or distance, but also include other factors related to opportunities or individual characteristics.

Table 3-1: Accessibility components (adapted from Geurs and van Wee (2004))

Accessibility components	Description
Land-use	Spatial distribution and characteristics of opportunities and demand
Transportation	Characteristics of infrastructure and location and travel demand of goods and people
Temporal	Time restrictions (e.g. opening hours and available time for activities)
Individual	Person based characteristics as e.g. income, gender but also vehicle ownership

These components comprise different accessibility measures. Ideally an accessibility measure would take all these components into account. However, often this is not done because of data or computational constraints. Geurs and van Wee (2004) provide also a categorisation for these measures as listed in Table 3-2. Quite often – but not always –these listed accessibility measures take an increasing number of variables into account.

Table 3-2: Accessibility measures (adapted from Geurs and van Wee (2004))

Accessibility measure	Description	Examples
Infrastructure-based	Used to describe functioning and performance of the transportation system (e.g. travel times or travel speed)	Travel time isochrones
Location-based	Distance or contour from one place to opportunities or the other way around; the amount of opportunities in distance to a zone	Hansen (1959)
Person-based	Considers the constraints for an individual in space and time	Hägerstrand (1970)
Utility-based	Two kinds are distinguished, a generalised cost measure or a logsum accessibility measure. Prior is an estimate of the total costs from an origin to a destination, considering all relevant costs in terms (monetary, temporal, comfort). Latter measure stems from random utility theory.	Ben-Akiva and Bowman (1998)

Typology indicators

When various metrics are combined, a qualitative typology can be derived from urban metrics. A well-known example of architectural interpretation of urban form is Spacemate or Space matrix by Berghauser Pont and Haupt (2009, p. 118). Another, similar example is the urban classification tool by Rådberg (1996). The space matrix (Figure 3-4) is a metrics interpretation tool to identify various archetypes of urban form typologies. This matrix comprises four factors: the floor-space-index (FSI), ground-space-index (GSI), open-space-ratio (OSR), and building layers (L), which are all built urban form indicators. Combining these factors enables for an indication of the type of building volumes on various scale levels.

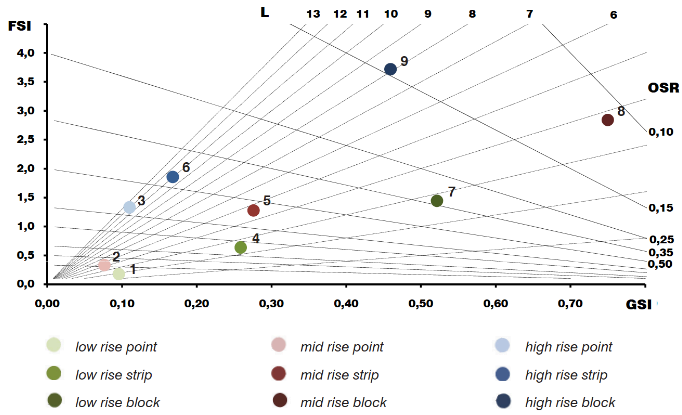


Figure 3-4: Archetypes of urban form (Berghauser Pont & Haupt, 2009).

The space matrix by Berghauser Pont and Haupt (2009) only considered physical aspects of urban spaces and therefore classifies only on physical appearance. An example of a model elaborates on different variables is the neighbourhood classification by ABF Research (2003). The typologies are depicted in Table 3-3 both in the division of five classes (hwm5) and thirteen classes (hwm13) and are an interpretation of density, town size, service proximity, degree of mixing, building period and accessibility.

Table 3-3: Neighbourhood typologies by (ABF Research, 2003)

Aggregated classes (hwm5)	Disaggregated classes (hwm13)
Centre urban area	Centre urban plus Centre urban Centre small urban
Peripheral urban area	Urban pre-war Urban post-war compact Urban post-war grounded Small urban
Peripheral low urban area	Green urban Green small urban
Village area	Centre village Village
Rural area	Rural accessible Rural peripheral
(Work)	(Work)

3.2 DYNAMICS IN THE URBAN ENVIRONMENT

Urban metrics describe various aspects of cities. Over time, these metrics change. Urban models evaluate how metrics change and what consequences this has on other aspects of the built environment. An important notion is that these changes are caused by the interrelation and interaction between different processes within cities. Some models focus on very specific processes within cities, whereas other models attempt to obtain a meta-understanding of urban processes. This section explains conceptual models behind urban development followed by different frameworks by which these conceptual models are implemented.

3.2.1 CONCEPTUAL MODELS OF URBAN DEVELOPMENT

Within urban models, initially two branches could be distinguished. The one branch with a strong focus on the interaction between land-use and transportation (Ort zar & Willumsen, 2011, p. 493; Waddell, 2011) and the other branch with a stronger focus on economic principle of land as a scarce good. The interaction between land-use and transportation can be explained by the land-use transport feedback cycle (Figure 3-5) by Wegener and Fürst (1999). The cycle illustrates the twofold character of the system:

1. On one hand, the spatial dispersion of land-uses and activities influences the performance of the transportation network;
2. Whereas on the other hand, the performance of the transportation network influences the attractiveness of areas for specific land-uses.

The first stated characteristic of the cycle is most obvious: The focus of the transportation system is to facilitate the mobility of goods and people to perform different activities in different places. However, the impact of the transportation system on the location choices is more complex and subject to debate (Wegener & Fürst, 1999). Many other processes are of influence in urban development as the scheme by Moeckel, Schürmann, and Wegener (2002, p. 11) in Figure 3-6 illustrates. Lifecycles of decision makers, governmental policies and interventions and other environment factors are also very important driving forces. Therefore, urban models that attempt to obtain some level of meta-understanding of urban development only are partly based on transportation models. Other aspects regarding policies, demographics etc. are often represented in various markets. These markets are typically as follows (Zondag, 2007, p. 66):

- Land market
- Real estate market
- Housing market
- Labour market
- Transport market

The word ‘market’ is used in the sense that this market represents the scarcity of space in relation to supply and demand and the interaction between the various decision makers. And through decision maker, markets influence each other. This characterises the system thinking behind meta-models. Transportation is only among the many markets (demand and supply between travel and road capacity), and therefore these models are also often called urban models. These urban models cover the goal of general understanding towards urban systems. The dynamics of these markets are the result of the interaction between different decision makers. In various urban models, the following decision makers are distinguished:

- Individuals or households
- Firms or employment
- Developers
- Government or authorities

Comprehensive urban models are therefore often organised like the conceptual model depicted in Figure 3-7.

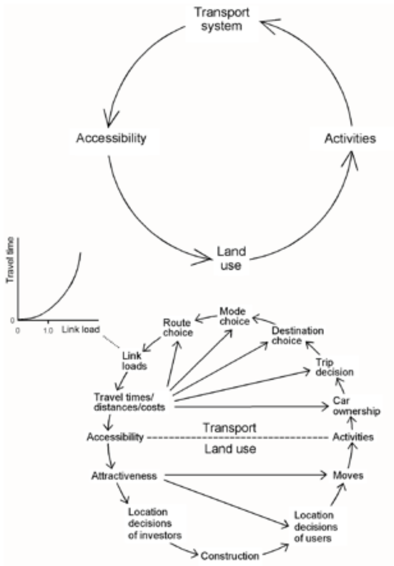


Figure 3-5: The land-use transport feedback cycle (Wegener & Fürst, 1999, p. vii)

Change of ... causes / ... change of...	Road network	Public transport	Industrial buildings	Retail buildings	Office buildings	Residential buildings	Firm lifecycles	Household lifecycles	Person lifecycles	Industrial location	Retail location	Services location	Labour mobility	Residential mobility	Commercial vehicles	Car ownership	Logistics	Household activities	Goods transport	Travel	Energy, CO_2	Air pollution	Noise	Land take	Micro climate
Road network	●		●	●	●	●				●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●
Public transport		●											●	●		●		●		●	●	●	●	●	●
Industrial buildings			●							●											●	●	●	●	●
Retail buildings				●							●										●	●		●	●
Office buildings					●							●									●	●		●	●
Residential buildings						●								●							●	●		●	●
Firm lifecycles							●	●	●	●	●	●	●		●		●		●						
Household lifecycles						●		●	●					●		●		●		●					
Person lifecycles						●		●	●					●		●		●		●					
Industrial location			●							●		●	●	●	●		●	●	●	●					
Retail location				●							●	●	●	●	●		●	●	●	●					
Services location					●							●	●	●	●		●	●	●	●					
Labour mobility													●			●		●		●					
Residential mobility						●						●	●	●		●		●		●					
Commercial vehicles															●		●		●		●	●	●		
Car ownership						●							●	●		●		●		●	●	●	●		
Logistics															●		●		●						
Household activities													●	●		●		●		●					
Goods transport										●	●	●			●		●		●		●	●	●		●
Travel																●		●		●	●	●	●		●
Energy, CO_2			●	●	●	●															●				
Air pollution											●	●		●								●			
Noise											●	●		●									●		
Land take														●										●	
Micro climate														●											●

Figure 3-6: Interaction between spatial and mobility related aspects in land use modelling (Moeckel et al. (2002, p. 11))

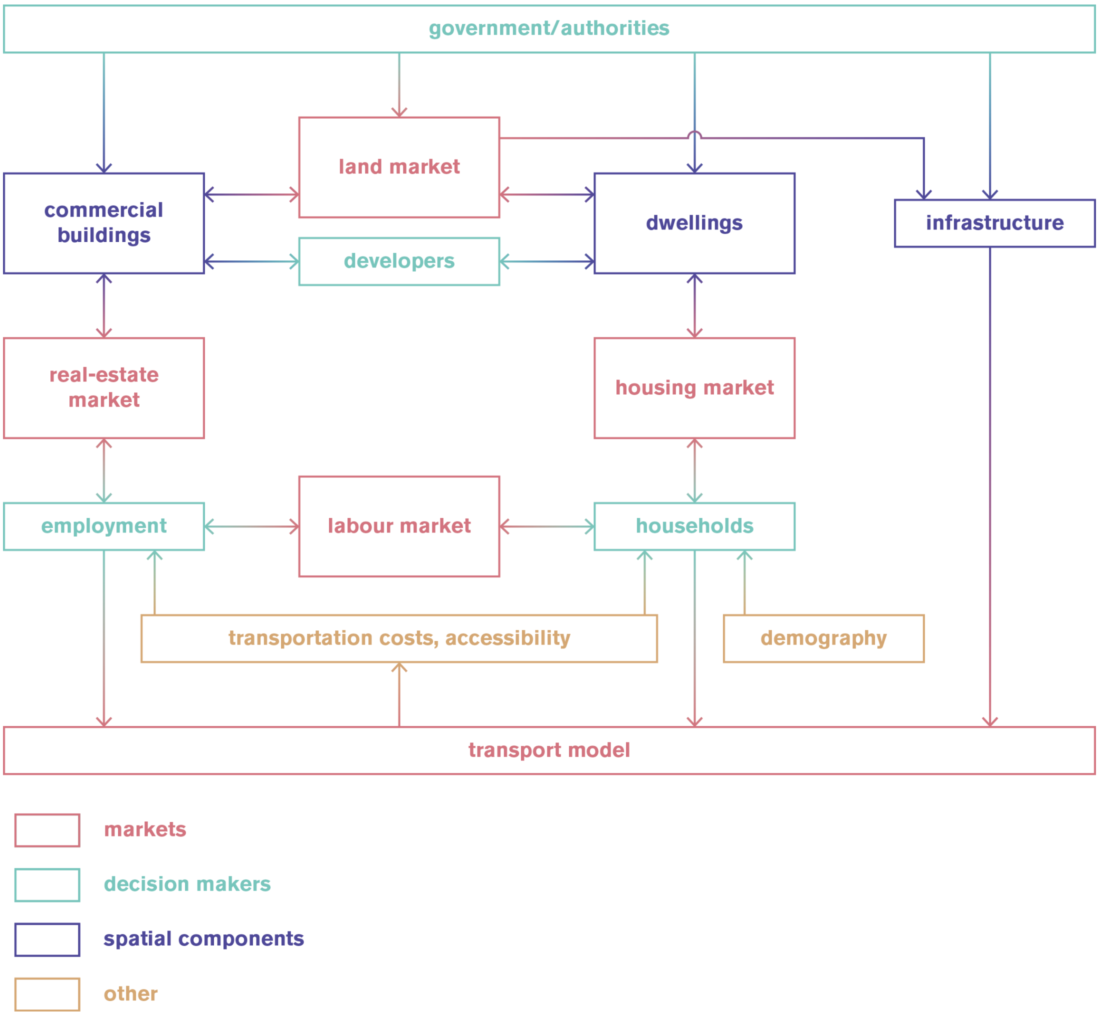


Figure 3-7: General overview of comprehensive urban models. The transport model and the demographic models are considered as exogenous models (adapted from van Nes (2014, p. 9)). The transportation model can be considered a market too.

3.2.2 DEVELOPMENTS IN COMPUTATIONAL URBAN MODELS AND METHODS

Most urban models comprise some characteristics of the system depicted in Figure 3-7. Yet how this interaction can be modelled differs significantly and has developed over time. Figure 3-8 shows the development of urban modelling frameworks over time. Four paths of urban models can be distinguished: spatial organisation models, spatial interaction models, discrete choice models and microsimulation models. As Figure 3-8 shows, microsimulation models often still rely on these economic based discrete choice models.

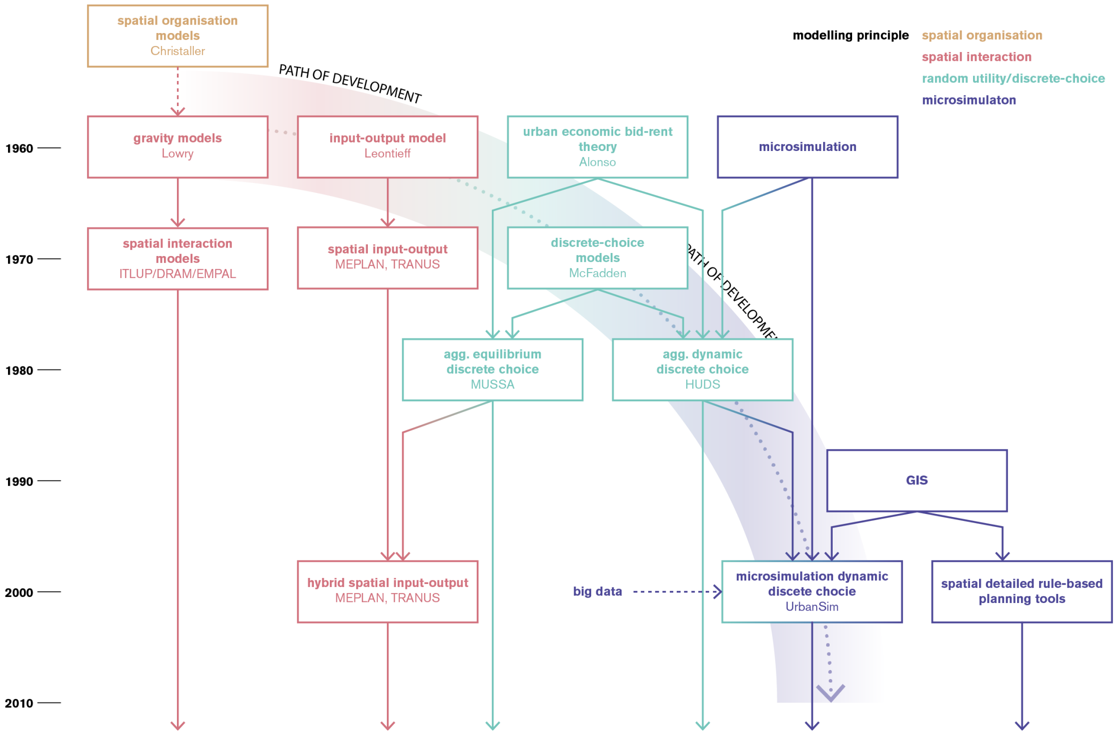


Figure 3-8: Development of urban modelling frameworks (based on Timmermans (2003); Waddell (2014)).

<u>Spatial organisation models</u>

Theories by e.g. von Thünen (1826), Christaller (1933) (Figure 3-9) or the gravity-based equilibrium model by Lowry (1964) have been applied in planning practice. All these models in some way elaborate on the relation between accessibility and land-use. Whereas the model by von Thünen (1826) and Christaller (1933) are considered means to describe observations, the model of metropolis by Lowry (1964) is one of the first modern LUTI models that is applied in a way that it is suitable to assess infrastructure mutations.

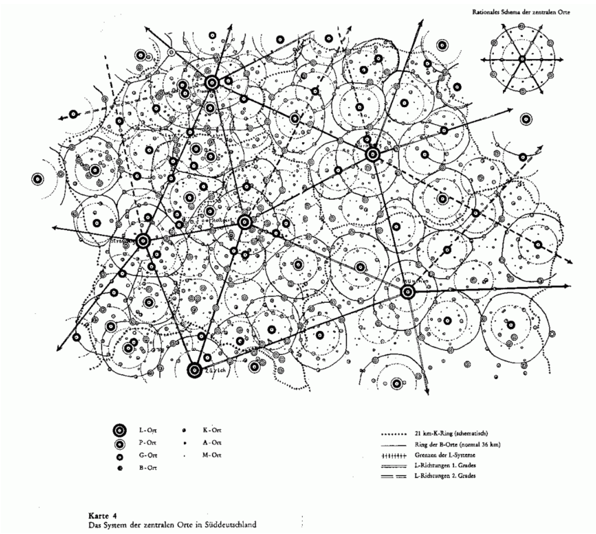


Figure 3-9: Scheme of the central places theory depicted on settlements in southern Germany (Christaller, 1933).

Spatial interaction models

Spatial interaction models are inspired by the analogy with Newton's law of universal gravitation and assume that the interaction between two entities are determined by their 'mass' (Koomen & Stillwell, 2007, p. 7). And this analogy seems obvious at first. The frequency of interaction of goods or people is relational to the size of a city, whereas the inverse applies for the distance between cities. The Lowry (1964) model is based on the gravity model and can therefore be classified as a spatial interaction model. Today, the pursue to reason spatial development by one of the most fundamental laws of physics seems elegant. Yet, it assumes an equilibrium that does not exist (Wegener & Fürst, 1999, p. 7). One of the main reasons for this disequilibrium is the difference in time-scales of behavioural change and urban change (Wegener et al., 1986). Hence, spatial interaction models proclaim an equilibrium that never establishes itself.

Logit models

A new class of models for land-use started from the notion of an economic basis for location decisions. Subsequently with the development of the model by Lowry (1964), Alonso (1964) developed a land-use theory based on the bid-rent concept as found in the von Thünen (1826) model. And also Leontief (1970) provided a framework to relate interdependencies between various sectors and clusters of economies with the input-output model. These economic models distinguish themselves from spatial interaction models. The economic basis of these models states the assumptions that decision makers always select the option which maximises the utility. The most common paradigm to formulate this behaviour is random utility theory in the discrete choice models by Daniel McFadden (1978). Discrete choice models are used to model the choice behaviour of decision makers that make a discrete choice; the choice set comprises a finite and integer set of alternatives.

Today, these choice models are still very important in many transport and land-use models. This implies that the outcome of urban models is the result of modelling choices of decision makers: the decision-making process is the core of the model. It is therefore relevant to briefly explain how these decisions are calculated. This explanation is based on Ort zar and Willumsen (2011, p. 230). For a more detailed overview of discrete choice modelling, this work is recommended.

Within discrete choice models, the assumption is made that decision makers $\bar{Q}$ always select the options that results in the maximal net personal utility. The choice set $\bar{A}$ comprises a certain set of alternatives. Within each alternative $\bar{A}$, each alternative comprises set $\bar{X}$ of measured attributes of the alternative. For each option A_n has a net utility U_{nq} specific for the decision maker.

$$U_{nq} = V_{nq} + \varepsilon_{nq}$$

with U_{nq} the systematic (non-stochastic) component, V_{nq} the observed utility of alternative n and ε_{nq} the stochastic component.

The observed utility V_{nq} can be calculated as follows:

$$V_{nq} = \sum_{k} \beta_{kj} x_{nkq}$$

with β_{kj} the sensitivity parameters of alternative attribute x_{nkq}.

The most common application of discrete choice models is the logit model. When a logit model assumes all error terms independent and identically distributed in a Gumbel distribution, one speaks of a multinomial logit model where the probability of choosing an alternative is calculated by evaluating the utility of one alternative over the utility of all other alternatives:

$$P_{nq}(i) = \frac{\exp\,(V_{inq})}{\sum_j \exp\,(V_{jnq})}$$

When the choice is sequential, a nested structure is applied. One nest counts in the choice process through a computed compound utility of the underlying alternatives. This will however not be further explained since this theory is not applied further within the research.

Microsimulation models

Some components as accessibility measures in Hansen (1959) have evolved to the more comprehensive modelling frameworks that nowadays play an important role in modern planning processes (Koomen & Borsboom van Beurden, 2011). Simple gravity models as Lowry (1964), input-output models, bid-rent theory models as Alonso (1964) have evolved under influence of random utility modelling and computational advances to dynamic microsimulation models with advances in the heterogeneity in decision makers, spatial and temporal resolution. Within microsimulation models, two types of models can be distinguished. One type provides an attempt of meta-understanding of urban development and comprises conceptual models like the scheme in Figure 3-7. Examples of such models are UrbanSim (Waddell, 2002), ILUTE (Salvini & Miller, 2005) or TIGRIS XL (Zondag & De Jong, 2011). The other types of microsimulation models focus on very specific aspects – rather than on obtaining meta understanding – or are very theoretical.

Often, microsimulation models where decision makers operate within a spatial environment to achieve a certain objective are classified as agent-based models. Agent-based modelling can be applied regarding many exercises. Yet, in the field of transportation planning, complexity analysis becomes more conventional by the means of agent-based modelling. The microscopic approach of agent-based modelling can be favourable when knowledge on macroscopic behaviour is lacking (Borshchev & Filippov, 2004). This gets to the core principle of agent-based modelling: By modelling microscopic behaviour and interaction, macroscopic patterns emerge (Figure 3-10).

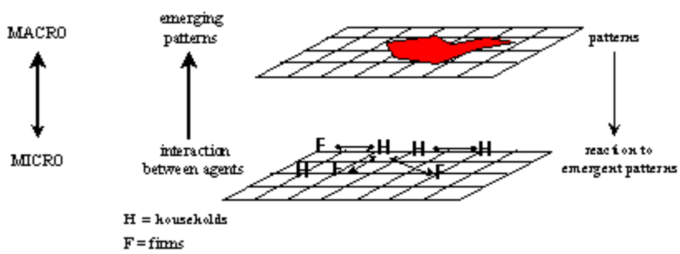


Figure 3-10: Conceptualisation of an agent-based model (Otter, van der Veen, & de Vriend, 2001).

Modelling the behaviour of the agents or decision makers within the model can be very challenging. Most Meta-LUTI models still rely heavily on discrete choice models, but are adapted to model choice behaviour in a disaggregated way. An advantage of this approach is that is has a solid scientific basis. Discrete choice modelling is used in practice for over 50 years (Flynn et al., 2014). Integrating discrete choice modelling modules within an agent based model framework can be considered an adequate way. Discrete choice modelling is suitable for both aggregated as well as disaggregated applications. The probability distribution function in aggregated modelling approaches is - as the name suggest – to distribute the decision makers over the number of alternatives. For disaggregated approaches, it is necessary to adapt the distribution function to microscopic choice behaviour by applying Monte-Carlo experiments in a multinomial logit model (Waddell et al., 2003) as depicted in Figure 3-11.

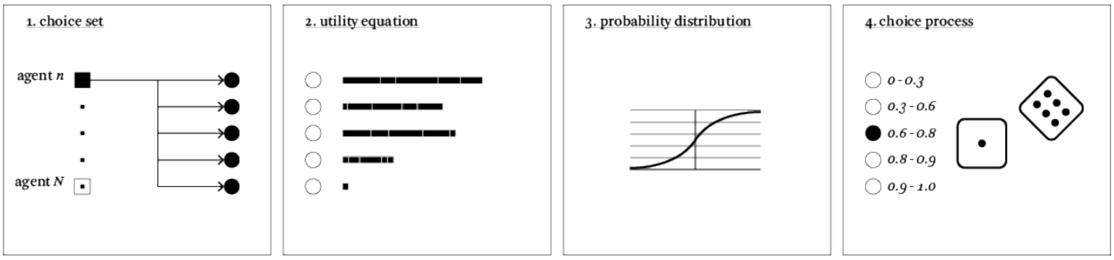


Figure 3-11: Adapting macroscopic discrete choice models to microscopic models (Based on Waddell (2010, p. 169)).

Other methodologies

Also, other methods exist to study changes in urban form and the transportation network. Some of these methodologies do fit to some extent within the paradigms of the three waves of LUTI models, but are not considered mainstream or state-of-the-art. Examples of these methods are:

1. system dynamics: a methodology to model complexity for many different cases on an aggregated level rather than a disaggregated level) (Forrester, 1969).
2. cellular automata: a predecessor of agent-based modelling, which only distinguishes the environment rather than individual decision makers moving through space.
3. Rule-based simulation: often applied in natural processes. Applied in cases when a known process is being imitated (Koomen & Stillwell, 2007).
4. Markov chains: a methodology in particular based on the fundament of historical development (van Schrojenstein Lantman, Verburg, Bregt, & Geertman, 2011, p. 41).

All these methods distinguish themselves in terms of comprehending complexity, spatial representation and aggregation level.

3.3 RESIDENTIAL LOCATION CHOICE MODELS

The prior section already elaborated briefly on the difficulty of modelling the behavior of decision makers in urban microsimulation models. Since this research scopes towards the residential location choice, models to elaborate on this choice are further explained. These models are all based on random utility discrete choice models.

The residential location choice is a determinant factor within urban development. The location of households and jobs is very interdependent. However according to Hoogstra, Florax, and van Dijk (2005), most empirically derived results in a wide number of studies indicate that residential locations are leading in this matter. Furthermore, most of the built environment in the Netherlands is occupied by the function of housing (Figure 3-12).

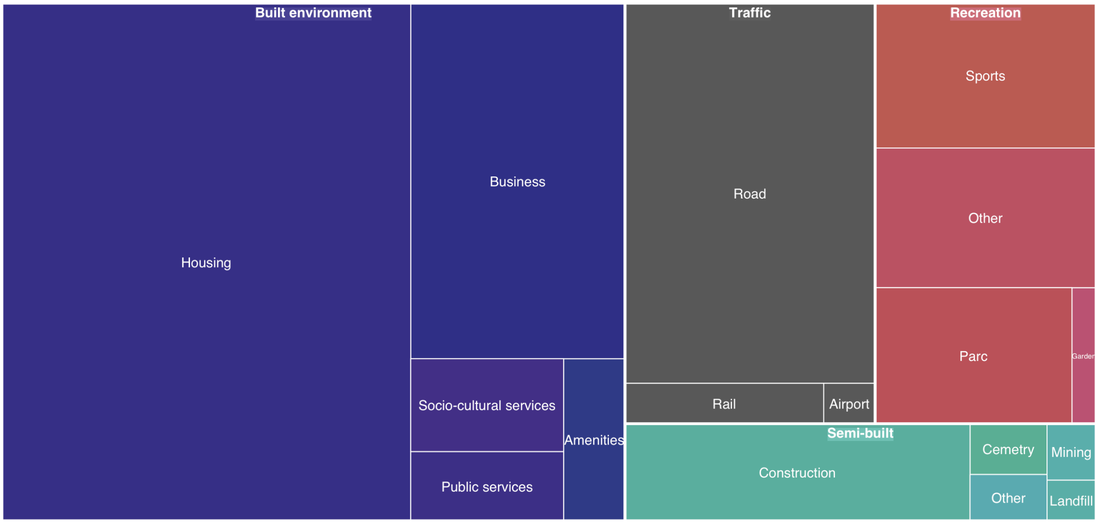


Figure 3-12: Land-use in the Netherlands in 2016 by area regarding built environment and corresponding land use categories (data obtained from CBS (2016b)).

Models for household allocation do exists already. The purpose of some of these studies is to examine the influence of one specific attribute in the location choice (e.g. Gabriel and Rosenthal (1989) on the role of race in location choice or Bayer, Keohane, and Timmins (2009) on the influence of air quality), whereas other research attempts to obtain choice models for urban models or other decision support tools (Waddell (2010) for UrbanSim or Zondag, de Bok, Geurs, and Molenwijk (2015) for TIGRIS XL).

In this light, one can consider the study by Hunt, McMillan, and Abraham (1994) for a broad overview. In this study (p. 80), a long list of evaluation attributes are listed found in other studies. In the case of residential location choices, usually households are chosen as the decision maker (although individuals or collectives of individuals is in theory possible as well). Besides characteristics of the household itself, the residential location choice is often considered on aspects in the following three characteristics (Figure 3-13):

- Dwelling attributes
- Attributes of the location
- Attributes of the neighbourhood

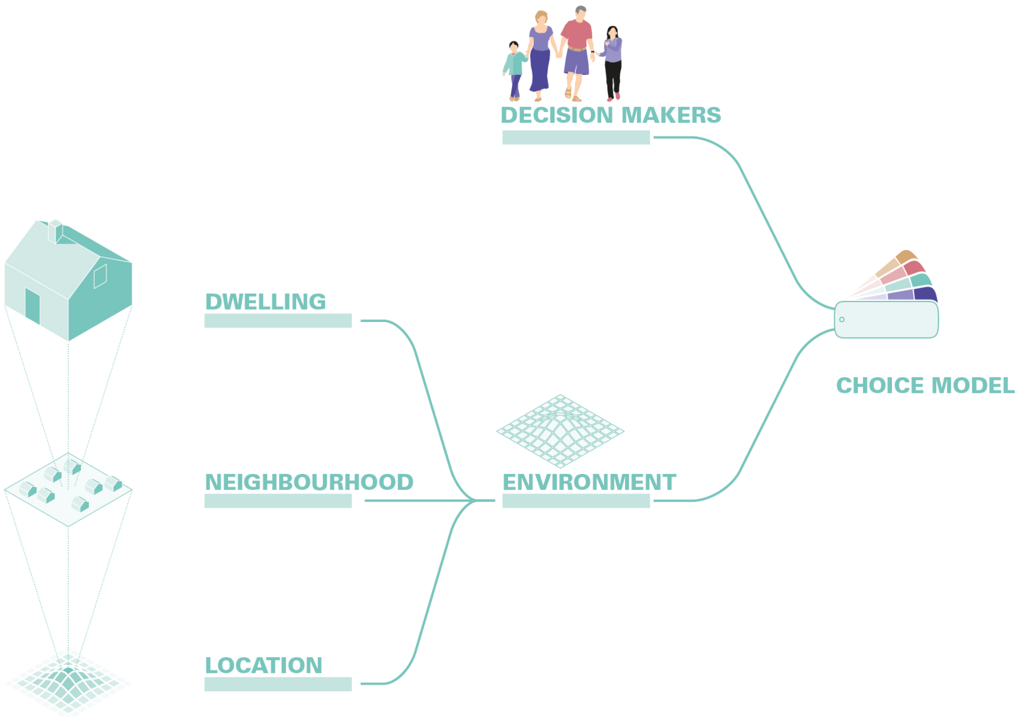


Figure 3-13: Urban form is the result of human behaviour, of which the residential location is a very important behavioural aspect. The residential location choice is based on environmental factors as well as on characteristics of the household itself.

The variables to describe households are often of socio-economic nature. One of the most considered household characteristics is income or level of education. This can be explained from the fact that most residential location models are based on economic principles. Also the size of the household, as well as age distribution and employment status is considered (Schirmer, van Eggermond, & Axhausen, 2014, p. 4). Another important considered characteristic is car ownership (Bhat & Guo, 2007, pp. 520-521). These aspects are most common within practice.

Attributes of the location are often expressed in accessibility measures to activity locations such as workplaces, education or amenities. In some studies, the availability of parking is considered. Several studies focus specifically on the impact of accessibility effects specifically on location choices (e.g. Tillema, Ettema, and van Wee (2006); Wenjia Zhang and Kockelman (2016) on road pricing or congestion). According to Zondag, de Bok, Geurs, et al. (2015, p. 124) the role of accessibility plays a modest role in residential location in the TIGRIS XL model for the Netherlands compared to companies (de Bok & Sanders, 2005). On the one hand, this can be assigned to the relative strong spatial planning policy in The Netherlands, but also on the relative limited accessibility differences in the Netherlands.

Neighbourhood characteristics can cover a wide range of factors. Within the TIGRIS XL land-use model for the Netherlands, neighbourhood characteristics are covered by using neighbourhood typologies as defined by ABF Research (2003) but also density and average housing value (Zondag, de Bok, Geurs, et al., 2015). The typology of a neighbourhood tells of course something of the physical appearance of an area, but implicitly bears characteristics such as level of service in the area or the socio-economic climate.

Dwelling characteristics are not always considered, this differs often on the scale of the research. Nonetheless, the price of the dwelling is in some way incorporated within the choice set. Often this is done by expression of the average house price of an area. However, some models offer higher spatial resolution and elaborate on the dwelling by e.g. specifying the number of rooms in a dwelling.

An important data source to derive residential location choice models is survey data. The models are often obtained through model estimation software as e.g. Biogeme (Bierlaire, 2003). In such processes correlating attributes are as much as possible removed from the choice set. The consequence is that some variables are not considered although these might indirectly matter. For instance, the case for the average housing value is that this value depends on many variables among supply and demand (Eskinasi, 2014). But also on qualitative aspects of the house and the area. Models that do not diminish the effect of correlation are hedonic pricing models. Hedonic pricing is an economic principle used to identify and quantify various influences on housing property value (Nicholls, 2004).

3.4 CONCLUSIONS

By defining cities and urban process explicitly in models and metrics, the core principles of urban development reveal. These models do not take all factors into account but are still proving increasingly capable at accurately simulating urban change on a macro scale. Various projects exist in which modelling applications are developed as attempt to obtain a certain level of meta-understanding of urban development by considering more factor with a larger heterogeneity in decision makers. Even though models are increasingly becoming microscopic of nature, the primary purpose is to examine system wide changes (driven by individual decision makers). This means that although some aspects on a smaller scale might be evaluated within the model, these aspects will not necessarily provide answers to these aspects. Some examples where one can think of relates to social cohesion in neighbourhoods or aspects related to spatial quality. Within more specialised and theoretical urban models, one can evaluate and examine such factors more adequate under the knowledge that many other factors are not considered.

Computational urban models can greatly support research in urban planning processes. Especially in cases where system-wide perspectives are relevant and/or processes arise that exceeds the human internal thinking capacities. Many state-of-the-art computational urban simulation models consider the choice behaviour of individual decision makers in space and time as the driving force of urban dynamics and development. These models can help to comprehend the complexity of urban planning problems from a systematic point of view. Therefore, urban models must not be considered as a tool for automation of urban planning processes but as a support tool. Urban models can prove useful as a 'laboratory' in two ways (Figure 3-14): It allows to study the urban environment on emergent patterns which prove too complex or too data demanding to obtain from real world. Because the urban system is formalised in a model, insights can be obtained which aspects and parameters drive emergent phenomena ins cities. Additionally, it allows to experiment and test policies and interventions within the modelling environment to examine the change in the behaviour of the urban system, i.e. the adequacy of interventions can be assessed.

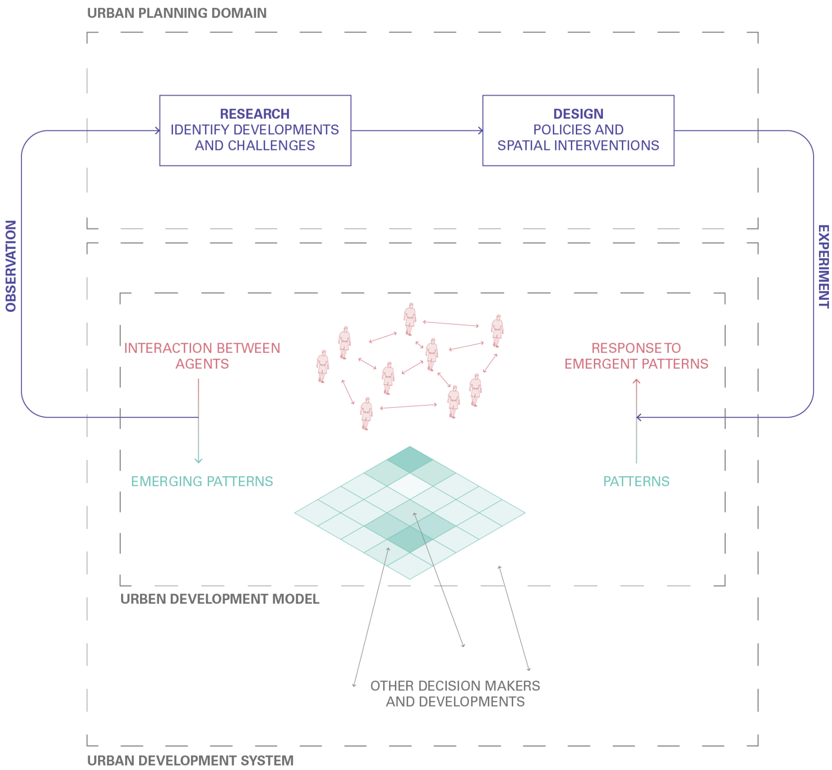


Figure 3-14: Using models in understanding the system of urban development in relation to the urban planning domain.

An important realisation is that models therefore do not answer all question. Instead of looking for an optimum solution, state-of-the-art models allow for understanding of the system under various situations. By altering parameters, one can reveal trade-offs, uncertainties and sensitives. This can help discipline the dialogue about options and make unavoidable judgments more considered. Models are only a small part in the broader social context in which urban planning problems are addressed. In discussions on which urban developments are desirable and by which means spaces can be defined to provide people good living environments, models can only play a modest role. Nevertheless, models are defining human behaviour as driving force in urban development and allowing for increasingly higher spatial resolutions. This prospects a development where urban models have the potential to provide valuable input to the broader social context of urban planning problems.

4 AUTOMATED VEHICLE VARIABLES

Automated driving is a technology under development. This chapter examines the state-of-the-art research on automated vehicle impacts on travel and land-use. Since automated driving is primarily a technological driven innovation, the technology will be then explained as such where after applications and implications are reviewed. This will provide for input of the remainder of the study, as the data obtained in this study. Additionally, the deployment factors of automated driving are explained to provide for the context in which automated driving must establish in a socio-technical regime. This helps to understand how automated driving as a technology relates to urban change and through which aspects and by which magnitudes. The chapter concludes by explaining the case of automated driving in relation to urban planning problems.

Automated driving is a trending research topic (Figure 4-1) and the number of research is increasing. Many state-of-the-art automated driving research relevant for this study is examined. However, the rate by which this research is developing makes it impossible to incorporate all latest publications.

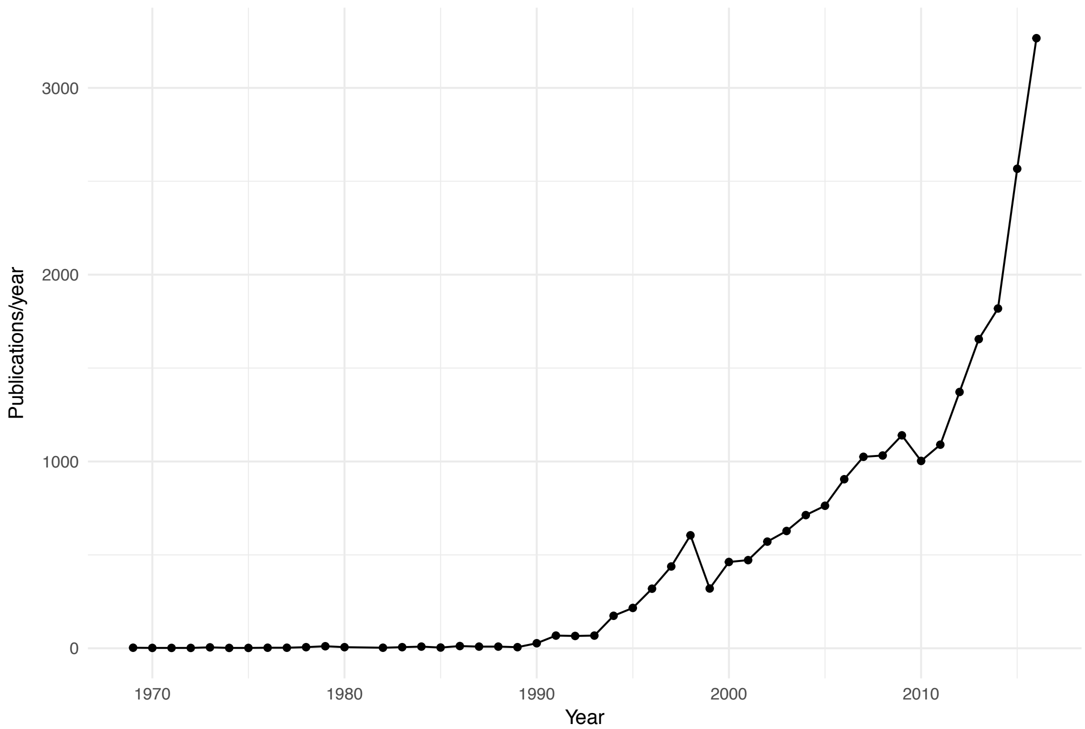


Figure 4-1: Records on Web of Science with topic 'self-driving cars', 'autonomous vehicles' or 'automated vehicles' (data derived at 2017-10-16, data for 2017 not included).

4.1 TECHNOLOGY

Various concurrent definitions such as self-driving car, autonomous vehicle or automated vehicle are used in the context of vehicle automation. Especially in popular media, the term self-driving car is frequently used. However, this does not cover the complete scope of vehicle automation. Vehicle automation is subject to the following two main developments in the automotive industry: automation of the driving task and connection vehicles through sensors and data with the environment and each other. This research speaks of automated vehicles when vehicles bear characteristics of autonomous driving as well as being in connectivity with other cars and the environment (Figure 4-2).

It is expected that these technologies can increasingly help to take over the tasks of the human driver and enhance the efficiency of the transportation system. The first development relates to the advances on the driving task itself, whereas the second development is about to the communication devices that are increasingly equipped in cars.

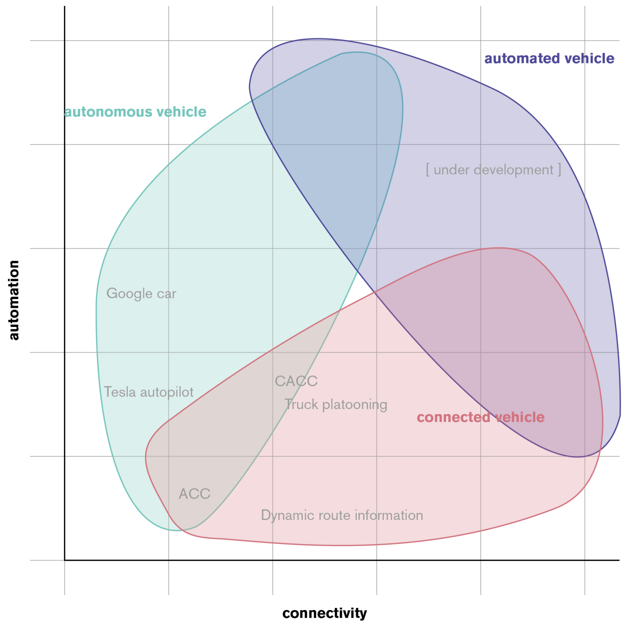


Figure 4-2: Automated driving is the technology where automation of the driving task and connecting vehicles with other vehicles and the data is brought together.

Another vehicle innovation is electrification, which is mostly beneficial in terms of environmental or energy related aspects (e.g. emissions or traffic noise). Yet, the effect of electrification on usage of vehicles and the driving experience is limited compared to the development of autonomous driving and vehicle connectivity (under the assumption that no significant changes in travel cost emerge) and will therefore be not considered.

4.1.1 AUTONOMOUS DRIVING

The main notion of vehicle automation is that the vehicle (or a computer) takes over specific tasks of the human driver. The human driver is to a certain extent replaced by an artificial agent that interacts between the vehicle and the environment. The human becomes in this system an outsider. To which extent the person is excluded from the driving tasks can be different. The SAE On-Road Automated Vehicle Standards Committee (2014) and the NHTSA (2013) have defined levels of automation from respectively 1 till 5 and 1 till 4, which describe the tasks of the human driver as well as for the vehicle computer. Naturally, with increase of the levels of automation, the computer tasks increase whereas the human driver tasks gradually become obsolete.

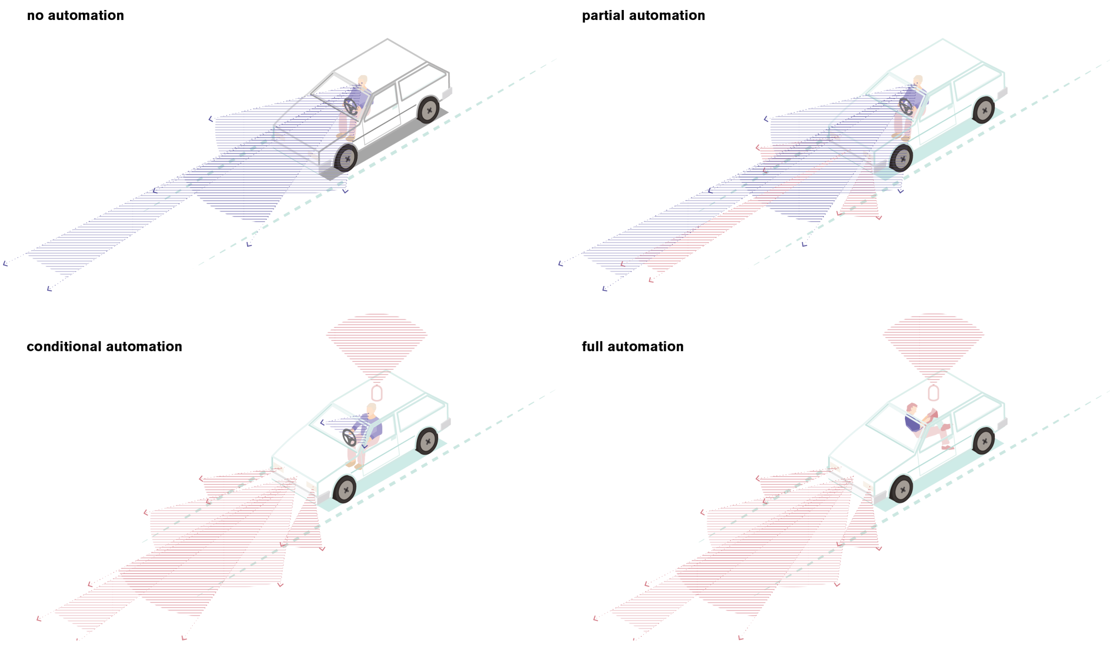


Figure 4-3: Different stages of automation of the driving task can be distinguished, ranging from partial automation where the car take over some of the driving task, to conditional to full automation where the vehicle performs all driving tasks.

The levels of automated driving are under constant revision. Therefore, this research concludes on the three incremental types of automation as depicted in Figure 4-3:

- None, the human driver performs all driving tasks
- Partly automation: vehicles only substitute specific driver tasks (e.g. adaptive cruise control).
- Conditional automation: cars perform more tasks, but the driver has still a responsibility in monitoring the environment or perform interventions in case of failure.
- Full automation: all tasks of the driver are replaced by the car system. Cars can even operate without any driver or passenger in the vehicle.

4.1.2 VEHICLE CONNECTIVITY

To what extent computers can substitute human driver tasks, depends not only on the relation artificial agent – vehicle, but also how the artificial agent is connected with its environment. Qualcomm Technologies (2015) distinguishes four types of vehicle communications (Figure 4-4):

- Vehicle-to-Vehicle (V2V)
- Vehicle-to-Infrastructure (V2I)
- Vehicle-to-Pedestrian (V2P), which can relate to all modes of slow/soft traffic.
- Vehicle-to-System (V2X) or Vehicle-to-Cloud (V2C), which can be an advanced version of V2V and V2I on a transportation system wide level.

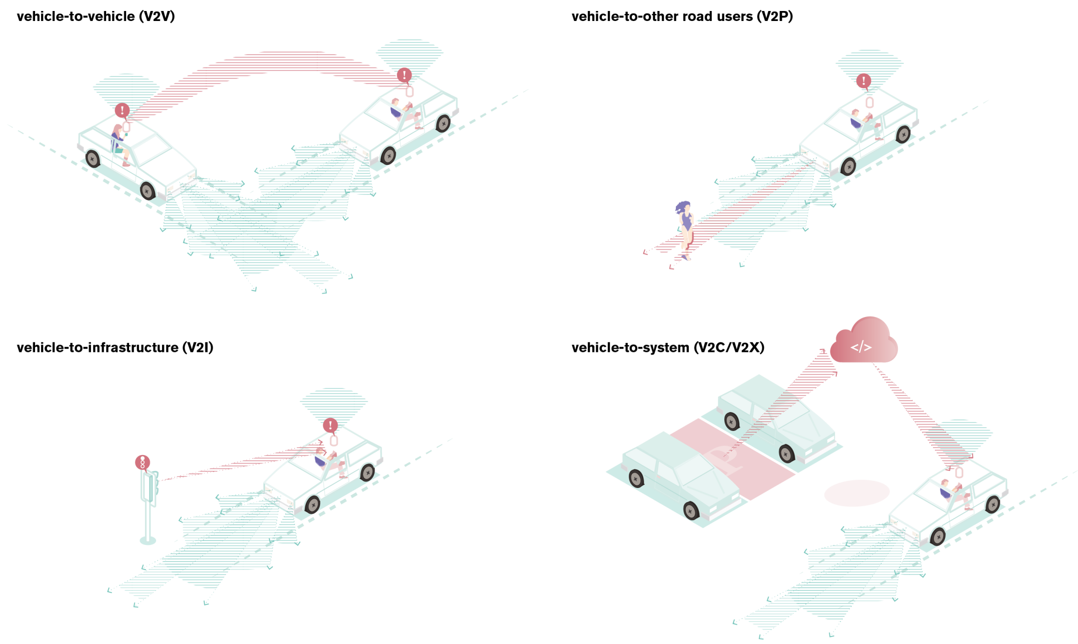


Figure 4-4: Besides automation, increased connectivity of vehicles with other road users, infrastructure and the whole transportation system is part of the automated driving development.

Most of these concepts are not new, but are already present in some way in modern cars and car technology. However, the definitions as listed above imply that communication works both ways (Swan, 2015, p. 7). Today, this is not the case most of the times. Especially V2V technology is emergent in automobiles, primarily with the main focus of collision avoidance by attending or warning the driver (Harding et al., 2014, p. xiv). The same applies to V2I: sensors embedded in infrastructure (e.g. loop detectors, Bluetooth beacons) can measure traffic to a certain extent, but vehicles do not actively transfer information to infrastructure. In this light, V2C communication can be considered most established, especially with the help of smartphones. Infrastructure sensors and cellular data are used to give dynamic routing advice to drivers.

4.2 APPLICATIONS OF AUTOMATED DRIVING

On vehicle level, automated driving is the combination of the application of automation and connectivity technology. These aspects on vehicle level can have various applications within the transportation system. The significant applications are sorted on the following scale levels:

- Vehicle level: elaborating on the driving task and driving applications;
- Microscopic level: elaborating on applications in relation to traffic;
- Macroscopic level: elaborating on applications on level of the transportation network.

4.2.1 APPLICATIONS ON VEHICLE LEVEL

One of the main innovations of automated driving is automation of the driving task itself. This means that the driver can perform other tasks while driving (Cyganski, Fraedrich, & Lenz, 2014; Memon, Ahmed, Ali, Memon, & Shah, 2016) or that vehicles can potentially drive without any person in the vehicle. Therefore, automation of the driving task not only influences the driving experience. New applications are possible as e.g. empty-ride allocation (Chen, Kockelman, & Hanna, 2016) for new passenger pick-up, valet-parking solutions with large ex-urban parking stations (Childress, Nichols, Charlton, & Coe, 2015; Cyganski et al., 2014, p. 5) or for the transportation of cargo (Townsend, 2014, p. 52). It also allows for car mobility for people without a driver license. Vehicles that drive themselves can therefore be very beneficial for the driving experience in terms of comfort, and can also allow for induced travel demand by car due to new user groups and by empty ride allocation (Figure 4-5).

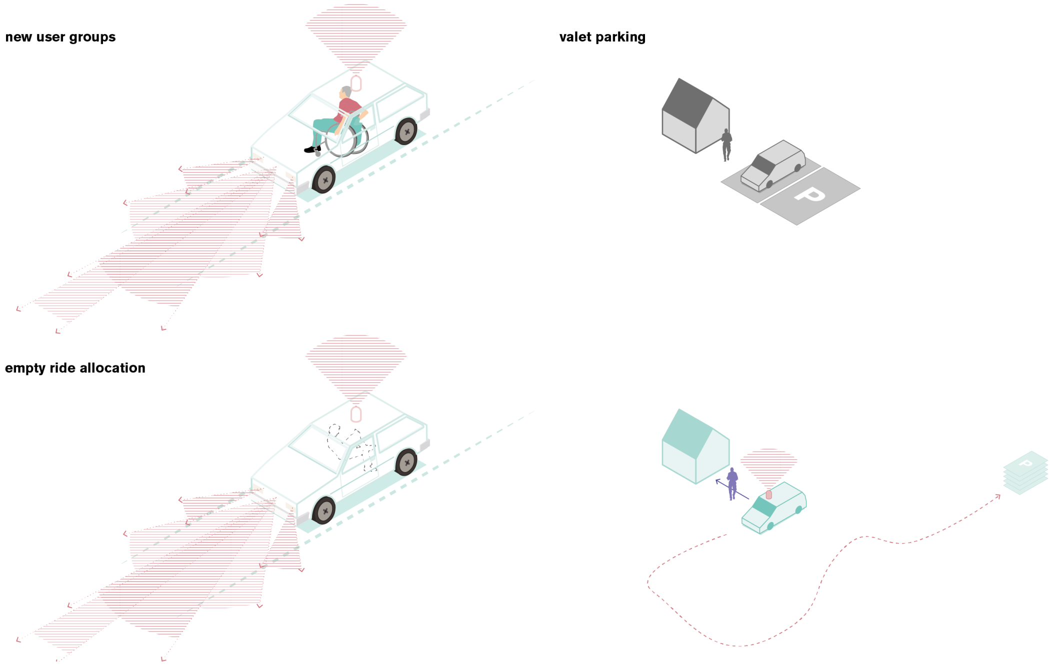


Figure 4-5: By automation the driver does not necessarily need to be qualified to drive a car. Or, the vehicle might drive without driver. This allows for cars to be used by new user groups, to relocate to pick up another passenger or to park on an alternative location.

4.2.2 APPLICATIONS ON MICROSCOPIC LEVEL

Replacement of the driving task is not the only application of automation. It can also be employed to improve traffic flow efficiency (Figure 4-6). Coordination between vehicles in combination with autopilot systems can be employed to increase road capacity and traffic stability. Such an example is platooning. Platooning allows for shorter headways between vehicles and therefore increased road capacity. Additionally, automated driving can make vehicles much more responsive and predictable and therefore also improve traffic stability. Similar to platooning on straight road parts is coordination between vehicles from different directions on intersections to enhance traffic flow (MIT Senseable City Lab, 2014).

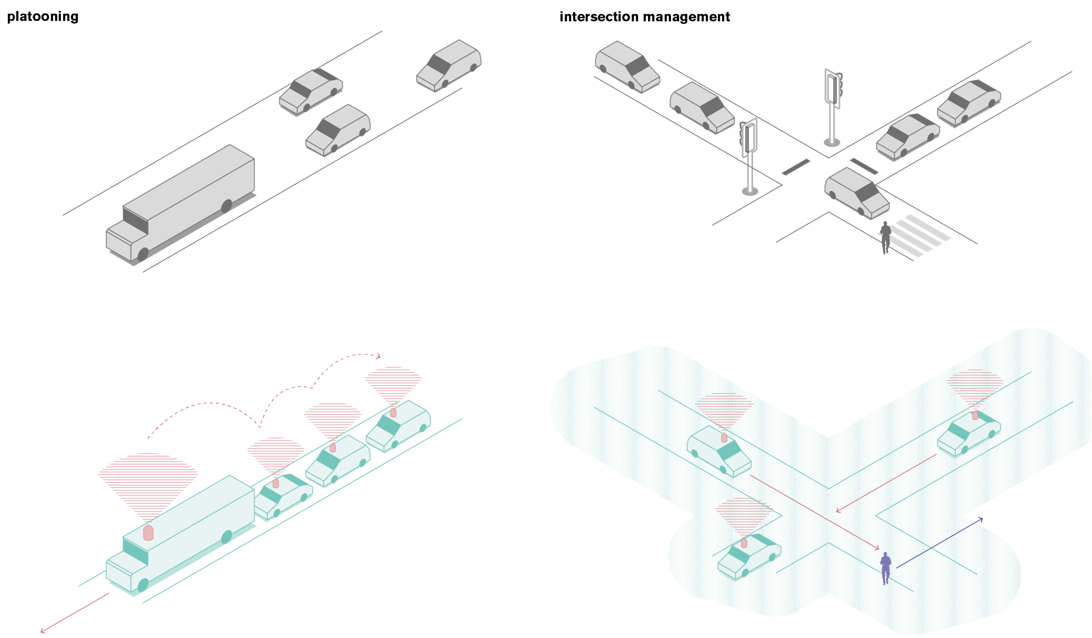


Figure 4-6: Examples of traffic efficiency improving applications are platooning or intersection management.

4.2.3 APPLICATIONS ON MACROSCOPIC LEVEL

On a system level, automated driving can prove beneficial in terms of new mobility concepts as ride-sharing or different public transport solutions. Also in terms of dynamic network wide traffic management, opportunities arise.

The advantages of automated vehicles are often propagated together with the possibilities of sharing vehicles. With higher automation levels, no driver is needed and therefore vehicles should be able to pick-up passengers on various locations. And in case of a driver at the wheel, communication technologies enable for better match between supply and demand of transit options or ride-sharing. A shared autonomous car fleet is a system of vehicles that cooperates to serve passenger transport in the most efficient way with a high level of service. Studies on shared autonomous car fleets considered these car fleets as a replacement for private transport or as a hybrid form between public and private transportation. Some studies examine the potential of automated vehicle as a mean enhance public transport. The first and last mile in public transport trip chains often take of a large portion of the travel time, while the distances covered is relatively low (Snellen, Nabielek, Hilbers, & Hamers, 2014, p. 21). Demand responsive automated vehicles could provide first or last mile transportation to make public transport trips more efficient and attractive (Townsend, 2014, p. 41). The study by Scheltes, Yap, and van Oort (2016) found the willingness for travellers to use such a system high and found that a personal rapid transit system can greatly reduce travel time. Ohnemus and Perl (2016) particularly reveal the potential of shared autonomous vehicles for first and last mile solutions in low-density areas where it proves for challenges to provide for profitable public transport solutions these days.

An application that is slightly underexposed within literature is the allowance for network-wide traffic coordination. Today, attempts are made to distribute traffic in a more efficient way over the network. This application relies often on real-time traffic data and travel demand which then must be processed and communicated to the road user. Increased connectivity of vehicle with the possibility to advice or even direct routes to road-users can allow for more efficient – or even system optimum – use of the network.

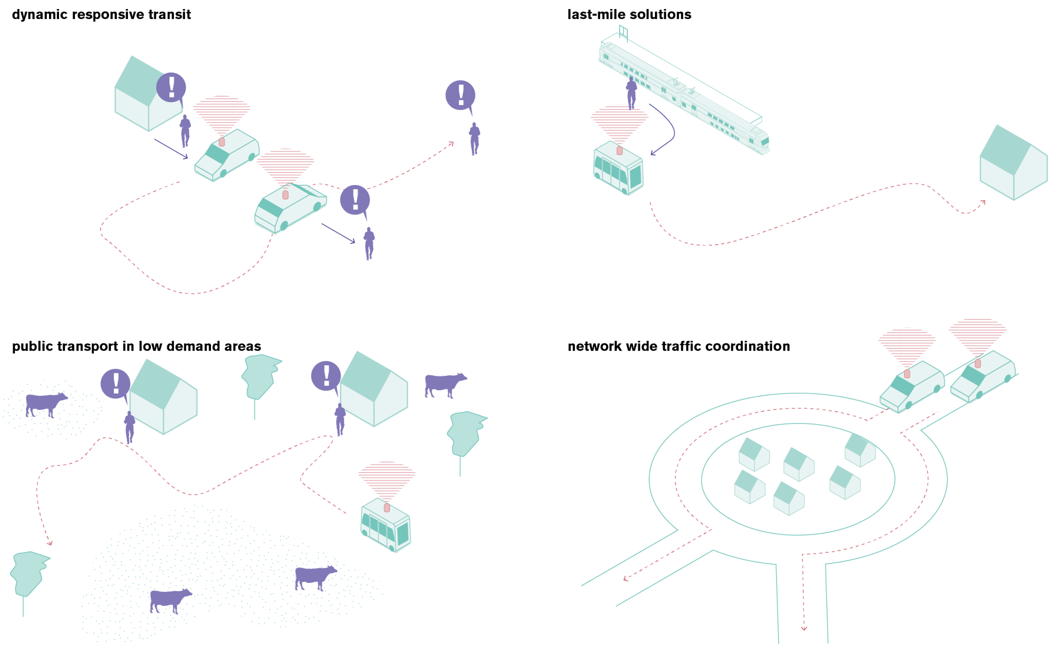


Figure 4-7: Applications on transportation network level.

4.3 IMPLICATIONS

Automated driving as a technology has potential to revolutionise the driving task but also enables new applications of mobility. Many studies investigate the various implications of these developments.

4.3.1 INFRASTRUCTURE CAPACITY

In terms of infrastructure capacity, prior paragraph identifies gains in the realm of roads and intersections. The effects of vehicle automation on infrastructure capacity is one of the most studied aspects regarding vehicle automation. It is important to state that many of these studies are based on computer simulation methods and study the highway capacity changes by car following or platooning models. With studies on infrastructure capacity, considerations need to be made regarding the theoretical nature of these studies: heterogeneity in highway design, flow direction vehicle type and in some cases even lane change behaviour are often not considered. One can argue to what extent these high capacities are realistic. Therefore, it is better to interpret these studies as illustrations of the optimal potentials of automated driving. This conception is supported by the expert group from the study by Milakis, Snelder, van Arem, van Wee, and Correia (2017) who are much more reserved in their assumption on increase in road capacity compared to the theoretical simulation studies.

<u>Ex-urban infrastructure</u>

Several researches study the potential increase in road capacity (especially in the domain of highways) that vehicle automation can trigger. Although these researches elaborate mostly on highways, these are considered as ex-urban infrastructure - roads with few to none intersections.

Today, the theoretical capacity of a highway lane is estimated around 1800 vehicles per hour per lane under the assumption of a headway of two seconds between each vehicle. In practice, these high capacities are rarely obtained because of traffic instability. Shladover, Su, and Lu (2012) showed a road capacity of 4000 veh/h/lane on the highway with a 100 percent penetration rate of CACC. Tientrakool, Ho, and Maxemchuk (2011) estimate an increase in highway capacity of 43 percent with a 100 percent penetration rate of ACC, and with CACC an increase of even 273%. Other studies have not only evaluated the impact of (C)ACC-system, but also proposed new algorithms to enhance efficiency on the motorway. These studies show even higher theoretical capacities of 6400 veh/h on a lane (Rajamani & Shladover, 2001) to 7200 veh/h on a lane (Fernandes & Nunes, 2015, p. 1186). Friedrich (2016) is more reserved, projecting an increase on ex-urban roads of 80%. Furthermore, the chances for congestion would reduce significantly because of better traffic management, leading to better usage of the road and more stable traffic flows by higher vehicle densities on the road (Hoogendoorn, van Arem, & Hoogendoorn, 2014, p. 118). This is also found in the study by Ngoduy (2013).

The prior mentioned computer simulation studies on road capacity show very high increases in road capacity. The expert in from the study by Milakis et al. (2017) predicts capacity gains ranging from five to 25%, which is significantly lower. Therefore, one should argue whether the theoretically derived highways capacities will ever be achieved. In that context, also human preference should be considered. Lewis-Evans, De Waard, and Brookhuis (2010) state that is not sure if human passengers are willing to accept shorter headways.

Intersections and urban roads

Urban roads and intersections are simultaneously elaborated on because they are very much related. The urban road network often comprises many intersections.

Not only on highways, automated vehicles can enable for higher capacities, also on intersections, automated vehicles can enhance traffic efficiency by means of V2V communication. MIT Senseable City Lab (2014) even illustrates that future intersections might work without traffic lights: vehicles from various direction can cross the conflicts zones without collisions and speed of approaching traffic can be adjusted to control the traffic demand, reducing queuing in front of the intersection. The latter is already applied in some dynamically controlled intersections. This concept has also been studied in terms of impact of (C)ACC-systems on intersection efficiency. Dresner and Stone (2008, p. 621) developed a mechanism that could achieve near zero delays. Similar results are found in studies by Gregoire and Frazzoli (2016), Clement, Taylor, and Yue (2004), Zohdy, Kamalanathsharma, and Rakha (2012, p. 1109) ("Savings in delay … range of 91 … percent relative to conventional signal control were demonstrated") and Kamal, Imura, Hayakawa, Ohata, and Aihara (2015, p. 1146) ("the stop delay of vehicles at the intersection is almost eliminated").

Few scholars explicitly make statements about capacity increases on urban roads. Among these scholars is Friedrich (2016) predicting a 40% increase which is half of his prediction on extra-urban roads. The expert panel in Milakis et al. (2017) predicts an increase between 2% and 6% depending on the scenario.

4.3.2 TRAVEL COST FACTORS

Travel has various cost factors. For the user, these factors can be classified as follows:

1. Costs that are directly related to expenses and need to be paid either directly as a fee, delayed (paying for gas) or through taxes.
2. Costs that do not have monetised manifestation, but are perceived through comfort, travel time etc. In transport modelling, this component is often expressed as value of time.

Parking fees

One of the cost factors for driving an automobile relates to parking costs. This cost is not only comprised of the fee, but also of the availability of parking places and the proximity of these parking places to the destination. No research is found on the specific cost component of parking and automated driving, but new parking concepts are mentioned such as valet-parking or idle driving instead of parking. This can have a significant impact on the parking price and therefore and the travel cost. However, since parking is also a matter of spatial integration, this will be elaborated on later in this section.

Value of time

When drivers can perform other tasks while in transit, this can further increase the utility of travel. Therefore, value of time is an important concept to make assumptions on future vehicle usage. No research has found conclusions on how to quantify value of time changes with higher levels of automations. For this reason, assumptions or scenarios have been made for value of time assumptions within research. Gucwa (2014) uses value of time scenarios with the value of high quality rail, half of current car value of time, and a zero-cost value of time for automated vehicles to study the impacts on mobility and energy impacts. These assumptions are therefore merely a mean to cope with the uncertainty rather than that it proves for a valid estimation. Childress et al. (2015) take on a similar approach assuming for reductions of 0% and 35%. The expert panel by Milakis et al. (2017) find a reduction of value of time between 2% and 41%. Studies by Cyganski et al. (2014); Pfleging, Rang, and Broy (2016) and Memon et al. (2016) make no quantitative statement of value of time reduction, but find that people would mostly relax in an automated vehicle rather than work.

4.3.3 CAR FLEET

The effect of sharing on the required car fleet to serve travel demand is examined in a few studies (Figure 4-8). Santi et al. (2014) studied the benefits of a vehicle pooling system in Manhattan, New York City. They concluded that the vehicle kilometres travelled by these taxis could reduce by 40% through a taxi sharing platform. Spieser et al. (2014) concluded that with a fleet of shared automated vehicles one third of the actual fleet size could provide the travel needs of the population of Singapore. Another study for International Transport Forum (2015), concluded by means of an agent-based taxi-bot modelling study for the city of Lisbon that mobility demand could be served with 10% of the current vehicle fleet. A similar conclusion was drawn by Boesch, Ciari, and Axhausen (2016): Fleet size reduction of up to 90% if waiting times up to 10 minutes were accepted for a case study of Zürich. Another agent-based modelling study, by Fagnant and Kockelman (2014), found a similar conclusion by a case study on a hypothetical grid network that one shared automated vehicle can replace eleven conventional cars.

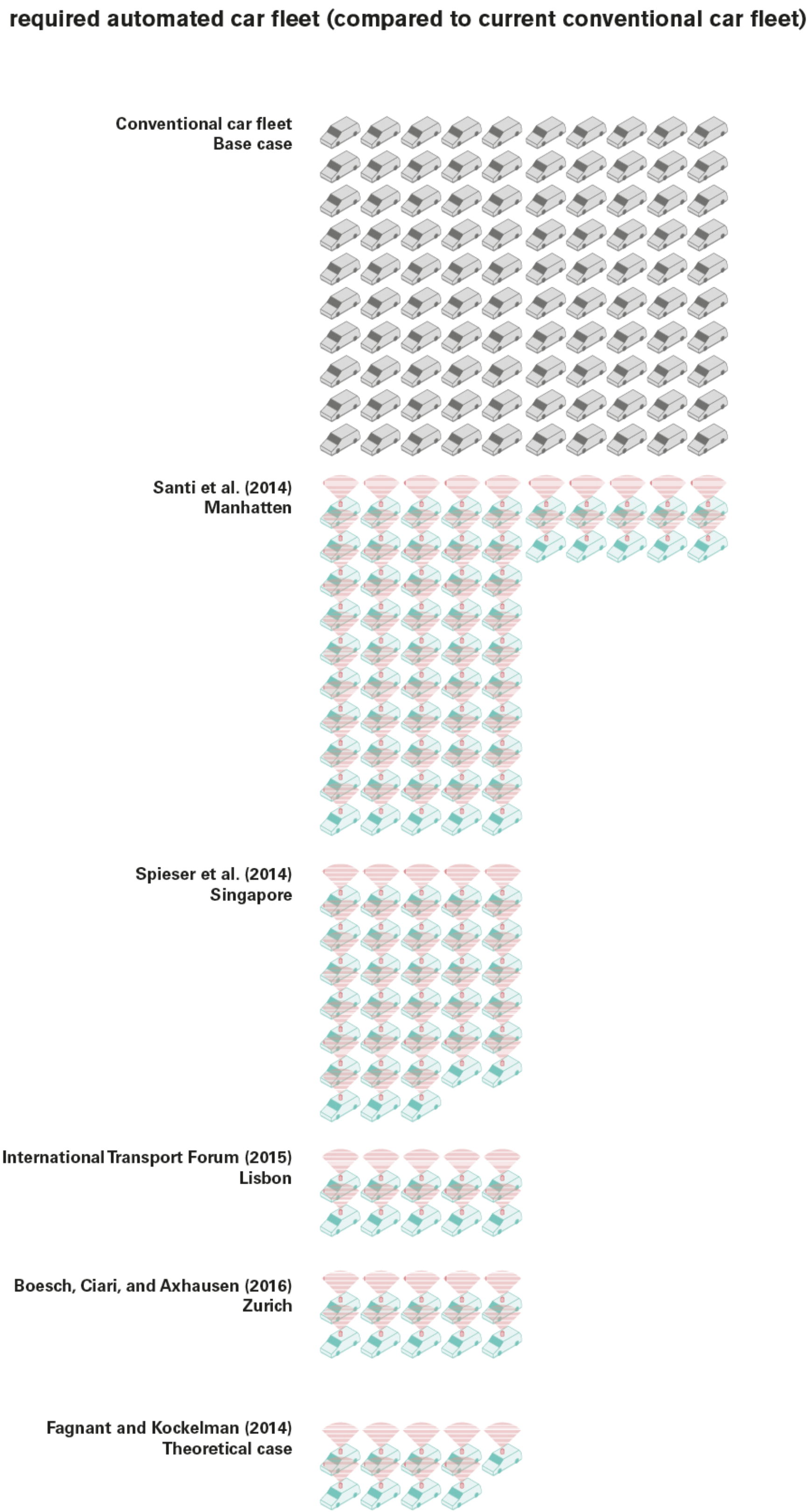


Figure 4-8: Estimated required fleet of automated taxis found in different studies to serve similar mobility levels compared to conventional car fleets.

4.3.4 TRAVEL DEMAND AND BEHAVIOUR

Vehicle automation can cause that vehicle use will rise. This change is often expressed in an increase/decrease in vehicle kilometres travelled (VKT - or in vehicle miles travelled (VMT) in the Anglosphere). Following reasons exist to contribute to this potential rise of distance crossed by vehicles.

- Induced travel demand caused by empty vehicle allocation rides.
- Induced travel demand caused by vehicle access of new user groups
- Induced travel demand caused by lower travel costs and increased comfort

Relocating of automated cars to pick up other passengers might result in an increase of travel. Fagnant and Kockelman (2014, p. 12) estimate this increase in travel to 11% in a theoretical network and 8% in a real situation case study (Fagnant, Kockelman, & Bansal, 2015). Correia and van Arem (2016) examine the impact of privately owned fully automated vehicles and value of time decrease in relation to different parking policies. This study does not take potential infrastructure capacity gains into account.

Another reason for increase in VKT can be expected from additional groups of users whom before had no access to using a vehicle; elderly, people with reduced mobility or children. Harper, Hendrickson, Mangones, and Samaras (2016, p. 8) estimate that access to automated vehicles for these user groups can lead to an additional 14% increase in travel (full automation/just access so not necessarily shared). Sivak and Schoettle (2015) come to 11% (privately owned/full automation/no change in travel pattern) and Wadud, MacKenzie, and Leiby (2016) to an increase between 2% and 10%.

Increased travel comfort can also lead to an increased number of trips made by cars, or an increase in distance travelled by cars. This effect has been examined in a number of studies, often under various scenarios, because there is no concise image of how travel costs or comfort will change. Childress et al. (2015, p. 102) found changes for respectively 3.6%, 5%, 19.6% and -35.4% under various scenarios. In the prior three scenarios, automated vehicles are either partly or fully employed, while value of time is either similar, lower for certain or for all trip purposes. In the last scenario, all costs are passed on to the user. This explains the decrease in VKT. Fagnant and Kockelman (2015) conclude a 26% VKT increase by 90% penetration system wide automated vehicles. Gucwa (2014) estimates an 4% to 8 % increase. According to the simulation study by the International Transport Forum (2015), an increase of VKT could be of 6.4% up to 44.3% if self-driving cars do not substitute public transport. In case ride sharing or car sharing systems would take over mass transit, this increase would range from 22.4% to 50.9%.

4.3.5 INFRASTRUCTURE SPACE REQUIREMENTS

Efficient use of vehicles and roads could drastically reduce the need for infrastructure or the number of vehicles on the road. Consequently also the spatial demand for infrastructure can decrease. Ambühl, Ciari, and Menendez (2016) performed a microsimulation study on a grid network and concluded that for automated vehicles 11-12% less infrastructure could facilitate a similar number of trips with conventional vehicle thanks to higher flows with similar densities (Figure 4-9). This reduction emerges from a change in car following models used in the simulation study. This means that equal flows with higher vehicle densities can be obtained. They did not consider induced demand factors caused by automated vehicles.

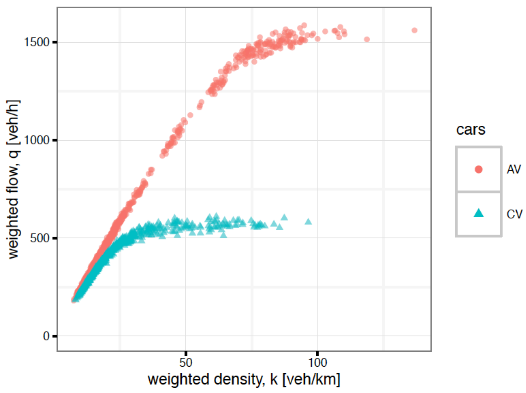


Figure 4-9: Network macroscopic fundamental diagram for automated vehicles (AV) and conventional vehicles (CV) (Ambühl et al., 2016, p. 5).

4.3.6 PARKING SPACE REQUIREMENTS

The International Transport Forum (2015, pp. 25-26) studied the impact of automated vehicles for ride sharing or automated taxis on parking spaces. Depending on the scenario that was studied, the need for parking spaces even slightly increased or decreased by maximum 24% in case of 50% of the vehicle fleet being automated, but reduce between 89-93%with all vehicles as automated vehicles. This effect as studied by the International Transport Forum (2015) can be assigned to more efficient use of vehicles. A similar study by Wenwen Zhang, Guhathakurta, Fang, and Zhang (2015) finds a reduction of 90% with a shared automated vehicle system.

The auto pilot option speaks to imagination for new ideas on parking. Today, the location is an important element in door-to-door trips and therefore, parking facilities and policies have their impact on travel behaviour (Christiansen, Engebretsen, Fearnley, & Usterud Hanssen, 2017). Naturally, one would like to park the vehicle in proximity of its origin or destination. A popular statement is that vehicles are idle most of the time and that parking is a waste of public space (Gehl, 2001). In that respect autopilot systems could provide for valet-like parking solutions (Sun, Gladstone, & Taplin, 2016, p. 8; Townsend, 2014, p. 18), where vehicles drive themselves to designated parking locations elsewhere, for instance in the periphery. Zakharenko (2016) studies the phenomenon of designated parking areas in archetypical American cities for automated vehicle from an urban economics perspective and finds that parking will shift towards the periphery allowing for increase of density and economic activity within city centres. Another solution possible involves vehicles driving endlessly on the (ring) road to avoid parking fees (Townsend, 2014, p. 27). These solutions could have a positive impact on public spaces, but can lead to an increase in vehicle kilometres.

4.3.7 ROAD AND STREET DESIGN

The design of roads and street is covered very limited within scientific research. However, within the urban design practice, it is the most covered aspect. Examples of such studies are described by Wilson (2016) (Figure 4-10) or by EXCEPT (2017) (Figure 4-11). These designs do not have a scientific basis and do not take into consideration the current challenges and uncertainties around vehicle automation. Instead, these visions are illustrations of the potentials automated vehicles can have in a positive sense on urban spaces.

Figure 4-10: Vision by studio Pensa how automated vehicles could help transform sidewalks (Wilson, 2016).

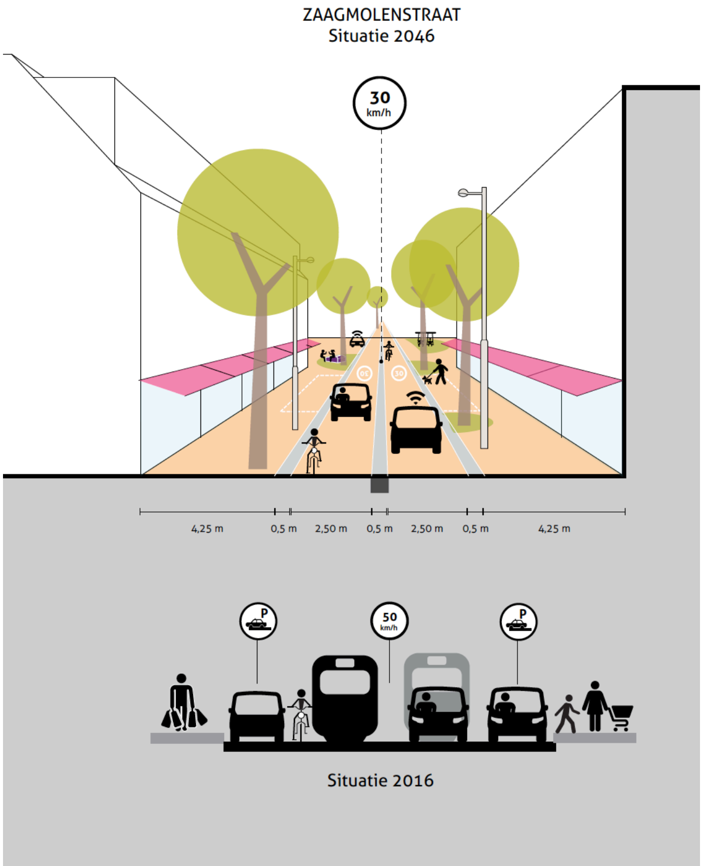


Figure 4-11: Redesign for a street in Rotterdam for a future situation with self-driving cars (EXCEPT, 2017, p. 27).

4.4 DEPLOYMENT FACTORS

The Hype Cycle for Emerging Technologies by market research organisation Gartner (2016) helps to evaluate statements of the possible effects of automated driving. The cycle describes the so-called hype cycle an emergent technology goes through before it establishes itself. Often there is a phase of high expectations. ccording to Gartner (2016) autonomous vehicles are just past the highest point of expectancies (Figure 4-12). If one follows the negative press of the past year on automated driving, this statement has indications to be valid. Following the hype cycle, one must conclude that expectations of automated driving are today higher than what this technology eventually might bring to the future.

How automated driving will develop is far from clear. It is not even sure if automated driving will become a mainstream technology. It is relevant to examine the factors that are of influence on the development of automated driving. Not all statements on automated driving that are made today will become truth and many potential problems are ahead before the technology can establish itself in the socio-technical regime. In this section, the factors related to the uncertainty around automated driving development and means scholars cope with this are examined.

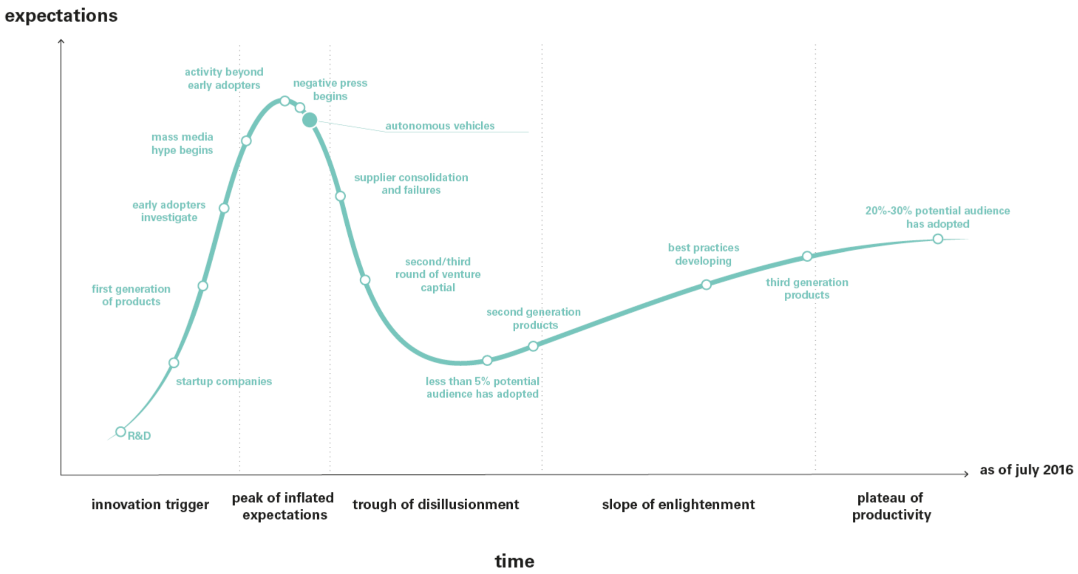


Figure 4-12: According to Gartner (2016), autonomous vehicles are just past the highest point of expectations, but still in the phase of inflated expectations (adapted from Gartner (2016)).

Scenario analyses are a popular tool to assess the uncertainty of future consequences of a decision or development (Peterson, Cumming, & Carpenter, 2003, p. 358) and provide a comprehensible framework for planning future actions (Schoemaker, 1995, p. 26). It is no surprise that scenario studies are conducted around the future of vehicle automation. Although the purpose of these studies vary, scenario studies provide for a listing of key uncertainties and basic trends (Schoemaker, 1995, p. 28).

How and if automated driving will prove disruptive for the transportation and the built environment depends on many factors. By evaluating existing scenarios (Table 4-1) of automated driving, constructed by scholars and institutions, most prominent uncertainty variables are found to be:

1. Technological development
2. Spatial deployment
3. Vehicle ownership and sharing
4. Social acceptance and behaviour
5. Policies and actor involvement

Table 4-1: Scenario analysis regarding automated vehicles and future mobility.

Publication	Scope	Variables	Scenario themes
Tillema et al. (2015)	Scenarios for future traffic and transport system involving self-driving vehicles	Degree of sharing, degree of automation	(1) Multimodal and shared automation, (2) Mobility as a service, (3) Letting go on the highways, (4) Fully automated private luxury
Gruel and Stanfort (2015)	Scenarios for a future mobility system with automated vehicles	Behaviour, Technology	(1) Technology changes, but we don't, (2) New technology drives new behaviour, (3) New technology drives new ownership models
Milakis et al. (2017)	Development of automated vehicles in the Netherlands	Technology, policies	Automated vehicles …(1) in standby, (2) in bloom, (3) in demand, (4) in doubt
Fraedrich, Beiker, and Lenz (2015)	Evolution of the automobile, deployment scenarios for fully automated driving	Technology, usage and business models	(1) evolution of driver assistance (2) revolution of automobile usage (3) transformation of personal mobility
Wadud et al. (2016)	Travel and energy impacts of automated driving	Technology and transportation system development	(1) Have our cake & eat it too, (2) Stuck in the middle at level 2, (3) Strong responses, (4) Dystopian nightmare
Townsend (2014)	Examination how automated driving impacts mobility and mobility concepts	Technology and transportation system development	(1) Growth, (2) Collapse, (3) Constraint, (4) Transformation
Childress et al. (2015)	Impact on travel and network performance	Capacity, Value of time, parking costs, travel cost	-

These scenarios all comprise either partly of fully the aspect of technological development. Other factors are for instance related to behaviour and sharing of rides and vehicles, the role of actors such as the government or commercial parties or social acceptance.

4.4.1 TECHNOLOGICAL DEVELOPMENT

When and in which form, automated vehicles will enter the market is very diffused. The pattern that emerges in Figure 4-13 reveals that there is especially a lack of consensus between various levels of expertise. It is no surprise that car development and manufacturing companies are most optimistic, potentially because of their interest in attracting investors. And (governmental) expectations regard a level of optimism in the development of driverless vehicles. Scholars predict the diffusion of automated vehicles far in the future, often by stating the difficulties regarding implementation. Consultancy firms take on an intermediate position in future predictions. An important aspect to mention is that also the level of predictions differs. Some predictions only specify that automated vehicles are expected in a certain time range, whereas other predictions elaborate on specific levels of automation under various scenarios.

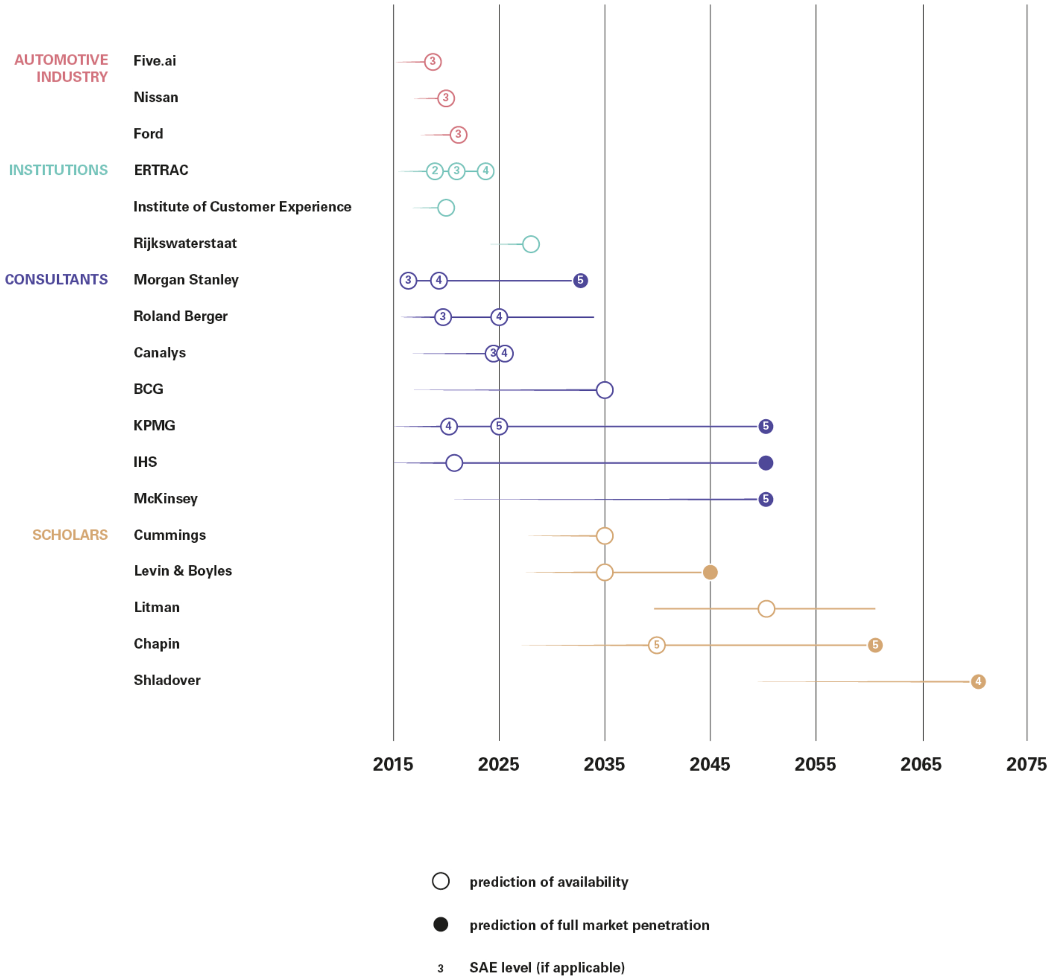


Figure 4-13: Predictions by various fields of expertise on the diffusion of automated vehicles (data derived from Alkin (2016); Bernhart et al. (2014); Bertoncello and Wee (2015); Chapin et al. (2016); ERTRAC Task Force (2015); Institute for Customer Exerience (2016); KPMG (2015); Krabbendam (2016); Levin and Boyles (2015); Litman (2014); Murphy (2016); Nissan USA (2017); Shanker et al. (2013); Shladover (2016); van der Aa (2016); Wong (2016))

4.4.2 SPATIAL DEPLOYMENT

One of the obstacles related to automated vehicles is deployment in space and time. Automated driving will not become omnipresent in an instance. Today, driverless vehicles only operate in very defined (often campus-like) areas. Mixing automated vehicles with conventional vehicles might prove for challenges, which leads to solutions as allowing automated driving only in specific areas, specific highways or specific lanes (Figure 4-14).

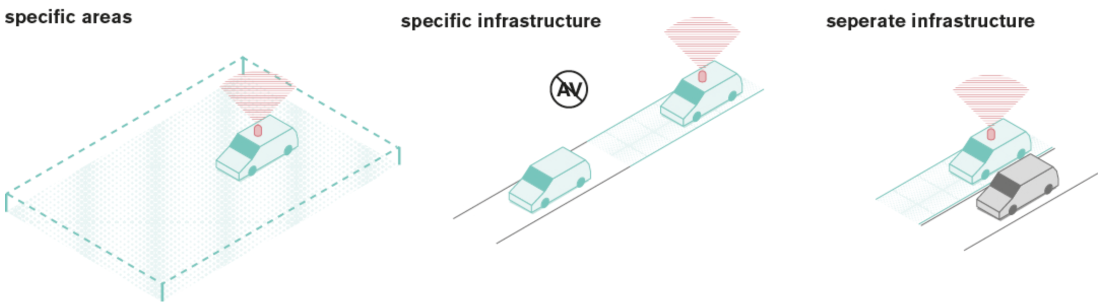


Figure 4-14: Intermediate solutions to allow automated driving in space before automated driving is allowed everywhere.

With this comes the obstacle of potential infrastructure and road network adaptations needed to employ autonomous driving. Another obstacle considered should be the availability of maps that can be read by autonomous vehicles. Not only sensory technology is a mean for a car to understand its environment, also map data can help in this matter. Efforts might be required to obtain map data for areas to allow for self-driving cars.

4.4.3 VEHICLE OWNERSHIP AND SHARING

One of the most optimistic views regarding vehicle automation relates to the potential of car-sharing or ridesharing. As references listed in section 4.2.3, the effects on vehicle fleet, traffic efficiency and parking requirements can be very significant when people give up private car ownership and use collective or shared ride or vehicle sharing services instead. However, one must consider that private car ownership has many benefits to people and is not only a transportation mean. Cars are also a mean of personal expression. So, both in terms of comfort and convenience as well as regarding status the question must be asked if people are willing to give up their private vehicle. Additionally, what role is the conventional car manufacturing industry taking in this matter. Today, it is in their interest to sell as much cars as possible.

4.4.4 SOCIAL ACCEPTANCE AND BEHAVIOUR

Several societal concerns can be of great influence of the deployment and adaptation of automated driving within society. A frequently mentioned aspect relates to the ethical case of the trolley problem. The study of Bonnefon, Shariff, and Rahwan (2016, p. 1573) finds that the participants in their study “approved for utilitarian automated vehicles (that is, AVs that sacrifice their passengers for the greater good) and would like others to buy them, but they would themselves prefer to ride in AVs that protect their passengers at all costs”. This is a very delicate issue, and might prove for challenges in the acceptance of automated driving. Other ethical and liability aspects relate to e.g.:

- The potential misuse of automated cars for attacks (Douma & Palodichuk, 2012, pp. 1168-1169).
- Or for the potential loss of jobs for people within the transportation industry (Barnhizer, 2016), which could be a driver for societal discourse.
- How well privacy concerns are covered (Glancy, 2012, p. 1239).

Not only vehicle automation in relation to society itself proves for challenges. Behavioural aspects related to being in a self-driving car knows potential obstacles too. Potentially, this could undermine the effect of automated driving on traffic significantly. Take for instance the case of driving comfort. Lewis-Evans et al. (2010) find constraints in time headway between vehicles related to comfort and to threshold awareness for the case of human driver intervention. Diels, Bos, Hottelart, and Reilhac (2016) state that motion sickness will be of a greater concern the more automated vehicles become. In that sense, the impact on traffic efficiency might even reduce as was mentioned in section 4.3.1 by citing Le Vine, Zolfaghari, and Polak (2015) on intersection capacity. König and Neumayr (2017) identify the knowledge gap regarding potential barriers of users towards self-driving cars and state the importance of keeping the end-users needs and opinions into account.

4.4.5 ACTORS

For past 50 years, the transportation system has been developed by the public sector. In the Netherlands, the national government has played an active role in the development of the national highway system, as well as in the development of the rail network. In terms of traffic management, one can observe a shift. Whereas in the past centralised institutions managed traffic flows, one can observe that by the increase of news services and navigation services private companies are providing travellers with traffic data.

What role public and private sectors will take within the development of automated vehicles is not clear. On the one hand, national governments of e.g. the Netherlands have set up programmes to stimulate the development of automated vehicles but in cooperation with the private sector (Schultz van Haegen, 2015). Today, the private sector is a strong driving force (Townsend, 2014, p. 3). The development of automated driving is not only triggered by research of conventional car manufacturers, but also by so-called start-ups and tech-companies (Fraedrich et al., 2015).

There is consensus among scholars that – even though it is unclear who takes the leading role in the development and deployment of vehicle automation – that governments needs to define supportive policies subsequently with other researching and planning efforts related to vehicle automation (Smith, 2012, p. 1142).

4.5 CONCLUSIONS

Examination of the wide range of literature and ideas related to vehicle automation reveals that the applications of automated driving technology (of which here the mainstream applications are considered) can have very significant implications on travel comfort, efficiency and costs and on the physical and the immaterial layout of the transportation system (Figure 4-15). However, groping the impact of automated driving still proves very difficult for three reasons:

- The interrelation of the applications and implications of automated driving causes many interrelated dynamics.
- A widespread range of predictions (under various assumptions and conditions) exist on implications of automated driving. To illustrate this statement, all literature listed Section 4.2 and 4.3 making a quantitative statement are plotted in Figure 4-16.
- Technological development is not the only uncertainty factor in the establishment of automated driving within society and might prove not to the most determinant factor in the first place.

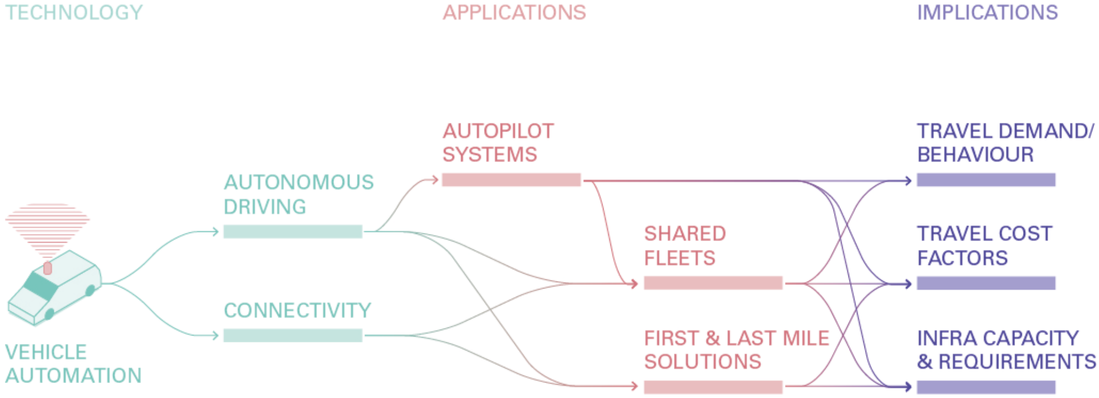


Figure 4-15: Automated driving as a technology has various applications which in turn have implications on travel behaviour, comfort and infrastructure requirements.

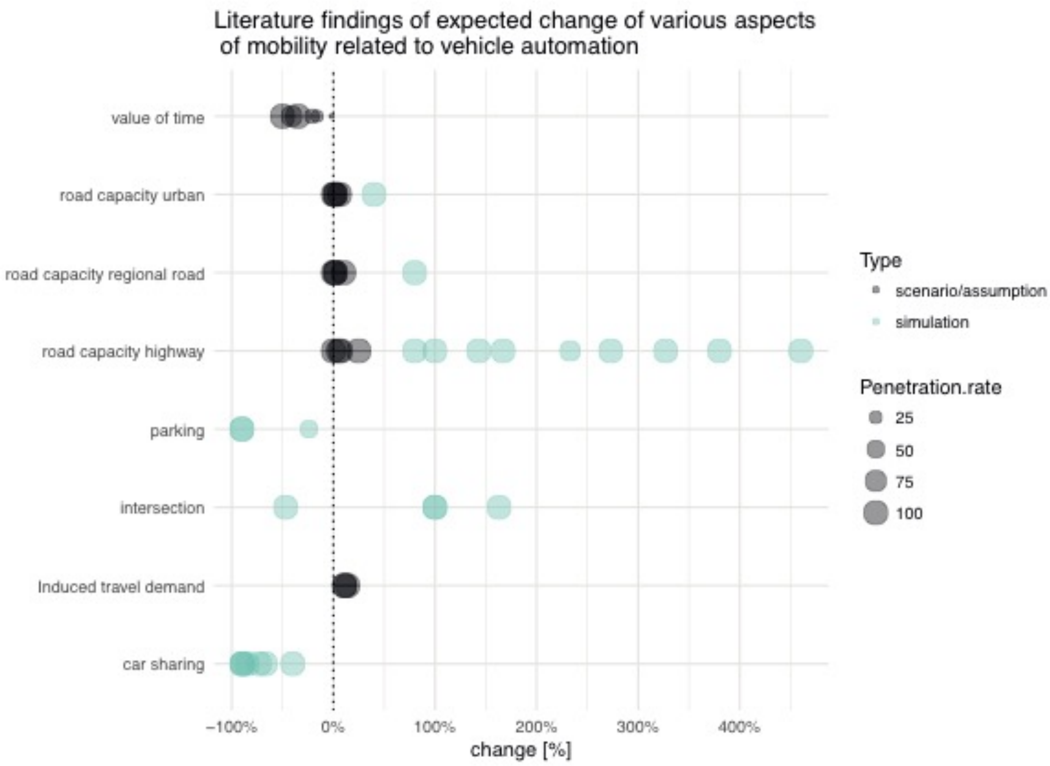


Figure 4-16: Quantitative statements found in the literature review on the impacts of automated vehicles on various aspects related to mobility and the transportation network.

How automated driving starting from a technology is eventually connected to urban development is the relevant question for this research. Through the examination of the implications in this research, the following dynamics reveal:

- Vehicle automation can have a significant impact on accessibility by reducing the generalised travel cost. This reduction is triggered by increased travel comfort (by taking over the driving task), reduced travel time _triggered by traffic efficiency and stability) and through vehicle access to potential new user groups.
- Changes in travel demand and in efficient use of infrastructure and vehicles can have significant changes in the requirements of the road network. New

applications of vehicles require specific interventions, e.g. for the application of valet-parking systems. And more efficient use of infrastructure might require for less infrastructure. This can pave the way for new urban functions.

For the case of the spatial impacts of automated driving, supporting the notion that the built environment is complex in its context and as a system is very important because this technological innovation can be potentially be disruptive on both aspects. This means that urban spaces can be designed differently with more regards to other urban functions and interests. Regarding system complexity, the impact relates to urban development. Advances in transportation technology in the past effected the built environment and drove changes in spatial development by changes in accessibility. The context as well as the system are not two closed systems, but by themselves integrated as well.

Understanding how accessibility changes affect urban development can be explained with the land-use transportation feedback cycle by Wegener and Fürst (1999), which was introduced in section 3.2. But land-use is also dependant on the externalities of infrastructure, hence the integration of the transport system must be added in the feedback cycle (Figure 4-17). If and how automated driving will establish itself within society is unclear. This makes it hard to predict what the effects of automated driving are on accessibility and spatial quality and therefore also on urban development.

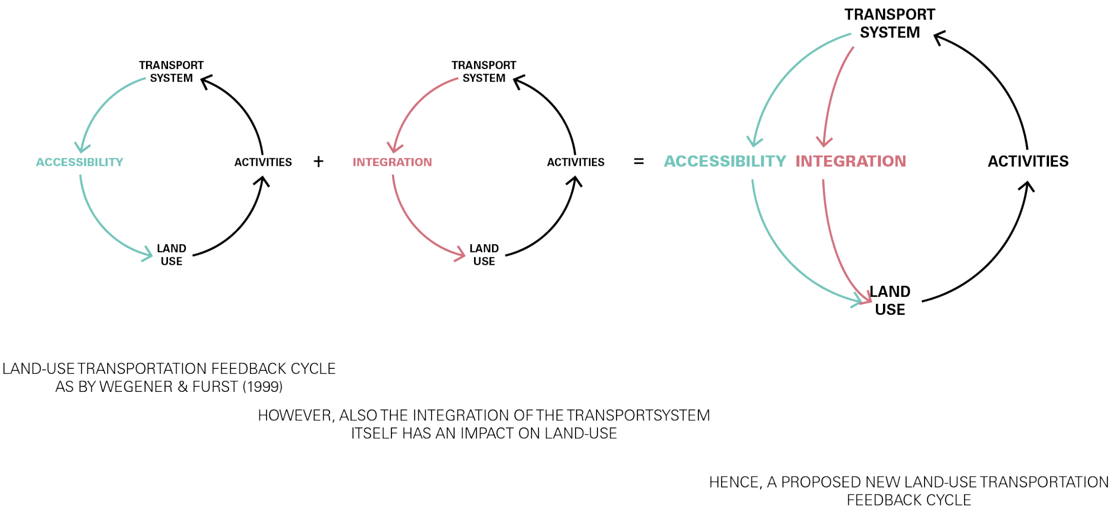


Figure 4-17: Transportation innovations not only influence land use by means of accessibility. Integration of the transportation system is a determinant. Therefore, the land-use transportation feedback cycle is augmented to a new feedback cycle.

By defining problem as above, it reveals that this problem cannot be addressed from one perspective only. It is not only a matter of filling knowledge gaps. Since it is an urban planning problem, values and the desire to employ automated driving for more sustainable cities are very relevant. Both (urban) designers and (transport) engineers can play an important role in finding answers how automated driving can affect the built environment.

PART II. METHODOLOGY AND APPLICATION

5 RESEACH SET-UP

This research investigates how quantitative models in urban planning problems can contribute to research and design processes through the case of automated driving. Distinct for this urban planning research is that it is primarily focused on filling knowledge gaps and not on solving a problem for a specific context (the latter is more common in design-based exercises). The first part of this report explains how computational urban models can help obtain understanding urban development by supporting the cognitive research act. To investigate the spatial impacts of automated driving from the perspective of cities as complex systems, a computational urban model takes an important position in the understanding of the structural changes that will manifest within the urban system.

To assess the disruptive character of automated driving, it is not sufficient to merely assess the integration of infrastructure and travel behaviour within the built environment. Instead, a system-wide urban development perspective is crucial. Using quantitative methods provided by the engineering disciplines in combination with the contextual perspective of designers, gives a comprehensive framework to assess complex urban problem from a holistic perspective.

In this chapter, the design of the methodology outlines the integrated method to assess the spatial impacts of automated driving. The purpose of the methodology is to provide understanding how automated vehicles will change cities. The primary purpose is therefore to fill a knowledge gap. The research process allows for a case study by which the main research question, which relates to an integrated methodology, can be answered.

Chapter 3 revealed that for understanding of urban planning problems with the help of computational models, one must define the system clearly. The first section explains how automated driving connects to urban development through the problem entity and elaborates on the research goals and requirements. Urban planning problems are strongly influenced by the specifics of the context and location and therefore section 5.2 introduces the case study and explains how a scenario approach grapples the uncertainty around vehicle automation. Section 5.3 and section 5.4 explain derive the necessary research steps and the means for interpretation of these results.

5.1 RESEARCH OUTLINE

By defining the problem entity, the most important research steps outline.

5.1.1 PROBLEM ENTITIY

The main purpose of defining the problem entity is describing how the innovation of vehicle automation is related to urban change (Figure 5-1). Chapter 3 identified choice behaviour of decision makers (e.g. households, firms) as main driving force in urban development processes. However, policies and design interventions cannot be neglected in the framework of interrelations. Policies and interventions are the primary tools to steer urban development. Their role is to respond to emergent urban developments.

Urban environments house different decision makers but chapter 3 defined the residential location choice as one of the main driving forces in urban development. The residential location choice depends on generally four factors: characteristics of the dwelling, characteristics of the neighbourhood, characteristics of the location and characteristics of the decision maker, in this case a household or people within a household. These factors by which households make their decisions are influenced by behaviour of other decision makers, external factors as e.g. economic development or policies/design interventions but therefore also by technological innovations as automated vehicle technology. Chapter 4 finds that automated driving influences the importance of location through accessibility effects. And the benefits for more liveable and attractive urban spaces through efficiency gains, can make certain neighbourhoods more attractive for residence. Based on the prior rationale the problem entity for this research is depicted in Figure 5-2. I.e. automated driving impacts the built environment through accessibility effects and spatial quality gains. This in turn is of influence on the residential location choice, which is crucial in understanding urban form transformation. Car ownership can be considered a household characteristic. This factor will be evaluated within the accessibility effects and is therefore not individually considered.

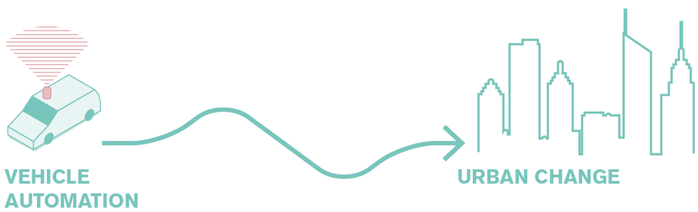


Figure 5-1: By defining the problem entity, vehicle automation is linked to the process of urban change

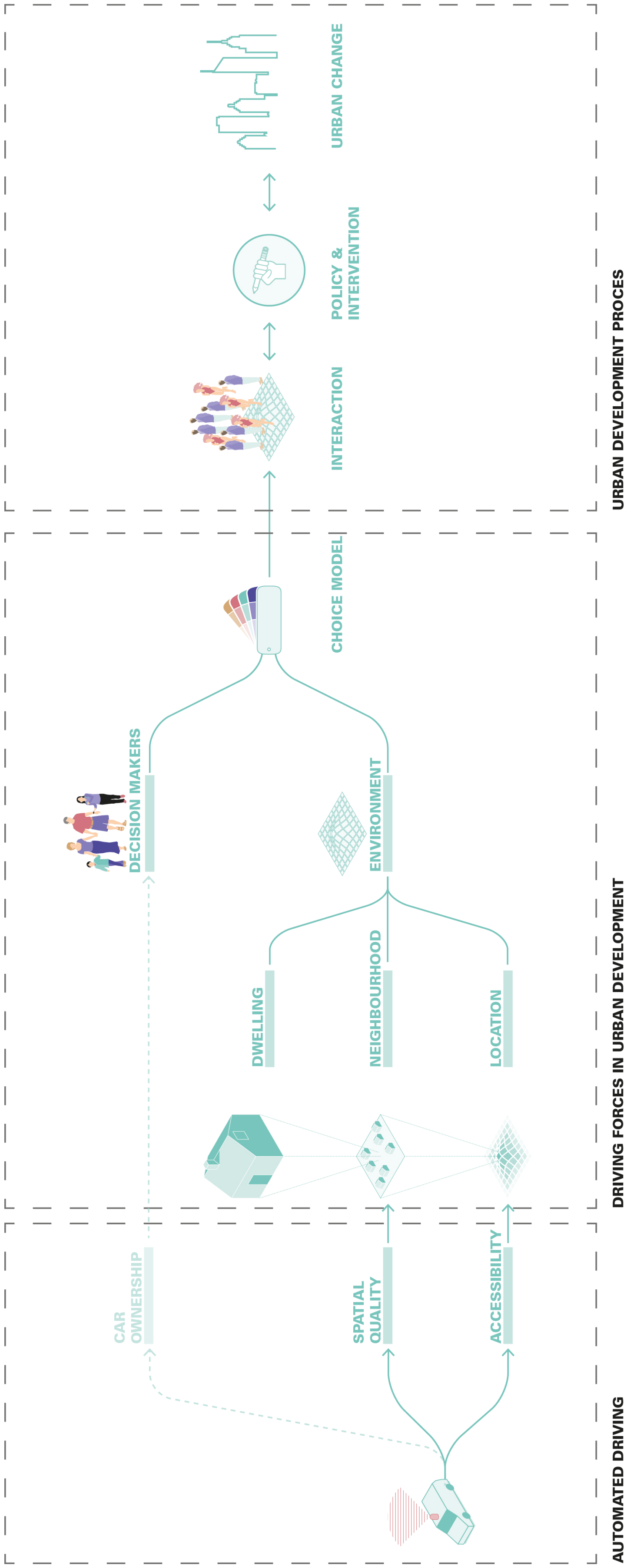


Figure 5-2: Problem entity

5.1.2 RESEARCH GOALS AND STEPS

The problem entity comprises many aspects and variables. In is not the purpose of this research to fully understand each aspect and predict the urban change to the most precise extent possible. The goal of this research is to obtain understanding in the relation between all the components of the problem entity. This allows to reveal the core principles on how automated driving drives urban development and the patterns it generates.

Based on the problem entity the necessary research steps to obtain data are the following:

- The most crucial element to process all automated driving aspects in relation to urban development is a (choice) model that evaluates the residential location choice within the spatial urban context. Within this model, the attributes by which decision makers base their behaviour are evaluated.
- For the case of automated driving some of these attributes are subject of change, hence the impact of automated driving on these attributes needs examination. The most relevant attributes are the accessibility effects and spatial quality effects. The spatial quality effects are examined with the help of a transportation model. The spatial quality effects are studied by a design exercise. Since the spatial quality benefits relate to the travel demand, the transportation model provides for input of the infrastructure requirements. The changes to the attributes can then be evaluated in the urban residential location choice model.

With the help of the prior listed research steps, the relevant aspects of automated driving are collected and processed. Based on these steps, a general understanding of automated driving dynamics on cities is established through the interaction of human decision makers. To fully comprehend the implication of these dynamics, the results must be interpreted in the broader context of urban development through interventions. The obtained data needs to be evaluated and interpreted in the physical and social domain of the urban environment. This is done by conducting a strategic framework that acts on the dynamics of the problem entity. As the spatial context is a determinant factor in this study and the external development of automated driving is uncertain, the research is put in the context of a case study with a scenario approach.

The research comprises therefore three components:

- The research context: the case study and the scenarios
- The data collection and processing phase: examination of the accessibility and spatial quality effects and the influence this has on the residential moving behaviour.
- The data evaluation and processing phase: interpretation of the dynamics in a spatial and societal context.

This leads to the research structure shown in Figure 5-3, by which the steps are executed. The research process shows that design-based research and computational modelling methodologies are combined to obtain conclusions. Within the remainder of this chapter the research steps and the interaction between the different research steps is further explained.

The data evaluation and processing phase is characterised by interpretation of the result. Therefore, this part of the research is explained in Part III: Synopsis as it concludes on the spatial impacts of automated driving.

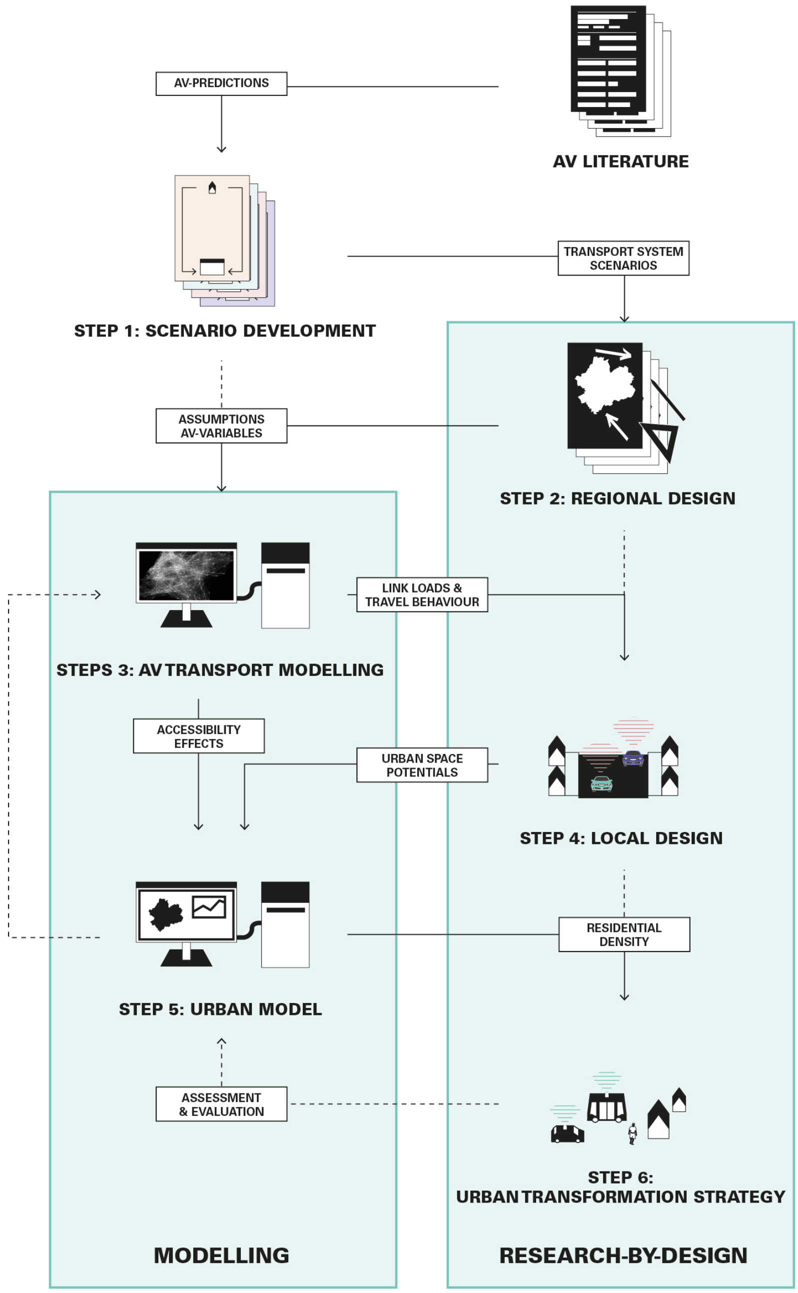


Figure 5-3: Research process

5.2 RESEARCH CONTEXT

The problem entity by itself is abstract. It is important to state that this research is conducted in a setting of uncertainty around the development and deployment of automated driving. And the research is performed from the context of the urban environment. A theoretical urban environment can be generated but this does no right to the proclaimed contextual complexity of urban planning problems as explained in chapter 2. Hence a real-world case-study is employed to provide for a real-world data source. The urban change process is driven by the development of automated driving. Scenarios are conducted to set coherent paths of development as trigger of the urban change process.

5.2.1 CASE STUDY

Context matters in this study and the question where to obtain the data from is therefore important. Especially in design-based research, the context provides for an important data source for the method to act on. But in this case, also the quantitative models depend largely on real-world data, partly because primarily knowledge of the system from empirical research is available. Therefore, this research will be applied on the region of Utrecht in the Netherlands to provide for data.

System boundary

Various definitions of the region of Utrecht exist. It is possible to define the region based on administrative border such as municipal border, COROP region (NUTS-3 region) or provincial border. Until January 1st, 2016, there was also a cooperation between several municipalities around the city of Utrecht, forming the Bestuur Regio Utrecht. Administrative borders are the process of a long historical, geographical and political development and do not necessarily represent the region as an entity. Regarding the topic of mobility, it is considered more suitable to define a region not by its administrative borders but as a daily urban system: an interdependent region based on commuting patterns and urban labour markets. An attempt has been made to obtain the boundaries of the daily urban system within the transportation model for the Utrecht region. However, this proved not feasible.

Therefore, the study area is limited to the provincial borders, which corresponds with the COROP. This coincides with the nested zonal structure of the residential location choice model used in this study and introduced later in subsection 5.3.1

Spatial resolution

Another important question is to what scale level this study is set to limit itself. Scholars write about the possibilities of smaller scale high spatial resolution urban modelling because of advances in geospatial data (Batty, 2000; Spiekermann & Wegener, 1999). And in terms of spatial design, it makes sense to assess the spatial impacts ranging from street profile to regional level. This does not mean that the modelling approach asks for a similar level of detail. And in terms of modelling to the smallest scale level enough difficulties still arise regarding spatial data, computation time and behavioural data. In terms of generalisation of the result that will come from the study, it is most relevant to examine up to the level of neighbourhoods. Neighbourhoods are spatial entities that can be characterised based on coherence in spatial entity and physical appearance. There is yet no standard definition of what a neighbourhood is.

This study will use zip-code areas as spatial entities for the modelling study because of the large availability of data on this level.

For this study, the zones considered are 4-digit postal zones (pc4). VRU zones are on some places more precise than necessary, and not all socioeconomic data is available on the respective zone level. Other zone classifications considered (see Figure 5-4) are district (in

Dutch: ***wijk***) and neighbourhood (in Dutch: ***buurt***), both defined by CBS (CBS, 2017). Districts are not considered since they are too large and incorporate sometimes a wide variety of districts in terms of typologies. The reason for not using neighbourhoods, is because these are differently defined in different towns and cities.

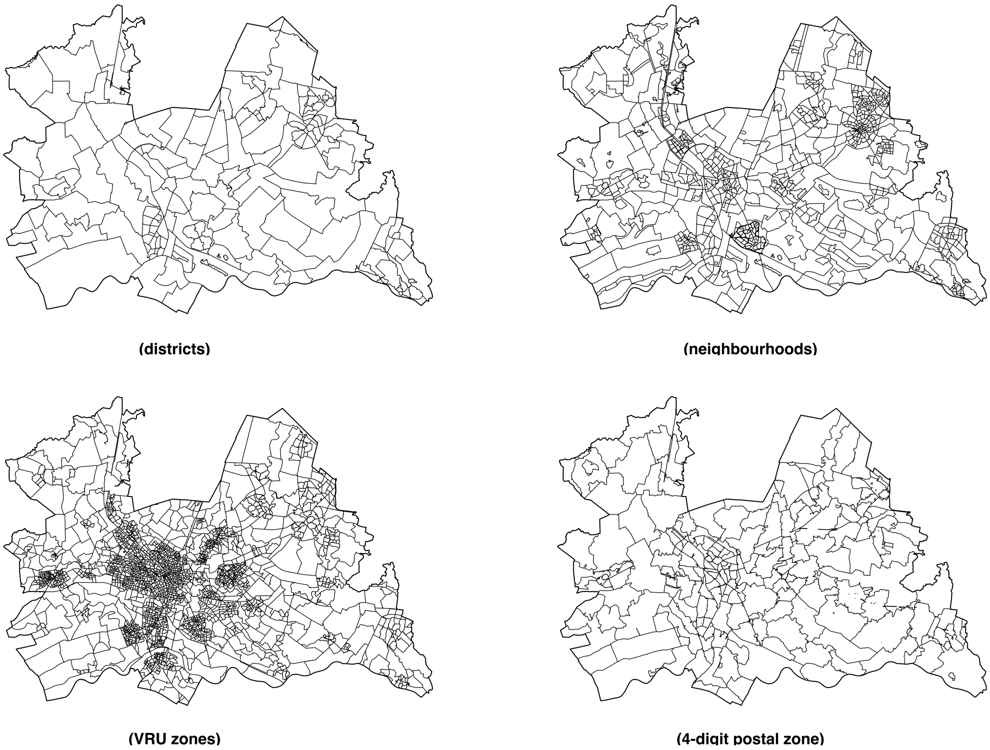


Figure 5-4: Different zone classifications

Study area characteristics

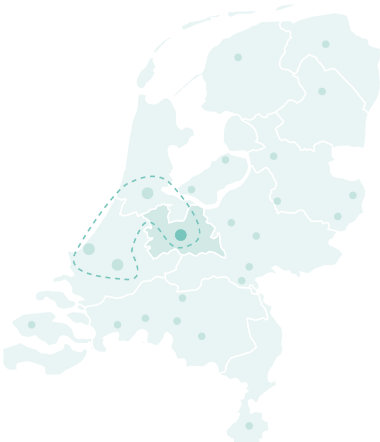


Figure 5-5: The region of Utrecht within the Netherlands

The region of Utrecht takes on a central place within the Netherlands and forms a gateway from the urbanised Randstad area in the west to the midsized cities and rural areas in the east (Figure 5-5). It houses a wide variety in urban environments from different building years (Figure 5-6, Figure 5-7). Other regions in the Randstad area know similar varieties but are less detached from surrounding urban centres. The urban regional structure of Utrecht is therefore easier to comprehend and more representative for other urban areas. The landscape in the west of the study area is mostly characterised by peat soils whereas the east has sand soils and forests (Figure 5-8).

The area is well connected by highways from all sides and the central railways station of the city of Utrecht is the most important train station within the Netherlands.

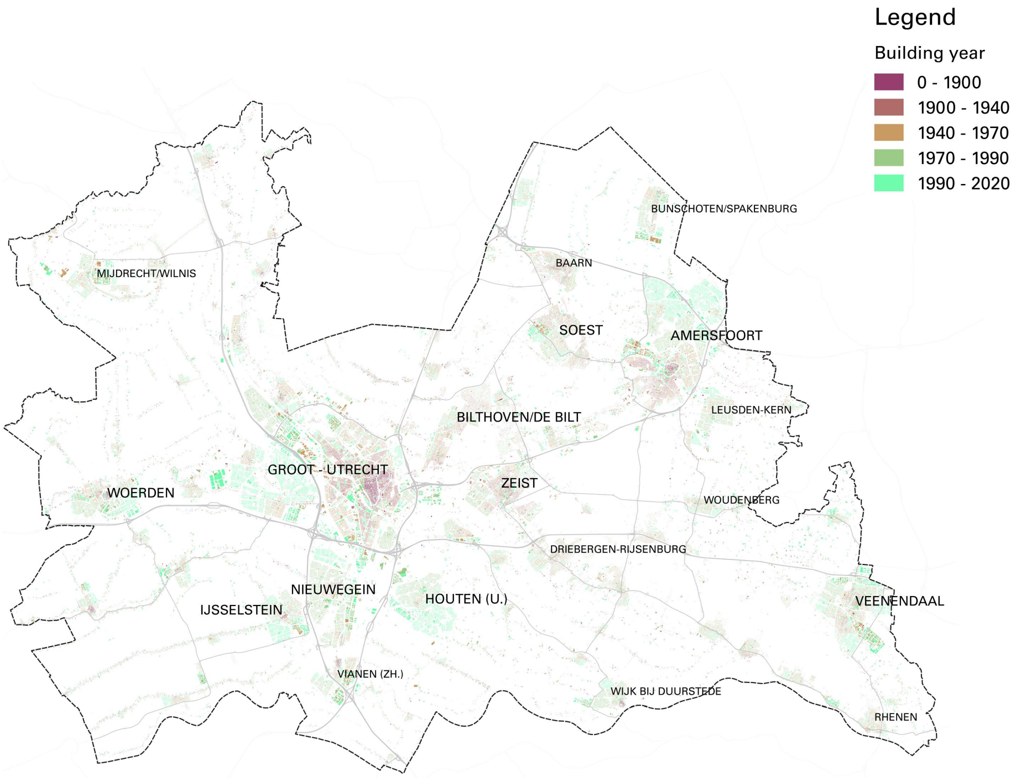


Figure 5-6: Buildings by year (data derived from Kadaster (2016a))

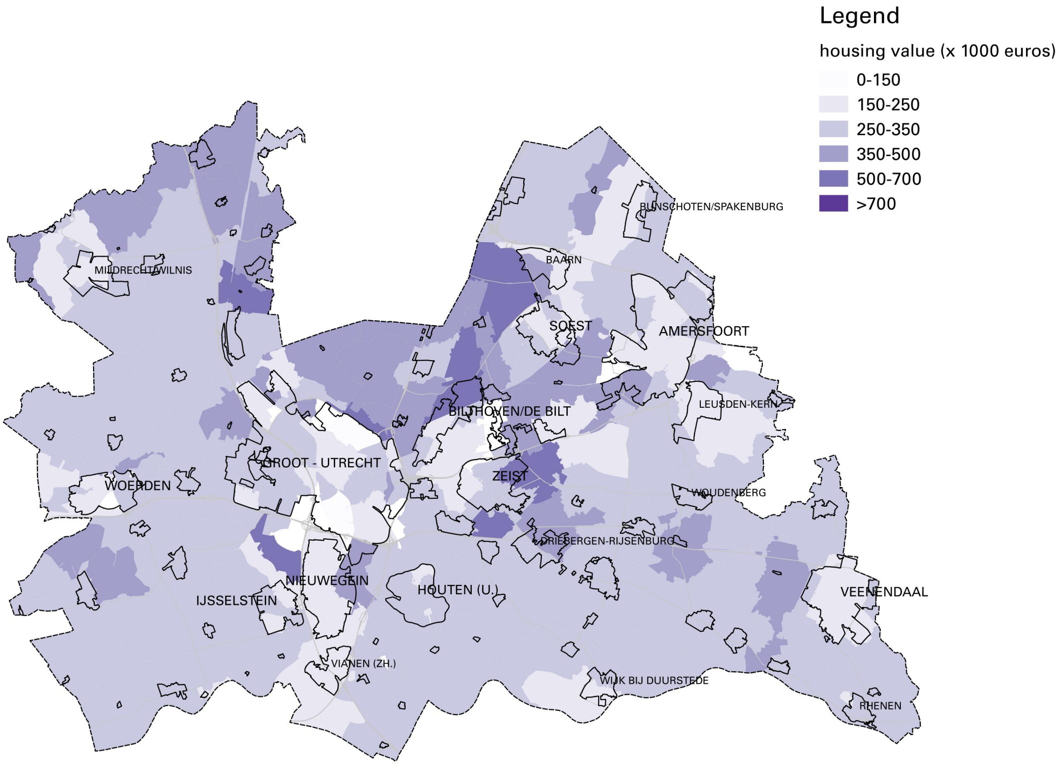


Figure 5-7: Average housing value (data derived from CBS (2017))

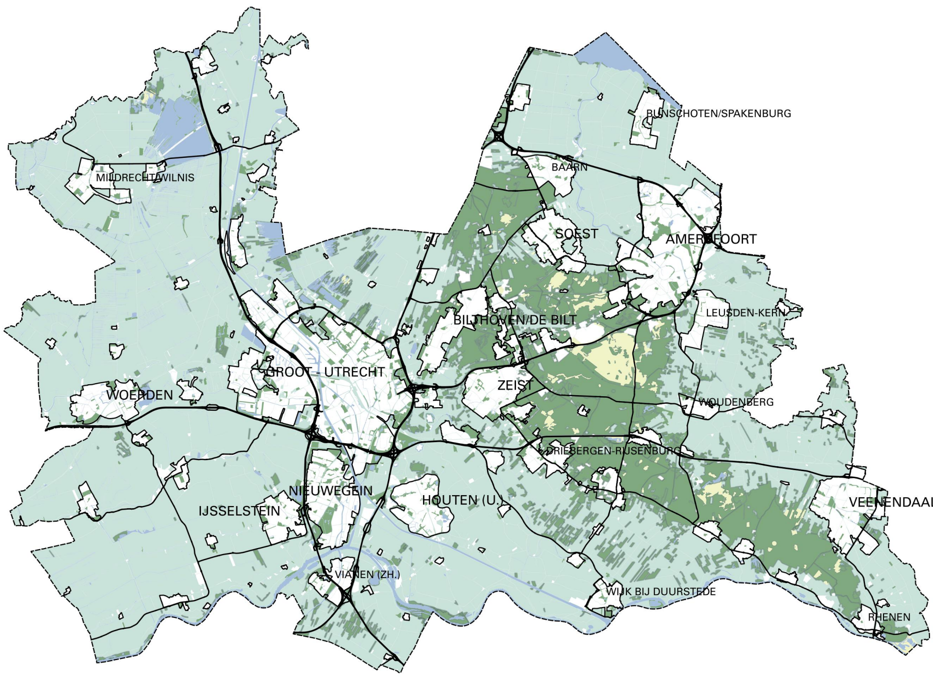


Figure 5-8: Landscape cover (data derived from CBS (2012))

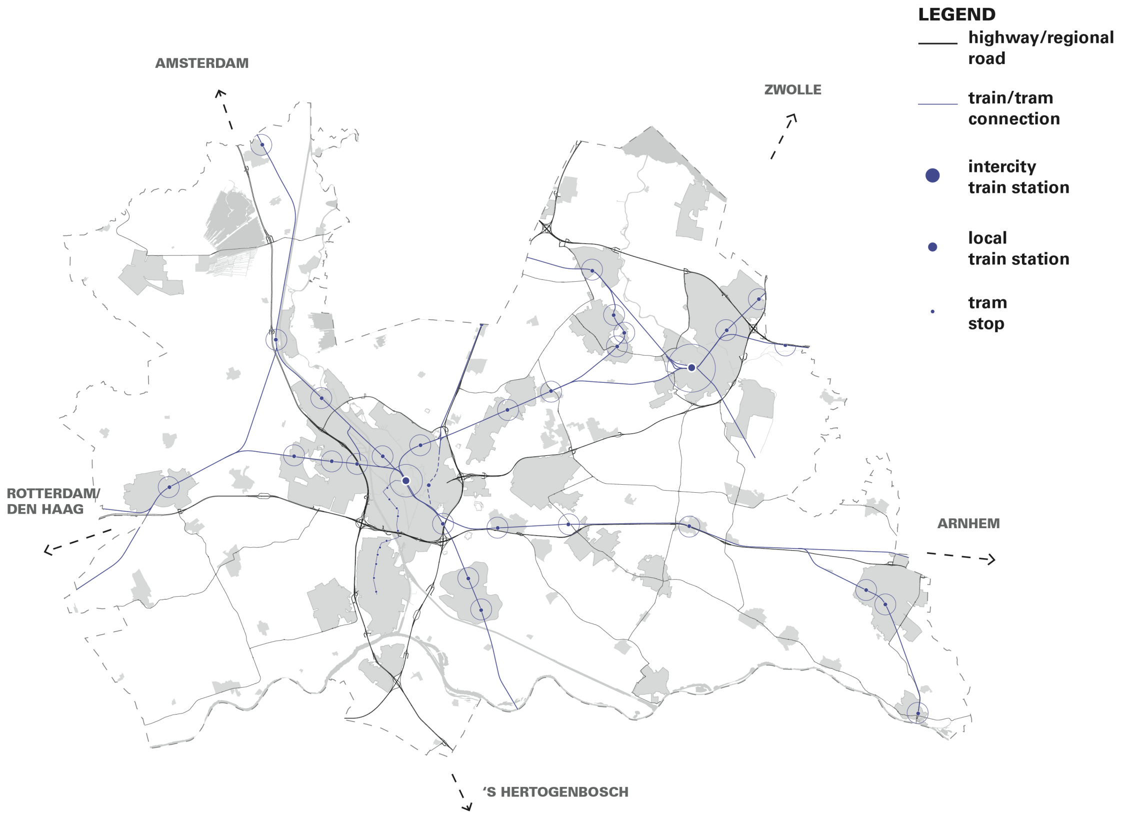


Figure 5-9: Infrastructure network (data derived from Kadaster (2016b))

5.2.2 SCENARIO APPROACH

Many factors regarding automated driving can have directly or indirectly an effect on residential location density and urban form in general. Literature on automated vehicle research reveals the wide range of predictions and the uncertainty about the development and deployment of automated driving due to the many underlying assumptions in these studies. To grapple uncertainty around vehicle automation a lot of assumptions must be made in this study. To make these assumptions explicit and deal with the uncertainty around predictions, a scenario approach is employed. The purpose of scenarios is to derive and justify assumptions for different paths of development of automated vehicles and their applications. This demands for scenarios of explorative character that help to identify the development of external factors (Börjeson, Höjer, Dreborg, Ekvall, & Finnveden, 2006, p. 727). In this context, external factors are values and applications of vehicle automation. These provide for input for the model and design study to evaluate urban impact.

Bishop, Hines, and Collins (2007) provide an overview study of scenario development and distinguishes eight techniques with corresponding advantages and disadvantages. Many scenario approaches as the popular Global Business Network matrix approach (as explained by e.g. van der Heijden (2005) (also known as the two uncertainties approach, or Shell approach)) bases itself on two or more driving forces or dimensions of uncertainty (Bishop et al., 2007, p. 18) resulting in four contrasting narratives. This provides for a sound basis for planning with uncertainty. However, this is not the mere purpose of the scenario study for this research. Additionally, the narrowing focus on key-uncertainties complicates assumptions on other relevant aspects, whilst this is necessary in this study. Therefore a broader scenario analyses methodology, the future scenarios methodology as illustrated by Dator (2009, pp. 5-10) is employed. This methodology classifies as an expected trend impact analysis in the categorisation of Bishop et al. (2007). In this approach, various paths of development of (in this case) automated driving are set. These paths are made tangible through a narrative. Based on these narrative, further assumptions per scenario are justified.

To connect the scenarios with the study areas, the assumed transportation systems are mapped on the study area. This allows for a first step towards integration of the transportation network. This step helps to make assumptions later in the process.

5.3 DATA COLLECTION AND PROCESSING

Within the data collection and processing stage, the accessibility and spatial quality effects of automated driving to be used in a residential location choice model. As the research overview in Figure 5-3 shows, this the sequential order in which these steps are executed. The set-up of the residential location choice model dictates how the prior two steps must be executed to allow the outcomes to be compatible with this choice model. Therefore, the residential location choice model is explained first.

5.3.1 RESIDENTIAL LOCATION CHOICE MODEL

Within the residential location choice model, the system of urban development is explicitly defined through the residential moving behaviour of households. In this model, prior obtained data needs to be synthesised to reveal new urban development patterns. Two important questions are by which method to model the household moving behaviour and by which model.

Modelling method

Chapter 3 explained various methods to model urban systems. Methods distinguish themselves in spatial resolution and complexity. State-of-the-art urban models allow for higher spatial resolutions and consider individual decision makers as driving force of the evolution of the environment. Since the problem entity identified individual decision makers as driving force in urban change, microsimulation of these decision makers is considered the most preferred method as it allows to simulate the individual behaviour. As it is the purpose to reveal new urbanisation patterns, an agent-based residential location choice model provides a suitable environment to execute the synthesis of the data.

Behavioural model

One of the most challenging aspects in making and using an agent-based model is defining the behaviour of human decision making processes. Behavioural models can be empirically derived from e.g. survey data. It has been considered to do this. This could be done by a survey specifically conducted for this research or by using the national housing survey (WoON). This would give some control over the variables used within the models, but proved too time consuming. Therefore, this research is limited to using an existing residential location choice model. Two directions for obtaining a behavioural model are considered:

- Using an existing rule based residential location model
- Using an existing residential location discrete choice model

The strength of rule-based models is their relative easy comprehensibility as well as their modest demand for data but are difficult to validate. This proves easier for discrete choice models, which are derived empirically and prove for a stronger scientific foundation (Flynn et al., 2014). Additionally, randomness is inherent to discrete choice modelling, which coincides with the notion of cities as complex systems. Studies by e.g. Hunt et al. (1994) or Schirmer et al. (2014) a wide range of existing residential location choice models. Most of these models are derived for locations outside the Netherlands or only focus on a specific aspect within the residential location choice. Since housing is a cultural phenomenon (e.g. Rapoport, 2000), models derived from data for other countries are not favoured. The choice for an existing model is limited to models for the Dutch context. The residential location choice models for Dutch households by Zondag, de Bok, Geurs, et al. (2015) Blijie and de Vries (2006), Ettema, de Jong, Timmermans, and Bakema (2007) and Tillema et al. (2006) have been considered in Table 5-1. For this study, the residential location choice model as described in Zondag, de Bok, Geurs, et al. (2015) and applied within TIGRIS XL is used. This model is chosen over other residential location choice models for its ability to better evaluate automated driving effects compared to other available residential location choice models in a Dutch context and its relatively good documentation.

Table 5-1: Evaluation of residential location choice models for Dutch households

	Model			
Evaluation criteria	Zondag, de Bok, Geurs, et al. (2015)	Blijie and de Vries (2006)	Ettema et al. (2007)	Tillema et al. (2006)
Scope	Residential location choice	Residential location choice of low-educated multi-person households <60 years	Residential location choice	Residential location choice i.r.t. road pricing and work location
Well documented for reproduction	Yes (paper and system documentation)	No (paper only)	No (paper only)	Moderate (paper and dissertation)
Ability to incorporate automated driving effects	Directly through accessibility, indirectly through housing value	Difficult, only commute *distance* considered	Difficult, only commute *distance* considered	Yes (travel time, travel cost) and indirectly through housing value
Scale, Spatial resolution	National, LMS zones	4-digit postal zone	Randstad North-wing, grid cells of 500*500 m^2	Not specified, house attributes are incorporated
Ease of implementation	Moderate, not all attributes are ready available to obtain (neighbourhood typology, accessibility)	Difficult, move-or-stay decision not incorporated, employment location of decision maker required	Difficult, employment location of decision maker required	Difficult, employment location of decision maker required

5.3.2 ACCESSIBILITY EFFECTS

The accessibility effects of automated driving can be obtained through various methods. An important consideration is that for the case of automated driving, not only the network properties are a factor. If that would be the case, the accessibility effects could be evaluated using a network analysis with the help of geospatial network data. Even more than the network properties, the infrastructure and network performance of the transportation system need to be evaluated to adequately study the automated driving effects. A transport model is needed to evaluate relevant factors such as travel time (and delay), costs and behaviour on a detailed level. The effect and role of car ownership can partly be incorporated within the transportation model.

The accessibility effects of automated driving will be examined using the transport model for the region of Utrecht (Verkeersmodel Regio Utrecht, VRU). VRU is a static macroscopic transport model owned by the Province of Utrecht. The model is made available to the author for this research. VRU is a very detailed transport model and therefore provides a broad range of vehicle automation aspects to study and consider. VRU has no designated function for modelling automated vehicles. Nevertheless, VRU offers possibilities to study automated vehicle effects on accessibility through adaptations to the model. This will be later explained in chapter 7 where the accessibility effects of automated driving are examined.

Calculating accessibility in a way which is applicable to the residential location choice model proves challenging. The choice model is designed to evaluate accessibility through logsum indicators obtained in LMS, the Dutch national transport model. This transport model has a different structure compared to VRU, which has consequences for obtaining accessibility indicators.

5.3.3 SPATIAL QUALITY EFFECTS

By examining the spatial requirements of the transportation network under various scenarios, the spatial quality effects of automated driving can be explored.

<u>Neighbourhood classification</u>

Main challenge of this research step is making the results compatible with the residential location choice model. The residential location choice model has no direct indicator for urban quality. However, it allows for interpretation of the spatial quality effects. This model evaluates the characteristics of the neighbourhood in the typological categorisation by ABF Research (2003) (which are introduced in subsection 3.1.2). For each neighbourhood type, one corresponding neighbourhood is chosen as representative for all neighbourhoods of this type. In each representative neighbourhood type, the spatial quality effects are examined. Using the neighbourhood typologies allows to use the results from specific areas and generalise them to other areas.

To assess the benefits for urban spaces, two scale levels must be considered:

1. The neighbourhood scale concerns the implementation of the transportation system and relates to the assumed transportation system projected in the scenarios.
2. The street level concerns the specific infrastructure requirements based on the usage of the network. On this scale, one can assess whether more street lanes or parking places are required. The transportation model calculates link loads and therefore provides for a design brief.

Compatibility of the results

On the neighbourhood scale, the spatial quality benefits cannot be expressed in a quantitative metric. The most important reason is that the spatial quality changes are subject to design decisions which are not made in this stage of the research. To illustrate this, the images in Figure 5-10. Imaging that in a scenario without mass transit, the station area of the city of Utrecht can be redesign. The spatial quality benefits depend strongly on which new function is given to the area. Instead of expressing the spatial quality benefits on neighbourhood level, the transformation potential is expressed in a qualitative measure (none – high). The results can be used to later identify areas of intervention.

On street level, the design decisions are smaller. Less or more infrastructure or parking space requirements can change the images of the street significantly. However, the space can be mostly used to enhance the view of the street. Literature as e.g. Luttik (2000) explains by using hedonic pricing methods how e.g. proximity of green streets results in premiums on the housing value. Since housing is a choice attribute within the residential location choice model, the spatial quality effect can be evaluated in this matter.

5.4 EVALUATION AND INTERPRETATION

The results of the data collection and processing show a pattern and developments of residential density. This is identified as the main driving force of urban development. However, throughout the data collection process, more insights are obtained. The data collection process is guided by the residential location choice modelling procedure. Within this process, the studies on accessibility and spatial quality effects, as well as the scenario narratives and the literature review on automated driving (chapter 4) provide for a comprehensive frame of reference regarding the spatial impacts of automated driving. To come to an adequate conclusion, these insights are synthesised towards an urban development strategy for the region of Utrecht. This is a design-based research step which allows to incorporate the broad magnitude of variables.

In this synthesis, the dynamics of automated driving in relation to urban development can be critically assessed from a value-based perspective. Urban development is the result of the dynamics in human-interaction and the policies and spatial interventions that act on this. By elaborating on the aspects of automated driving and assess the desirability of the developments, an urban strategy is conducted to illustrate how planners can deal with the emergence of vehicle automation.

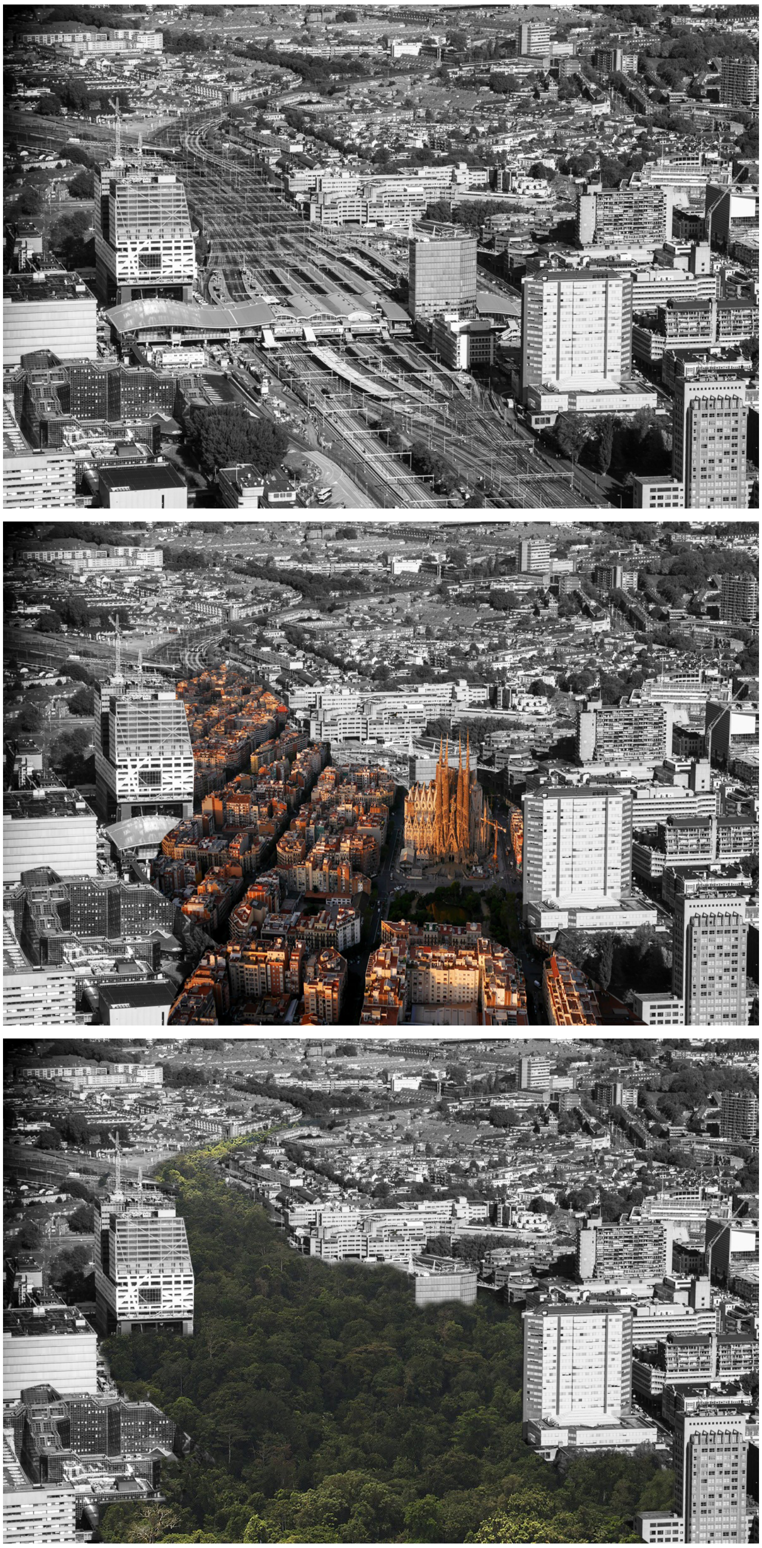


Figure 5-10: Different new land-use possibilities emerge for the Utrecht Central Station area if public transport happens to become absolute. What land-use function is best, should not primarily be answered by a model study. Instead, a model study should provide for insights to citizens, designers and policy makers to answer that question based on a broader range of evaluation criteria.

6 SCENARIO DEVELOPMENT

Given the uncertainty of the development and deployment around automated driving, a scenario approach is employed. Scenarios are defined in the form of an expected trend impact analysis. Four scenarios are distinguished alongside a base scenario without automated driving. The literature review on automated vehicles shows that the implications of automated driving strongly depend on the development of the technology and its applications. In each scenario, a different path of development of automated driving is set, ranging from automated driving having a negative impact on the transportation network to automated driving transforming mobility. With help of these scenarios, meaningful and coherent assumptions based on the implications of automated driving can be made and justified. These assumptions provide for input parameters in the remainder of this study. Goal of the scenarios is to specify a wide range of possible futures to obtain insights in the dynamics of automated driving. This means that different effects can be studied through different scenario and can still come together in the future.

In this chapter, the first section presents the trends considered. To make the scenarios more tangible to derive more detailed assumptions, the scenarios are translated in narratives by setting the story how automated driving develops as a technology. Thereafter the scenarios are further shaped in travel aspects and large-scale spatial deployment to relate the scenarios to the case study. By doing so, the scenarios provide for adequate basis to further justify assumptions.

6.1 DEVELOPMENT TRENDS

The development trends corresponding to the scenarios are depicted in Figure 6-1, along with corresponding names. These names are used throughout the remainder of this study. Each name coincides with a specific trend.

Within the base scenario, automated driving will not develop further as of 2017 and will therefore save as a base case, hence the name. For the transformation scenario, automated driving is set to develop towards an advanced technology that will also transform the way personal travel is configured. Within the scenario of growth, technology develops similarly as in the transformation scenario but to support current transportation system rather than enabling new transport applications. In the constraint scenario, some developments around automated driving will prove beneficial but technology will not establish fully. The decline scenario assumes negative aspects and considerations to broaden the perspective in this scenario approach. These trends are inspired by the work of Townsend (2014) and Dator

(2009) but the specific paths of development and assumptions are specifically set for this study.

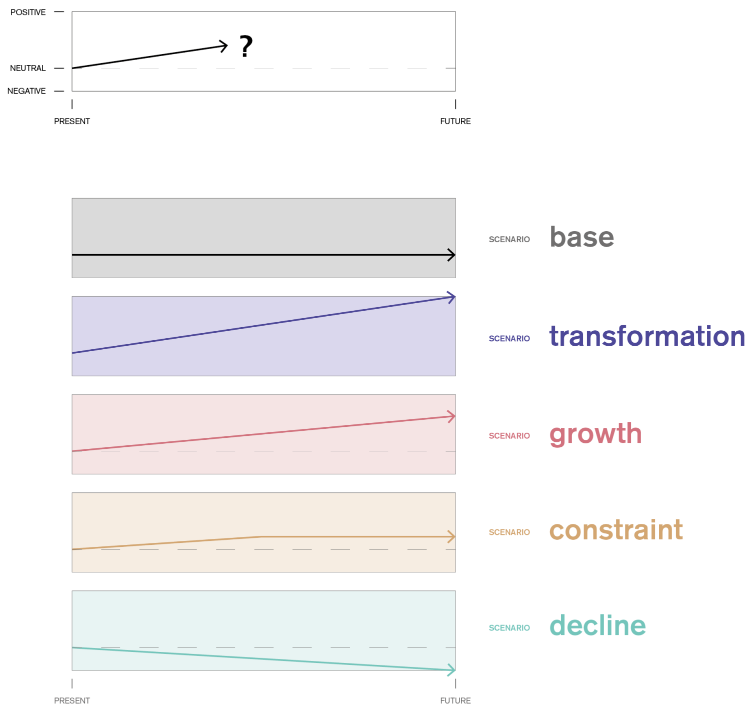


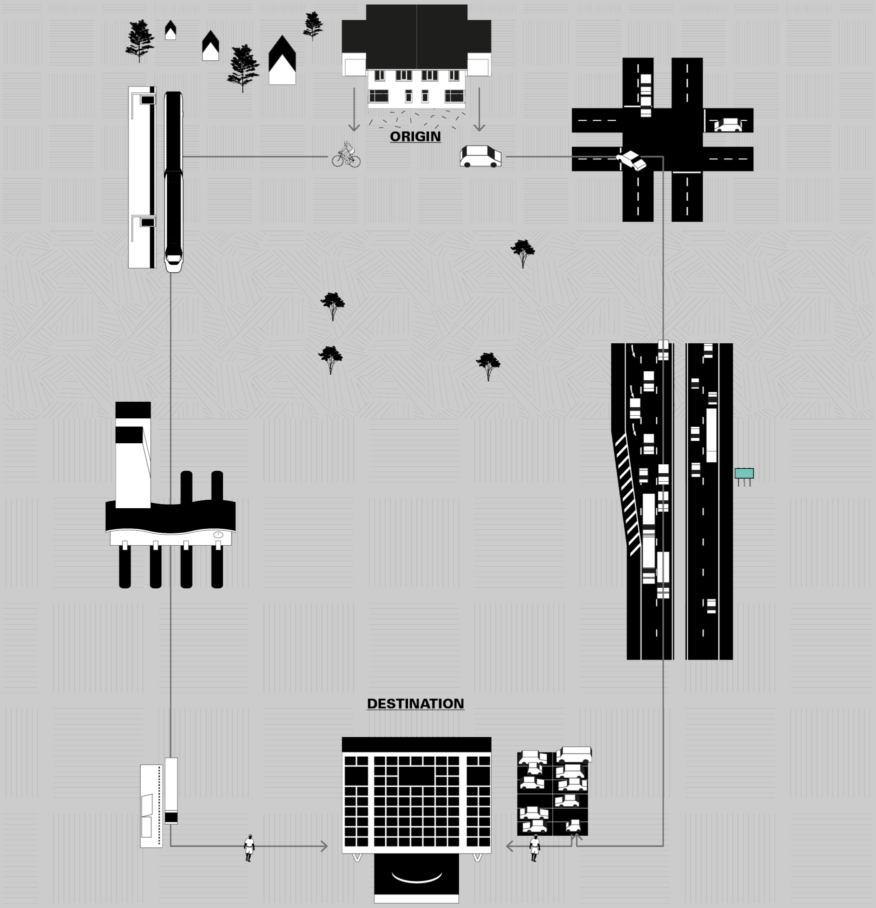
Figure 6-1: Different trajectories for the corresponding scenarios. These are the trends for the trend impact analysis.

6.2 SCENARIO NARRATIVES AND ASSUMPTIONS

On the following pages the scenario narratives are presented. These are based on the development trends and help assessing the plausibility of the trends. With the help of the narratives, assumptions are derived which are primarily related to the technological development of automated driving and the deployment of the technology in the transportation system. These technological aspects are derived from the applications and implications of automated driving in chapter 4. Together with the assumptions per scenario, these are depicted in Table 6-1.

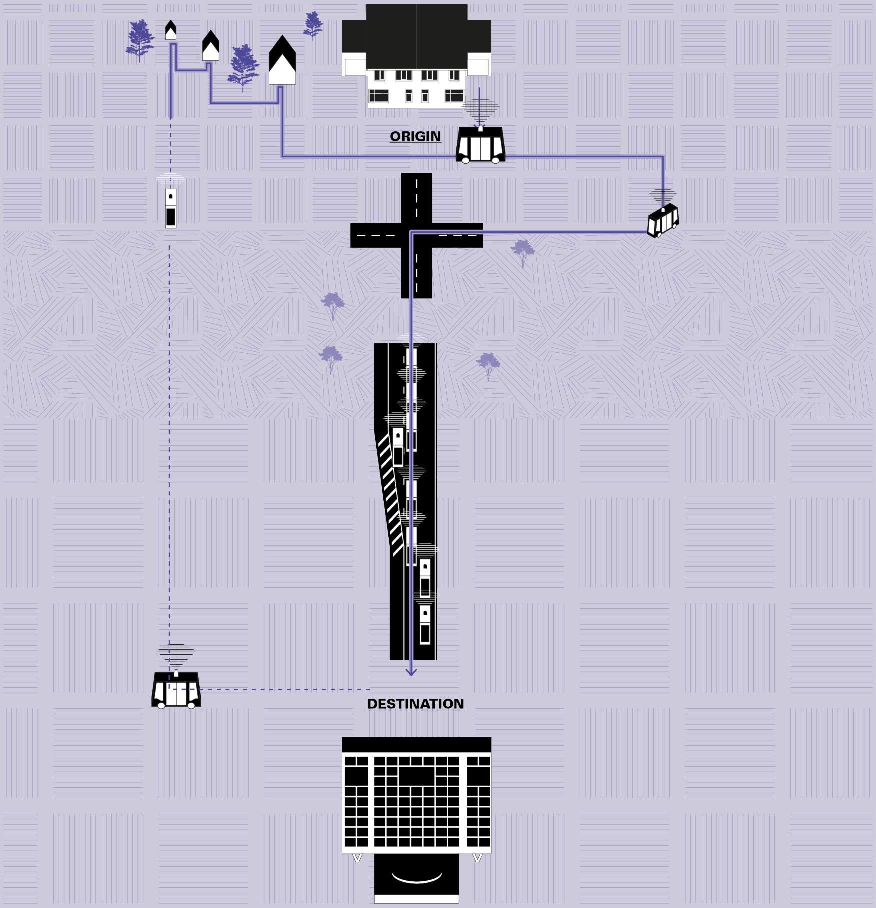
Table 6-1: Variables with corresponding developments considered within the scenarios.

Aspect		Development	Scenario 0: Base	Scenario 1: Transformation	Scenario 2: Growth	Scenario 3: Constraint	Scenario 4: Decline
Technology	Automation	None/partly	x				
		Conditional				x	
		Full		x	x		x
	Penetration rate	None	x				
		Mixed				x	x
		Full		x	x		
Application	Public transport	Same as today	x			x	
		Improved first/last mile			x		
		Shared taxi bots		x			
		Non-existent					x
	Private mobility	Same as today	x		x	x	x
		Shared taxi bots		x			
	Connectivity	Non	x				x
		Limited			x	x	
		High		x			
	Parking	Conventional	x			x	
		Valet-parking services			x		
		Idle driving					x
		Other		x			



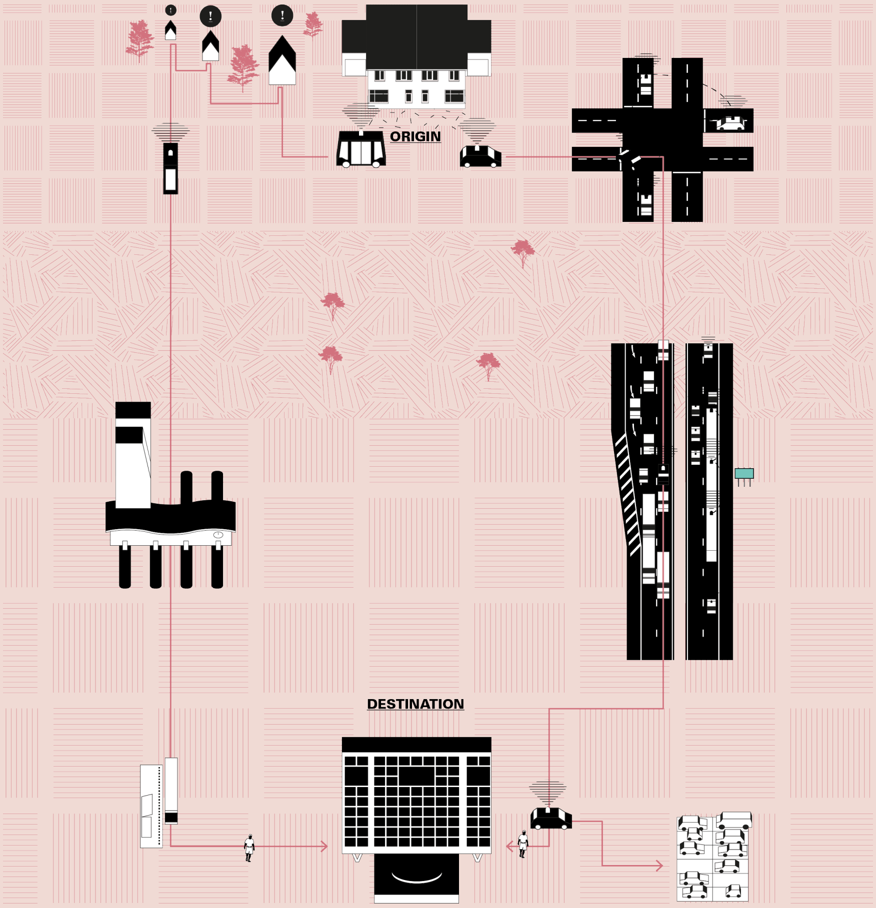
Scenario 0: Base

Around 2015 – 2016, vehicle automation is at the top of hyped expectations, as Gartner (2016) predicts. Automated driving is not able to meet these expectations and will not develop further to the level of partial automation. Self-driving cars have not managed to pass the threshold from being a gimmick. After some severe accidents happening with vehicles that have some characteristics of self-driving (lower levels), the public does not buy cars with these characteristics anymore. Car manufacturers stop their self-driving cars projects. Also, institutions and politics lose their interest and confidence in self-driving cars.



Scenario 1: Transformation

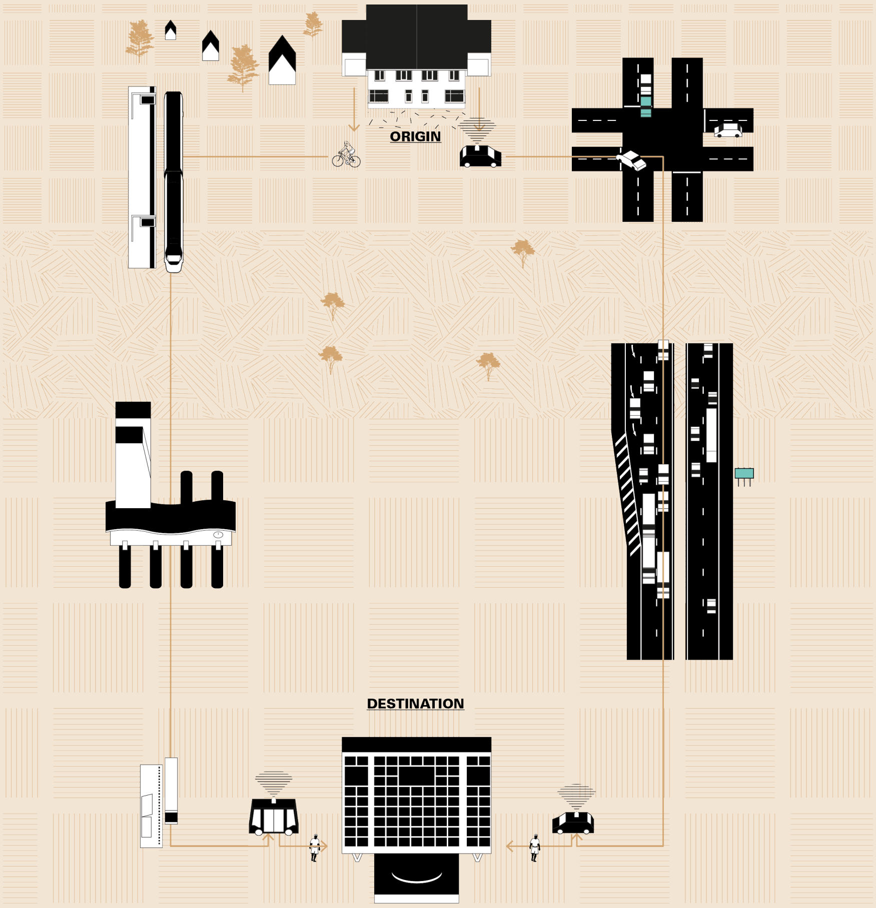
Vehicle automation develops rapidly towards full automation. Driving force behind vehicle automation are technology companies and start-ups. These companies are disrupting the transportation market with new innovative mobility concepts based on sharing demand responsive taxi solutions. The traditional car manufacturing companies keep in their traditional canvas by marketing private cars. These cars are gaining increasingly less attention, especially by younger generations. The government has set supportive policy measures in an early stage and allowed for many pilots on the public road. The taxi-bots are very cost competitive. People quite easily sell their car or simply do not use it anymore and public transport becomes obsolete. Flexible fees that are related to mobility demand allow for efficient use of the available vehicles.



Scenario 2: Base

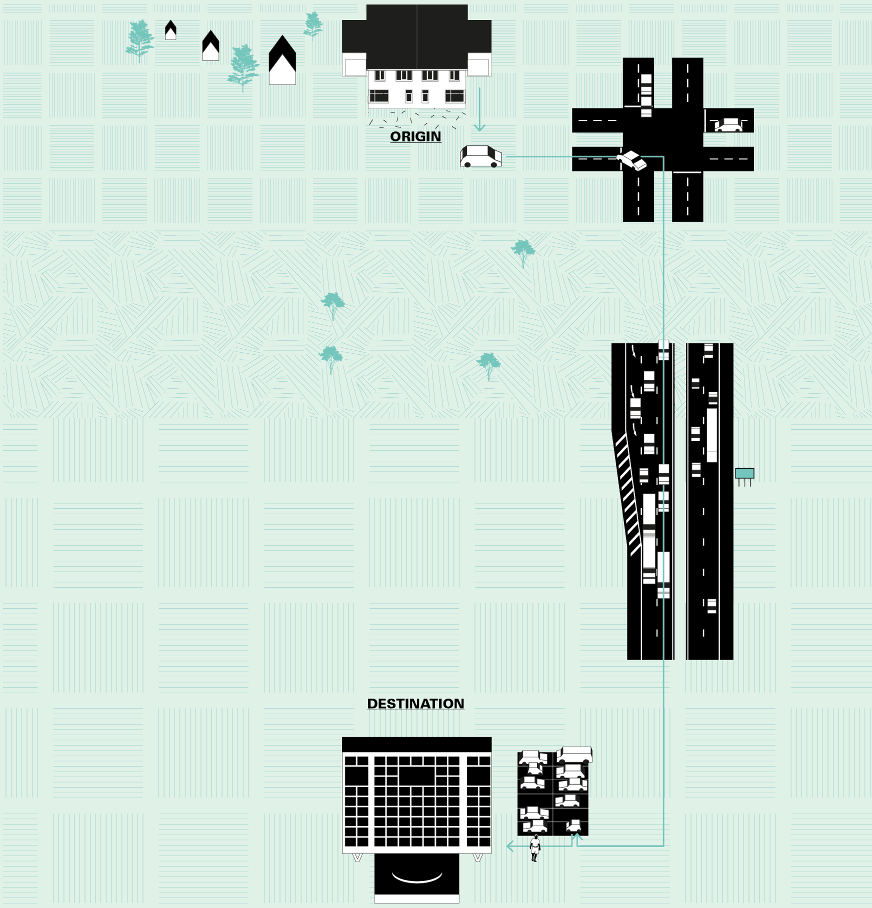
Vehicle automation develops gradually towards full automation. The driving force behind vehicle automation is the conventional car companies. Advanced driver assistance systems gradually develop towards full autopilots, making automated driving in private automobiles mainstream. Protectionism of national government on their automobile industry makes tech companies and start-ups that attempt to disrupt the transportation largely incompatible.

Remote areas, where it is hard to establish a profitable public transport services are now connected with on demand public transport services for people who do not have access towards cars yet. Because of the large number of cars, parking still proves for challenges. This has led to that residential areas still demand for a specific area of parking spaces. In mixed-use urban areas more restrictive policies towards parking are enforced, which made valet-parking systems on the outskirts of cities mainstream, as also explained by Zakharenko (2016).



Scenario 3: Constraint

Automated driving develops towards quite an advanced technology but due to legal and safety concerns, full automation will never be achieved on urban roads. Only on highways, automated driving is allowed. This does not mean that everybody enables automated driving while driving on the highway. A considerable number of drivers prefers to drive vehicles themselves.



Scenario 4: Decline

Automated vehicle technology develops towards full automation, but not everybody is equally keen to drive automated. This causes mixed traffic conditions that affect traffic conditions negatively. Many highways are equipped with an additional lane for automated vehicles only. This proves for safer traffic conditions, but has a negative impact on the traffic flow because human drivers have a hard time adjusting to automated vehicles within traffic. Another unforeseen effect is the parking demand of automated vehicles. Automated vehicle users, let their vehicles drive idle on the road network instead of paying for parking. Conventional car users still have a need for parking.

Because of the low price of automated vehicles, car ownership has increased drastically, fully diminishing public transport.

6.3 REGIONAL IMPLEMENTATION

Since the scenarios need to be implemented within the transport model to study accessibility effects, it is on the one hand of importance to find corresponding values to use as input for the transport model simulation. However, this is not only a matter of deriving adequate parameter values from existing literature and estimations. It is also a matter of the spatial context. In travel behaviour, also location matters. Implementation of the assumed scenarios should therefore be integrated within space. Since this depends on a wide range of factors, that cannot explicitly be considered beforehand, a mapping design exercise is employed to conduct a spatial map of the scenarios within the study area.

Basis of the mapping exercise is the base case which is depicted in Figure 5-9. Within the transformation scenario (Figure 6-2), the road network is extensively used and demand responsive autonomous vehicles drive from one place to another to pick-up passengers who request a ride. These passengers can either live in urban areas or in the country side.

In the growth scenario (Figure 6-3), public transport plays still an important role in traffic from one urban area to another. However, on the country side, demand responsive transit picks up passengers. The larger cities enforce a parking policy by which automated vehicles drop off passengers in the inner city and then drive to remote parking areas which are assumed on the current park-and-ride facilities. Based on data from the transport model, the total numbers of cars that require parking for the city of Utrecht alone is found to be 50 000 for the morning. Based on conventional parking requirements this would ask for 50 000 * 25 m^2= 125 hectares for parking. This is expected to be smaller for automated parking systems. However, the value illustrates the large spatial requirement for such facilities, even when stacked. For the constraint scenario in Figure 6-4, no significant changes occur compared to the base case. The decline scenario (Figure 6-5) has no significant consequences regarding implementation except for the diminishment of public transport.

Figure 6-2: Regional implementation of scenario 1: Transformation

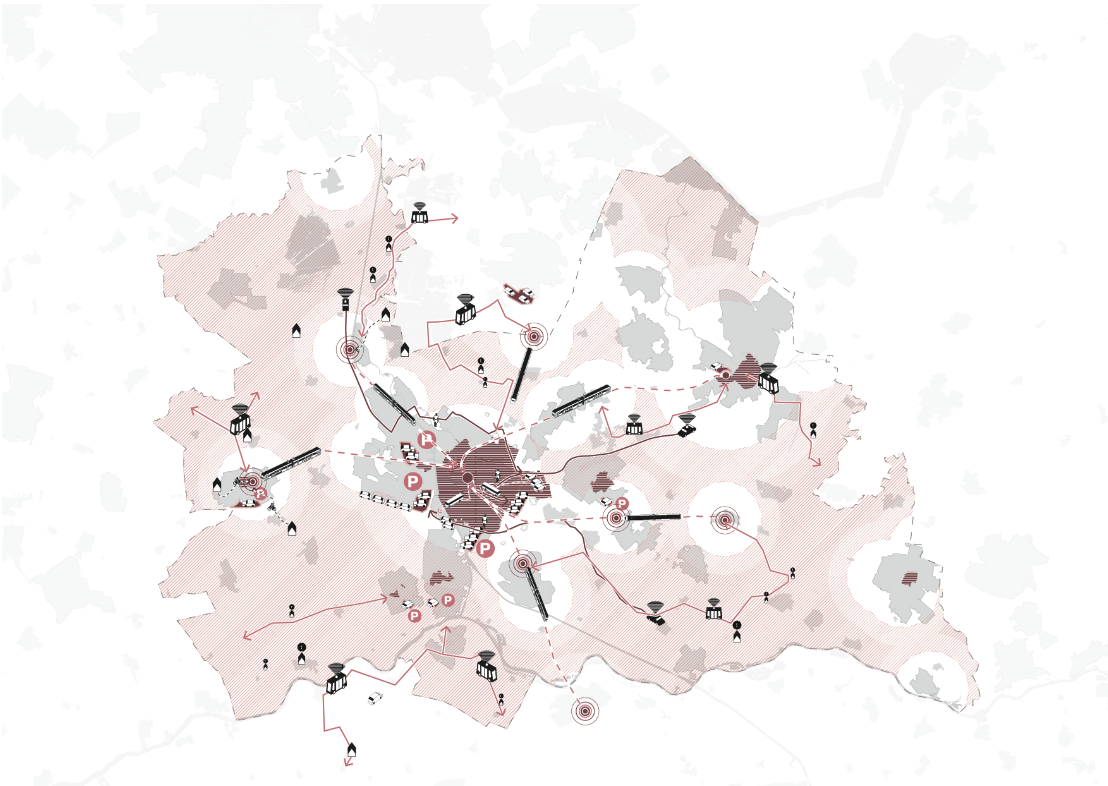


Figure 6-3: Regional implementation of scenario 2: Growth

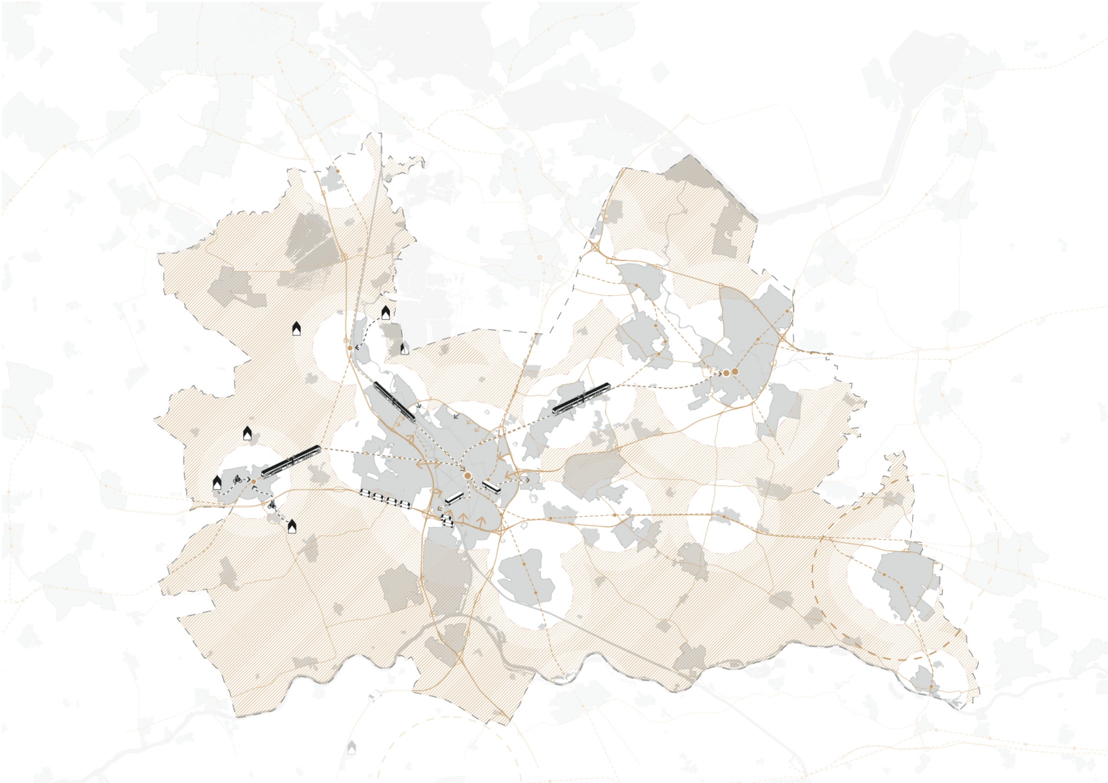


Figure 6-4: Regional implementation of scenario 3: Constraint

Figure 6-5: Regional implementation of scenario 4: Decline

7 ACCESSIBILITY EFFECTS AND TRAVEL IMPLICATIONS OF AUTOMATED DRIVING

Accessibility is found to be one of the residential location choice factors that is subject to change through automated driving. Calculating accessibility of places and the change in accessibility under the various scenarios is crucial input for the residential location choice model. Accessibility is calculated using the Verkeersmodel Regio Utrecht (VRU) which was provided by the province of Utrecht for this research.

This chapter starts with a brief introduction of VRU and an examination of the possibilities to model (or emulate) automated driving within this transport model and how accessibility is to be calculated with this model. This examination provides for insights to which parameter values and settings to use or change to model vehicle automation. These assumptions are made in the second section and are therefore an elaboration on the scenarios. The third section elaborates on how accessibility is calculated and the fourth section presents the results. Due to the comprehensive feature of this model, the runs will be used simultaneously to examine other affects among traffic loads and travel demand. These will be explained briefly in the results section.

7.1 MODEL FRAMEWORK

The Verkeersmodel Regio Utrecht (VRU, in English: Transport model region Utrecht) is the transport model owned by the province of Utrecht and managed by Goudappel Coffeng/DAT.mobility. It is a static multimodal transport model implemented within OmniTRANS version 6.1.4 (Figure 7-1), a macroscopic transport modelling software platform. For a detailed description of the model, one can consult the manual for the model (Goudappel Coffeng, 2013). For this study, version 3.2 of VRU is used. VRU has no designated functionality to model automated vehicles. Hence, adaptations within the model on values and modules are necessary to emulate – rather than truly simulate – self-driving cars. The model framework is examined to find the means to evaluate the automated driving scenarios.

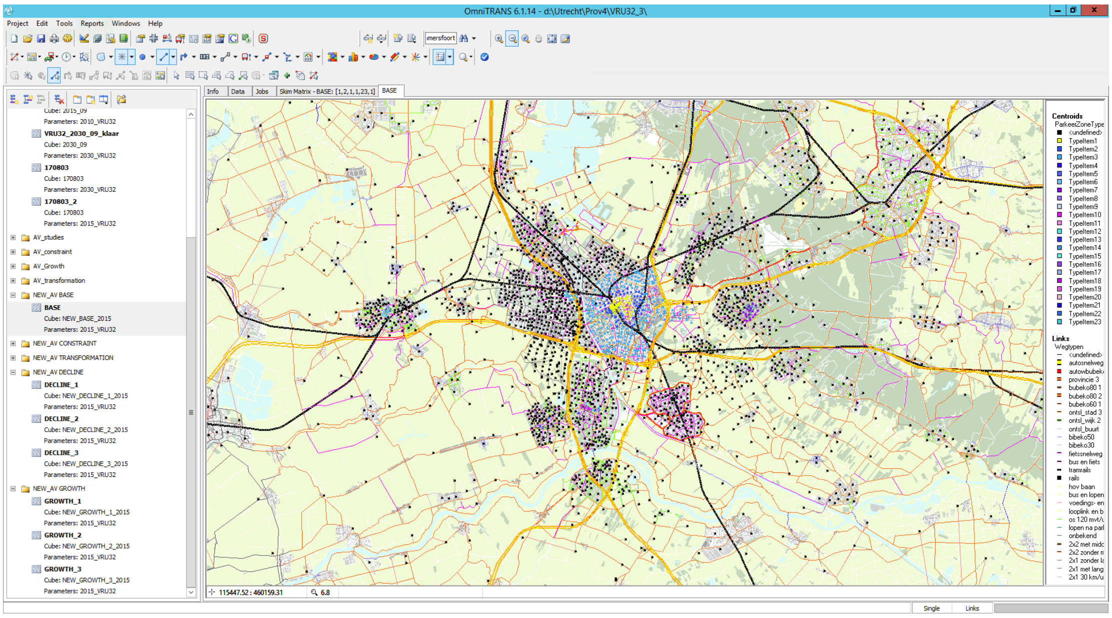


Figure 7-1: VRU within OmniTRANS 6.1.4.

VRU is an elaborate macroscopic modelling through the four-stage modelling structure with simultaneous trip distribution and route choice calculation by a gravity model (Figure 7-2). The model considers following transport models:

- Automobiles (driver or passenger);
- Public transport (distinguished by access and egress mode);
- Bikes;
- Freight.

Three day-times are considered:

- Morning-peak;
- Evening-peak;
- Rest-of-day.

Trip purposes distinguished are:

- Employment;
- Business;
- Shopping;
- Education;
- Other.

Trip generation is calculated externally. Thereafter, a simultaneous gravity model iterates three times based on the infrastructure network loads. Based on the transport mode, the iteration of the network loads calculation goes in 1 round (bike), 10 rounds (freight), 30 rounds (car and public transport). The remainder of this chapter will explain the model processes depicted in Figure 7-2.

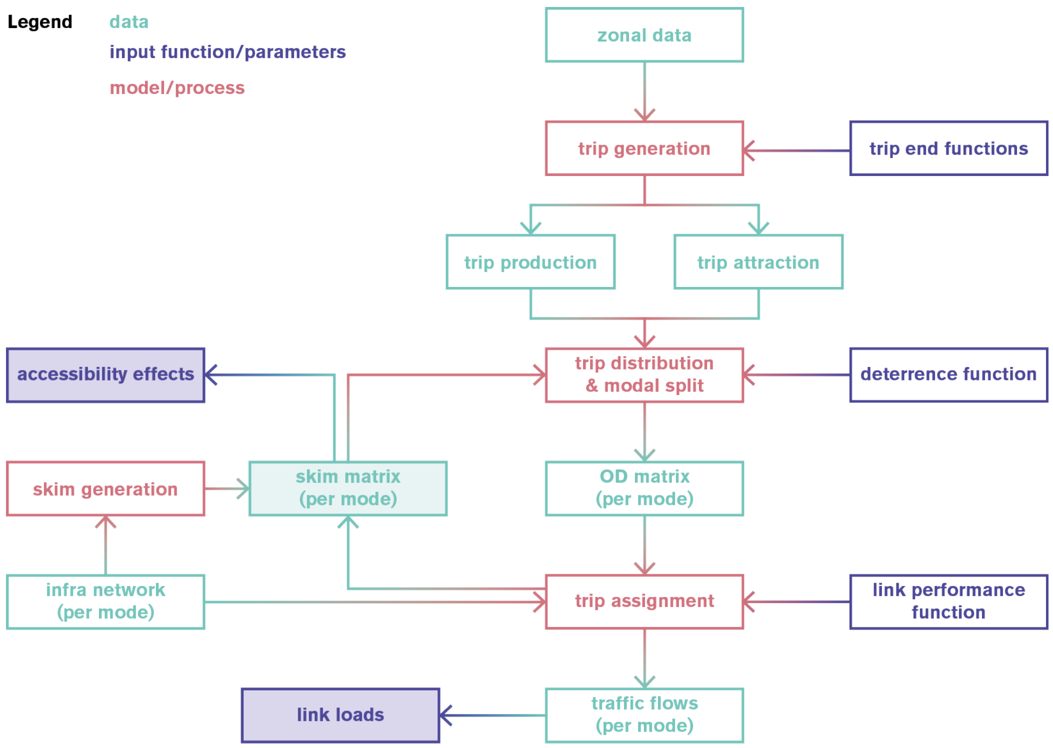


Figure 7-2: Model framework of VRU within OmniTRANS. (adapted from van Nes, van der Gun, Goñi Ros, and de Romph (2015, p. 64)). The working of the model is explained in this section by elaborating on the different model processes

7.1.1 TRIP GENERATION

Zonal data provides for the input of the trip generation model. VRU comprises the province of Utrecht represented in 2500 zones/centroids and 1900 centroids outside the provincial borders with higher densities in in surrounding areas to few centroids in neighbouring countries. Within the centroids zonal data is stored to generate the travel production and attraction per motive per time of day. The generation of the travel demand is evaluated within the trip-end functions. These functions are externally calculated within spreadsheets evaluating the following factors:

- Labour population;
- Jobs;
- Inhabitants < 35 years old;
- Student places;
- Inhabitants;
- Workplaces in retail sector;
- Households;
- Urbanity;
- Car availability.

7.1.2 SIMULTANEOUS GRAVITY MODEL (TRIP DISTRIBUTION AND MODAL SPLIT)

Within the simultaneous gravity model, destination and mode choice are calculated for each trip. The result is an OD-matrix (Origin-Destination Matrix) per mode. The deterrence function describes the impedance of traveling from one zone to another zone by a specific mode. Variable in this function is the travel impedance, which is often expressed in a monetary unit and which is in the case of VRU for cars the sum of the following factors:

$$Cost_{car;i,j} = travel\ time_{i,j} * value\ of\ time + travel\ distance_{i,j} * value\ of\ distance + parking\ resistance_j$$

where:

$$parking\ resistance_j = f(\sum parking\ fee_j,\ availability\ of\ parking\ information\ system_j, availability\ of\ parking\ places\ _j,\ availability\ of\ parking\ places\ nearby)$$

For public transport, the cost function looks as follows:

$$Cost_{PT;i,j} = travel\ time_{i,j} * value\ of\ time + travel\ distance_{i,j} * value\ of\ distance + route\ factors_{i,j}$$

where:

$$route\ factors_{i,j} = f(\sum waiting\ time, transfer\ penalty, transit\ fare_{i,j})$$

Through multiplications with various parameters, the value obtained through the deterrence function carries no monetary factor, although the function is to some aspect a function of the travel cost:

$$F_m(Z_{ijm}) = \alpha_m * \exp(\beta_m * \ln^2(Z_{ijm} + 1))$$

with F_{ijm} being the travel impedance between zone ***i*** and zone ***j*** for mode ***m***, α and β the cost sensitivity parameters of the costs Z_{ijm} between zone ***i*** and zone ***j*** for mode ***m***. Figure 7-3 displays the deterrence function per mode for all trip purposes aggregated.

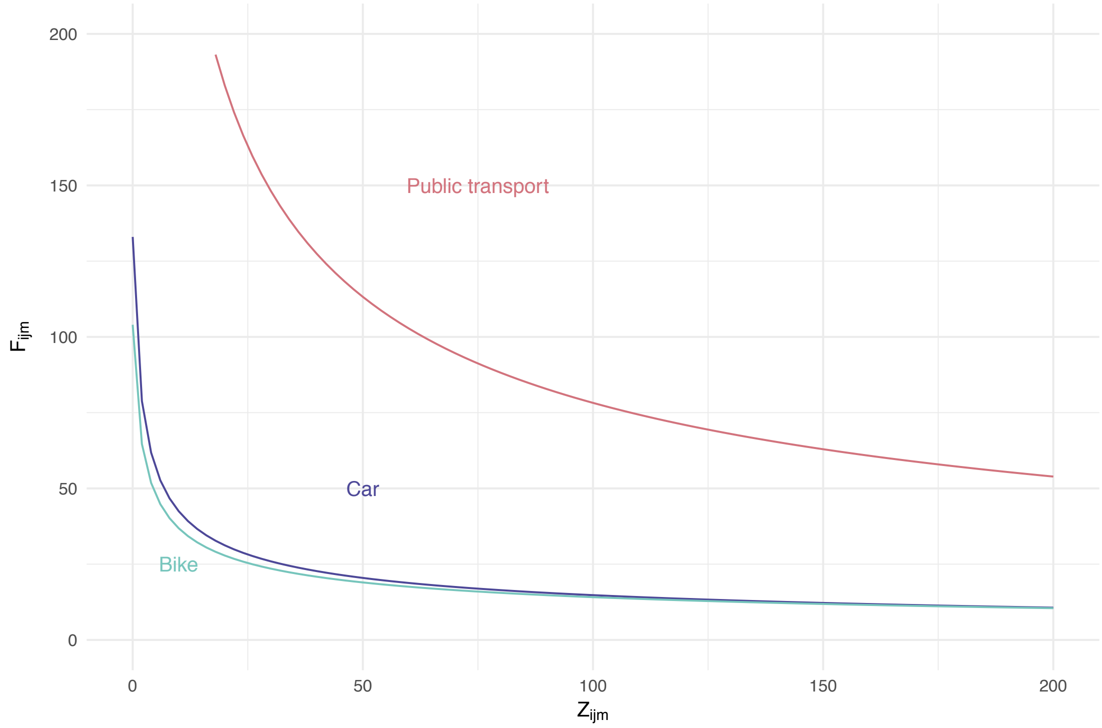


Figure 7-3: Deterrence function per mode for all trip purposes. The diversion of public transport is probably cause of some other sensitivity parameter in the parameters of the simultaneous gravity model.

7.1.3 TRIP ASSIGNMENT

Within the trip assignment process, the OD-matrix is assigned to the network. In this step, the link performance of every link in the network is evaluated with a link performance function. The link performance function (which is often called BPR curve) describes the average travel time or costs on a link for a vehicle as a function of the flow on and the capacity of the link (Figure 7-4). Often the BPR curve is described using following equation:

$$T = T_0(1 + \alpha\,(V/Q)^{\beta})$$

with:

T	Travel time
T_0	Free-flow travel time
V	Volume
Q	Capacity
α, β	Function coefficients

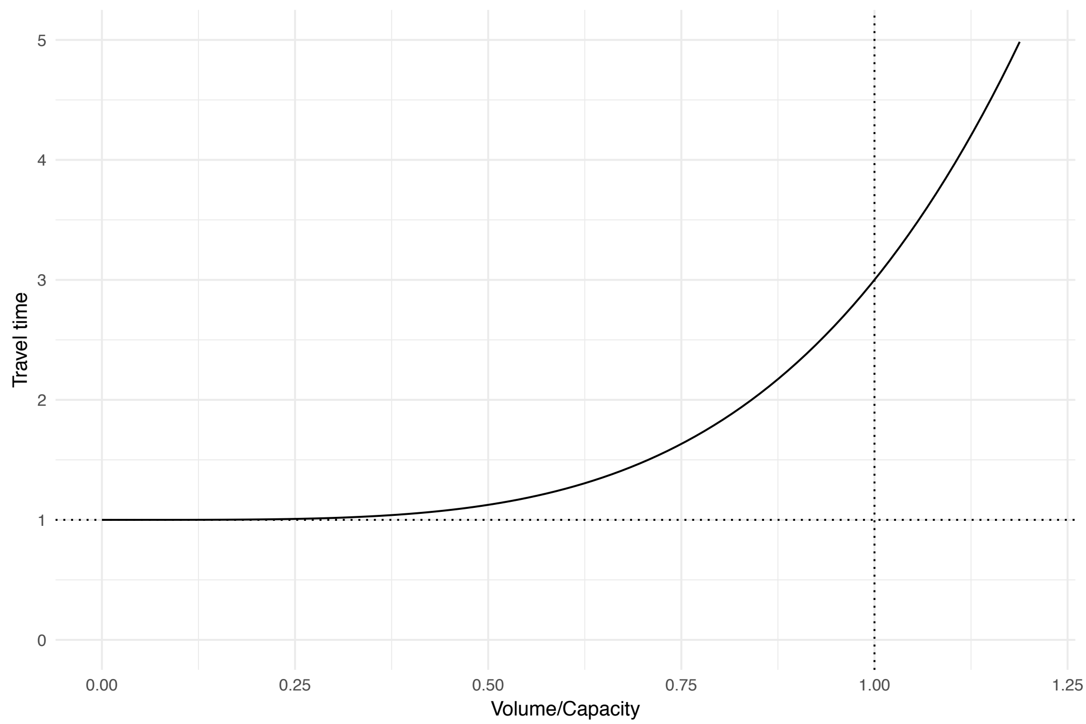


Figure 7-4: Example of a link performance function.

Intersections are modelled with an intersection delay factor that evaluates the possibility of having to wait one or more green cycles to pass. The values are 0.25 for quiet intersections, 0.375 for intersections busy with cars, 0.5 for intersections busy with cars and bikes or public transport and 0.625 for intersections busy with cars and bikes and public transport (Goudappel Coffeng, 2013).

Based on the travel times on the link, traffic is assigned to the network. First freight is assigned to the network. Thereafter, other traffic is assigned with freight as external load. Assignment for bikes is done through a single all-or-nothing assignment, where all volume is assigned on the single fast links. All other modes are assigned through a method-of-successive-averaging (MSA assignment, or Volume Averaging). For an elaborative explanation of this assignment method see Ort zar and Willumsen (2011, pp. 370-371).

7.2 CALCULATING ACCESSIBILITY IN VRU

Before studying the accessibility effects of automated driving according to each scenario, the accessibility of the existing situation must be calculated. This section explains how accessibility is expressed through a potential accessibility to opportunities measure and the results that gives for the base scenario.

Accessibility is determined according to the performance of the transportation system and therefore the associated travel impedance and by the opportunities within reach from a specific place. This accessibility measure is called potential accessibility to opportunities. Since trip distribution is determined within VRU using a simultaneous gravity model, the model offers no possibility to derive destination utility. A consequence of this is that accessibility cannot be expressed by means of utility-based indicator. Instead, a potential accessibility measure is used as indicator to examine accessibility changes:

$$A_i = \sum_{j=1}^{n} D_j * F_m(Z_{ijm})$$

with:

D_j	Measure for attraction in zone $\boldsymbol{j}$
F_{ijm}	the travel impedance between zone $\boldsymbol{i}$ and zone $\boldsymbol{j}$

The measure of attraction cannot be expressed by a utility value. This does limit expressing the attraction of a zone to number of a specific function, e.g. jobs. In this research, the accessibility indicator will be limited to commute accessibility for this is most determinant for the residential location choice as revealed from chapter 3. It would be most favourable to derive an accessibility measure that considers the several modes available within the model. One could for instance take a weighted average of accessibility indicators based on the modal split in the study area. However, since the deterrence function of public transport is so divergent from the deterrence functions for the car and bike modes, this result is not likely to be realistic nor representative. Hence, the accessibility measure obtained from this study is limited to employment accessibility by car.

Accessibility values can change through new infrastructure, traffic management measures or technological developments (scope of this research). But economic development in general has a significant impact on travel behaviour too. This question is always a concern in travel forecasting. VRU 3.2 allows to run the model for the years 2010, 2015, 2020 and 2030 where the latter two are based on prognoses. These prognoses comprise changes in demography, land-use and the transportation network and economic development. Many of these assumptions are based on the Global Economy scenario, which is the most positive scenario regarding economic development of the four WLO scenarios (Janssen, Okker, & Schuur, 2006). Choosing a future year for accessibility calculations seems a logical choice at first. To wit, vehicle automation still needs to establish within the transportation system. However, there is no close consensus how long this process of establishment will take. This makes choosing a future year a speculative decision. Another consequence is that by using a future year, more assumptions are put in the model. Therefore, using 2015 as model year has benefits too. It provides for a validated and calibrated modelling basis without assumptions on economic development. Additionally, it allows for compatibility with other data sources that do not provide for future data values.

Figure 7-5 shows car accessibility for trip purpose commute in the year 2015. Accessibility is particularly high around the highway and surrounding the city of Utrecht. Eastbound, strong decrease in accessibility can be observed. These zones are further distanced to large urban centres like Utrecht or Amsterdam. What also reveals is that a few areas show significantly lower accessibility levels than surrounding zones. Particularly the city centres of Woerden and Nieuwegein catch the attention. And to a fewer extent also the city centre of Zeist shows lower accessibility levels than its neighbouring zones. One would not expect this as it often shows that city centres offer high level of service and jobs and therefore have higher accessibility levels. These areas all have some sort of parking policy and one of the cost factors is likely to weigh substantially much in the travel impedance. Another area, southeast of Woerden shows low accessibility values too compared to its neighbours. The area houses mainly agricultural land and is in VRU only accessible with one feeder link with capacity zero. This adequately explain the low accessibility levels for that zone.

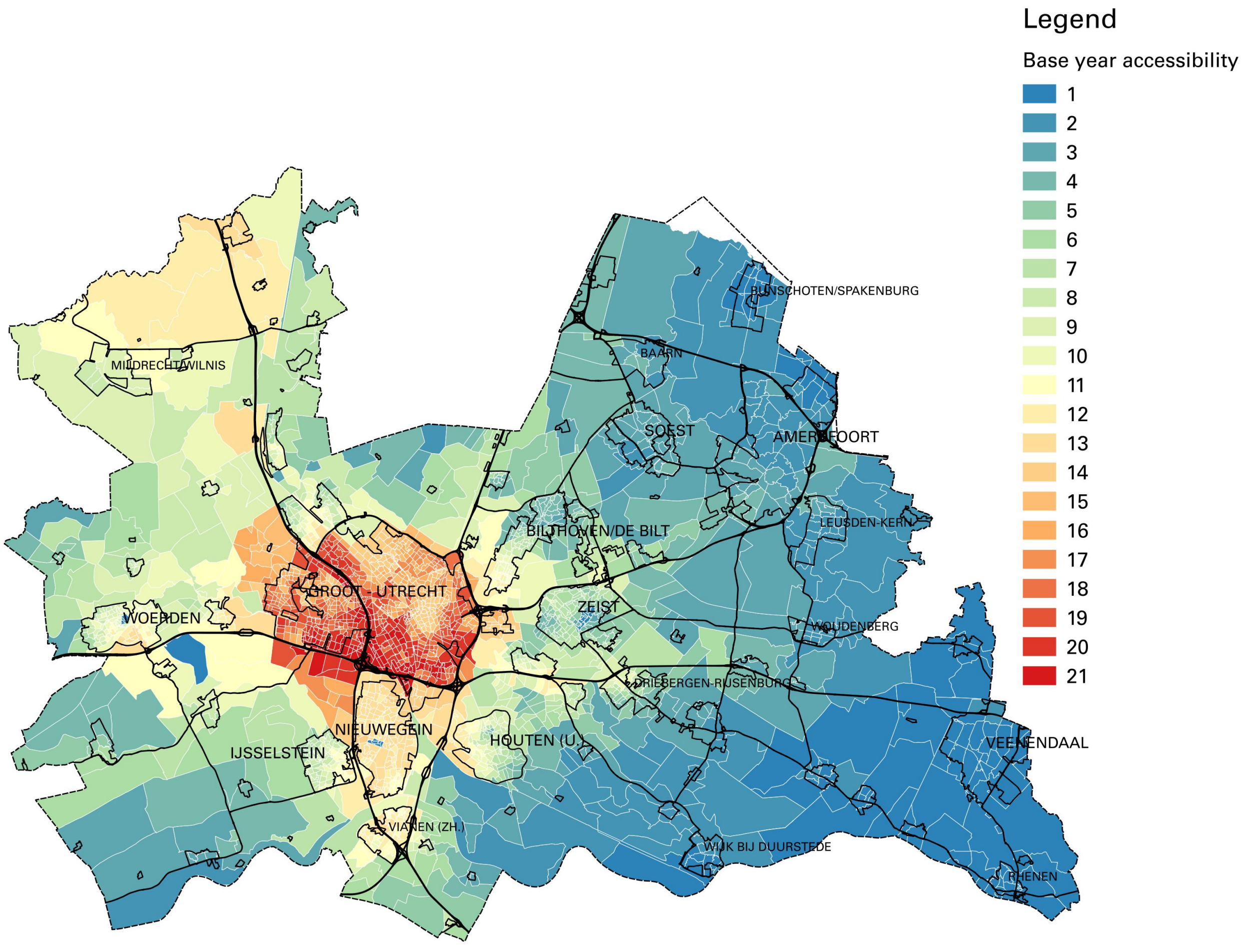


Figure 7-5: Accessibility to opportunities for trip purpose commute, mode car for the 2015 situation.

7.3 IMPLEMENTING AUTOMATED DRIVING IN VRU

To implement the defined scenarios within VRU to study the effects of automated driving on mobility, first the possibilities to simulate automated driving within the transport model are assessed. Chapter 4 explained how automated driving has implications on travelling through changes in travel demand and behaviour, travel cost factors and traffic efficiency measures. These implications must be integrated within VRU to assess the impacts of automated driving on accessibility and traffic.

7.3.1 TRAVEL DEMAND AND BEHAVIOUR

Most natural way to integrate changes in travel demand would be through the adjustment in the trip-end function. Car availability is a factor within the trip generation model. This could theoretically be altered within the model to account for the induced demand by new user groups. However, since this part of the model under encryption this is not possible from a practical perspective. Additionally, if it would be possible, one cannot be certain of the validity of the results. Prior studies on induced demand factors by new user groups, empty ride allocation or parking concepts provide a better starting point to evaluate automated driving effects. These factors can then not be directly implemented within one of the models but must be externally implemented by mutation of the OD-matrices within the model where after these matrices are then assigned to the network.

7.3.2 TRAVEL COST FACTORS

Factors that affect the travel cost have two categories. There are the route factors, which comprise additional comfort or cost factors such as parking costs or public transport transfer fees. Another aspect relates to value of time and value of distance. These factors relate more to the cost of travel in general. Through changes in value of time parameters, increased travel comfort by performing alternative tasks in-vehicle while driving can be evaluated. Value of distance could relate to different travel costs, but no reliable data has been found to assess that aspect. Parking route factors can be assessed by changing the role of parking fees or availability.

7.3.3 TRAFFIC EFFICIENCY MEASURES

Within the trip assignment process, the OD-matrix is assigned over the network. In this step, the link performance of every link in the network is evaluated with a link performance function. How traffic divides itself over the network depends on the trip assignment methodology.

Within VRU, the link capacity and maximum speeds are stored within the infrastructure network. It is possible to alter these values for the specific road types the model distinguishes. The literature review shows a lot of research on potential capacity increase, but research on (maximum) speeds is non-existent. Another factor that has impact on the travel resistance in terms of the network is the delay at intersections. VRU deals with this using delay factors. Depending on the configuration of the intersection, a delay factor is applied. Studies on the traffic effects of automated driving on intersection capacity show a potential positive impact. This effect can be incorporated by reducing delay factors. Taking the link performance into account for public transport proves for larger challenges because VRU assumes an infinite capacity for public transport modes. In other words, VRU does not consider crowding.

Trip assignment for car traffic is done through the method of successive averages as explained in subsection 7.1.3. Network wide traffic coordination of vehicles could allow for more efficient assignments. In theory, this can be modelled by assigning vehicles to the network by a system-optimum algorithm. This has been attempted but proved not feasible due to long runtimes (in order of magnitude of days).

7.4 SCENARIO PARAMETER DERIVATION AND IMPLEMENTATION

From rationale in prior section, the aspects to evaluate automated driving effects in VRU is set to the following:

- Transformations to the OD-matrix to account for induced travel demand;
- Change of road capacities and intersection delays to assess travel efficiency gains;
- Value of time and route factor changes to account for travel comfort and convenience factors.

Table 7-1 lists the aspects along with corresponding chosen parameter values per scenario. To each scenario, a section in this chapter is dedicated to explaining the derivation of these values and the implementation within the transport model. The detailed implementation is explained below.

Table 7-1: Modelling procedure per scenario.

		Scenario			
Aspect		Transformation	Growth	Constraint	Decline
Travel demand	For road travel by new user groups	All public transport transferred to cars on road network	+10%	N/A	All public transport transferred to cars on road network
	By empty ride allocation to pick-up other passengers	+20%	+10%	N/A	+10%
	By empty ride allocation to designated parking zones	N/A	All arrivals in zones with parking policies are redirected to designated parking zones	N/A	N/A
Network aspects	Inter-urban roads	+ 100%	+40%	+40%	-20%
	Intra-urban roads	+ 50%	+20%	+0%	+0%
	Intersection delay	All 0.1	All 0.25	+0%	+0%
Travel impedance factors	Value of time (all purposes)	-35%	-50%	-15%	+0%
	Parking cost factors	0	Availability plays no role	N/A	N/A

7.4.1 SCENARIO 1: TRANSFORMATION

In this scenario, automated driving develops to a full automated shared vehicle system which replaces both public transport as well as conventional car travel.

Travel impedance factors

Milakis et al. (2017) sketch a scenario called “AV…in bloom” which matches most closely with this scenario. A group of experts on average predict a value of time decrease of 31%. These values also are not that far off with the other assumption of a decrease of 35% used by Childress et al. (2015, p. 101). Hence, this study follows these assumptions and sets the decrease in value of time to 35%. This is not the highest value found in literature. This is for the assumption made that travellers are not considered to be in their own vehicle experiencing less comfort than if it would be their own. Since the vehicles drive to another passenger after drop off the traveller, parking is no factor in the travel impedance.

Travel demand

Induced demand factors are applied based on the existing demand pattern derived from the demand model. Since the demand model takes travel impedance factors into account, firstly the OD-matrix is generated with impedance related values for the scenario. Value of time is changed within the parameter values of the model. Infrastructure capacity is changed within the model network. Parking is not considered in the travel impedance function. Within this scenario, all travellers have access to a shared automated vehicle. Additionally, all trips prior made using public transport are now made with shared automated vehicles on the road network. The public transport OD-matrix is therefore also assigned to the road network.

$$T'_{ij;\,car} = T_{ij;\,car} + T_{ij;\,PT}$$

with:

T_{ij} Travel demand between zone $\boldsymbol{i}$ and zone $\boldsymbol{j}$

The number of empty rides for allocation of shared automated vehicle fleets are examined by various researchers. Fagnant and Kockelman (2014, p. 12) find that vehicle kilometres would increase by 11% in theoretical case study and by 8.0% in a study with a case study in Austin, Texas (Fagnant et al., 2015, p. 105). Santi et al. (2014, p. 13292) estimate 8-10% a case study in Manhatten. Both studies use a dense urban area as case study. Based on the study by Boesch et al. (2016) the suspicion is raised that this number might be higher regarding the case study of this research. This study states that most – but not all – request for a shared automated vehicle can be met within 5-10 minutes but that density of travel demand is an important factor: In the late peak, most requests can be served since most travel demand comes from concentrated (employment) areas. In the morning peak, most common origins are the residential locations which are more dispersed. It is therefore more challenging for a shared automated vehicle fleet to meet all demand, leading to higher vehicle kilometres in less dense areas. Therefore, induced demand by empty ride allocation in this scenario is set to 20%:

$$T''_{ij;car} = T'_{i,j;car} * 1{,}2$$

Road capacity and efficiency

The assumption is that V2V-communication sensors are equipped in every vehicle. And therefore, high capacities can be achieved. Yet, the same concern remains towards theoretical studies. Therefore, the decision is made not to follow experiments that show highway capacity increases as found in chapter 3. Instead, a rigorous capacity increase of 100% on ex-urban roads and 50% on intra-urban roads is assumed. Intersection delays factors are reduced to 0.1. This is lower than the lowest delay factor of intersections within VRU (0.25). This is done to almost fully diminish intersection delay. Note: the factor 0 is not considered for the risk of computation errors.

Because of high vehicle connectivity, assigning vehicles to the network by means of a system optimum algorithm has been considered but is not applied due to high calculation times.

7.4.2 SCENARIO 2: GROWTH

In this scenario, automated driving develops to full automation, but stays within the realm of private car mobility. Therefore, access to a vehicle is still restricted to households owning a vehicle. Technology matures to full extent, which means that both within the urban environment as well as outside the built environment, infrastructure facilitates automated driving. Areas that enforce parking policies will transfer to valet-parking concepts to the outskirts of cities.

Travel impedance factors

The largest decrease in value of time is assumed because private mobility is characterised by the lowest values of time. The most radical assumed decrease in value of time found in literature is a decrease of 50% by Gucwa (2014). Under the assumption that travellers perceive more comfort in their own vehicle than in a shared vehicle, the assumption by Gucwa (2014) is followed to use a lower value in time in this scenario than in scenario 1: transformation. Because of valet-parking concepts, availability of parking places does not play a role anymore within the travel impedance for car travel.

Travel demand

In this scenario, owning a driving license is not required to operate a vehicle. However, access to a car is still constraint to households owning a car. Induced demand of 10%VKT by new user groups is assumed to follow the existing travel demand pattern and is therefore applied as a factor to the OD-matrix:

$$T'_{ij;car} = T_{ij;car} * 1{,}10$$

This assumption is made based on the following existing literature: Harper et al. (2016, p. 8) estimate that access to automated vehicles for new user group can lead to an additional 14% in travel. Sivak and Schoettle (2015) come to 11% increase in travel with no change assumed in travel pattern. Wadud et al. (2016, p. 10) estimate a 2-10% increase.

Induced demand by empty ride allocation is mostly accounted for by allocation rides between family members. Most studies drawing conclusions on induced demand by ride allocation, elaborate on shared vehicle fleets. For a privately owned automated vehicle within a household, only Correia and van Arem (2016, p. 85) find the magnitude of empty ride allocation caused by automated vehicles to be 11.5%. Therefore, the assumption on induced demand by empty ride allocation is set to 10% (round off from 11.5%), however, in the opposite direction of the existing travel demand pattern:

$$T''_{ij;car} = T'_{ij;car} + 0{,}10 * T'_{ji;car}$$

In this scenario, areas with limited parking spaces available or with strict parking policies will prohibit parking on the streets but obliges vehicles to park in designated parking zones outside the urban core. Correia and van Arem (2016) find that the percentage of empty kilometres in such parking scenarios is to be found around 50-65%. However, this result also comprises empty kilometres caused by ride allocation. Additionally, this study uses the city of Delft, the Netherlands as a close system case-study. In a larger system, parking zones potentially can – in relative terms – be closer to the destination of the vehicle, resulting in lower percentage of empty vehicle kilometres. Therefore, it proves challenging to implement these finding within this scenario. Instead, all arrivals in the morning peak within the parking restriction zones are after reaching the destination sent to specific parking zones at the outskirts of the built environment as described by Zakharenko (2016). To incorporate the cost of such additional trip to the OD-pair, the parking model is altered to such extent that all zones have unlimited capacity and a parking information system.

$$T'''_{ij;\,car} = T''_{ij;car} + \left(\sum_{j \in P} T_{ij;\,car}\right)_{jQ}$$

for zones with a parking policy $\boldsymbol{P}$ to parking zone $\boldsymbol{Q}$.

Road capacity and efficiency

The assumption is made that vehicles are equipped with sensors, but that V2V systems do not reach optimal state. To not overrate the potential increase in highway capacity based on theoretical studies, we follow the increase of 43% by Tientrakool et al. (2011) and round that off to 40% for ex-urban roads. For urban roads, we assume half of that increase to generate a similar pattern as Milakis et al. (2017). Regarding intersections, the delay factor for all intersections is set to 0.25.

7.4.3 SCENARIO 3: CONSTRAINT

In this scenario, automated driving develops to conditional automation. Automated driving is only allowed yet obligated on highways. Automated driving therefore contributes to infrastructure capacity and travel comfort, yet no induced demand will occur.

Travel impedance factors

One can derive an assumption for a decrease in value of time based on the "AV …in standby" and "AV…in demand" scenarios by Milakis et al. (2017) in which a decrease in value of time is estimated to be respectively 21% and 16%. The constraint scenario uses a 15% (round off 16%) decrease in value of time, also to differ from the value of time changes in other scenarios. Other factors in the travel impedance remain unchanged.

Road capacity and efficiency

Similar benefits in road capacity in extra-urban roads on road capacity is assumed as for scenario 2: growth. Automated driving is not allowed within urban areas and therefore no adjustments are made to roads within the urban environment nor to intersection delay factors.

7.4.4 SCENARIO 4: DECLINE

Automated driving develops to full automation but in various occasions drivers still prefer to drive the vehicle themselves. For that reason, there is still a considerable number of conventional vehicles on the road. However, because of the possibilities of using automated vehicles without owning a licence, public transport will disappear. This scenario might seem far-fetched. Mostly, studies elaborate on the positive effects of automated driving. This scenario is conducted to also explore the negative side of the spectrum of automated driving. No changes in travel impedance are considered.

Travel demand

Within this scenario, all travellers have access to an automated vehicle. Additionally, all trips prior made using public transport are now made with shared automated vehicles on the road network. The public transport OD-matrix is therefore also assigned to the road network.

$$T'_{i,j;car} = T_{i,j;car} + T_{i,j;PT}$$

Some induced demand by empty ride allocation emerges. A similar percentage is assumed as for scenario 2: growth, namely 10% in the opposite direction of the pattern of the OD-matrix.

$$T''_{i,j;car} = D'_{i,j;car} + 0{,}1 * x'_{j,i;car}$$

Road capacity and efficiency

Idle driving instead of parking shows already that this scenario has also negative aspects of automated driving on road capacity. Additionally, this scenario assumes that mixed-traffic of automated and conventional vehicles leads to a capacity decrease of 20% on ex-urban roads.

7.4.5 OMNITRANS MODELLING PROCEDURE

To calculate accessibility using VRU, one must derive the travel resistance or impedance between zone ***i*** and zone ***j***. Naturally, such procedure is executed by skimming the model network. However, OmniTRANS only allows for a syntax to skim for factors concerning the route choice (cost and time). The factors relevant for this study do not only comprise these factors. Also, other factors which are considered in the destination choice process executed in the simultaneous gravity model. Most relevant factors in this case are related to parking resistance. Skim matrices with data on the full travel impedance can therefore only be obtained through running the whole demand model procedure. This asks for additional modelling steps for evaluating induced demand effects since it is not possible to assign a custom OD-matrix to the network and perform a network skim for adequate accessibility calculations: after assigning induced demand to the network, the demand model must be executed once again to obtain the required skim matrices. This leads to the procedure in four sequential steps:

- Step 1: Run the demand model with parameter changes but without induced demand. Output is the OD-matrix without induced demand.
- Step 2: Add induced demand to the OD-matrix. For some scenarios, this is simply applying a factor to the matrix. For other scenarios, more complex operations are necessary. Output is a mutated OD-matrix.
- Step 3: This OD-matrix is assigned to the network. Output is the link loads on the network from this OD-matrix.
- Step 4: To obtain the required skim, the demand model must be executed again. However, new OD-matrix estimations must not be performed. Therefore, the network loads from step 3 are defined as pre-load on the network. The trip ends for each zone and purpose are set to zeroes. By running the demand model, the skims are generated with the network conditions set in step 3 without making changes to this condition.

Because of runtime limitations (the full procedure for one day part takes around 2.5 days on a remote desktop high performance computer) the simulation is only limited to the morning peak.

7.5 RESULTS

The primary purpose of the transport modelling study is to examine the accessibility effects of automated driving. Yet since the transport model used goes through various phases of a traditional four-stage model, additional information can be obtained. Therefore, the result section also briefly elaborates on link loads and network conditions. These provide for input of the urban quality design study of the next chapter.

7.5.1 ACCESSIBILITY EFFECTS

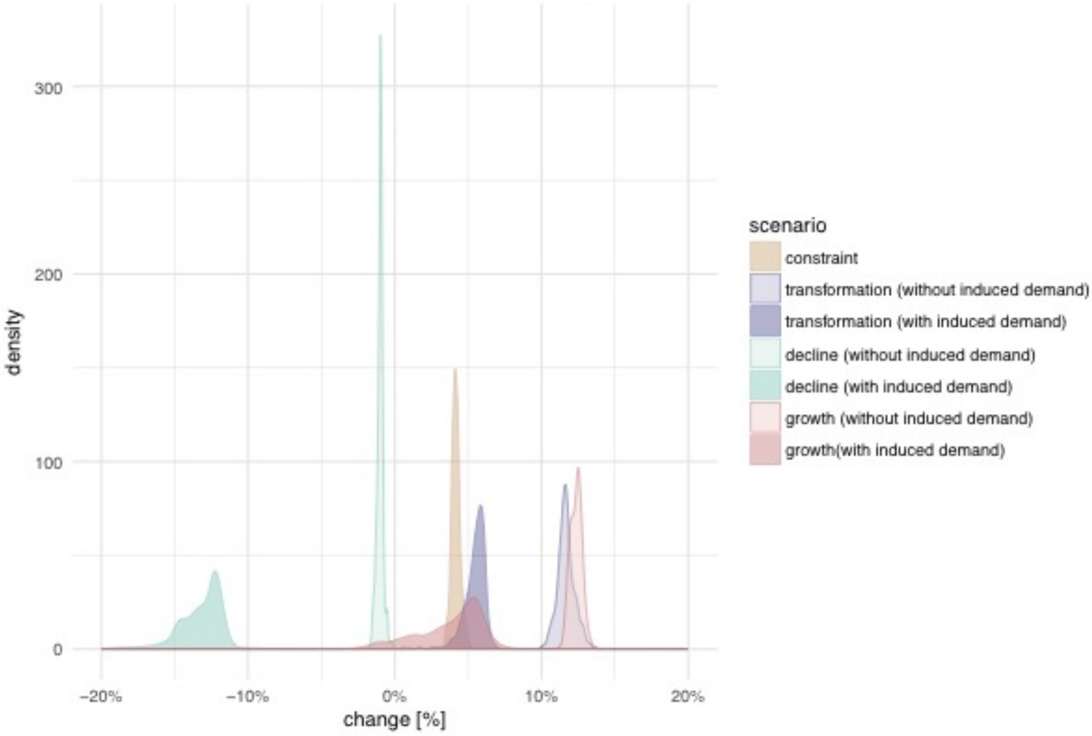


Figure 7-6: Distribution of accessibility changes in percentages for each scenario for purpose commute, mode car.

Figure 7-6 shows the distribution of accessibility change in percentages for each scenario for each VRU zone in the province of Utrecht. In Figure 7-7 - Figure 7-13 the accessibility changes are depicted on maps. What reveals is that the change in accessibility across all zones is to some extent homogenous within a scenario. However, the changes between scenarios is large. Many of the improved efficiency measures of automated driving benefit accessibility. However, these benefits are in all cases reduced due to induced demand on the road network.

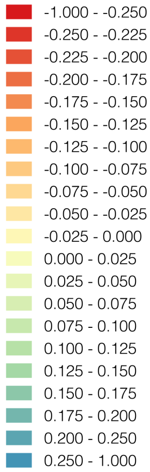
Some areas show up for their contrasting accessibility change compared to the other zones within the study region. These zones are in the city centre of Nieuwegein, Woerden and Zeist. In these areas parking policies are enforced which is a possible explanation for the contrasting values. However, also an industrial area on the east skirt of Veenendaal appears as an outlier. For some reason, a lot of congestion emerges around the on-ramp/off-ramp in these zones. The most plausible explanation could be that it passes excessive traffic because it is on the end of the focus area of the model. East of Veenendaal the transport model becomes less detailed and coarse.

By making comparisons between scenarios, it reveals that both transformation scenario and growth scenario show similar accessibility changes when induced demand is not considered. Transformation knows higher road efficiency but lower value of time reduction compared to the growth scenario. When comparing the two scenarios including the induced demand, similar magnitudes of accessibility changes are found although induced demand in the transformation scenario is significantly higher. This can be explained to the higher assumed road capacity. Roads are therefore able to serve induced demand similarly. However, the distribution of accessibility change is less homogenous in the growth scenario compared to the constraint scenario. In and around the city centre of Utrecht, lower accessibility gains and even slight losses are observed. This is due to the new mobility pattern from the city centre to the valet-parking zones.

The constraint scenario knows no induced demand and only capacity benefits on the ex-urban roads. It results in a homogenous accessibility increase of around 4% for all zones. The decline scenario, in which road capacities decrease and public transport is induced to the road, significant decreases in accessibility are observed. When induced demand is not considered, a similar pattern reveals as in the constraint scenario, yet to the negative side of the spectrum. However, by adding induced demand, accessibility levels decrease significantly, especially in the north-eastern area of the province. All public transport traffic is assigned as cars to the road network and this proves disastrous for accessibility.

Overall, a conclusion can be drawn that the differences in accessibility between different zones is limited but that the accessibility will rather homogenously increase (or decrease) in various scenario. From that perspective, this does not mean that no significant changes in accessibility are expected. When evaluating the accessibility effects through the perspective of a logit model, not the relative differences but the absolute differences lead to changes in utility. With that in mind, one can conclude that the absolute differences between higher and lower accessible places will increase, leading to higher utility for residence in already better accessible areas.

From a welfare perspective, society benefits from a homogenous increase in accessibility. Better levels of accessibility prove beneficial for matches on the housing market, larger opportunities to share investments and more interaction for innovative processes (Duranton & Puga, 2004).



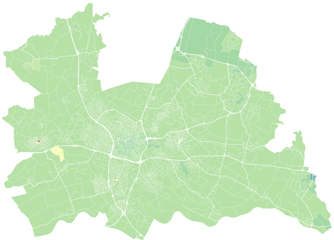


Figure 7-7: Transformation without induced demand

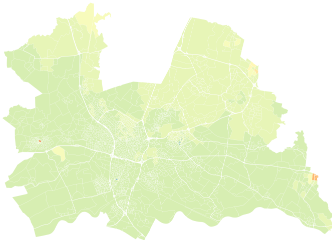


Figure 7-8: Transformation with induced demand

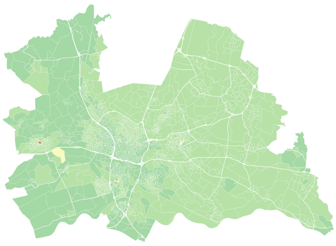


Figure 7-9: Growth without induced demand

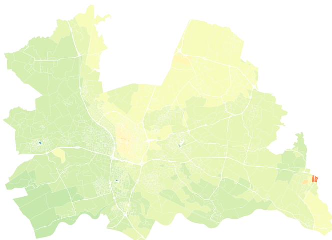


Figure 7-10: Growth with induced demand

Figure 7-11: Constraint

Figure 7-12: Decline without induced demand

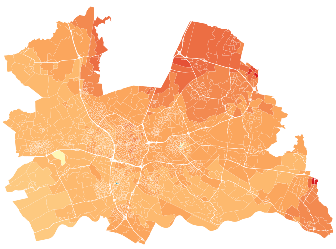


Figure 7-13: Decline with induced demand

7.5.2 LINK LOADS AND NETWORK CONDITIONS

The full runtime procedure has been executed and therefore the link loads on the networks can be obtained. This provides for a good indicator to assess the adequacy of the infrastructure (capacity). The results of the simulations are depicted on maps as an indicator where congested roads are. The indicator used for congestion is the so-called I/C-value (intensity divided by capacity). When the I/C-value is 1 or greater than one, it means that more traffic passes the link than theoretically possible. This is an indicator for heavy congestion. The reason why it is possible to observe higher intensities than capacities allow, is because all traffic within a day part must reach its destination.

In the current situation, VRU shows no significant congestion by I/C-values greater than 1 in urban areas. On the highways, congestions occur on some parts of the A1 and A2 highways, plus on the A27 (Figure 7-14).

Figure 7-14: Roads with I/C value >1 for the base scenario, morning peak

Highway capacities double in the transformation scenario, resulting in less congestion on the road sections where congestion occurs in the current situation (Figure 7-15). However, congestion occurs on access roads to the city centre of Utrecht. This congestion is caused by an additional number of cars entering the city centre, carrying passengers that would previously enter the city centre with public transport. A similar pattern in the infrastructure loads can be observed in the growth scenario (Figure 7-16) regarding inner city congestion. However, this congestion is not the result of induced demand entering the city centre, but by cars leaving the city centre to reach the designated parking areas. This also leads to more congestion on some parts of the Utrecht ring road.

For the constraint scenario, the automated driving changes only occur by a modest capacity increase on the ex-urban roads. This increase is enough to have no congestion in the morning peak (Figure 7-17). For the decline scenario, almost all highways show congestion due to the decrease in capacity and increased demand. Also, the inner-urban roads of Utrecht find congestion because of the diminishment of public transport.

Figure 7-15: Roads with I/C value >1 for scenario Transformation, morning peak

Figure 7-16: Roads with I/C value >1 for scenario Growth, morning peak

Figure 7-17: Roads with I/C value >1 for scenario Constraint, morning peak

Figure 7-18: Roads with I/C value >1 for scenario Decline, morning peak

7.6 DISCUSSION

The results obtained in this chapter provide for input in the residential location choice model and for the assessment of the spatial quality effects of automated driving. The accessibility is an evaluation factor within the residential location choice model hence it will be further applied in that research step. By obtaining the link loads, requirements for the integration of infrastructure within the urban environment is obtained and can provide for input to assess the spatial impacts of automated driving on a lower scale.

The accessibility effects of automated driving are beneficial for scenarios that assume higher infrastructure capacities and travel comfort. However, induced demand has a negative benefit for accessibility gains. Additionally, the accessibility effects are found to be homogenous around the study area. This can be partly explained to by the relative good quality infrastructure present within the area. Areas with underdeveloped infrastructure or geographical constraints are likely to show less homogenous accessibility effects.

The impact of automated driving technology on highway performance can prove beneficial when induced demand is modest. If traffic flow would be reduced due to automated driving (e.g. under mixed traffic conditions), serious congestion on the highways might be a consequence. Considering urban areas, the performance of the transport system remains rather stable except for the city of Utrecht. This area generates and attracts traffic in a much larger magnitude than surrounding settlements. This poses challenges for the urban network. If automated driving replaces public transport or if valet-parking solutions on the outskirts of town are becoming reality, significant changes to the urban road network are needed to accommodate these developments. Another solution lies in different concepts such as local parking solutions or alternative mass transit systems.

8 SPATIAL TRANSFORMATION AND QUALITY EFFECTS OF AUTOMATED DRIVING

This chapter elaborates on the integration of the infrastructure within neighbourhoods and the consequences of automated driving on this integration. Regarding this integration of infrastructure, two different scale levels are considered. The first level is that of the neighbourhood. On that level, the spatial occupation of infrastructure and related land-use functions are considered. The second level is the street level. On this level, not the function of the road is addressed primarily, but the lay-out and design of the road. The goal of this assessment is to generate data on how neighbourhoods can transform in terms spatial quality related to mobility. Chapter 3 shows that the spatial quality of a place is a factor in the residential location choice, hence it is assessed in this study.

Because it is not feasible to assess every neighbourhood and every street on spatial effects, the assessment is based on the neighbourhood typologies by ABF Research (2003) (also referred to as hwm typologies, which are introduced in subsection 3.1.2) . This typology of neighbourhoods is an indicator of the environment and therefore comprises explicit quantitative factors but also qualitative factors that coincide with the defined variables. Main reason for using this typology is that it allows to consider specific zones representative for other zones with a similar typology. Subsequently, the neighbourhood typologies coincide with input for the residential location choice model and must therefore be obtained at some point in this study. Therefore, the chapter starts with a section on the classification of the neighbourhoods. To make this classification an algorithm using geospatial data has been developed.

The potentials for transformation to enhance spatial quality are assessed through a design exercise. This design exercise is less an algorithmic process compared to research steps where quantitative models are applied. Still, a schematic approach to this design research process has been attempted to maintain reproducibility. This is crucial since the design process is a mean to generate data. The scenarios are implemented within the spatial context by means of drawing. With help of the network loads obtained in chapter 7 by the transportation model study, it is possible to assess whether infrastructure meets the required demand in the scenarios. If possible, the amount of infrastructure in the streets can be reduced. Within this process, a certain degree of abductive reasoning is applied (Figure 8-1). This might be perceived to be speculative. However, by assessing this problem based on the existing spatial context, many answers will be provided through this context.

Output of this research step is in the first step visual by nature. This is because the research process is primarily based on data and research. However, this material is not directly compatible with the other research steps. For each scale level, a different solution is applied. On the neighbourhood level, a qualitative rating is given about the transformation potential for new urban functions, ranging from ***none*** to ***high***. This information then provides for information later in the process of strategy development. On street level, the findings will provide for direct input in the residential location choice model. With the help of hedonic pricing models (explained briefly in section 3.3), assumptions can be made to express proximity and spatial quality effects on the value of properties (Crompton, 2001). This will be further explained accordingly in section 8.3.3.

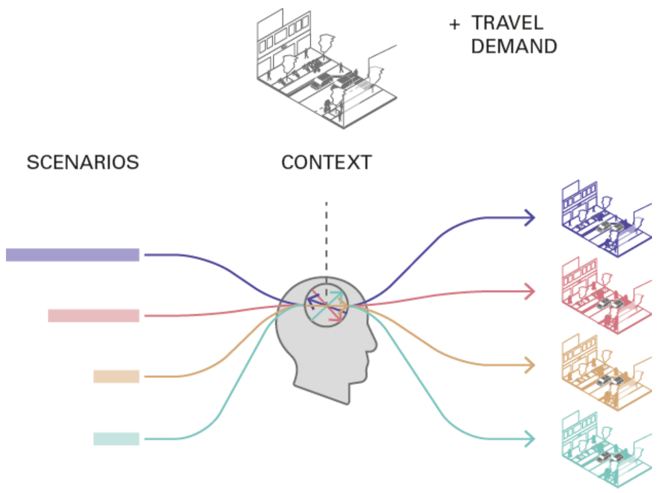


Figure 8-1: The transport system requirements and the travel demand on the infrastructure for each scenario is implemented in the neighbourhoods and streets to enhance quality of the urban space.

8.1 TYPOLOGY CLASSIFICATION AND SELECTION

The hwm neighbourhood typologies administered by ABF Research (2003) provide input to the residential location choice model used within TIGRIS XL and in this study to evaluate qualitative aspects of automated driving regarding the neighbourhood environment. Consequently, it is of importance of this study to classify zones within this study accordingly.

8.1.1 TYPOLOGIES

The neighbourhood typologies know two classes. The aggregated and the disaggregated typologies. The disaggregated typologies go by the name of hwm13 and are a further specification of the hwm5 typologies. The neighbourhood typologies do not specify the neighbourhoods from a morphological point of view. Instead, it is a hybrid indicator for the town size, building stock and level of service (ABF Research, 2003). By combining these metrics an indicator is obtained that reveals the characteristics of the neighbourhood itself, but also of the town in which it is situated. An overview of the typologies is depicted in Table 8-1, augmented with information on the typologies provided in Zandbelt&vandenBerg (2009). Some minor adjustments have been made to the classification for this study. The original neighbourhood typologies distinguish rural accessible and rural peripheral. Rural peripheral areas are more than 20 minutes of travel distance of a centre urban neighbourhood environment. Very few areas within the study area meet this classification additionally, no significant difference is expected in appearance with the rural accessible typology. Therefore, these are considered both as rural accessible. The typology 'work' has been added too since some areas comprise mostly employment and few residential purposes. When an area is classified as work, it will not be further elaborated.

There is only data available about the classification of hwm5 neighbourhoods in some part of the study area (Figure 8-2). To make a classification according to the hwm13 classification for the study area, a spatial analysis is conducted to come to the right classification. To achieve this, a deterministic geospatial data algorithm is developed.

Table 8-1: Quantitative characteristics for the neighbourhood typologies (based on: ABF Research (2003); Zandbelt&vandenBerg (2009)

Aggregated typology	**Disaggregated typology**	**Town size**	**Degree of mixing**	**Density of housing area/ha**	**Total dwelling density/ha**	**Dominant building period**
Centre-urban	1. Centre-urban-plus	Large town	Housing between amenities and employment	> 60	> 30	Mixed
	2. Centre-urban	Town	Housing between amenities and employment	40-60	10-30	Mixed
	3. Centre-small-urban	Small town	Clustered amenities and employment	20-40	10-30	mixed
Outer-centre	4. Urban pre-war	Town/large town	Clustered amenities and employment	> 60	> 30	< 1940
	5. Urban post-war compact	Town/large town	Mostly housing	40-60	10-30	1940-1970
	6. Urban post-war ground-level	Town/large town	Mostly housing	20-40	10-30	1940-1990
	7. Small-urban	Small town	Mostly housing	20-40	10-30	1970-1990
Green-urban	8. Green-urban	Town/large town	Only housing	20-40	10-30	< 1940 or > 1990
	9. Green-small-urban	Small town	Mostly housing	20-40	3-10	Mixed
Centre-village	10. Centre-village	Small town/village	Mostly housing	20-40	< 3	Mixed
	11. Village	Small town/village	Only housing	20-40	<3	1940-1970
Rural	12. Rural	Village	Only housing	<20	<3	mixed
Work	Work	-	-	-	-	-

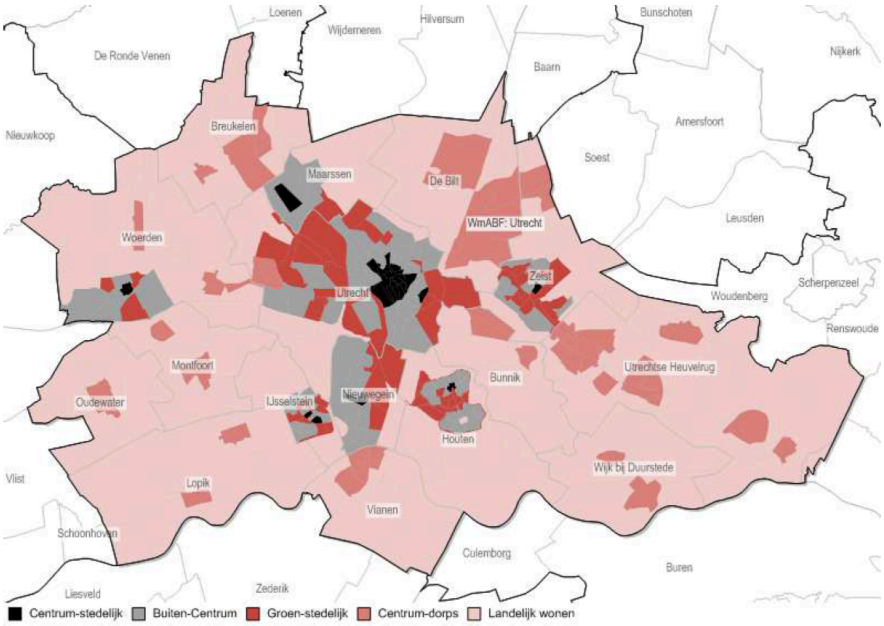


Figure 8-2: Classification of zones according the hwm5 categorisation for a region defined as the housing market area Utrecht.

8.1.2 DETERMINISTIC NEIGHBOURHOOD CLASSIFICATION ALGORITHM

With the help of an algorithm, the classification of neighbourhoods can be automated. This makes it possible to classify many zones at an instant based solely on data. The algorithm is primarily as such. After that, some minor changes have been made to improve accuracy. The algorithm is conducted in a GIS. An extract of the graphical representation of a part of the model is depicted in Figure 8-3.

The data sources used in the analysis are the following:

- ***CBS bevolkingskernen in Nederland 2011*** dataset (CBS, 2014): This dataset provides among other things the boundaries and population numbers in an urban core.
- ***Basis Administratie Gebouwen (BAG)*** (Kadaster, 2016a): This dataset contains all buildings in the Netherlands with information about their function and building year.
- ***Bestand Bodemgebruik 2012 (BBG)*** (CBS, 2012): Specifies the land-use cover in the Netherlands.
- ***Areas of 4-digit postal zones*** (ESRI Nederland, 2015).

The datasets do not correspond in year. This is due to availability of the datasets. For the ***CBS bevolkingskernen*** and **the *Bestand Bodem Gebruik***, the most recent datasets are used. The BAG is revised every year, however not publically available for individuals. The 2016 version was made available for this research. Postal zones have not been revised in the study area for the last years.

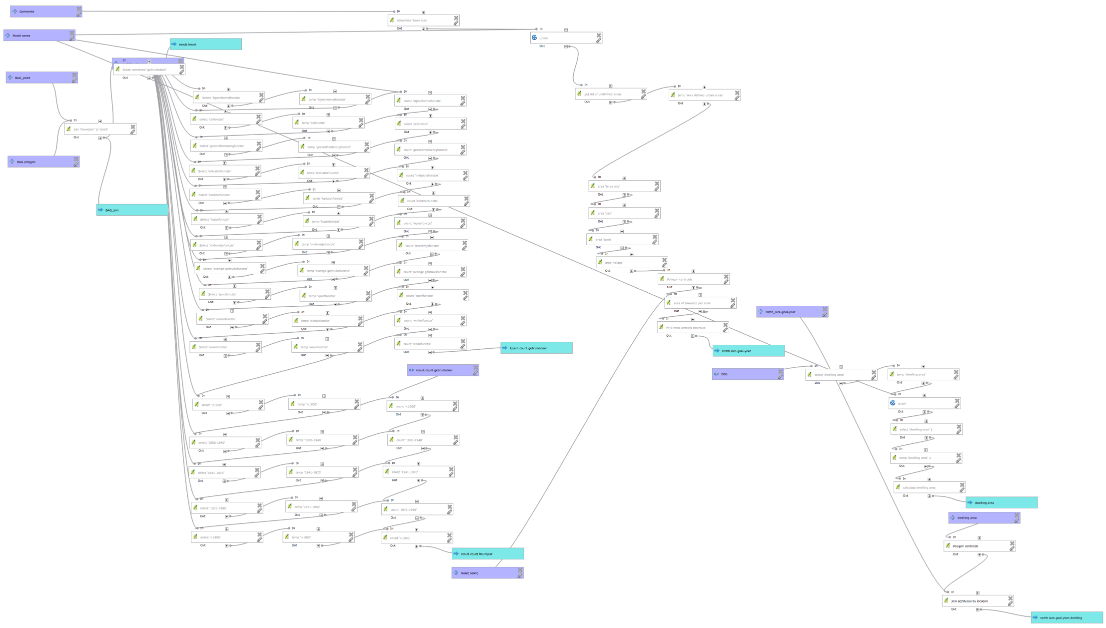


Figure 8-3: Graphical representation of a part of the algorithm. The algorithm has been cut in various sections to prevent errors in spatial join procedures.

The datasets need to be prepared to run the algorithm. This is done by the following steps, which are also depicted in Figure 8-4.

First step of the analysis is to prepare the zones. The zones are classified according to 4-digit postal zones. However, if a zone comprises both country side and built core, the zone is split accordingly. Rural area is area outside the areas of a build core as defined in the ***CBS bevolkingskernen*** dataset. Town size is determined based on **the** ***CBS bevolkingskernen*** dataset. This dataset provides the population size in an urban core. According to ABF Research (2003), large towns are the four large cities in the Netherlands plus Eindhoven and Groningen. For this research, the population threshold to classify as a large town is therefore set to 200 000 inhabitants. The city of Utrecht is the only large town in the study area. Towns are set to a population between 50 000 and 200 000 inhabitants, which coincides with the threshold of 27 500 inhabitants used by ABF. Small towns and villages are chosen for populations under 50 000 inhabitants. It is not required to further specify small towns and villages.

The variety in building years and functions of buildings are derived from the ***BAG***. The count of the number of buildings in time is made in the ranges <1900, 1900 -1940, 1941-1970, 1971-1990 and > 1990. The functions are classified in three categories: amenities (purpose of the building contains meeting, or healthcare, lodging or retail), employment (purpose contains industries, office or education) and housing. Hence, also the dwelling density can be determined.

The dwelling area and employment area are obtained from the ***BBG***. The dwelling land-use function is specified as a specific land-use function in this dataset. For employment, areas described with land-use function business park are classified as employment areas. This does neglect smaller employment areas and mixed use areas. This is not a problem since the mere purpose of this step is to classify larger mono-functional employment areas. With these data, it is also possible to determine the density of the dwelling area in the zone when combined with the count of dwellings derived from the ***BAG***.

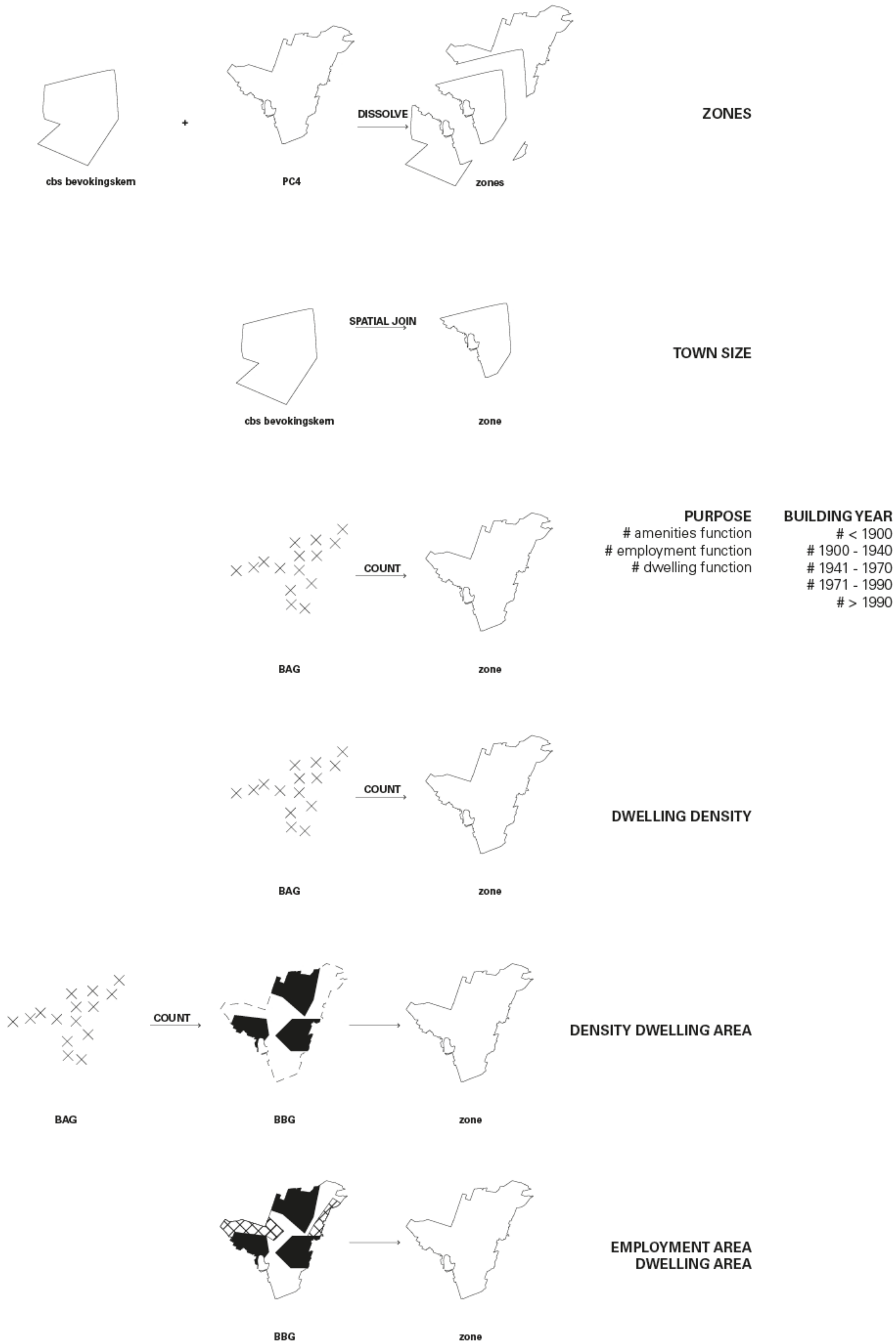


Figure 8-4: Data preparation process.

By running the algorithm based on the qualitative values depicted in Table 8-1, maps can be generated with the zones classified by neighbourhood typology. The algorithm can be run on any location in the Netherlands.

8.1.3 CLASSIFICATION

The algorithm generates the map in Figure 8-5 by classifying all zones according to the hwm13 typologies. The outcome of the constructed algorithm cannot be fully validated. However, from qualitative judgement and comparison with Figure 8-2 from Faessen, Gjaltema, and Vijncke (2011, p. 13), it is considered accurate for this study. One of the main explanation for different area classification can be concluded from the differences in zone sizes and boundaries. The classifications are later aggregated to hwm5 typologies to provide for input in the residential location choice model. In Figure 8-7, pictures of the corresponding neighbourhoods are displayed. It shows that the neighbourhoods have to some extent different appearances.

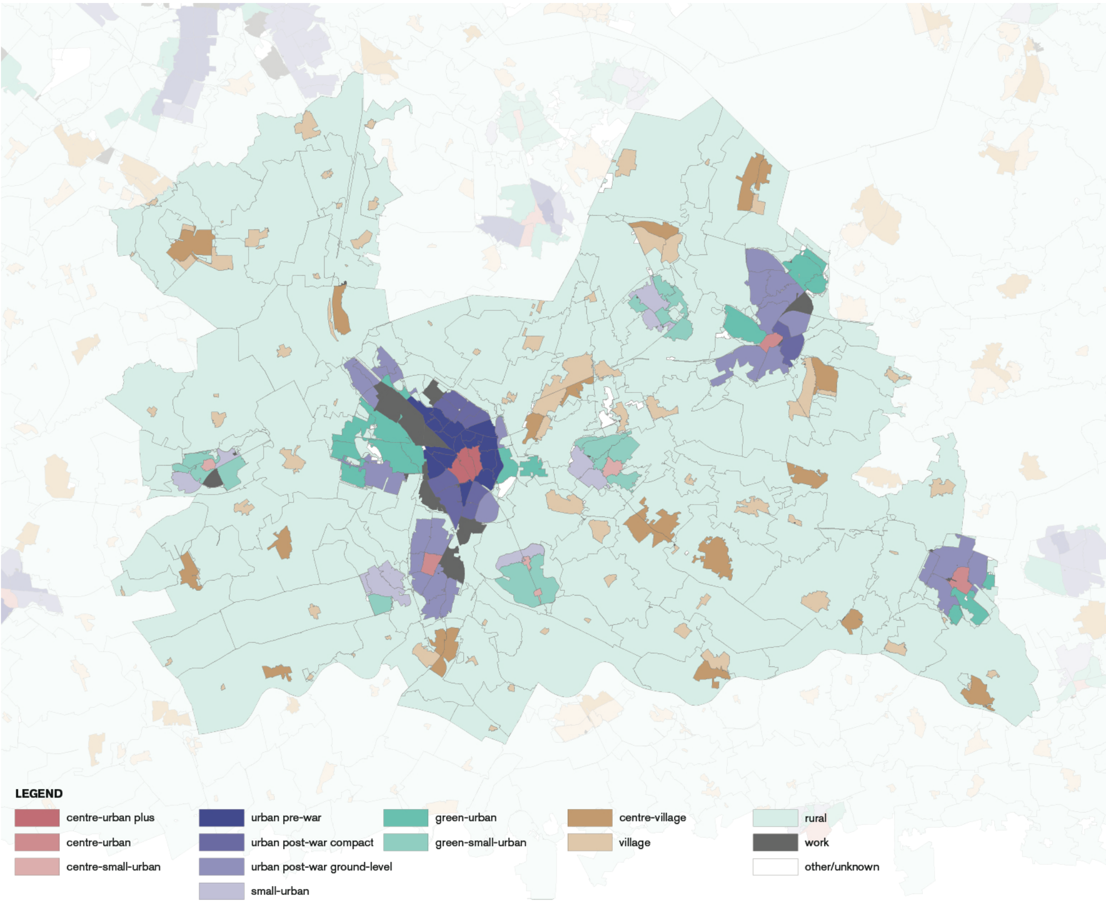


Figure 8-5: Neighbourhood types according to the hwm13 classification.

Some typologies show strong similarities in appearance. This can be assigned to the fact that the classification also relates strongly on the size of town in which the neighbourhood is located. This is a good indicator for the level of services for the proximity of this neighbourhoods as well as other qualitative factors. However, from a mere spatial and morphological point of view, some neighbourhood typologies show some commonalities. Overlap is found between various small-urban, green-urban and village environments from a morphological perspective. For instance, some areas of Lunetten and the area of the north of

Houten are classified as resp. urban post-war grounded and small-urban. However, from a morphological perspective, both areas can be classified as so-called cauliflower neighbourhoods with a similar layout (Figure 8-6). Although the classification of neighbourhood typologies reveals its flaws from a morphological perspective, it still proves beneficial to assess the spatial quality through this classification for its correspondence with the residential location choice model. By classifying the zones solely from a morphological perspective (see e.g. Berghauser Pont and Haupt (2009)), some characteristics of the urban environment related to the e.g. activities would get lost. Such factors relate directly and indirectly to the travel demand. This aspect is very important in relation to this research. Additionally, classifying an area from a morphological perspective asks for data for building heights or levels. There is no dataset readily available that incorporates these data, hence complicated spatial analysis would be necessary.

Figure 8-6: Layout of two neighbourhoods both bearing morphological characteristics of a 'cauliflower' design. However, within the neighbourhood typology algorithm, the areas are classified differently.

Figure 8-7: Overview of the appearance of neighbourhood typologies with pictures as example.

8.1.4 SELECTION OF REPRESENTATIVE ZONES PER TYPOLOGY

With the strengths and limitations of the classification methodology in mind, a representative zone or ensemble of zones for each typology is selected to further assess the spatial quality impacts of automated driving on lower scale levels. Each selected area is for the sake of simplicity considered to be representative for all areas bearing a similar classification. The considered areas are displayed in Figure 8-8.

The spatial quality effects and transformation potentials of the neighbourhood are considered on two scale levels. The first step is to determine the transformation potential on the level of the zone or the ensemble of zones. After that, the potentials for transformation and spatial quality enhancement on street level are evaluated.

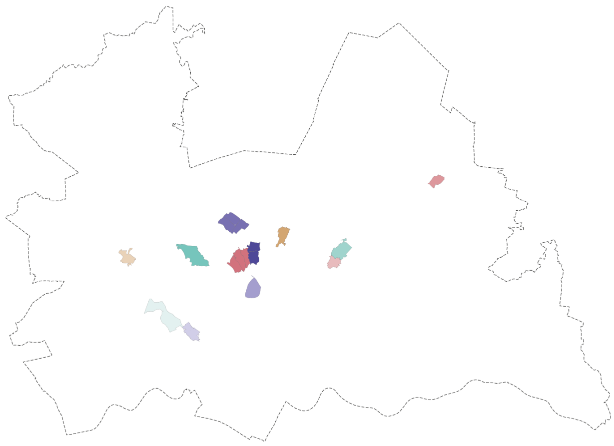


Figure 8-8: Selection of the neighbourhoods that are used to further assess the urban quality effects of automated driving. Each zone or group of zones represents one neighbourhood typology.

8.2 TRANSFORMATION POTENTIAL ON NEIGHBOURHOOD LEVEL

On the scale level of the zones, the transformation potential of each neighbourhood type is examined based on a representative zone per neighbourhood type. In this assessment, the procedure is to a significant extent led by the context because the transformation potential is very context related. Transformation potential on this scale level means the ability to employ new urban functions on spaces restricted for transformation in the base case - either directly or through external effects. By obtaining insights in the development potential for new functions, an indication is found where opportunities lay for urban development.

8.2.1 APPROACH

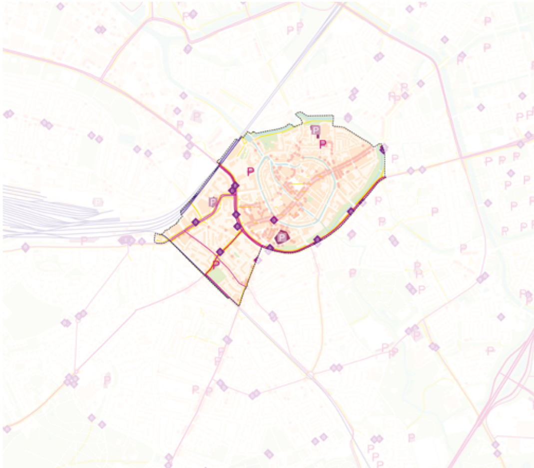
The first step in the process is the generation of maps that show the infrastructure and land-use within the specific zones. Hence the maps in Figure 8-9 and Figure 8-10 are generated based on following geospatial data sets:

- ***TOP10NL*** (Kadaster, 2016c) for the buildings, buildings with parking function, land-use and infrastructure;
- ***BAG*** (Kadaster, 2016a) for amenities
- Public transport data of Provincie Utrecht (2016).

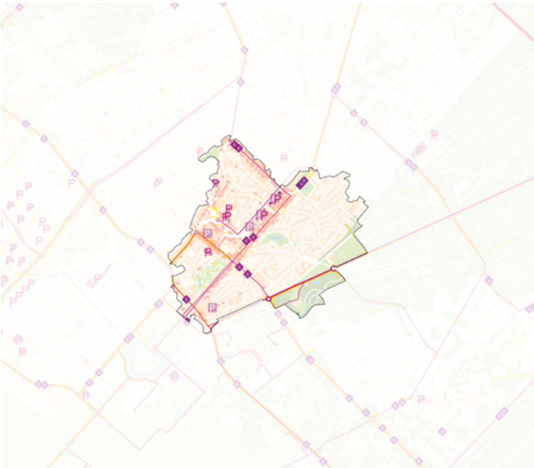
With the maps as basis, the transformation potential is examined. This is done by studying the infrastructure requirements within the urban area based on the future transportation system that are assumed in the scenarios and by examination of the network loads derived from the transport model in chapter 7.

1. Centre urban plus

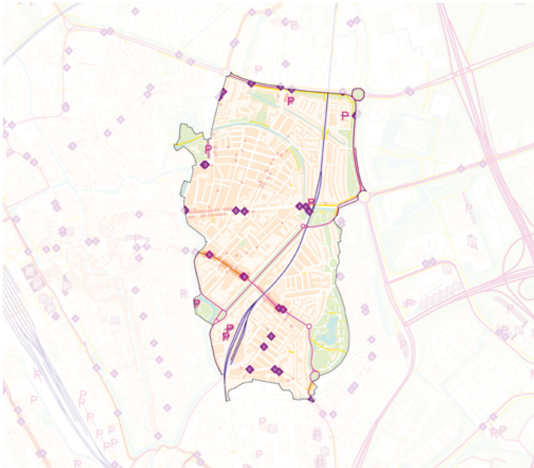
2. Centre urban



3. Centre small-urban



4. Urban pre-war



5. urban post-war compact

6. urban post-war ground-level

Figure 8-9: Maps of the infrastructure integrated within the urban environment in each example zone. (1/2)

Figure 8-10: Maps of the infrastructure integrated within the urban environment in each example zone. (2/2)

8.2.2 RESULTS

Mapping the infrastructure requirements on the study areas reveals new aspects. This is explained by the example of examination of the centre-urban plus zone of the city centre of Utrecht (Figure 8-11). This area is characterised by its high urban environment. What characterises the area is the presence of the central railway station, unique services and therefore also a relatively high parking demand adjacent to the city centre and the Jaarbeurs area. Within the transformation scenario, public transport is replaced by an on-road on demand automated driving system. This diminished the need for a public transport hub in the current configuration. Instead, another drop-on and drop-off system must be accommodated. Yet this needs a different layout and allows to be less concentrated which enables for rethinking the station area (see earlier example in Figure 5-10). Also, the need for parking on street and in large parking buildings can be re-considered. The shift from mass transit to on-road on demand solutions requires no adaptations in this scenario. However, there is a need for the Catharijne single to be reconsidered as an important access point to the city centre. For the growth scenario, mass transit still provides an important role within the transportation system. Parking within the city centre is diminished because of valet-parking solutions. Just as in the transformation scenario, new functions or drop-on/drop-off infrastructure can be assigned to the parking buildings and areas. However, as the transportation modelling study reveals, the load on some roads in the network will increase because of additional traffic movements. This asks for upscaling of some links or other solutions. The constraint scenario has no significant effects on the network performance nor on the configuration of the transportation system itself. Benefits are mostly found on the network outside urban areas. Therefore, also no transformation potential is found for this area. This is different for the transportation potential of automated driving under the decline scenario. Just as in the transformation scenario, the need for a large scale public transport hub within the area diminishes. However, many adaptations are necessary to the network to facilitate accommodating traffic.

This exercise has been applied to all example areas. The result is depicted in Figure 8-12 - Figure 8-14. From these results, it reveals that the potential of transformation differs between the scenarios, and therefore the opportunities for new urban functions is very dependent on how automated driving develops. Neighbourhoods that provide for a lot of parking garages or fields and zones that facilitate a significant area for public transport infrastructure have the highest transformation potential under the assumption of obsolete public transport or valet-parking solutions. These benefits are especially considerable in the neighbourhood typologies that are placed within bigger cities. The smaller towns often consist of neighbourhood types with few larger parking areas. Parking is often located on the plot or on the streets. Additionally, neighbourhoods in smaller towns are often not directly connected to mass transit services such as train or metro.

By assessing these neighbourhoods, the benefits of renewed highway design are not considered. That is because – especially in the case study area – highways are often tangential. Only in the case for the example zone of Lunetten, it is found that the buffer area between highway and dwellings allows for new program.

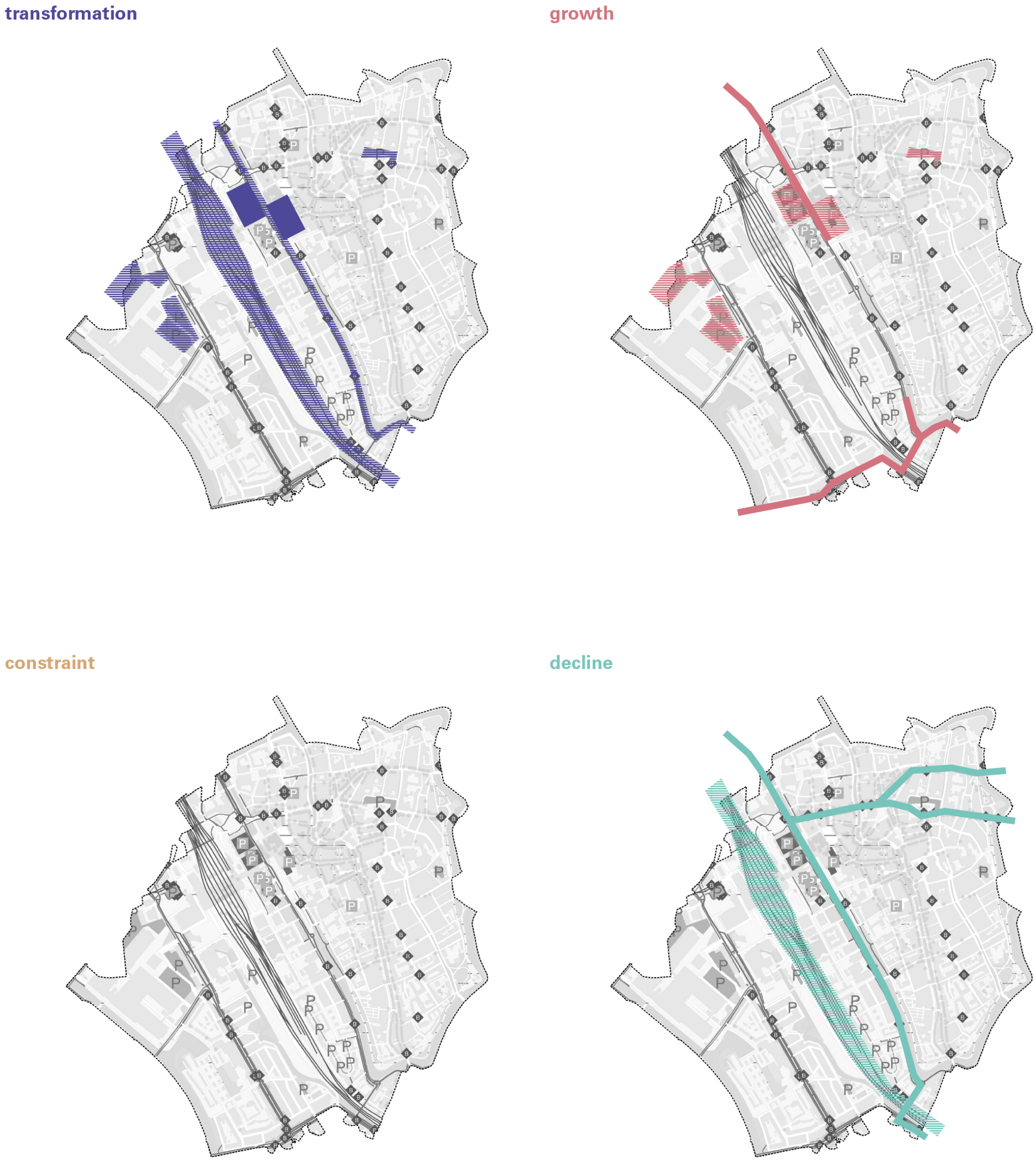


Figure 8-11: Transformation potentials mapped for the city centre of Utrecht under the four scenarios

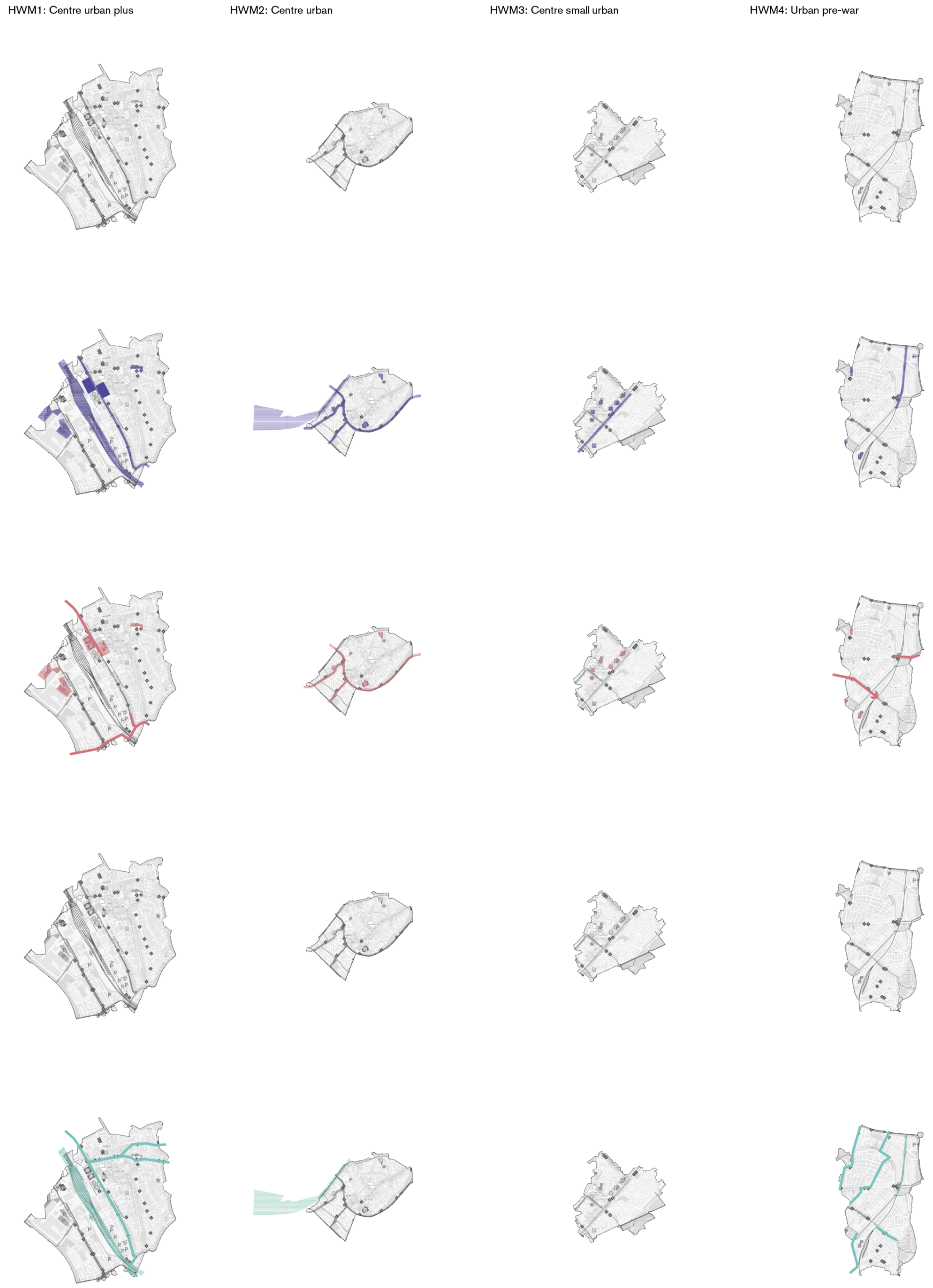


Figure 8-12: Highlighted areas for transformation and adaptation per neighbourhood type under the corresponding scenarios (1/3).

Figure 8-13: Highlighted areas for transformation and adaptation per neighbourhood type under the corresponding scenarios (2/3).

Figure 8-14: Highlighted areas for transformation and adaptation per neighbourhood type under the corresponding scenarios (3/3).

8.2.3 CONCLUSION

Next step is to generalise the insights obtained from this study to the whole study area. This is done by scoring the zones by transformation potential following the criteria defined in Table 8-2. With the help of these criteria, the transformation potential for each neighbourhood type under each scenario is listed in Table 8-3.

Table 8-2: Evaluation criteria for assessment of the transformation potential for zones.

Score	Criteria
High	For zones where either a large area or a significant number of smaller areas (e.g. parking lots) bear opportunities for new urban functions, the transformation potential is considered high.
Moderate	For zones where some smaller areas (e.g. parking lots) bear opportunities for new urban functions, the transformation potential is considered moderate.
Low	For zones where a small number of smaller areas (e.g. parking lots) within the zone bears opportunities for transformation, the transformation potential is considered low.
None	When no areas are suitable for new urban functions caused by automated driving, no potential is considered.

Table 8-3: Transformation potential per neighbourhood type under the corresponding scenarios.

Aggregated typology	Disaggregated typology	Transformation	Growth	Constraint	Decline
Centre-urban	1. Centre-urban-plus	High	High	None	High
	2. Centre-urban	High	High	None	Medium
	3. Centre-small-urban	Medium	Low	None	None
Outer-centre	4. Urban pre-war	Medium	Low	None	Low
	5. Urban post-war compact	High	High	None	None
	6. Urban post-war ground-level	High	High	None	None
	7. Small-urban	Medium	None	None	None
Green-urban	8. Green-urban	Medium	None	None	Low
	9. Green-small-urban	None	None	None	None
Centre-village	10. Centre-village	None	None	None	None
	11. Village	None	None	None	None
Rural	12. Rural accessible	None	None	None	None

8.3 SPATIAL QUALITY EFFECT ON STREET LEVEL

The prior subsection studied the infrastructure requirements on the neighbourhood scale. However, also changes on street level must be considered. The study with the transportation model in chapter 7 reveals that some streets are not able to facilitate the traffic demand in some scenarios, hence adaptations are needed. Other streets can adequately facilitate traffic and need no adaptation or even allow for a reduction of infrastructure for streets to become more attractive by implementing other functions.

8.3.1 APPROACH

For the examination of the spatial quality effects on street level, two type of roads are considered: arterial roads and streets (roads with only local traffic and no defined function for through traffic). In case of specific parking solutions for neighbourhood types, these are considered too. For each example of a neighbourhood typology distinguished in the introduction of this subsection one representative arterial road and local street are selected on which the spatial quality aspects are studied. The results obtained are then assumed to be similar for neighbourhoods with the same typology.

The potential spatial quality gains (or losses) under the different scenarios are examined by drawing an isometric section over a 10 meter stretch of road. An example is displayed in Figure 8-15. The design exercise was the following: with the help of the link loads of the transportation model, judgement was made if the base road profile still meets the demand or that less or more lanes are necessary. Also, the need for existing parking facilities, traffic calming measures etc. are reconsidered based on the assumptions on automated driving in the scenarios. Changes needed are then drawn into the section. Space becoming newly available is filled in with green to enhance spatial quality. Of course other measures are possible too (the design study as described by Wilson (2016) shows the possibility of using this space for pop-up restaurants or street vendors). The reason that other functions than public green are not considered is because these are not omnipresent and can only thrive in very specific locations. This design exercise is applied to roads and streets in each considered representative neighbourhood zone.

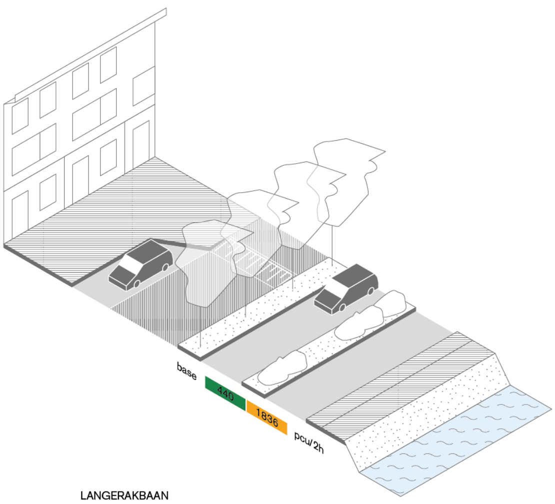
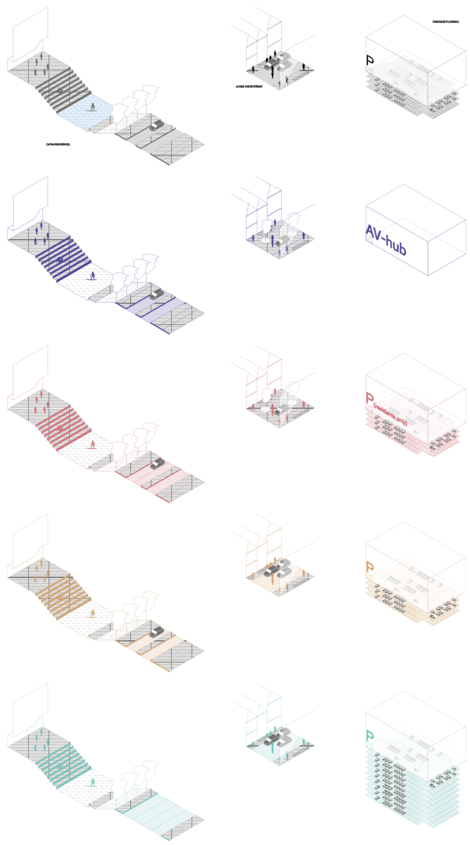
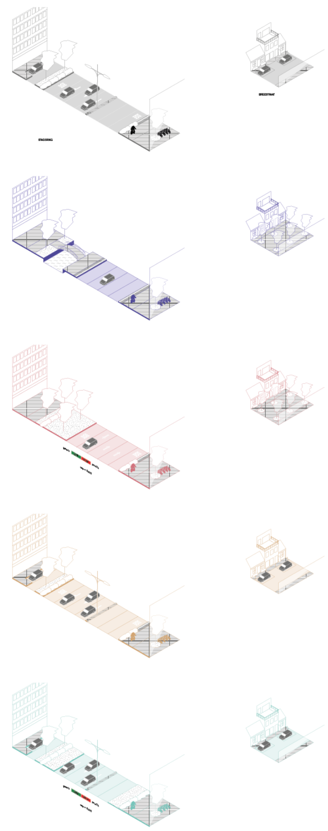


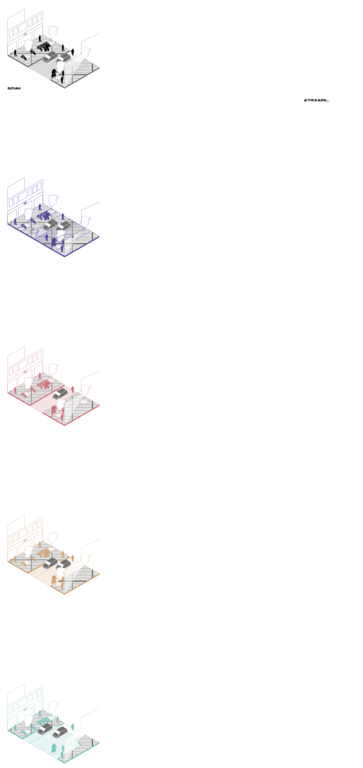
Figure 8-15:The spatial quality effects are investigated by 10-meter road stretches isometric sections.



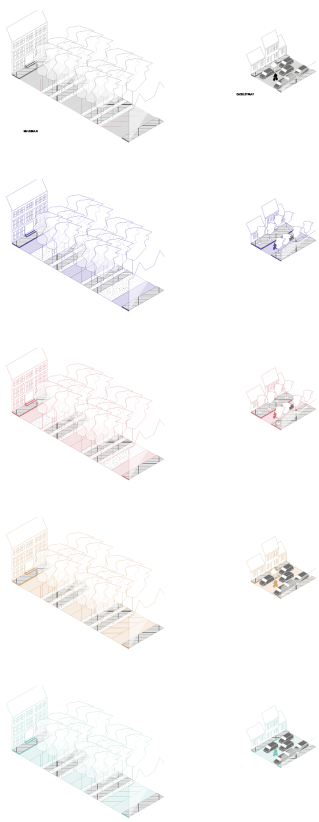
HWM1: Centre urban plus



HWM2: Centre urban

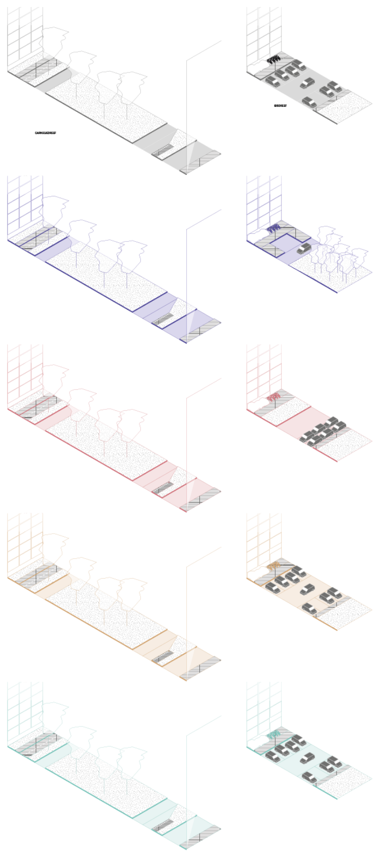


HWM3: Centre small urban

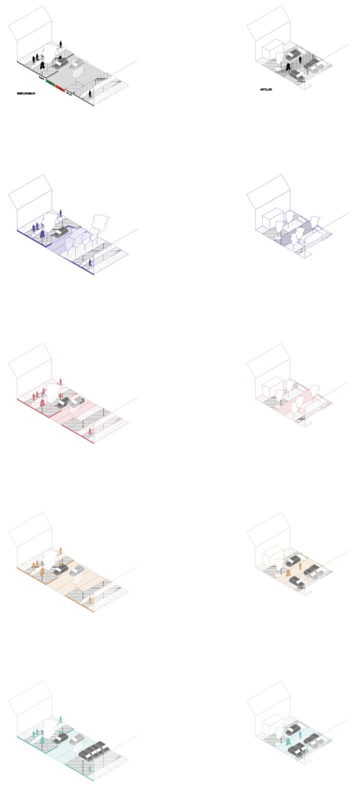


HWM4: Urban pre-war

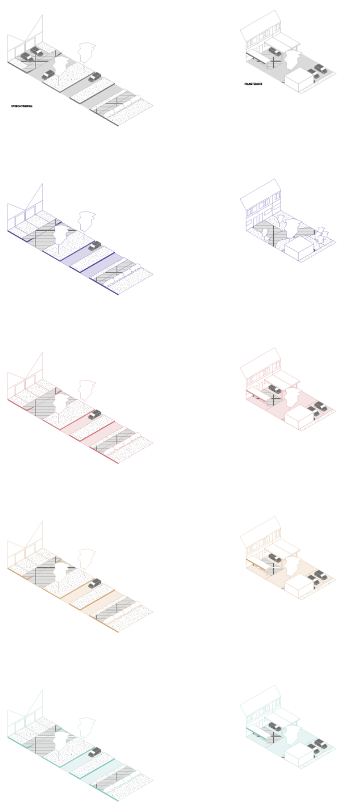
Figure 8-16: Overview of the considered road sections and the corresponding designs for each scenario (1/3).



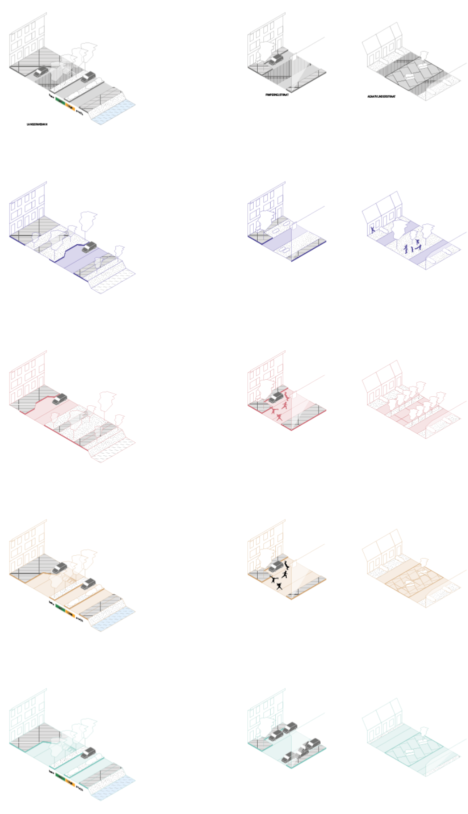
HWM5: Urban post-war compact



HWM6: Urban post-war land-based



HWM7: Small urban



HWM8: Green-urban

Figure 8-17: Overview of the considered road sections and the corresponding designs for each scenario (2/3).

Figure 8-18: Overview of the considered road sections and the corresponding designs for each scenario (3/3).

8.3.2 RESULTS

A summary of the results is depicted in Figure 8-16 - Figure 8-18. For a more detailed overview, see appendix B. The results comprise a lot of data and drawings. The most important conclusions are explained by some examples.

Although the ideas of less infrastructure required sparks imagination, no significant potential is found for many streets to enhance spatial quality. The most important reason is the already current low traffic demand in these streets. Residential streets are often not particularly wide, especially in areas with a predominantly pre-war building stock with narrow street profiles or neighbourhoods designed with traffic calming measures. The largest gain for such streets is to be found in the diminishment of parking places. This must however be facilitated in the scenario and can in turn lead to higher demands in other roads. In Figure 8-19 the transformation potential for the Minckelerlaan in Zeist, neighbourhood typology green small-urban is studied. Because of the front-gardens, the street profile is already attractive for residents. Only for the scenario transformation, significant improvements can be realised through the diminishing of parking. Similar conclusions can be drawn for other residential streets in many neighbourhood typologies, particularly the ones with mainly residential buildings (Figure 8-20).

Green small-urban (hwm9)

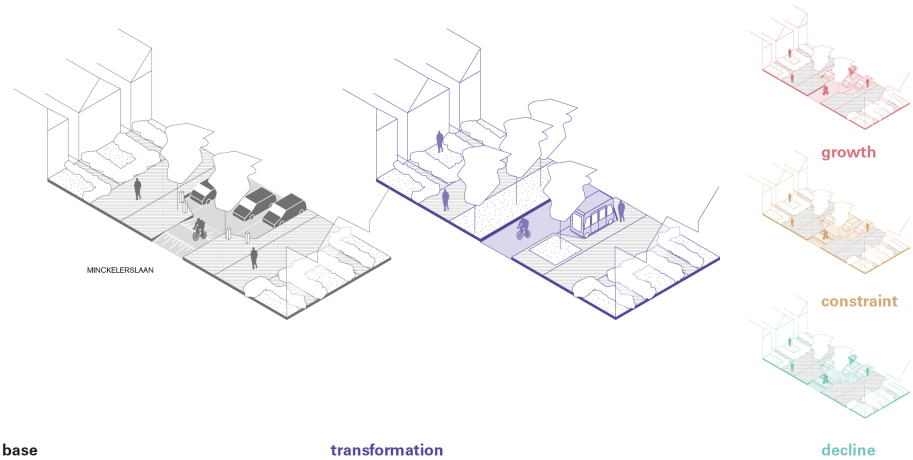


Figure 8-19: Spatial quality transformation potential for a street in a green small-urban environment.

Small-urban (hwm7)

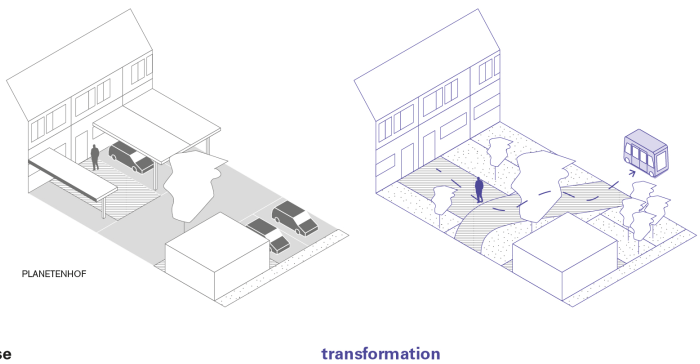


Figure 8-20: Some residential streets are dominated by parking. Through a shared autonomous system, the spatial quality potentials can be high.

For arterial roads, the potential for improved spatial quality differs between various archetypes of such urban roads. Especially (but not exclusively) in some post-war urban neighbourhoods, through traffic is often separated from traffic with a destination in or around the street. The consequence is that such streets are hard to fully redesign (Figure 8-21). The street profile in its totality can be considered wide. However, most of the road configurations comprise mostly one lane per direction, integrated in some green area. The parallel road for local traffic is often designed for mixed traffic conditions and facilitates on street parking. Merging these road functions together in one road-section is feasible but not favourable when dwellings are adjacent to the street. In that case, it is only possible when demands are sufficiently low or when direct access to a road is not necessary because of for instance a shared autonomous driving system as in the transformation scenario.

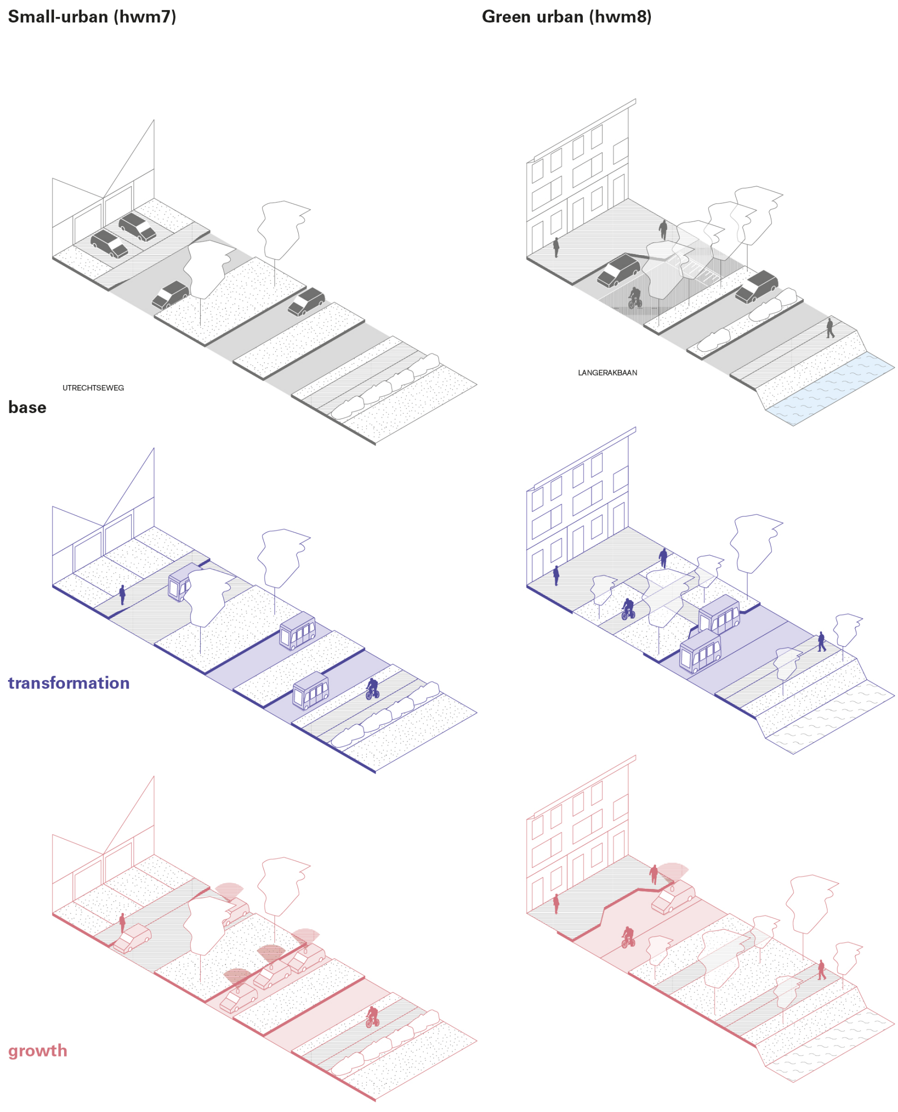


Figure 8-21: Streets with parallel roads are difficult to redesign if demand is high (left). If demand is low (right), the parallel road and road for through traffic can be merged.

Some streets in dense urban areas are expected to attract for more traffic, which has consequences for the lay-out of the street (Figure 8-22). For example, the Catharijnesingel (arterial road in centre urban plus environment) has been transformed in the last years to a more attractive urban boulevard. On the one hand this means that the potential for improvement is limited, and that in the case of induced demands some of the benefits diminish. For the pre-war urban neighbourhoods around the city centre of Utrecht, induced demand can be a threat for some of the streets. In the growth scenario, where valet-parking solutions are evaluated, even high travel demand on local streets was found. This has consequences for the liveability in the street.

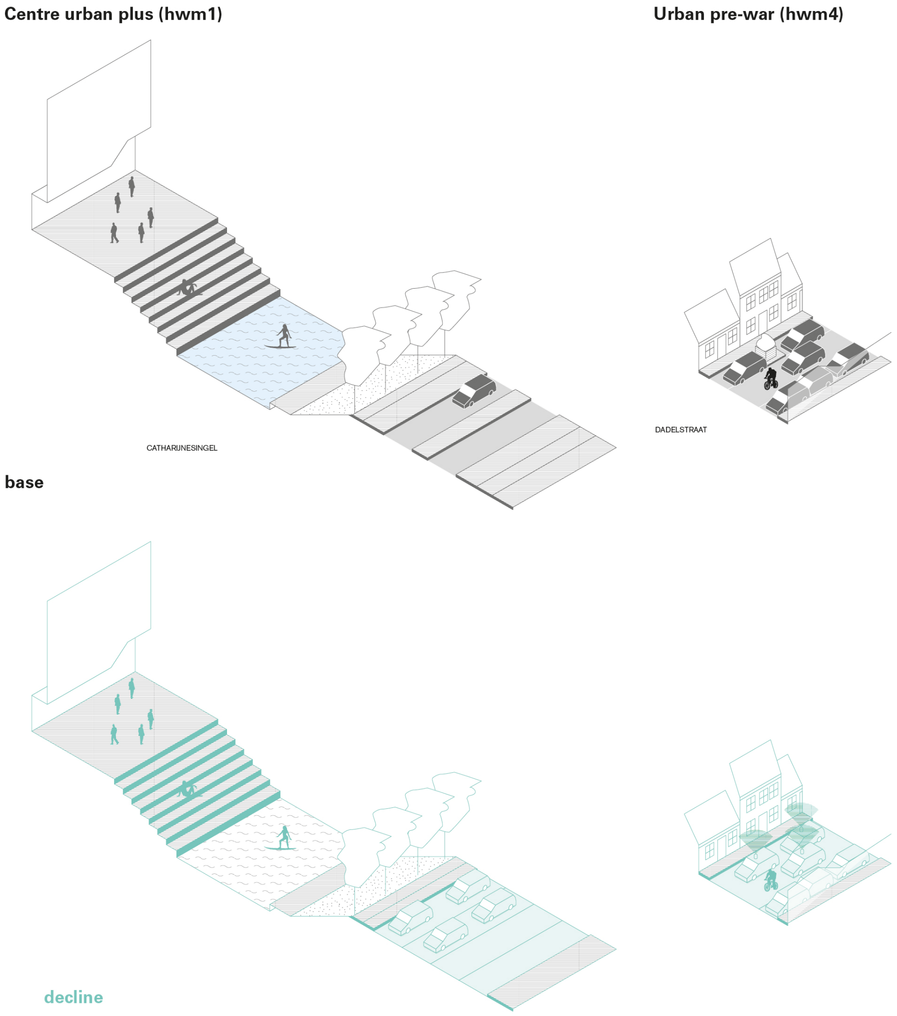


Figure 8-22: Induced demand can have negative effects on street quality

8.3.3 COMPATIBILITY OF THE RESULTS

The potential increase in spatial quality is not directly transferable within a quantitative model environment. Nonetheless, there are indicators that spatial quality around dwellings increases the attractiveness. This attractiveness manifests itself in increase in value of property (Crompton, 2001). By means of hedonic pricing models, the various influences of property values can estimated (Nicholls, 2004). A wide number of studies exists that attempt to obtain a general hedonic understanding of property values and take a wide range of factors into account. Other studies focus on specific factors in relation to the property values, e.g. for green or traffic hinder (Bateman, Day, Lake, & Lovett, 2001). However, the number of hedonic pricing models for the Netherlands is limited. Only the study on the effect of natural elements and open spaces by Luttik (2000) is found to give specific information on housing value premiums regarding landscape factors in a Dutch context. Results of studies from other countries such as the UK or the USA differ considerably due to different urban-rural settings compared to the Netherlands. The urban pressure in the Netherlands is higher because of strict planning policies. This causes higher demand for green spaces and therefore also higher value (Luttik, 2000, p. 162). Other studies rendering a Dutch context (e.g. or Sijtsma et al. (2017) or Daams, Sijtsma, and van der Vlist (2016)) provide hedonic pricing values for larger natural bodies in and around cities, but make no statements about the effect of green in proximity of the view from the house. Therefore, the results from Luttik (2000) are used to derive housing value premiums. In the study, also the effect of traffic noise is found to be significant. Since tires-road surface contact noise is most significant in urban environment, even if automated vehicles drive electric, the effects are not considered. Based on her study, the assumption is made that if the street becomes significantly greener, a housing price increase of 5% is considered. However, if infrastructure demands increase, a reduction of -5% is considered. The total housing value premium is weighted average of 0.2 times the premium from arterial road plus 0.8 times the premium of the streets. The values for the housing value premiums are summarised in Table 8-4.

Table 8-4: Housing value premiums in each scenario for all neighbourhood typologies based on spatial quality changes caused by vehicle automation.

Aggregated typology	Disaggregated typology	Road type	Transformation	Growth	Constraint	Decline
Centre-urban	Centre-urban-plus	Arterial	+ 0%	+ 0%	- 5%	- 5%
		Street	+ 5%	+ 5%	+ 0%	+ 0%
		Total	**+ 4%**	**+ 4%**	**- 1%**	**- 1%**
	Centre-urban	Arterial	+ 5%	+ 5%	+ 0%	+ 0%
		Street	+ 5%	+ 5%	+ 0%	+ 0%
		Total	**+ 5%**	**+ 5%**	**+ 0%**	**+ 0%**
	Centre-small-urban	Arterial	+ 5%	+ 5%	+ 0%	+ 0%
		Street	+ 5%	+ 5%	+ 0%	+ 0%
		Total	**+ 5%**	**+ 5%**	**+ 0%**	**+ 0%**
Outer-centre	Urban pre-war	Arterial	+ 0%	+ 0%	+ 0%	+ 0%
		Street	+ 5%	+ 5%	+0%	- 5%
		Total	**+ 4%**	**+ 4%**	**+0%**	**- 4%**
	Urban post-war compact	Arterial	+ 0%	+ 0%	+ 0%	+ 0%
		Street	+ 5%	+ 5%	+0%	+0%
		Total	**+ 4%**	**+ 4%**	**+0%**	**+0%**
	Urban post-war ground-level	Arterial	+ 5%	+ 0%	+ 0%	+ 0%
		Street	+ 5%	+ 0%	+ 0%	+ 0%
		Total	**+ 5%**	**+ 0%**	**+ 0%**	**+ 0%**
	Small-urban	Arterial	+ 0%	+ 0%	+ 0%	+ 0%
		Street	+ 5%	+ 0%	+ 0%	+ 0%
		Total	**+ 4%**	**+ 0%**	**+ 0%**	**+ 0%**
Green-urban	Green-urban	Arterial	+ 5%	+ 5%	+ 0%	+ 0%
		Street	+ 5%	+ 0%	+ 0%	+ 0%
		Total	**+ 5%**	**+ 1%**	**+ 0%**	**+ 0%**
	Green-small-urban	Arterial	+ 0%	+ 0%	+ 0%	+ 0%
		Street	+ 5%	+ 0%	+ 0%	+ 0%
		Total	**+ 4%**	**+ 0%**	**+ 0%**	**+ 0%**
Centre-village	Centre-village	Arterial	+ 5%	+ 0%	+ 0%	+ 0%
		Street	+ 5%	+ 0%	+ 0%	+ 0%
		Total	**+ 5%**	**+ 0%**	**+ 0%**	**+ 0%**
	Village	Arterial	+ 5%	+ 0%	+ 0%	+ 0%
		Street	+ 5%	+ 0%	+ 0%	+ 0%
		Total	**+ 5%**	**+ 0%**	**+ 0%**	**+ 0%**
Rural	Rural accessible	Arterial	+ 0%	+ 0%	+ 0%	+ 0%
		Total	**+ 0%**	**+ 0%**	**+ 0%**	**+ 0%**

8.3.4 CONCLUSIONS

From an aggregated perspective, one can conclude that the spatial quality effects of automated driving on street-level differ per scenario with the scenario for transformation scoring very high, and the constraint scenario very low. Within the decline scenario, the results can even be considered negative in some situations. Additionally, not all street types and neighbourhood typologies bear the same potential. Rural areas but also streets with a lot of green already present will see very few benefits of automated driving since these streets are not dominated by infrastructure that significantly. The largest potentials for spatial quality transformation are found in the more populated urban areas.

8.4 DISCUSSION

In this chapter, the transformation potential and spatial quality effects of automated driving are examined on neighbourhood and street level. By performing a design exercise, a better sense of the location can be developed within the research process. Outcomes of the transportation model become tangible and are critically assessed in the urban environment. The neighbourhoods or zones are classified according the neighbourhood typology defined by ABF Research (2003). Per typology one representative zone was considered. The results obtained for that zone are assumed to be similar for all other zones with the similar typology.

By overlapping the transformation potential and the spatial quality increases gains. It reveals where the largest potential for urban change can be expected (Figure 8-23 - Figure 8-26). This depends strongly on the scenarios. Within the transformation scenario, significant changes can be expected in all urban areas, where the growth scenario a stronger focus on larger urban towns can be observed. For the constraint scenario, only a small increase in spatial quality can be observed in the city centre of Utrecht but not in the rest of the region. In the decline scenario, the most significant changes are expected within the urban centres. The city centre of Utrecht shows some potential for spatial quality gains. However, this will be at the cost of spatial quality in the surrounding pre-war neighbourhoods. On a larger scale level, the transformation potential can be large if the possibility emerges to develop in areas prior occupied by rail infrastructure. Besides that, not many benefits are gained. On the lower street level, the transformation potential is rather limited too. Many roads these days are already configured to one vehicle in each direction and this lets itself not easily change. The largest quality gains can be expected from the reduction of parking places.

The results of this part of the study provide for input of the residential location choice model, as well as for a direction of where larger conversions of urban areas are possible beyond the perspective of residential density.

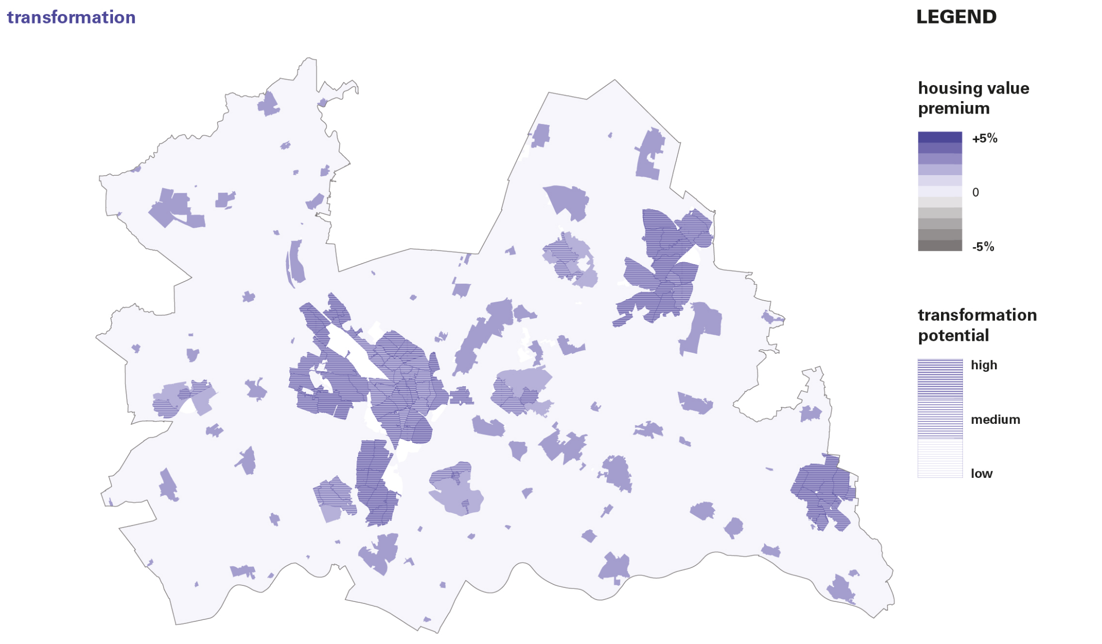


Figure 8-23: Spatial quality and transformation potential obtained from the zone studies overlapped and extrapolated for the transformation scenario.

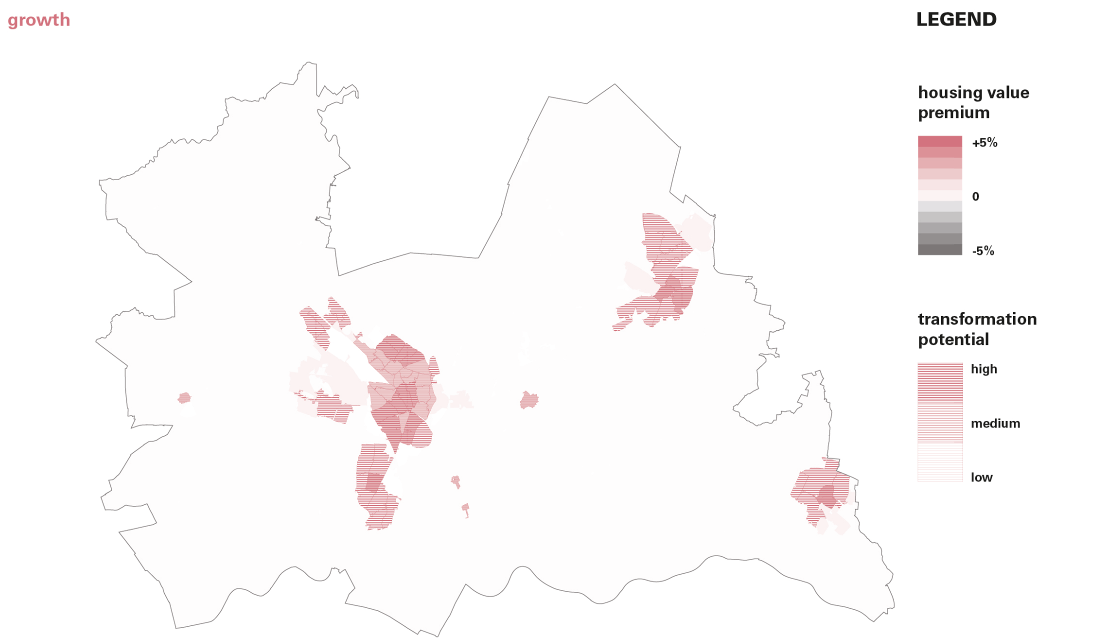


Figure 8-24: Spatial quality and transformation potential obtained from the zone studies overlapped and extrapolated for the growth scenario.

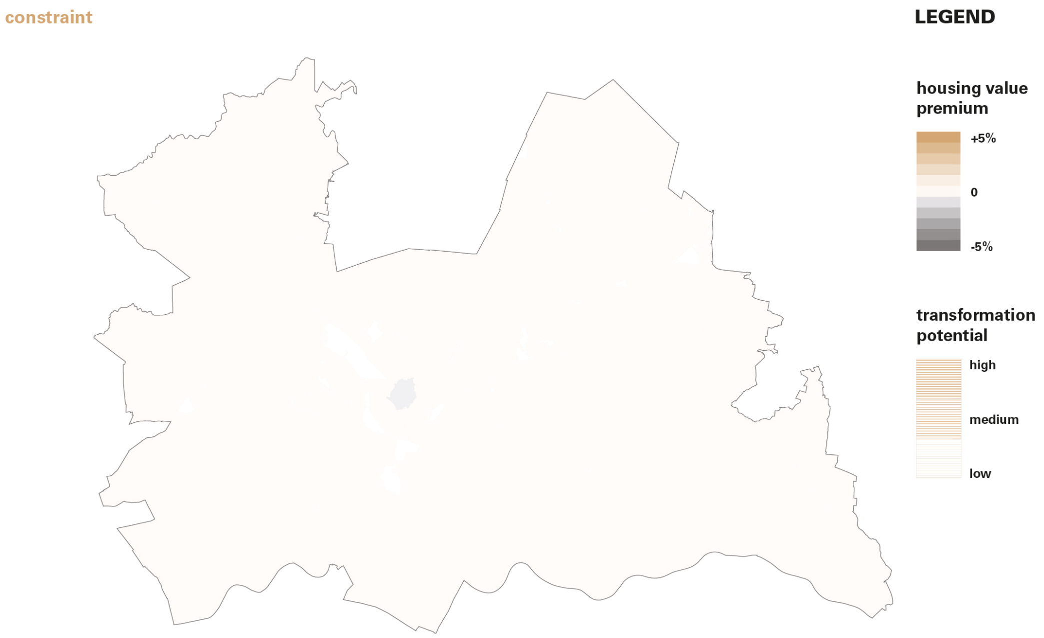


Figure 8-25: Spatial quality and transformation potential obtained from the zone studies overlapped and extrapolated for the transformation constraint scenario.

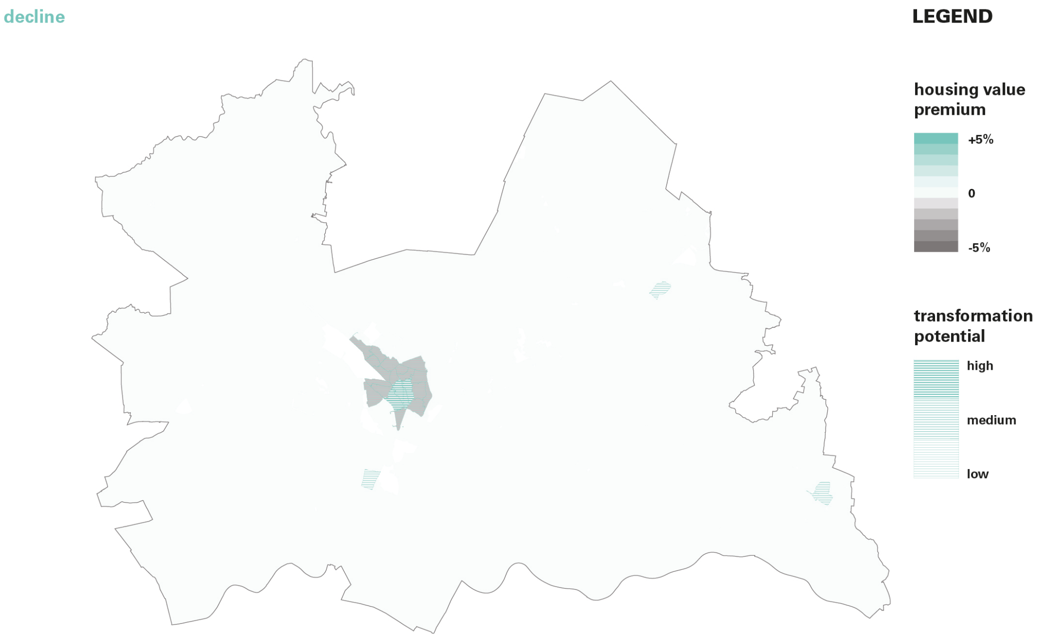


Figure 8-26: Spatial quality and transformation potential obtained from the zone studies overlapped and extrapolated for the decline scenario.

9 RESIDENTIAL URBAN DEVELOPMENT MODEL

In the prior two chapters, insights are obtained on the accessibility and spatial quality effects of automated driving. Based on these understandings, a strong knowledge basis is built on how automated driving can change urban spaces. However, to fully comprehend the spatial impact of automated driving in the built environment, one must assess it through choice behaviour of decision makers in the city. For this study, the residential choice behaviour of households is considered crucial to assess the disruptive character of automated driving on the built environment.

Purpose of the residential location choice model is not to precisely simulate the household moving behaviour through time with all factors related to this aspect. Instead, the goal is the reveal new urbanisation patterns caused by vehicle automation. The amount of decision makers in the built environment - both in numbers as in heterogeneity - is large and the relations between these decision makers are numerous. Hence, this research considers the built environment a complex system. By using agent-based modelling, a tool is employed that extends the cognitive capacities of the researcher; urban change is evaluated according to the paradigm of cities as complex systems. In the remainder of this chapter, the term 'model' is used for the agent-based residential location choice urban model.

Due to time constraints, it has proved not feasible to develop the model to a fully operational version. Nonetheless, the design of the model, its possibilities and prior conclusions that can be drawn from the study are explained in this chapter. First the design of the model is explained. Here all theoretical aspects and thereafter data requirements are described. The construction of the model together with its open ends is explained in the third section. In the fourth section in this chapter, the insights that can yet be obtained from the preliminary model are presented and the fifth section previews the possibilities for applying the model in urban planning processes.

9.1 MODEL DESIGN

The purpose of the model is to obtain insights in the urban development patterns of the residential function and the effect automated driving has in this development. Households are considered the main decision maker in these processes. Therefore, the purpose of this module is not to obtain a meta-understanding of all urban processes in a computational environment. This allows for some simplifications to be made to the model beforehand. No demographic developments are considered. Only residential location choice behaviour is modelled. Firms are considered static in space and time. Outcomes of the model need to be therefore interpreted in the broader context of urban development as depicted in Figure 3-7 in chapter 3. First step in the design of the model is to determine the model structure and relations around residential choice behaviour. Additionally, the procedures to be modelled are listed.

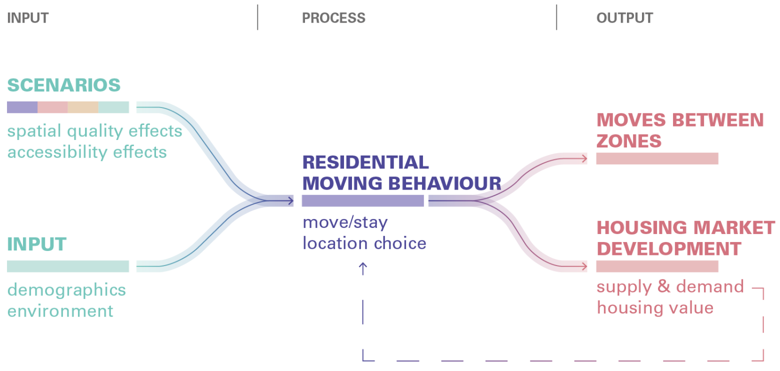


Figure 9-1: Model structure and relations within the residential location choice model.

Figure 9-1 displays the model structure and relations around residential choice behaviour. Within agent-based models, decision makers and the environment are distinguished. These provide therefore the input of the model. Scenarios provide for the input to evaluate the automated driving effects within the choice behaviour. The choice behaviour is dependent on characteristics of the decision makers, the environment and the interaction between the decision makers. First the formalisation of residential choice behaviour is explained. Thereafter, more detailed elaboration on the decision makers, environmental variables and interaction is provided.

Some aspects are not considered within the model framework. Demographic dynamics are not considered. These are data demanding processes and might overrule the automated driving effects that this study examines. Economic prognoses and developments are not considered for a similar reason. Additionally, no coupling between the transportation model and residential location choice model is considered due to long runtime procedures of the prior. Furthermore, the stochastic nature of the behaviour of the decision makers asks for multiple replications, which complicates the coupling and runtime even more since no automated connection between the two model environments can be established. The moving behaviour of firms and amenities is outside the scope of this study.

9.1.1 TIGRIS XL RESIDENTIAL LOCATION CHOICE MODEL

One of the main challenges in conducting an urban development model is to provide adequate mathematical description of the behaviour of the decision makers. For this research, it was not possible to derive a choice model particularly for this urban model. Instead, this research derives the choice behaviour from the Dutch LUTI model, TIGRIS XL as described by Zondag, de Bok, Geurs, et al. (2015); Zondag, de Bok, Willigers, et al. (2015). The elaboration on which model this research bases the behaviour of the decision maker is explained in chapter 5. The chosen model dictates the variables to be considered for this model study. The model distinguishes two different decisions. The move-or-stay decision and the residential location choice itself which are evaluated in resp. a binary logit model and a nested logit model. The variables for each corresponding event are depicted in Table 9-1.

Table 9-1: Explanatory variables of the move-stay decision and the residential location choice (adapted from Zondag, de Bok, Geurs, et al. (2015, pp. 118, 120), Zondag, de Bok, Willigers, et al. (2015, p. 65)).

Model	Type of variable	Variable	Unit
Move-stay model	Model specific	Alternative specific constant for stay alternative	0/1 dummy
	Environmental	% of zone peripheral urban area (ref.)	Percentage
		% of zone village area	Percentage
		% of zone city centre area	Percentage
		% of zone peripheral low urban density	Percentage
		% of zone in rural area	Percentage
	Socioeconomic	% vacant dwellings	Percentage
	Accessibility	Accessibility of location for commuting tours	Logsum
		Accessibility of location for education tours	Logsum
		Accessibility of location for shopping tours	Logsum
		Accessibility of location for other tours	Logsum
Residential location choice	Model specific	Nesting coefficient for inter or intraregional choice	-
		Nesting coefficient for regions	-
		Alternative specific constant for origin region	0/1 dummy
		Alternative specific constant for origin zone	0/1 dummy
	Socioeconomic	Average dwelling price in zone (woz)	Euros
		Population density	Pop/m^2
		No. of vacant dwellings	Dwellings/zone
		Average yearly income of a household	Euros/year
	Environmental	% of zone peripheral urban area (ref.)	Percentage
		% of zone village area	Percentage
		% of zone city centre area	Percentage
		% of zone peripheral low urban density	Percentage
		% of zone in rural area	Percentage
		Area of facilitating functions	m^2
		Area of work related functions	m^2
		Area of water surface	m^2
	Accessibility	Inverse distance for intraregional relocations	km^{-1}
		Accessibility to alternative	Logsum
		Accessibility to alternative for intraregional alternative	Logsum
		Accessibility for trip purpose other for location within 10 km	Logsum
		Accessibility for trip purpose other	Logsum

9.1.2 PROCEDURES

By elaborating on the data of the TIGRIS XL choice model, the procedures to be modelled already partly revealed. The following procedures take place:

- Move-or-stay decision: calculating the probability of moving;
- Determining vacant dwellings: calculating the vacant dwellings;
- The location choice: calculating the desired area to move to, incorporating the supply and demand and calculating the actual area to move to.

Move-or-stay decision

The move-or-stay decision is calculated differently for different households. Since this decision knows only two alternatives, the probability of moving is calculated with a binary logit function where the utility of staying is calculated with the following equation:

$$V_{z,h,t}(stay) = \overline{\alpha_h} * \overline{X_{z,t}}$$

with:

V	The observable and quantifiable part of the utility of the alternative
X	Attributes for the choice alternative stay
α	Sensitivity parameter
z	Zone
h	Household type
t	Year

The attributes that comprise the utility calculation are displayed in Table 9-1. These attributes are accessibility attributes, neighbourhood typologies, the percentage of vacant housing in a zone and an alternative specific constant for the stay-alternative.

When the utility of not-moving is calculated, the probability of moving can be calculated:

$$P_{z,h,t}(move) = \frac{1}{1 + \exp\left(V_{z,h,t}(stay)\right)}$$

with:

$P_{z,h,t}(move)$	The probability for a household to move
z	Zone
h	Household type
t	Year

Vacant dwelling

By obtaining data on how many households intend to move, the number of vacant dwellings can be derived. The number of vacant dwelling determines the possible influx in a zone. The number of vacant dwellings is calculated as follows:

$$VD_{z,t} = D_{z,t} - \frac{\sum_h \left(\left(1 - P_{z,h,t}(move)\right) * H_{z,h,t}\right)}{H_{z,t}/D_{z,t}}$$

with:

VD	Number of vacant dwellings
D	Number of dwellings in a zone
H	Number of households in a zone
z	Zone
h	Household type
t	Year

Location choice

The location choice is primarily determined by the attributes of the candidate zones (z2), or by the values attributes unique to a pair of zones (origin zone z1 and candidate zone z2). The probability of moving to the candidate zone from a specific origin zone is therefore:

$$P_{z1,h,t}(z2) = \frac{VD_{z2,t} * \exp\left(\overline{\alpha_h} * \overline{X_{z1\rightarrow z2,t}} + \overline{\beta_h} * \overline{X_{z2,t}}\right)}{\sum_{z2\in r}\left(VD_{z2,t} * \exp\left(\overline{\alpha_h} * \overline{X_{z1\rightarrow z2,t}} + \overline{\beta_h} * \overline{X_{z2,t}}\right)\right)}$$

with

P	The probability of choosing zone z2
D	Dwellings in a zone
H	Households in a zone
X	Attributes for the location choice alternative
α, β	Sensitivity parameters
$z1$	Origin zone
$z2$	Candidate zone
h	Household type
t	Year

The attributes that comprise the utility calculation are displayed in Table 9-1. The inter-COROP parameters are not considered. Therefore, the residential location choice model has the structure depicted in Figure 9-2.

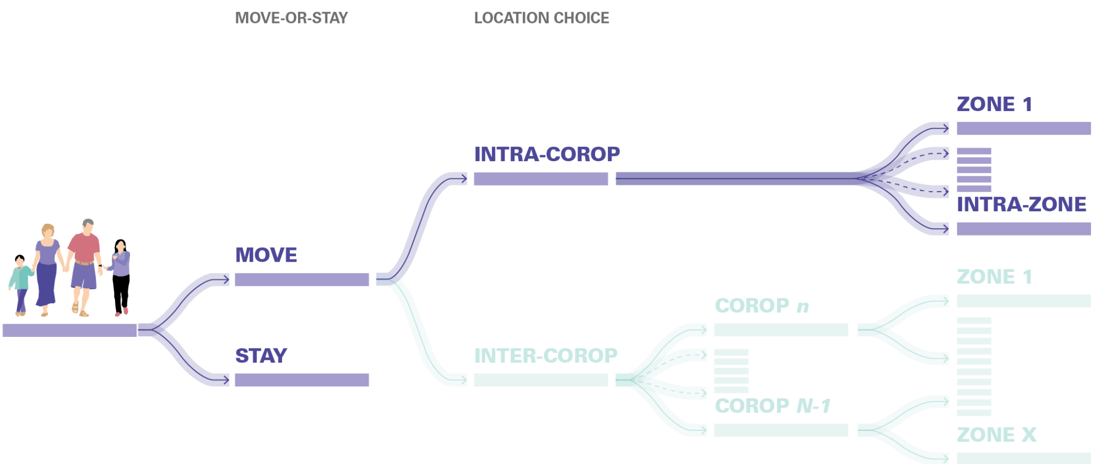


Figure 9-2: Structure of the residential location choice model for this study (purple) compared to TIGRIS XL (Zondag, de Bok, Geurs, et al., 2015, p. 118).

It is of importance to take supply and demand in the housing sector into account to prevent that some zones get unrealistically overpopulated. The mean to do this is by using a balancing factor that evaluates the supply and demand and decreases the attractiveness of a zone when supply exceeds demand. This is an iterative process where

$$BF_{z,it} = \min\left\{\frac{BF_{z,it-1}}{DS_{z,it-1}}, 1\right\}$$

with:

BF	The balancing factor
DS	Demand/supply factor in the zone
z	Zone
it	Iteration

The balancing factor is used to reduce the utility of candidate zones with excessive supply and is limited to be maximum. This is to prevent that areas with significant vacancy become additionally attractive. After the last iteration, households move to the final candidate zone. The last balancing factor value from the iteration is used to adjust the housing value to incorporate the attractiveness of an area in the housing price:

$$WOZ_{z,t} = \frac{WOZ_{z,t-1}}{BF_t}$$

with:

WOZ	Housing value (WOZ-value)
BF_t	The final value for the balancing factor

Model structure

The prior explained equations together comprise the model framework to model the moving behaviour of households (Figure 9-3). Within the model framework, the moving behaviour and the housing market are evaluated. What makes this system complex is that this process is not isolated for one household (as depicted in the figure). Instead, the variables that determine the choice behaviour as well as the interaction on the housing market is driven by the simultaneous choice behaviour of other households and therefore the interaction between other decision makers. Within an agent-based model, the agents are programmed to follow this behaviour while being autonomously moving through space. The interaction comes therefore natural with the paradigm of agent-based modelling and of cities as complex systems.

The model will reveal the development of numbers of households in zones and therefore the residential density transformation is obtained. Additionally, the developments on the housing market allow for the examination of housing price development, giving indicators of the desirability and social transformation of urban areas.

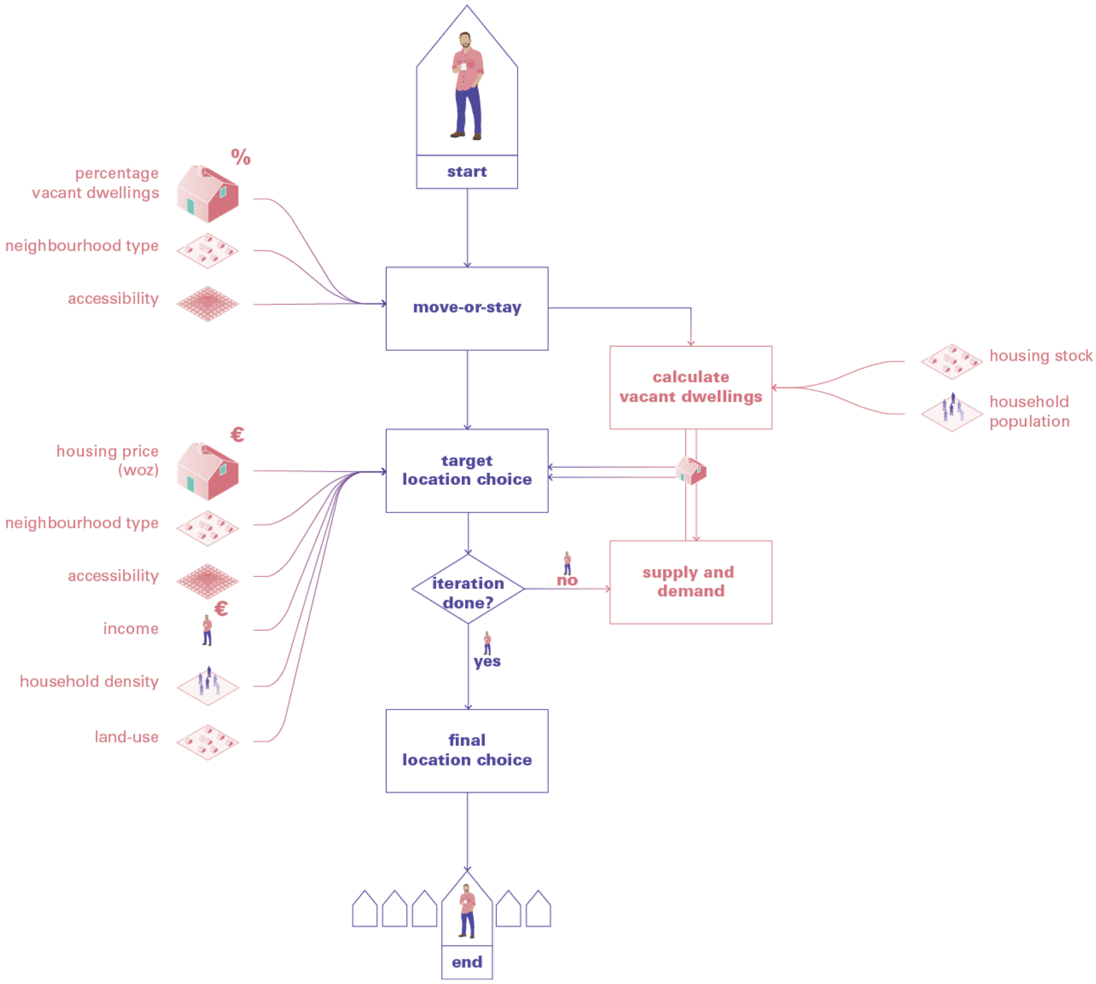


Figure 9-3: Model structure of the residential location choice process.

9.2 DATA COLLECTION

Within this section, the data collection process for the model is explained. The base year for the data collection is set to 2015 since this corresponds with the year the transportation model run is performed. Additionally, most required data is available for this year or at worst only a few years divergent.

9.2.1 SPATIAL RESOLUTION

First step for preparing the environment is to determine the zone size. Although scholars as Batty (2005) and Spiekermann and Wegener (1999) proclaim new access methods of geospatial data leading to possibilities of using grid cells instead of zones, not all data – especially socioeconomic– is available on such disaggregate level. As VRU is based on zones (mostly 4-digit postal zones outside main area and smaller zones within main area) the agent-based residential location choice model is based on zones too. This is not inferior to grid-cells in this case since this research attempts to find urban transformation assignments for different neighbourhoods. Often zones do follow boundaries around defined urban entities.

For this study, the zones considered are 4-digit postal codes (pc4). VRU zones are on some places more precise than necessary, and not all socioeconomic data is available on the respective zone level. Other zone classifications considered are district (in Dutch: ***wijk***) and neighbourhood (in Dutch: ***buurt***), both defined by CBS (CBS, 2017). Districts are not considered since they are too large and incorporate sometimes a wide variety of districts in terms of typologies. The reason for not using neighbourhoods, is because these are differently defined in different towns and cities.

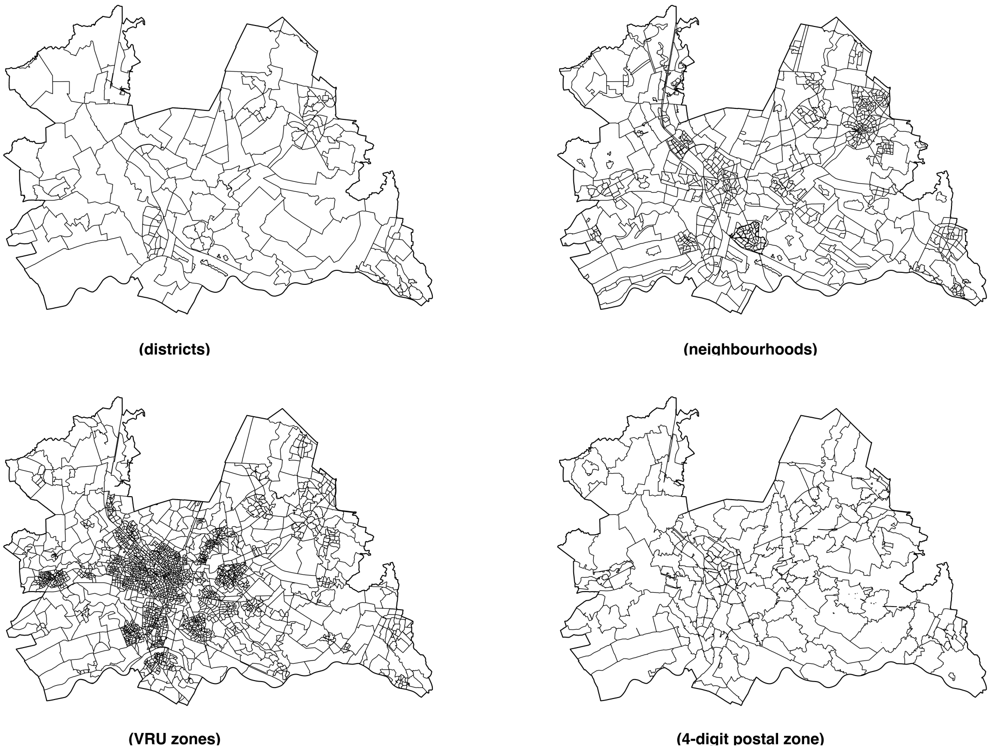


Figure 9-4: Different zone classifications

9.2.2 SYNTHETIC POPULATION

The TIGRIS XL model distinguishes 13 different household types. The household types are not obtainable through a dataset because of confidential constraints. Therefore, the population must be created based on synthetic data or a simplification. It is relevant elaborate on heterogeneity in decision makers because different households have different moving behaviour. Creating a synthetic population based on data from OVIN has been considered. However, due to small sample sizes in some zones, it is not feasible to generate an accurate distribution of household types per zone. A dedicated synthetic population model (e.g. Nowok, Raab, and Dibben (2015)) that can consider many socioeconomic variables could prove helpful but is not applied due to time constraints. Instead, based on available household data, three different household types are considered that can be determined from available data on different household types per zone. The dataset ***bevolking per postcode*** (CBS, 2016a) distinguishes three household types, which are applied for aggregation of the households:

- Single households;
- Multi-person households with children;
- Multi-person households without children.

Table 9-2 lists the household types distinguished in TIGRIS XL with their characteristics listed, as well as their share in the sample within the national housing survey WoON.

The most preferable simplification would be to consider TIGRIS XL household type with the highest representation in the WoON per CBS (2016a) household as representative.

This means that the behaviour of household type 12 determines the behaviour of single households, type 11 of multi persons with children and type 13 of multi-person households without children. This allows for about a forty-five percent accurate representation. However, this method over represents households over the age of 65 years old. Therefore, the choice is made to assign the behaviour of household type 3 to the single household. This allows to distinguish three different households (Figure 9-5).

- Single person household between 35 years old and 65 years old with a job;
- Family with two children with both adults employed;
- Two-person household with an age of 65 years old.

Figure 9-5: Distinguished households

Table 9-2: Household types distinguished in TIGRIS XL and their correspondence to the household types distinguished by CBS (2016a) (Data for the TIGRIS XL households is derived from Zondag, de Bok, Willigers, et al. (2015, p. 59))

CBS (2016a) household type	TIGRIS XL household type	No. of persons	No. of children	No. of workers	Age 65+	Age <35	% of sample in WoON 2009
Single household	1	1	0	0	No	-	5.5%
Single household	2	1	0	>0	No	Yes	4.4%
Single household	**3**	**1**	**0**	**>0**	**No**	**No**	**8.7%**
Multi-person w/o children	4	>1	0	0	No	-	3.4%
Multi-person w/o children	5	>1	0	1	No	Yes	1.5%
Multi-person w/o children	6	>1	0	1	No	No	5.2%
Multi-person w/o children	7	>1	0	>=2	No	Yes	4.3%
Multi-person w/o children	8	>1	0	>=2	No	No	7.8%
Multi-person w/ children	9	>1	>0	0	-	-	3.7%
Multi-person w/ children	10	>1	>0	1	-	-	11.2%
Multi-person w/ children	**11**	**>1**	**>0**	**>=2**	**-**	**-**	**20.3%**
Single household	12	1	0	-	Yes	-	11.6%
Multi-person w/o children	**13**	**>1**	**0**	**-**	**Yes**	**0**	**12.6%**
							Σ = 100%

9.2.3 SPATIAL VARIABLES

The population of households moves autonomously through space. The interaction between households and spatial attributes determine the behaviour of the decision maker. The environmental variables are collected in a GIS on 4-digit postal zone level. The spatial data classes considered are environmental data, socio-economic data and accessibility values.

Environmental variables

The environmental variables describe the physical appearance of areas. Within the choice behaviour, the neighbourhood typology as well as several land-use are evaluated. The neighbourhood typologies are classified according to the aggregated hwm5 classes by ABF Research (2003). This classification has been obtained in section 8.1 for the disaggregated hwm13 class. By aggregating these typologies, the classification in Figure 9-6 to describe the neighbourhood typology is obtained. The neighbourhood typology is evaluated in the utility function (see also subsection 9.1.2 and Table 9-1) as a percentage of the typology present in the zone. Land-use cover data is available through the BBG 2012 (CBS, 2012). From this data source, following environmental variables relate to the land-use of the area are obtained:

- Area of facilitating functions (Figure 9-7, retail & restauration, public services and cultural services)
- Area of work related functions (Figure 9-8, business area)
- Area of water surface (Figure 9-9)

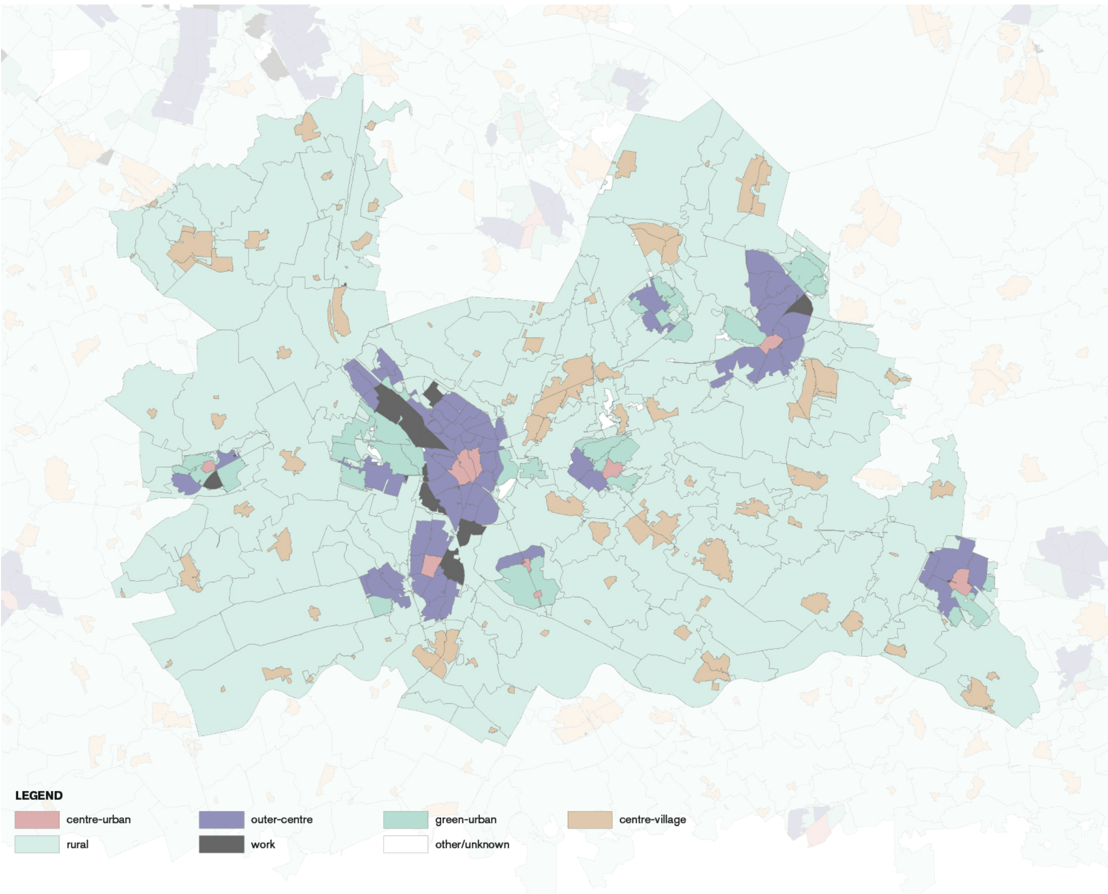


Figure 9-6: Classification of neighbourhoods according to the hwm5 categorisation.

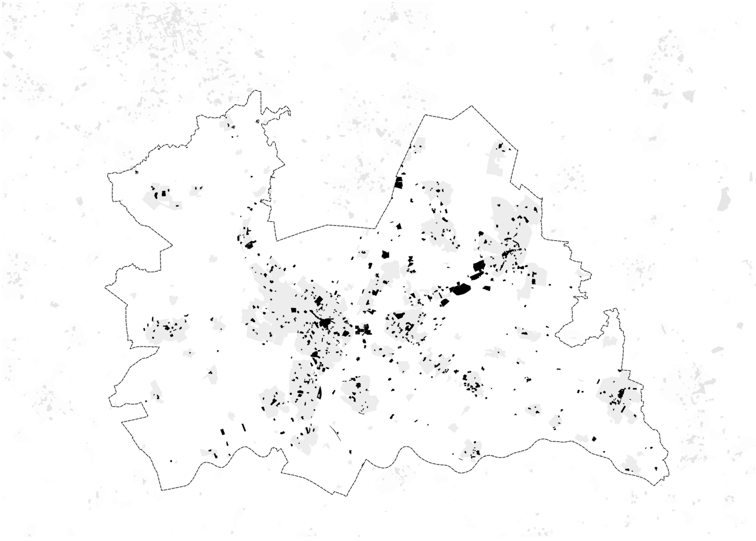


Figure 9-7: Areas with facilitating functions (CBS, 2012)

Figure 9-8: Areas with work functions (CBS, 2012)

Figure 9-9: Water areas (CBS, 2012)

Socioeconomic data

Socioeconomic variables for population density, housing value and household income are readily available through various data sources of the CBS. Obtaining data for the housing stock is harder, yet crucial for the model. The problem lies in the distinction between dwelling unit and dwelling. A dwelling unit is defined as a unit for one household, whereas a dwelling can be e.g. an apartment building accommodating multiple households. Information is available on the stock of dwellings, but not on the stock of dwelling ***units***. This poses for problems to accurately determine the percentage of vacant housings needed for the initial time step in the model. This is because the number of vacant dwellings within the modelling procedure is calculated only after calculating the probability of moving even though the probability of moving is a function of the dwelling vacancy among others. To overcome this the initial vacancy is calculated before running the model based on a moving probability of all decision makers of 8.7%. This coincides with the average moving probability in the Netherlands for 2002, found by Ekamper and van Huis (2004, p. 85). Data for a more recent year might be available. However, it is expected that the fluctuation within the number will not vary significantly. Furthermore, it has solely the function of allowing the model for some housing availability to start the simulation.

Accessibility values

The accessibility indicators are obtained in VRU in chapter 7. In case when multiple VRU zones compound one 4-digit postal zone, the maximum accessibility value of a VRU zone is set as the accessibility value of the postal zone. As elaborated on in subsection 9.2.4, the accessibility measures derived from VRU differs from the intended logsum accessibility measure compatible with the behavioural model. Therefore, calibration is necessary to obtain adequate simulation results. To ease the calibration process, each choice process only takes one accessibility measure into account for one motive, instead of four as listed in Table 9-1. The inverse of interregional distance is still incorporated. Intra-zonal distance is set to half of the distance to the closest zone.

9.2.4 IMPLEMENTATION CHALLENGES

As the assessment in Table 5-1 in chapter 5 shows, no model can be implemented without drawbacks. This is because each model is conducted for specific studies or applications. In the case of this study the behaviour of agents is derived from the the TIGRIS XL model which leads to the following drawbacks:

- Accessibility is calculated in the LMS in a logsum measure. VRU is not able to calculate logsum accessibility indicators but can at best provide data to calculate potential accessibility as indicator. Consequence is that estimated parameters regarding accessibility must be calibrated differently. This asks for complex statistical methods to do that for all accessibility indicators listed in Table 9-1. Instead, one accessibility indicator per choice process can be considered.
- The TIGRIS XL model has a scope for the whole Netherlands, and considers intra and interregional moving processes. Some spatial data of areas surrounding the study area lacks to adequately incorporate the interregional allocation. Therefore, the COROP (NUTS-3) region of the province of Utrecht is considered as a closed system.
- TIGRIS XL is designed for LMS-zones. These zones are large in the sense that one zone covers various neighbourhood types. For this study, a smaller zone classification

that more naturally follows neighbourhood typologies is desired. This is not necessarily a problem, since the number of vacant dwellings is a multiplication factor in probability calculation (Zondag, de Bok, Willigers, et al., 2015, p. 63). Yet some variables are correlated to the zone size (e.g. area of specific function). Some factor is needed to compensate for smaller zone sizes. Additionally, one must be aware that also other factors determine the decision of the residential location on smaller scale levels. Literature in chapter 3 found that models with higher spatial resolutions consider dwelling characteristics. This cannot be considered in this model.

9.3 MODEL CONSTRUCTION

Due to time constraints, it has not been feasible to construct a fully operational model. When constructing a computational model, one can stumble on many unexpected errors. Therefore, the decision is made to not develop the model further. The model will be further developed in the follow up phase of this research. Nevertheless, the general lay-out of the model has been implemented. It is however not bug free, nor is the code developed to fully analyse the data generated by the model. In this section, the general lay-out of the model is not explained from a theoretical perspective (as in section 9.1) but from an operational perspective. First, the NetLogo platform in which the model is conducted is briefly explained. Second, the general layout of the coding structure and procedures is presented. This section closes of with a preview on the calibration and validation process.

9.3.1 MODELLING TOOL

The residential location choice model is constructed within NetLogo (Wilensky, 2003) (Figure 9-10). After examining multiple agent-based modelling platforms through Abar, Theodoropoulos, Lemarinier, and O'Hare (2017), Kravari and Bassiliades (2015), Crooks and Castle (2012) and Railsback, Lytinen, and Jackson (2006) as well as some ease-of-use assessment by the author, NetLogo is chosen for its relative ease of use, open-source license, approachable syntax, GIS compatibility and specific design purpose for agent-based modelling of complex systems.

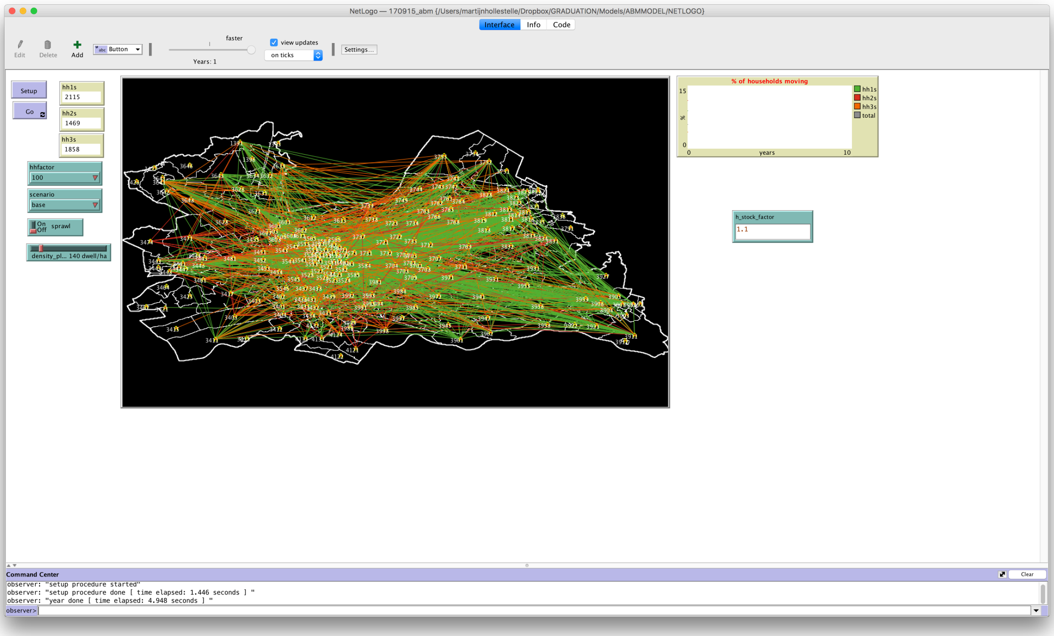


Figure 9-10: GUI of the residential location choice model in NetLogo

9.3.2 IMPLEMENTATION

The model follows the general structure of procedures as explained in section 9.1. However, some additional considerations are relevant for implementation. These are distinguished in two groups: the setup and the runtime procedures.

Setup procedure

The data collected in section 9.2 must be loaded within the NetLogo environment using the GIS extension. Along with the zonal data, it is of importance to enclose area data of each zone since NetLogo does only support non-oblique projections with degrees as unit (this also explains the skewed projection of the study area in Figure 9-10).

The households can be generated by obtaining the values for the number of households per type from the zonal data. These are the input to generate the households as agents. Within the graphical interface of the model, an input window to set the household factor is integrated. This is done to control the workability of the model and allows to generate a population that is smaller than the total number of households in the study area. If a household factor of 1 is applied, the model comprises 572 980 households. This demands for a lot of memory and CPU of the computer and causes runtimes of around 90 seconds per time step. Considering the stochastic nature of the events, many replications of the simulations are necessary. Therefore, short runtimes are crucial. With e.g. a household factor of 0.1, one household represents ten households. Runtime per time step can be reduced to around 8 seconds.

Runtime procedures

Two choices are evaluated within the runtime procedure. The move-or-stay decision and the location choice. The equations calculate the probability through a logit function. To transfer the probability into an actual choice, a weighted random single draw is made by using a Monte Carlo simulation technique.

For the move-or-stay decision, only the utility of staying must be calculated because of the binary logit structure. The actual location choice has the structure of a multinomial logit model. Therefore, the utility must be calculated for each alternative. The utility of the alternatives compounds to parts: the first part depends on the actual characteristics of the alternative (z2) and for the second part on attributes specific for the combination of origin zone and the alternative (z1→z2, the interaction variables, see subsection 9.1.2 - location choice). This calculation must be done in sequential steps. The first step can be done on zone level: the first part of the utility can be calculated per zone per household types. The interaction variables are obtained in a looping procedure where from one zone z1, the interaction variables to all other zones are obtained to calculate the second part of the utility. From there, the total utility between the origin zone and all different alternatives can be calculated. This utility value is stored within a temporary variable to prevent excessive memory use. Based on the calculated utilities, the households in the origin zone set a candidate zone to move to. This looping procedure is then repeated for all other zone.

Before the households can move to their candidate zone, the dynamics of the housing market need to be evaluated. To evaluate the demand in a zone, households hatch a shadow agent that moves to the selected candidate zone. The sum of the shadow agents divided by the vacant dwelling determines is the supply and demand factor. Based on this value, the balance factor is calculated. After that, the shadow agents are deleted. The procedure of calculating utilities times the balance factor, setting candidates and hatching shadow agents is repeated until the set number of iterations is done. Subsequently the households move to their final candidate zones.

The final step in the runtime procedure is to update the environmental values for the housing prices and population density. Ideally the accessibility values would also update based on the new dispersion of households. However, due to coupling issues and long runtimes, this is not considered as explained in section 9.1.

9.3.3 CALIBRATION

Due to time constraint, the model has not been calibrated. Nevertheless, some foresights for the calibration process can be projected. All calibration processes must be performed in the base scenario for the base year 2015. Two aspects especially ask for calibration:

- The influence of land-use attributes expressed in square meters in relation to the zone size;
- The sensitivity for accessibility.

Another consideration within the modelling process, is the choice for the number of iterations for the calculation of the balancing factor. This will probably relate to the household factor used within the modelling environment. More decision makers will lead to relative smaller differences between supply and demand, asking for less iterations. This development of the balancing factor must be monitored until a desired level of convergence is observed.

Land-use attributes

The utility of an alternative regarding land-use parameters is expressed in square meters (facilities - Figure 9-7, employment - Figure 9-8, water - Figure 9-9). The sensitivity parameters are estimated for LMS-zones (1308 zones for the Netherlands (Zondag, 2007, p. 95)). These zones are significantly larger than the 4-digit postal zones used in this study (4053 for the Netherlands in 2015 (ESRI Nederland, 2015)). On average, the area of the specific land-use function is smaller and therefore less utility is assigned to every alternative. The consequence is that the households become less sensitive to the land-use attributes. Since the model also must be calibrated for accessibility it is difficult to set an objective based on an external data source to calibrate to. Instead, two possibilities are considered. The first is to increase the value of the sensitivity parameters of the land-use attributes by a factor of the number of 4-digit postal zones divided by the number of LMS-zones: $\frac{4053}{1308} = 3.1$. The second option is to perform a spatial buffer around the zone by the same factor and count all square meters within the buffered area. The second option is expected to be more suitable because large differences in the presence of land-use attributes between neighbouring zones are not emphasised. However, this option asks for additional spatial operations in the data collection process.

Accessibility sensitivity

The values for accessibility are obtained in VRU which leads to a strong difference both absolute and relatively between the zones compared to the intended accessibility values needed to adequately simulate the household moving behaviour. This reveals by comparing the obtained accessibility values for the study area in section subsection 7.2, Figure 7-5 with other studies that obtain accessibility values that relate to the choice model used for this study. For this study, the bandwidth of accessibility values for commute trips ranges between 4E+8 and 5E+8. The study by de Bok (2007, p. 95) displays values ranging from <7.0 to >12.5 for the South-wing of the Randstad area. This significant difference must be considered in the calibration process.

Objectives to calibrate towards to are e.g. the distribution of moving distance provided by Feijten and Visser (2005, p. 79) (Figure 9-11). This is time consuming due to the stochastic processes within the model, but might be possible using the behaviour space tool for parameter sweeping within NetLogo.

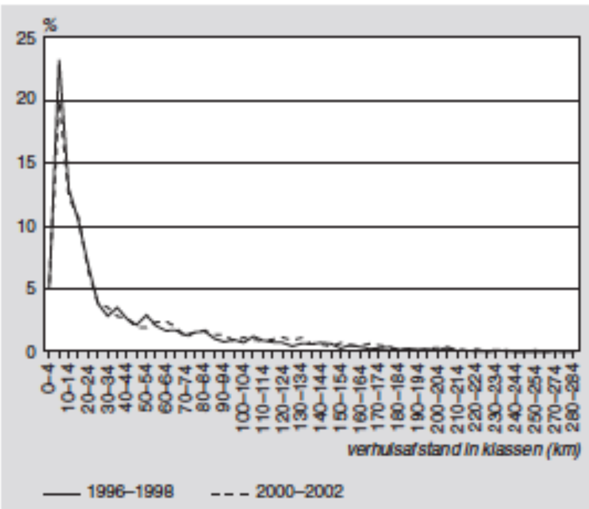


Figure 9-11: Distribution of moving distance in kilometres for 1996-1998 and 2000-2002.

9.4 PRELIMINARY RESULTS

Although hitherto no operational model has been obtained, the behavioural processes within the model do allow for some preliminary interpretation to provide insight in new development patterns caused by the emergence of automated driving.

9.4.1 APPROACH

Per scenario, the change in attractiveness of areas for the residential location choice is displayed for the household type multi-person with children as this is the most represented household in the modelling environment. The change in attractiveness has been considered for four example zones (Table 9-3) corresponding with the different aggregated hwm5 typologies, excluding rural areas are considered. The latter is excluded because these areas are often part of a zone with one of the other typologies. By elaborating on different reasons, the attributes specific for an origin zone and a destination zone ($z1 \rightarrow z2$, the interaction variables, see subsection 9.1.2 - location choice) are considered too. However, no significant different in pattern has been found as Figure 9-12 - showing the results for the transformation scenario – reveals. Therefore, the results are displayed only from the perspective of the origin zone for the inner-city of Utrecht.

Table 9-3: Considered origin zones for which the utilities for moving to other zones is calculated.

Typology	Town	Neighbourhood name	4-digit postal code
Centre-urban	Utrecht	Inner-city	3512
Outer-centre	Utrecht	Lunetten	3524
Green-urban	Houten	Houten Southeast	3994
Centre-village	Montfoort	Montfoort	3417

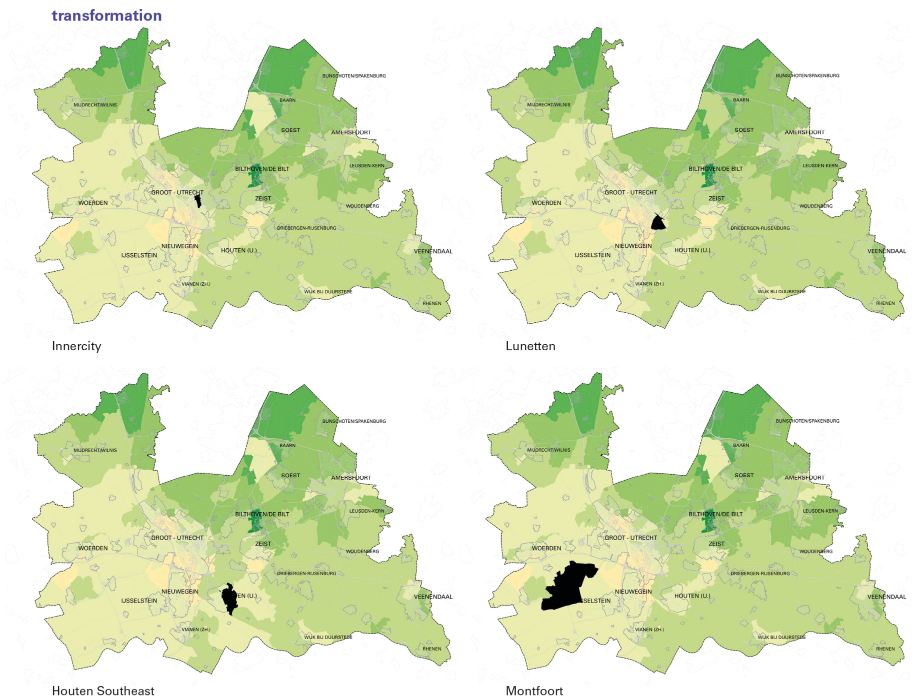


Figure 9-12: Uncalibrated observed change in probability of choosing a zone from the origin zone coloured in black for multi-person households with children under the transformation scenario.

The change in attractiveness is calculated based on utility. However, since no housing market dynamics are considered, the vacancy of dwellings is not included in the calculation. The change in attractiveness is calculated by therefore calculated using the following equation:

$$change\ in\ attractiveness = \frac{P_{z1,h,t0,scenario}(z2)}{P_{z1,h,t0,base}(z2)} * 100\%$$

with:

$$P_{z1,h,t,scenario}(z2) = \frac{\exp\left(\overline{\alpha_h} * \overline{X_{z1\rightarrow z2,t0,scenario}} + \overline{\beta_h} * \overline{X_{z2,t0,scenario}}\right)}{\sum_{z2\in r}\left(\exp\left(\overline{\alpha_h} * \overline{X_{z1\rightarrow z2,t0,scenario}} + \overline{\beta_h} * \overline{X_{z2,t,scenario}}\right)\right)}$$

Some attempts are made to make the results more representative although these are not calibrated. The sensitivity for land-use attributes is increased by a factor 3.1 as explained in subsection 9.3.3. However, this is no requirement since within logit models only the absolute change in utility influences the relative change in attractiveness. To grapple the large difference in accessibility values obtained from VRU and the magnitude of accessibility values expected for the choice model, the accessibility values are divided by 5E+7 to achieve a similar magnitude. Only commute accessibility is considered.

9.4.2 RESULTS

The results need to be interpreted with some restraint. Accessibility and spatial quality effects are collectively considered. There is some suspicion that the sensitivity between accessibility and spatial quality is in balance but this cannot be guaranteed. The relative changes in attractiveness for residing for each scenario are depicted in Figure 9-13 - Figure 9-16. The maps help to indicate the development of urbanisation patterns under the establishment of automated driving.

What shows is that under the constraint scenario, no significant changes are found. This coincides with earlier findings. The accessibility effects are modest and homogeneously spread over all zones and there are no spatial quality benefits. The other scenarios show an increase in attractiveness on towards the east compared to the west. This increase largely follows the pattern of accessibility increase.

The growth scenario shows an increase in attractiveness of the urban core of Utrecht. The transformation scenario shows slight increase towards the areas in the east. The difference between the transformation scenario and the growth scenario has two possible explanations. The accessibility benefits for the transformation and growth scenario are similar but the spatial quality gains are very different. For the transformation scenario, the shared taxibot-system allows for more attractive streets on most built areas. The growth scenario with private automated vehicles is mostly beneficial in the denser urban areas where the scenario assumes valet-parking systems.

The decline scenario generates a similar pattern compared to the growth scenario but without an increase of the attractiveness of dense urban areas. What characterises the decline scenario is a decreased attractiveness of inner-city areas. The increase of the attractiveness of the northeast area in the province cannot be explained since this area shows a strong decrease in accessibility under the corresponding scenario. This must be further explained in the follow-up phase of this research.

On a general level, most striking is the observed attractiveness from west to east of the province. The city of Utrecht and the surrounding province take on a unique location within the Netherlands. Utrecht is part of the Randstad area which extends from the city to the west. The east is less populated and knows a very green attractive environment. This area becomes significantly popular. Another important realisation is that automated driving can have the possibilities to make dense urban areas like the inner-city of Utrecht more attractive if one puts efforts in specific interventions that gives these areas a comparative advantage to other areas. Nevertheless, the shift in attractiveness from west to east still applies.

transformation

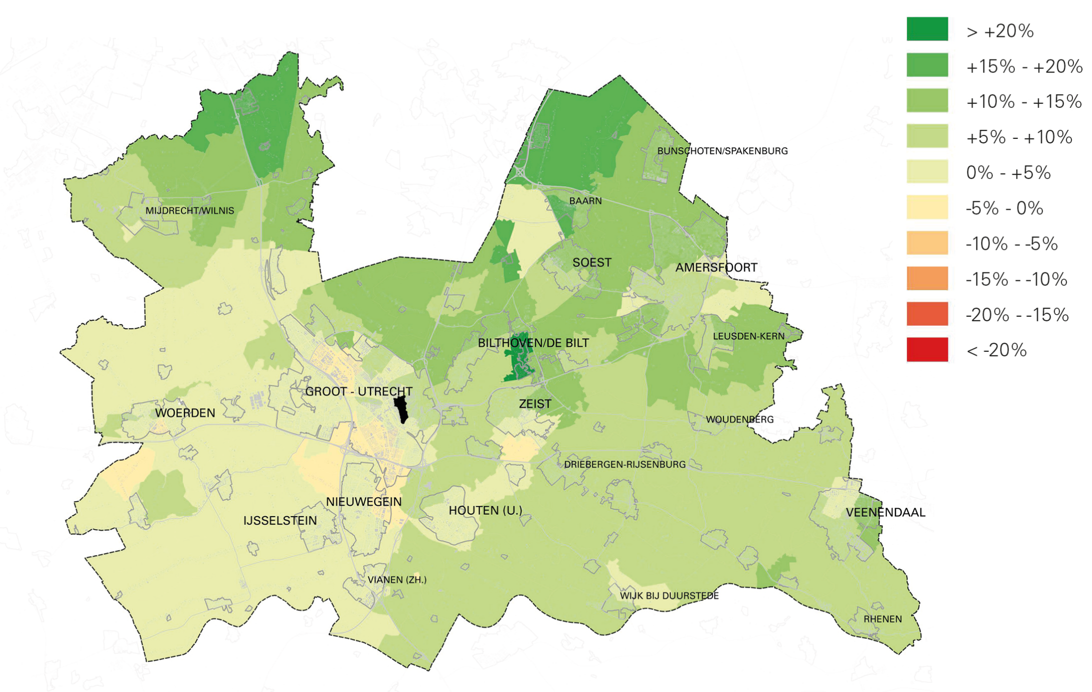


Figure 9-13: Relative change in attractiveness for the residential location choice under the transformation scenario for households of the class multi-person with children, living in the inner-city of Utrecht. For households of the same class living in other zones, similar results apply. Note: the results are not calibrated.

growth

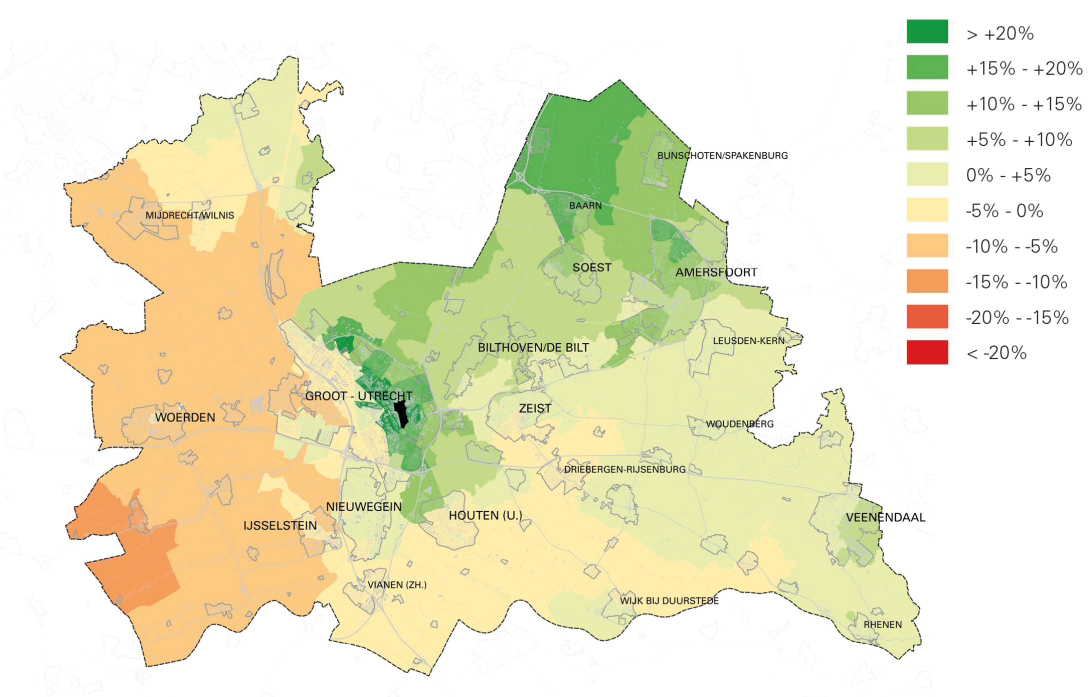


Figure 9-14: Relative change in attractiveness for the residential location choice under the growth scenario for households of the class multi-person with children, living in the inner-city of Utrecht. For households of the same class living in other zones, similar results apply. Note: the results are not calibrated.

constraint

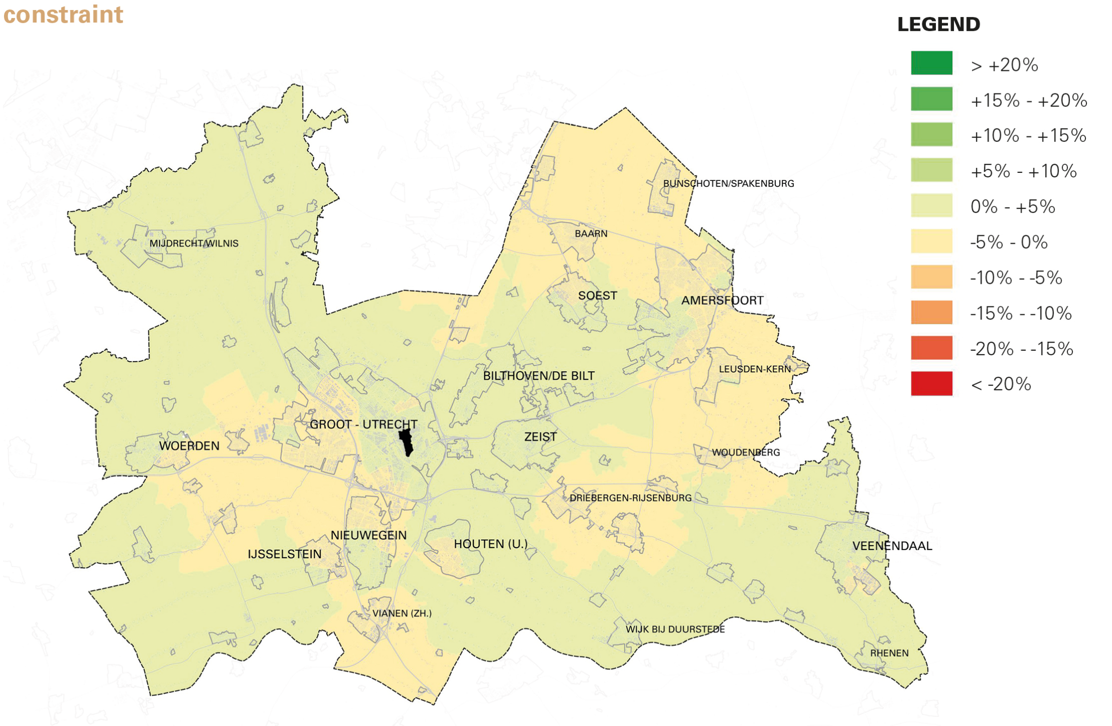


Figure 9-15: Relative change in attractiveness for the residential location choice under the constraint scenario for households of the class multi-person with children, living in the inner-city of Utrecht. For households of the same class living in other zones, similar results apply. Note: the results are not calibrated.

decline

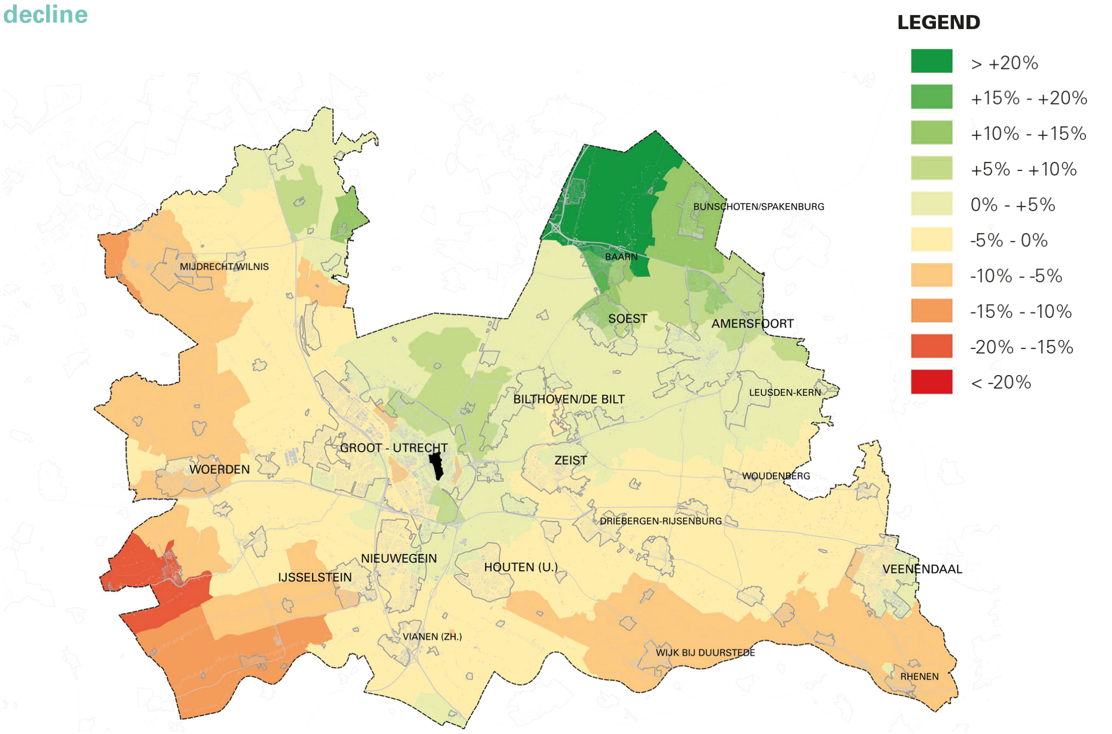


Figure 9-16: Relative change in attractiveness for the residential location choice under the decline scenario for households of the class multi-person with children, living in the inner-city of Utrecht. For households of the same class living in other zones, similar results apply. Note: the results are not calibrated.

9.5 TOWARDS A URBAN STRATEGY AND DESIGN EVALUATION TOOL

The preliminary results show the influence of automated driving on urban development patterns. However, interventions are necessary to facilitate this development. One must erect new dwellings for instance. This is not always possible nor desirable. Some developments can be steered by setting policies and creating interventions. The urban development model outlined and partly built in this study can help to evaluate these aspects. This subsection gives a brief forecast on how the urban development model can be further developed to become a strategy and evaluation tool. Housing stock and infrastructure are cogitated as representatives of land-use and transport (interaction). On the broader aspect of assessing plans and designs within an urban model environment will be elaborated in the conclusion of this chapter in the following section.

9.5.1 HOUSING STOCK DEVELOPMENT

Until now, the residential location choice model only shows the desire of households to move to specific places. However, no statements have been made regarding the development of the housing stock. This aspect is very relevant for to assess the spatial impacts of automated driving from the perspective of this study. Chapter 3 finds that comprehensive urban models also comprise a real-estate market for housing and offices. For this study, the choice is made to not incorporate this aspect in the urban model.
Several variables exist to address differences in housing market regulation policies (Zondag, de Bok, Willigers, et al., 2015, pp. 47-49). It would be very extensive to include developers as agents within the model environment. Modelling the interaction of the housing development market with developers asks for data on housing development plans and/or parameters regarding the oligopoly of developers on the housing market. Especially when one considers a very liberal market, there is a good reason to incorporate such aspects. However, the Dutch housing market is strongly regulated. Developers play a role but their decisions are strongly bound by policies set by the government. This means that institutions set policies to have the developers work in such a way that certain goals are obtained. The Dutch housing markets are characterised by exogenous dwelling projections or semi-regulated market corrected for supply and demand or free market within contours. These projections are often the result of democratic processes. The location of construction of houses is still driven or at least influenced by the preferences of the households (Zondag, 2007, pp. 26-27, 107).

It is therefore more suitable for this study to use the model to evaluate housing projections in the model. The development of a housing development plan is something that can come forward from an urban design strategy for instance. It is possible to add housing stock to an area which can be evaluated by assessing how much households decide to reside there and by examining the development of the housing price. It is additionally possible to include characteristics regarding the neighbourhood typology and the level of services.

9.5.2 INFRASTRUCTURE AND MOBILITY INTERVENTIONS

Designs and plans regarding infrastructure and mobility measures in general are harder to evaluate. This is partly because not all aspects are directly implementable within the modelling environment. This research process itself is a good example of this. Automated driving is a mobility innovation. Some aspects regarding the integration of infrastructure can have significant influence on the programme or typology on a neighbourhood. Or through hedonic pricing models, qualitative aspects can directly be evaluated. However, if the interventions concern aspects that are of influence on the performance of the transportation network, these need to be implemented within a transportation model first. Thereafter, these effects can be evaluated using accessibility indicators.

9.6 DISCUSSION

This chapter explains the means and presents the steps to develop an agent-based model that simulates the moving behaviour of individual households. With such model, it is possible to evaluate the effects of automated driving on urban form aspects. Although all theory and most data available, it reveals how challenging it is to make such model operational by coding as well as allowing it to generate adequate results. This is consequently not achieved yet.

Nevertheless, what also reveals is that already by defining urban development explicitly as a computational model, valuable insights are obtained. As the preliminary results show, it is possible to project changes in the attractiveness of certain areas under different automated driving scenarios. In all scenarios that show large implications on travel by automated driving (all but the constraint scenario), a shift in housing preference can be observed from the areas in the west to the areas in the east. This means that the areas further from the densely-populated Randstad increase in attractiveness. Furthermore, what reveals is that on a lower scale, only significant changes reveal if the implementation has also distinct differences within different urban areas. In the transformation scenario, all neighbourhood typologies benefit from the spatial quality effects of automated driving, hence no significant differences between inner-urban and outer-urban areas or between towns and villages is observed. The spatial quality gains between such areas are larger in the growth scenario. This scenario shows that if automated driving succeeds in making populated urban areas more attractive, the desirability of such areas for households increases accordingly. However, this phenomenon emerges subsequently to the prior explained phenomenon of an increased interest in the less dense urban areas that also occurs in the other scenarios.

One important consideration is that these conclusions are drawn from a model which does not consider the interaction between different decision makers. As the urban environment is characterised as a complex system, it bears properties of unpredictability and emergent patterns. These aspects have not been confronted in the study. However, the initial results give an indication of the propulsion automated driving brings to this complex system and in which new context urban and regional development strategies must be developed.

Further development of an urban model can help to evaluate such strategies and provide for input of these strategies by revealing the most important factors. For the latter, full development of the model is not even a requirement since the conceptual model already provides valuable insights. An urban model can help evaluating housing projections and infrastructure interventions. Peculiar about design and design processes is that – although often considered a problem-solving act – in initial stages, the outcome is very open. This means that some ideas are not suitable for evaluation within the model environment, while it might be very worthwhile implementing. This is something to keep in mind regarding urban models and design. Design will always challenge the functionality of the model. By applying models as evaluation tools, these can be challenged and improved.

The results obtained in this chapter built upon the prior chapters in this part of the report. Knowledge is obtained on the spatial implications of various aspects of automated driving. With these insights, the development of automated driving can be assessed in a broader value-based context on which the next chapter elaborates.

PART III. SYNOPSIS

10 STRATEGY DEVELOPMENT: CONCLUSIONS ON AUTOMATED DRIVING

In part II of this report, the assessment of automated driving effects has been led by the problem entity from the perspective of the scenarios established in chapter 6. The result is a stepwise presentation of the findings where the accessibility and spatial quality effects are examined to reveal changes in urban development patterns triggered by vehicle automation. The guidance of this research process allows to comprehend a holistic perspective on urban development. To draw conclusions on the impacts of automated driving, this chapter reflects to all insights obtained in part II and assesses and interprets the findings. By conducting a spatial strategy to plan and act on the emergence of automated driving, the results are interpreted and assessed in the socio-spatial context. The strategy translates the automated driving aspects and the emergent pattern it generates to the physical manifestation of cities (Figure 10-1). This allows to evaluate the results in the socio-spatial context of cities to comprehend the automated driving aspects as an urban planning problem. Technology is not the only driving force within urban change. Urban planners will and must act through policies and interventions to employ automated driving as an opportunity to improve cities.

This chapter starts by concluding on the results obtained in part II. Based on the aggregated insights obtained through the research, the most important automated driving factors and consequences are listed. Thereafter these findings are interpreted on their desirability for attractive cities. Based on these conclusions, the main assignment for urban development strategies are decided. The third section explains the development of an urban strategy that can be employed to act and prepare on the emergence of automated driving. The final section provides a broader conclusion and reflection on automated driving and the role urban planning and design has in the matter.

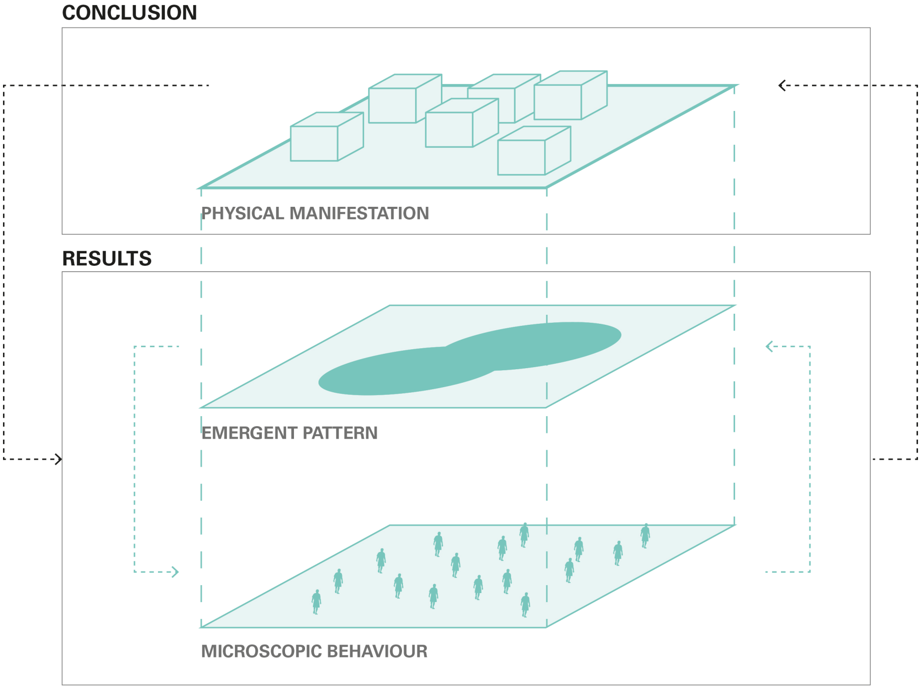


Figure 10-1: By conducting an urban strategy, this research concludes on the physical manifestation (and therefore the spatial impacts) of automated driving in a socio-spatial context.

10.1 CONCLUSION AND INTERPRETATION FROM THE RESEARCH

The main findings from the research are explained. The findings relate to the outcomes and dynamics of the problem entity. The second part of this section elaborates on the findings from a value-based perspective.

10.1.1 MAIN FINDINGS FROM THE RESEARCH STEPS

For conducting a strategy, the primary step is to derive the most significant challenges and opportunities from the scenarios that emerge from automated driving. Each scenario has different assumptions on automated driving, grouped in optimistic views (transformation and growth), a neutral view (constraint) or reluctant view (decline). For understanding the impacts of automated driving, the results from the scenario study ask interpretation with acknowledgement of these assumptions.

Despite all potential efficiency, safety and comfort gains, no scenario is without implementation challenges, except for the constraint scenario. Within this scenario - where only accessibility gains on the highway were assumed – a diminishment of bottlenecks on the highway system was found. Other effects on accessibility, spatial quality or significant changes in the residential location choice did not reveal. All other scenarios show impact of automated driving on these aspects as they manifest changes not only on highways but also in urban mobility. On different scale levels, principles are derived from the scenarios.

To derive main findings, most important observations are presented and interpreted based on the underlying assumptions that influenced these findings. The assumptions represent the ranges of uncertainty in automated driving. By understanding consequences of the assumptions, the most important dynamics and insecurities around spatial impacts of automated driving uncover.

Findings are interpreted on three different scale levels. The macroscopic scale level to conclude on urban development patterns, the network level and the street and neighbourhood level.

Urban development

Changes in urban development are driven both by spatial quality and accessibility effects of automated driving. in each scenario (except for the constraint scenario), a shift in attractiveness from the areas in the west to the areas in the east can be expected (Figure 10-2), especially when the spatial benefits are also evenly distributed over all areas. The growth scenario reveals and additional urban development pattern of increased attractiveness of the city centre and surrounding neighbourhoods (Figure 10-3).

The most important explanation for this observed difference can be assigned to the reason that both transformation and decline scenarios, show homogenous accessibility and spatial quality gains over all zones within the study area. The growth scenario also shows homogenous accessibility gains but knows a stronger difference of spatial quality effects between areas. This leads to the conclusion that if the effects of automated driving in terms of accessibility and spatial quality show equal distribution over all areas, mostly large scale modest shifts away from the large urban centres can be observed. When specific areas benefit more than other areas, these areas do reveal an increase in attractiveness for housing. The reason why this specific result emerges in the growth scenario can be assigned to the deployment of a valet-parking system within the city of Utrecht. This diminished on-street parking and allowed for more attractive street design. In the transformation scenario, the shared system diminished parking requirements in all areas (overnight parking has not been considered), whereas the decline scenario asked for parking as in its current configuration.

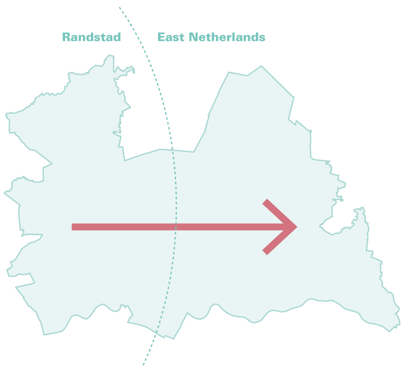


Figure 10-2: A general shift in housing preference from areas to the west to areas in the east can be observed.

Figure 10-3: If automated driving develops as a private fully automated system, valet-parking services can generate an increased housing preference in the urban areas of Utrecht.

Network

Despite infrastructure capacity gains, automated driving is not expected to make congestion obsolete. Depending on the development of automated driving, the demand on the road network shows increases for different reasons.

Capacity gains on the highway are largely expected on longer continuous road stretches. When more intersections are part of the highway network (e.g. ring roads), the capacity gains are considered less. However, the growth and especially transformation scenarios assumed high capacity gains. The induced demand exceeds the capacity benefits and therefore the existing highway network is not capable to adequately facilitate this induced demand. Under a shared and efficient system, the highway system might be capable to meet the demand requirements. But if the highways are also used by cars for valet-parking services, congestion will arise (Figure 10-4). Under strong induced demand, one cannot exclude that additional capacity is required.

Similar developments arise for the arterial roads providing access to urban centres. Especially within denser urban areas, where the current share of public transport is relatively high, additional road capacity is required under the assumption that automated driving systems replace mass transit services (Figure 10-5). Without infrastructure expansion, congestion towards the urban core can be expected. When valet-parking solutions are applied, congestion towards the urban fringes occurs under the assumptions that valet-parking facilities are located there (Figure 10-4).

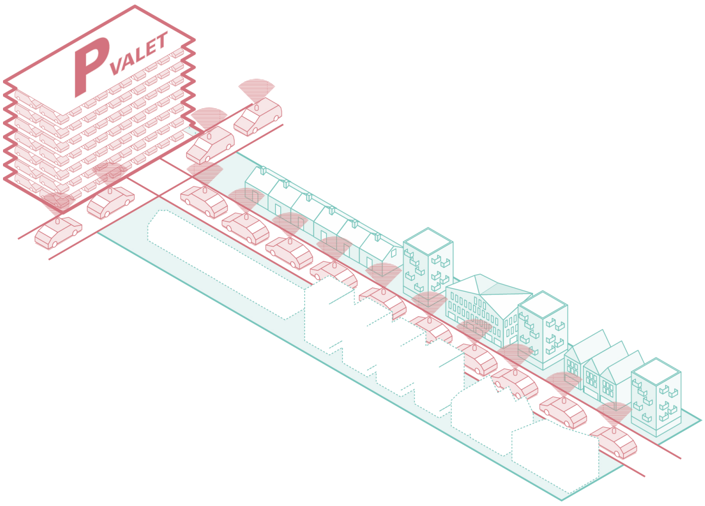


Figure 10-4: Valet-parking solutions allow for car free streets in urban areas, but will the challenge capacity of arterial roads and rings roads.

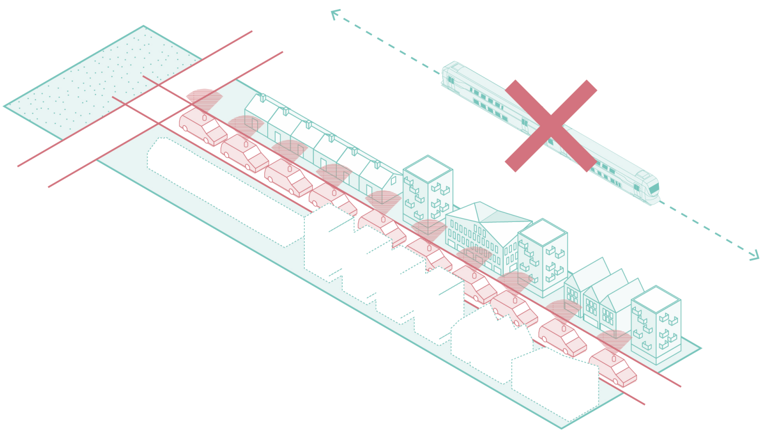


Figure 10-5: When mass transit solutions become obsolete, arterial roads towards urban centres will face congestion.

Neighbourhood level and street level

On the neighbourhood scale, the potential for transformation most strongly depends on how automated driving transforms the transportation system. Infrastructure makes a large land-use claim on urban areas. For instance, station areas require for large areas of rail infrastructure. In some areas, larger scale parking terrains or buildings dominate the urban environment. Areas where this was to be found are most often urban centres or areas adjacent to these centres. No large transformation potential has been observed for the diminishment of highway areas as the main road network still facilitates large travel volumes.

On street profile level, the spatial quality gains relate strongly to the travel demand for the street as well as current design of the road. Arterial roads facilitate relatively high travel demands and this is not expected to change under automated driving. How arterial roads are integrated within the urban fabric differs significantly within different neighbourhood typologies. Particularly in residential areas, such streets are integrated within a relatively green environment. In more urban-areas, the benefits for arterial roads are considered higher. On street level, the largest benefits are expected to emerge from the diminishing of on-street parking. Streets know relatively low travel demand as they are mainly used for local traffic. Hence no large change in the demand on street level is expected. The possibility to diminish on-street parking in residential areas depends on whether automated driving will deploy as a shared system or if specific policies or systems are developed that facilitate alternative parking solutions. Valet-parking solutions are a possibility, but generate a lot of extra travel movements. On-street parking might then prove more attractive, especially since some urban residential streets do not significantly suffer from parked cars.

10.1.2 INTERPRETATION OF THE FINDINGS

By deriving the most important conclusions from the scenario studies, the next question is which actions to undertake to allow automated driving technology to steer towards sustainable urban development. Therefore, it is of importance to interpret the findings from a value-based perspective and determine objectives where an urban development strategy can work towards. Furthermore, the strategy must be able to provide answers to urban planning questions under the uncertainty of automated driving.

Not all projected impacts of automated driving are equally desirable. As this study shows, automated driving can cause an increase in congestion on the urban road network. This is not favourable in perspective of both travellers and residents. Making street free of parking is an option, but can come at the cost of increased congestion as well. It is unclear whether automated driving will develop as a shared system or a private system (or a hybrid form). It is therefore required to not abandon the role of parking within urban areas. Parking must be taken into consideration within urban development and transformation assignments, and it will therefore be a consideration whether parking as alternative solutions is worth the increase vehicle travel. Furthermore, an important subject is how to integrate these parking solutions within the urban fabric or within the landscape.

Another question that will at some point in time be of importance of answering relates to the role of mass transit and public transport in general. Public transport has two roles. On the one hand, there is a social role to provide for transportation to people who do not have access to private transportation means for any reason. On the other hand, it is a very efficient mean to transport large number of people in urban areas. Especially the latter aspect relates to the performance of the transportation network. Mass transit is crucial to provide access to the urban centres but lays also a large spatial claim on these areas.

Regarding urban development, no very threatening patterns are found that automated driving might cause. By a very threatening pattern, one could think of large moving patterns from the urban areas towards the rural side. This would leave large building stock undesired and would harm the openness of the landscape. Nonetheless, the observed shift from the denser areas in the west to areas east with a more open character shows reason for caution and should not harm the quality of the landscape.

10.2 STRATEGY ASSIGNMENT

Based in the interpretation of the findings, the assignment for a strategy to elaborate on automated driving can be drawn up by posing the objectives. An important consideration for the strategic framework, is that it must also prove valuable and useful even if automated driving will not develop at all or only very modestly. A distinction is made between aspects related to urban development and aspects related to the infrastructure.

Urban development assignments

Regarding urban development, observed increased attractively of the areas in the eastern part of the study area for housing asks for plans and action. A consideration must be made whether this development is desirable and how it can be accommodated in an adequate way. This area in the east is characterised by valuable landscape assets and high housing prices. When no interventions are undertaken, an even stronger increase in housing prices will be observed. By adding housing stock to the area, this development can be altered and allows households from various income classes to reside there. If one decides to undertake no action or not develop any specific policy, municipalities might find incentives to initiate housing developments that might harm the landscape or promote an unstainable mobility lifestyle. It is therefore important that the towns in the east of the study area (e.g. Amersfoort Soest or Veenendaal) provide for densification strategies either in proximity of the highways or close to stations. From a contemporary point of view, the latter strategy is more desirable. However, from the perspective of automated driving, housing development in proximity of highway areas might be more desirable to prevent congestion on the urban network. It is key to design these housing developments for promoting sustainable mobility.

One of the uncertainties regarding automated driving is whether it leads to an increase in specific urban areas or in all urban areas. In case of the prior, dense urban areas – in this case the inner-city of Utrecht – housing demand will increase in those areas. Dense urban areas are today already characterised by a tight housing market. This is partly undertaken by urban transformation and densification programmes. This development has all the reason to be continued in the future.

Infrastructure and transportation assignment

Facilitating urban mobility is an important assignment today and will also be an important challenge in a future with automated driving. Vehicle automation is not the solution to all urban mobility problems. Dense urban areas generate many trip ends for the large concentration of activities. This study reveals that mass transit is still essential to allow for this movement pattern; large groups of people needs to be transported to and from the city centre by large capacity transportation systems. It is important that such system will always be attractive for travellers - even with an automated vehicle system - to prevent congestion in the inner-urban road network.

Valid reasons exist to diminish parking from street in specific areas and allocate the unused vehicles elsewhere. However, the induced vehicle travel poses challenges for the urban road network. External parking must be allocated either locally on a small scale or implemented carefully only in areas that suffer most from on-street parking. Based on this rationale the urge is expressed to carefully consider valet-parking services in residential areas and in the urban centres.

Regarding developments on street-level, no assignment for the strategy will be stated. It is important to maintain hierarchical road network structures where larger volumes are concentrated on arterial roads. Automated driving can trigger for more attractive design of these main urban roads but are no requirement. In residential streets, the largest potential for transformation lies in the diminishment of parking. This aspect relates mostly to decisions and developments on a larger scale. If on a larger scale the planning principles for automated driving are adequate, urban spaces on a lower scale level benefit accordingly

Goals

Automated driving is not the solution to all urban mobility problems and might challenge the functionality of the inner-urban road network and the highways around the City of Utrecht. It is important that mass-transit either stays attractive to enter the city or that the inner road-network can facilitate the induced demand of individual cars on the road. Therefore, the strategy must act on a road network structure and coinciding urban development plan by which these challenges can be facilitated.

10.3 STRATEGY DEVELOPMENT

The presented strategy explains some guiding principles for urban development to allow the city to benefit from automated driving for when the technology establishes itself as mainstream transportation mode. The development is completed in two steps. In the first step, a strategic map image is drawn that shows the most important principles. Some of these principles are further elaborated on.

The goal of the urban strategy is to set the conditions that allow cities to benefit from automated driving. A strategic framework must be adequate and flexible and benefit urban areas even when automated driving will not develop at all. Evaluation of the results shows that the largest challenges arise in areas that generate a lot of traffic. Therefore, the strategy should focus on the City of Utrecht primarily. Within other urban areas also challenges will arise regarding the integration of automated driving or the change in housing demand it involves. However, these challenges are considered detached urban planning problems. Within denser urban areas, the case of automated driving and urban development is more interrelated and therefore asks for a more comprehensive vision.

10.3.1 STRATEGY MAP

The strategy proposes urban development areas around the ring of Utrecht and the station area through the concept of nodes. These nodes have several purposes (Figure 10-6):

- Promoting mass transit and bundled flows towards the city centre;
- Allow for urban development for housing and other programmes.
- Nodes can develop as parking areas. A large distribution of valet-parking areas evenly distributes the flow from the city centre to these areas over the network;

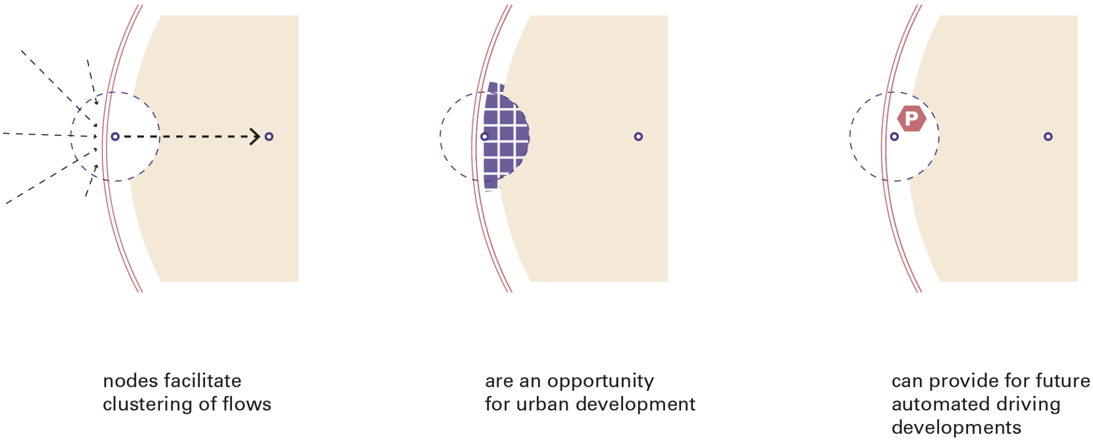


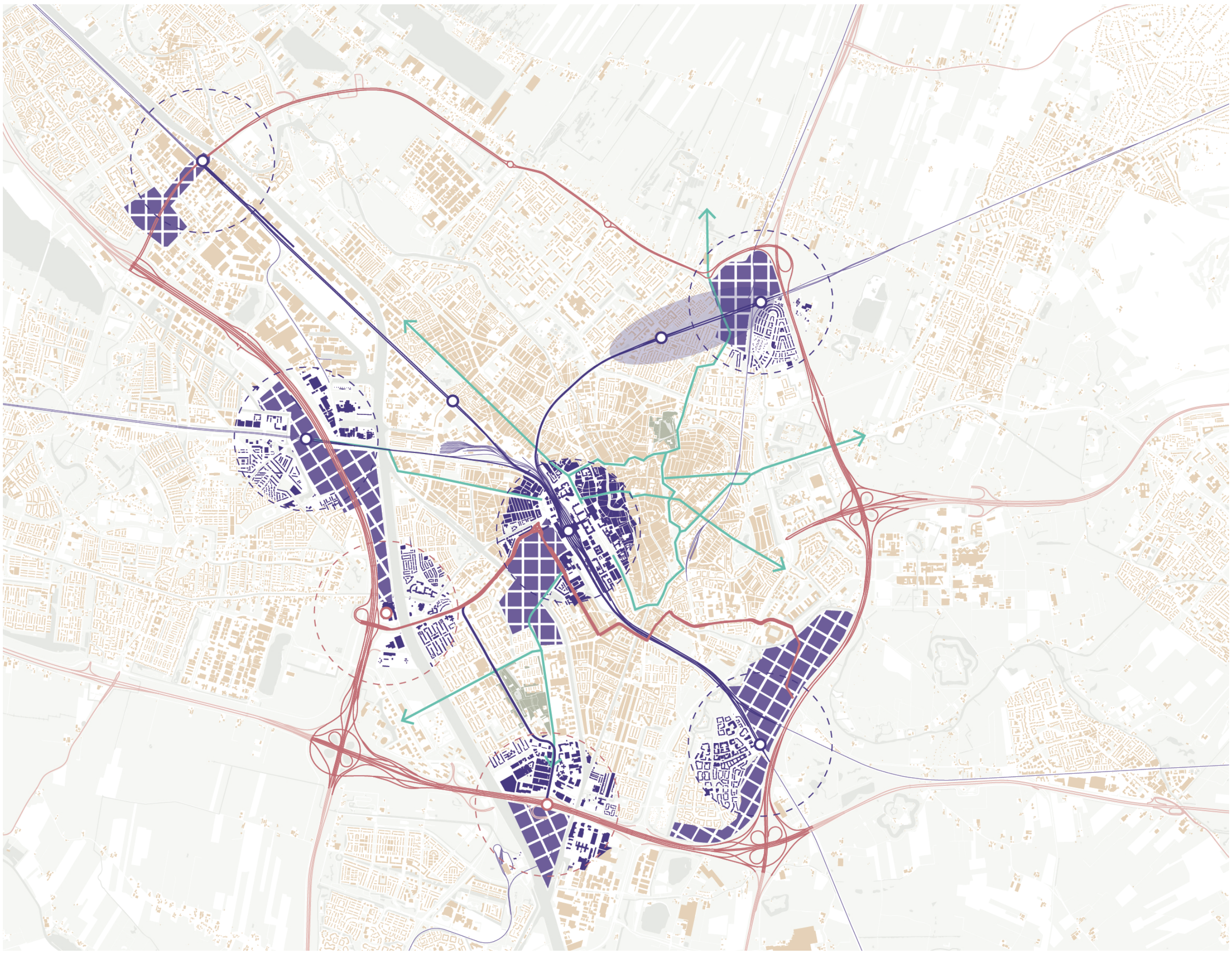
Figure 10-6: Purposes of the node development program proposed in the strategy.

By focussing on nodes, the possibility exists to control how to distribute traffic to the city: it allows for bundling of flows and defines a clear road hierarchy. Unnecessary travel movements on the road network can be limited by allowing efficient transfer possibilities to mass transit systems and by adding program the areas can develop to attractive areas and generate enough travel demand to provide for public transportation services. The goal is to find an adequate balance between proximity to the network to reduce vehicle kilometres by simultaneously providing for an urban environment that facilitates public transportation and slow modes.

Although these nodes ask for physical long-term interventions, the development can be considered flexible in relation to automated driving development. The locations are strategically considered around stations or other public transport services. These provide therefore a basis to always allow for park and ride facilities. Furthermore, as the nodes bundle traffic, also the flows on the urban network can be better directed. Therefore, the existing road capacity can be better utilised, also in future situations with induced demand. This helps to downgrade other important roads for active modes and public functions.

Subsequently, the areas allow for urban development. The area around the ring-roads are the fringes of the city today, but with attractive urban design and adequate transit solutions, these areas are promising areas for future urban densification programmes within the ring road of the city.

Figure 10-7 shows how the concepts can be implemented by showing locations for nodes and corresponding areas for urban development. By providing a clear network structure towards the city centre, other areas can be designed as local street hence spatial quality can increase or can be maintained even under factor as induced demand or disappearance of public transport. Some locations of the nodes are considered in proximity of the rail track. This allows to transfer the rail track to future roads to facilitate a potential shared autonomous car fleet.



LEGEND

development node

programme development

main road connection

main rail connection

local street

Figure 10-7: Map with the urban development strategy for the City of Utrecht.

10.3.2 INTERVENTIONS

To elaborate on the strategy in more detail, the potential development of the station area and one of the nodes along the ring is further explained.

Ring development

Places for urban development emerge along the ring roads. Especially areas where the railroad intersect the highway can be considered strategic locations (for this example the area Lunetten-Amelisweerd along the A27 is displayed (Figure 10-8, Figure 10-9)). The area provides for space for new urban development which potentially can grow further towards the highway road. Within the rail stretches, large scale parking solutions can be realised to facilitate park-and-ride or later provide for valet-parking solutions. As mass transit proves crucial the railway network is required to play an important role in providing access to the inner-city. For the case that automated driving makes public transport absolute, the rail stretches potentially can be transferred to roads that provide access to the city centre. This allows to facilitate induced demand without consequences for the urban road network.

Station area

No matter how automated driving will develop, large traffic flows are expected at all time towards the inner-city of Utrecht. It is important that these flows can be accommodated, bundled and coordinated. It is therefore important that there is an area in which these flows can be coordinated. It makes sense to use the existing station area (Figure 10-10) for that purpose as it has a central position within the transportation network. To maintain attractiveness of the node within the future and limit travel demand, transit oriented development (Figure 10-11) is even more crucial to act on the induced demand challenges of automated driving and reduce travel.

Figure 10-8: Current situation of the area Lunetten-Amelisweerd.

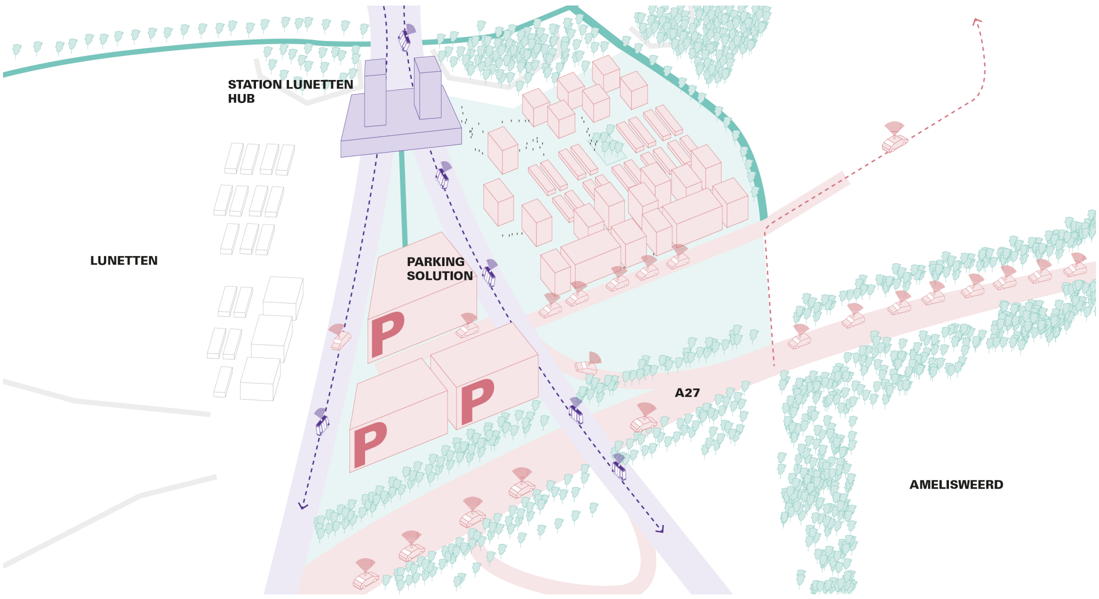


Figure 10-9: Development of the Lunneten-Amelisweerd area as access hub towards the inner-city.

Figure 10-10: Current situation of the station area

Figure 10-11: Development of the station area to maintain the attractiveness of mass transit.

10.4 CONCLUSION

The strategy shows a planning principle that urban planners and policy makers can use to steer urban development in a way that the city can benefit from automated driving in various scenarios. However, the principles shown in the strategy are somewhat generic and do not require automated driving for successful implementation. From the holistic perspective by which automated driving is examined in this study – by elaborating on spatial quality effects, travel and residential moving – this study concludes that automated driving is not expected to be disruptive in the sense that completely new urban development patterns reveal. Some urban development patterns revealed, but the magnitude of the results seem limited and have not considered housing market developments into consideration. Housing market dynamics are expected to have a balancing effect.

The most important realisation is that urban areas will always generate a lot of traffic. These large flows of traffic will require roads, parking, etc. This is not expected to change in the future. Nevertheless, the study also shows that automated driving can make our cities more attractive. Urban life can benefit from diminished large parking areas or parking spaces in public streets and from less infrastructure requirements in general. However, one can doubt if vehicle automation is a requirement for this. By effective infrastructure and urban planning policies, similar results are feasible too.

11 CONCLUSIONS & RECOMMENDATIONS

Chapter 10 concluded on the spatial impacts of automated driving in the form of an urban strategy. In this chapter, conclusions and recommendations are drawn in relation to the main research question. The main research question does not relate to the topic of automated driving but asks how an integrated research methodology, as employed in this graduation process, can lead to better understanding of urban planning problems.

This research is an attempt to integrate engineering thinking and design thinking in one research process. Hence, the conclusions are drawn from the theoretical framework on engineering and design approaches in research and from the research process and the results of the study on automated driving. This chapter closes off with practical recommendations for further research and development of methods to support integrated research in the future. These recommendations are closely related to the conclusions, but are presented in the current form as these concern executable measures

11.1 CONCLUSIONS

The conclusions explain how an integrated engineering-based and design-based research leads to better understanding of urban planning problems and how this influences the research process. The first part of the conclusion explains the strengths of an integrated approach on the understanding of urban planning problems and the result these studies achieve. In the second subsection, the aspects crucial for an integrated research process are illuminated. The conclusions elaborate on an integrated research approach to obtain better understanding in urban planning problems. Due to time constraints, the research has not grasped upon the possibility to use computational urban models as a design evaluation tool. This aspect is further explained in the recommendations in section 11.2. The conclusions are drawn based on the three research steps which are displayed in Figure 11-1. Therafter, the conclusions elaborate on the consequences for the research processes. The conclusions are completed by repeating the most important requirements for an integrated research.

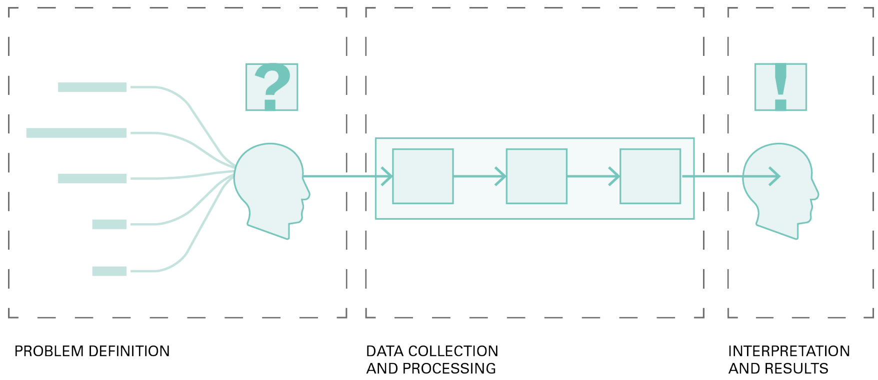


Figure 11-1: Steps within an integrated research process

11.1.1 UNDERSTANDING OF THE PROBLEM

Urban complexity knows both a systematic character and a contextual character. The systematic character relates to the dynamic interactions between various decision makers that move through and shape the urban environment. The contextual character relates large range of variables that matter within the specific spaces of the urban context and the social processes that these spaces facilitate. To comprehend the full scope of urban planning problems, it is crucial to address both facets or urban complexity.

An integrated perspective allows to better comprehend the full scope of urban planning problems and leads to better defined problem statements. Engineering disciplines will narrow down the problem to the main essence but the holistic design perspective challenges that narrow focus through its associative thinking attitude. In this research, the resulted in better elaboration on the spatial quality effects of automated driving within the fundamental description of an urban planning problem. Integrated research makes the problem statement more complete and clear. An explicitly stated model illuminates the core system of the process that is studied and guides the data collection as the most crucial components of the problem are listed. In this research, this can be deserved in the derivation of the problem entity in chapter 5. Household choice behaviour was identified as an important driving force in urban development. By understanding this choice behaviour in relation to vehicle automation, the research steps to assess spatial quality and accessibility revealed as most relevant factors to examine.

Urban planning problems are different from other problem-solving acts in the artificial domain that involve engineering and design. Within urban planning problems, the primary act is to fill a knowledge gap instead of specifically constructing or blueprinting an artefact. However, deriving policies or interventions to integrate within the urban environment are important conclusions of the research process. As the strategy for automated driving in this research shows, the way how to act on urban planning problems is inherent to the answer opposed to knowledge gap. Therefore, an integrated research allows to understand the role of the intervening party within the urban planning problem.

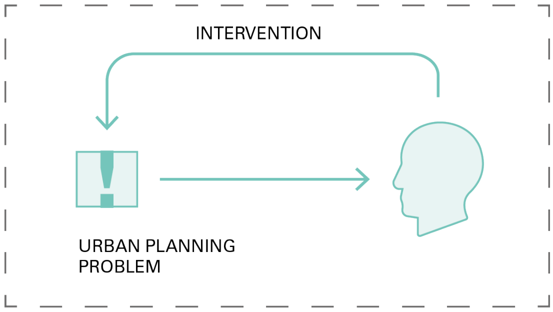


Figure 11-2: An integrated perspective helps to understand the role of the interventions in the urban planning problem.

11.1.2 DATA COLLECTION AND PROCESSING

The use of the transportation model and a residential location choice model helped to study the dynamics in human behaviour in space and time under the hypothetical context of automated driving. The insights obtained in this part of the study would not have revealed through design methods and would have asked for more assumptions, compromising on the accuracy of the results. The models employed by engineers are not primarily strong to make accurate predictions. Instead, they allow to study the urban system under various scenarios. By using computational models within research, less speculation regarding uncertainty is necessary.

Engineering-based methods do not always provide a state-of-the-art method to assess a relevant variable within the urban planning problem. An example for this is e.g. related to spatial quality. The design-approach allowed to assess this spatial but abstract data within the specific urban context. This did not only provide for interpretation of the results in the built environment, but also allowed to obtain information within the data collection process itself. This is not the easiest method to solve things as challenges arise regarding the compatibility of the findings. Nevertheless, this study shows that design can prove important in the data collection process when no other method is available.

11.1.3 RESULTS AND CONCLUSIONS

Integration of design-based and engineering-based research methods leads to different results. In chapter 2, the relation between the research process and the result is explained. A distinct difference between engineers and designers is that engineers evaluate the results based on probability and plausibility. Designers take a more personal stance in which results are considered desirable and come up with propositions to achieve such results. These attitudes seem conflicting at first but allow for more adequate and agile results.

By employing a computational model within research, some aspects of the ***thinking-process*** are transferred to an artificial process. This artificial process is a computerised model that is prior conducted based on empirical findings and data. Such a model will give very honest results and spectacular outcomes are not guaranteed. That was to some extent also the result in this case study: Accessibility changes were modest, homogenously distributed over the study area and network and travel flows still asked for a large infrastructure claim within space. Such results limit the possibilities of the designer to project an attractive future image. But by interpreting the results as an assignment for the development of an urban strategy and deriving action perspectives, solutions are found to still aim for attractive urban development plans. The insights that are provided in the computational model study reveal the most important factors to act on. This allows to develop plans and frameworks that act on the most relevant aspects and consider the dynamics that influence the outcome.

11.1.4 CONSEQUENCES FOR THE RESEARCH PROCESS

An integrated methodology leads to better understanding of urban planning problems. It is most beneficial if the perspective is not sequential but that a strong interaction can be established throughout the process. The prior subsections revealed that integrated thinking leads to better understanding of the problem, more methods to collect and process data and more agile results.

Integrated design and engineering thinking has consequences for the research process. To allow for engineering research strategies and design research strategies to work together, it is important to agree on the actual urban planning problem and the system through which it is assessed. It is therefore of importance to first derive a conceptual model through which the problem is assessed. To operationalise a computerised model within the research, this model needs to be expressed in equations. An explicit model strongly dictates the research steps and the variables that can be considered and states the research steps. This gives the research process a more algorithmic character compared to conventional design research processes. This poses the largest challenge in an integrated research from an operational point of view. As the process gets more algorithmic, the compatibility between various research steps gets increasingly important. The result of research step ***a*** provides input for research step ***b***. This complicates the research steps and makes it harder to relate directly to the final solution since the synthesis of the data is partly executed by a model instead of by the researcher.

Interpretation of the results becomes increasingly important within an integrated methodology. No matter how comprehensive the data and model is, the relation to the context is more indirect or simplified compared to conventional design research processes (as all models are a simplification of reality). Making computational models operational is very intensive and ask for a lot of efforts. The decision to use an integrated approach within research will lead to a research process where first the computational modelling methodology must be formalised before the actual design process can begin.

11.1.5 REQUIREMENTS FOR AN INTEGRATED APPROACH

The existence of two cultures as identified by Snow (1959/1965) and introduced in section 2.2 are an obstruction to make an integrated research approach mainstream. But bringing together both cultures has potential to bring the urban planning practice forward. The key is not to merge the two perspective together but come to mutual understanding. The reason why this is so hard is because both perspectives ask for a certain level of specialism and skill which is not easy to obtain. Using quantitative models is difficult and time consuming. It is no wonder that engineers make decisions to narrow these models down. Designing is a peculiar act which the personal judgement matters to evaluate all the variables. Today there is not enough understanding between the two fields of practitioners and a common language or method to transfer findings and results is not always available on an adequate level.

11.2 RECOMMENDATIONS

The recommendations build on the conclusions. First recommendations concern further research on integrated research methodologies. Second recommendations are of practical nature for researcher that want to use an integrated research perspective on urban planning problems.

11.2.1 RECOMMENDATIONS FOR FURTHER RESEARCH

The following recommendations are given for future investigation to obtain better understanding in integrated computational modelling and design research approaches.

Computational models as design evaluation tools

In this research, computational models are used together with design-based research to obtain better insights in urban planning problems. The residential location choice model described in chapter 9 has not been developed to a fully operational model due to time constraints. Without a fully functional model, the prototype has provided valuable insights for the research. However, if the model will be developed to be fully operational model, it would allow for a design evaluation tool (Figure 11-3). For instance, in the development of the urban strategy, the impact of the proposed multimodal hubs, or the housing development programmes could be implemented within the model environment. This would allow to study the change in behaviour of households on these implementations and the new dynamics on the housing market.

This research only elaborated on the first part of an integrated methodology; using two perspectives to obtain understanding in urban planning problems. The next step is the use the same methodology to evaluate the outcomes

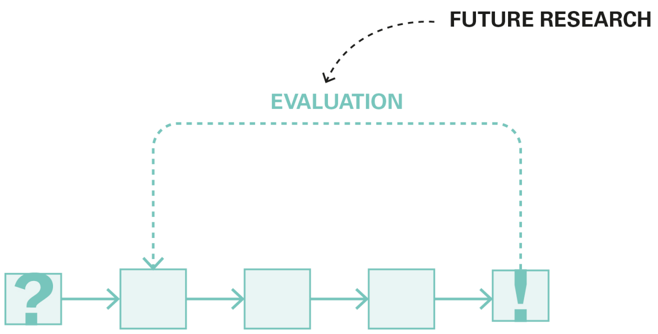


Figure 11-3: Evaluation of the result within has not yet been considered in this research.

Compatibility between different research stages

The compatibility or transferability of results of one research step to a following step is an important requirement for an integrated research approach. Within the field of science and engineering, the methods are often quantitative which allows that results are easily transferred. This proved a challenge in an integrated research. For the case study in this research, the neighbourhood typology classification dictated by the residential location choice model has been used as an indicator for urban environments and spatial quality has been expressed in housing value through hedonic pricing models. These methods were available and applicable solutions to the problem. These methods were not flawless but did illustrate and prove that transferability between qualitative design steps and quantitative modelling approaches are possible. However, these steps still asked for many assumptions. An integrated methodology can greatly benefit from better understanding how to classify and assess qualitative urban aspects. This research therefore recommends to further study the possibilities of hedonic pricing models and advanced hybrid urban metrics (as explained in section 3.1.2) to express qualitative aspects of the urban environment.

11.2.2 RECOMMENDATIONS FOR INTEGRATED RESEARCHER IN THE URBAN PLANNING DOMAIN

Based on the experience obtained in this research, recommendations are listed for researchers that will conduct integrated research.

Data dependency

The statement to not fall in love with data is made by Pidd (1999, p. 127). The purpose of any model is to process variables and data. By using a computational model, part of the evaluation task is executed by a computer, a machine specifically designed to process quantitative data. These computers and the models they run ask for specific data. Nevertheless, the underlying theory is even more important. Modelling should drive the data collection and not the other way around. Understanding the theory by which the data is evaluated provides more valuable insights.

Besides the fact that data should not obstruct the theory, one should not let the data obstruct the focus on the study object. If one only elaborates on the urban context by the variables defined in the model, the sense of location becomes weaker. For designers, it is important to get familiar with the study area through site visits, sketching, mapping etc. If one lets these steps over to data and automated computer processes, the designer loses the ability to adequately grasp the broader contextual complexity.

Modelling is a tool and no goal

Complex urban planning problems can greatly benefit from computational models. However, for such problems there is often no model readily available nor easily applicable. Constructing an operational model is time consuming and asks for a lot of competences. It is worthwhile to conduct a conceptual model according to the paradigm by which the model can be assessed. Thereafter one must make the consideration whether it is worth the efforts to formalise the model or use the insights obtained in the conceptual modelling exercise. In many cases the conceptual model provides for valuable insights in urban planning processes. However, if the study asks for a design evaluation tool, other considerations might apply.

Use design thinking when theory and models do not provide an answer

Meta understanding of urban planning will always be comprehended from the perspective of the researcher and not by the tools the researcher uses. The variables, uncertainty and societal context will always ask for human interpretation. When the context is too complex, controversial or comprises too much variables a design approach can help. By constant prototyping and assessing the this to the context, valuable and comprehensive answers to urban planning problems can always be attained.

A knowledge gap is no problem statement

Simon (1969/1996) states that design is a problem-solving discipline. Within the research process of this study, the process was driven by a knowledge gap from a methodological perspective. Furthermore, the case study had the character of a filling knowledge gap rather than a context specific problem statement too (***what are the spatial impacts of automated driving?***). By analysing the study area on the topic of mobility, a contextual problem statement would have helped to connect the research to the case study, which would have led to more specific design outcome.

12 REFLECTION

12.1 REFLECTION ON DESIGN AND THE PROJECT

The relationship between research and design

one must have a clear image of what design and what research compels for adequately elaborating on the relationship and the difference between research and design. This research states a strong difference on design as a process of blueprinting an artefact and design as a method to understand urban planning problems. By assessing design as such, design is part of the research act. Design is different from other research acts as it distinguishes itself from the scientific discipline.

This study shows that design is an important aspect within research in urban planning problems. Urban planning problems are always influenced by the societal context and therefore carries value-based decisions, which in turn influence the problem. Design is one of the few approaches that can evaluate this complex context and comprehend the wide range of variables attached to the problem, especially in problems where other research approaches provide no answer. Design takes on a holistic approach to problems but proves in this research also a mean to generate data. Where other research approaches would be required to make assumptions, or generalise findings, a design approach can provide answers through abductive reasoning and a close relation to the context.

From a personal perspective, I think that not everything is a design problem unlike many designers might believe. The engineer in me is eager to further explore the possibilities of quantitative methods to understand the built environment from a model perspective. By understanding urban development as a system, one learns the impact of different variables. Many of the variables are outside the domain or consciousness of the designers and therefore design cannot pose answers to all research questions. I do however think that there is always a role of design somewhere in the research process because all urban planning problems relate context and values.

The relationship between the project and a wider societal context

Cities will face many transition challenges in the future and automated driving is only one of those challenges. This research provides for a strategic framework on which cities can take a plan of action. In a wider societal context, the research helps to explain which position society should take on technological transitions. A certain degree of optimism can be observed in this matter. In the case of automated driving, it is often propagated as a solution to many urban mobility problems. However, this research shows that not all this optimism is justified. The main lesson this research gives to society is to not wait for technological transitions, but use contemporary methods and ideas to improve cities as of today.

Within the societal context of the professional and academic world in the domain of the built environment, this research shows the importance of collaborative attitudes between different specialisations and attempts to give an example how this collaboration can be established. Integrated research approaches will become increasingly important in urban planning problems and this research attempts to cast a light in the dark.

The methodological line: considering the city as a complex city

One of the most determining decisions in this research is the problem perspective of cities as complex systems. This decision was the single most design decision in this research. Although this perspective triggered the use of engineering methods, it asks for a holistic vision to urban planning problems. Cities as complex system is a beautiful and fascinating paradigm and can provide an important bridge between various domains within the realm of urban planning.

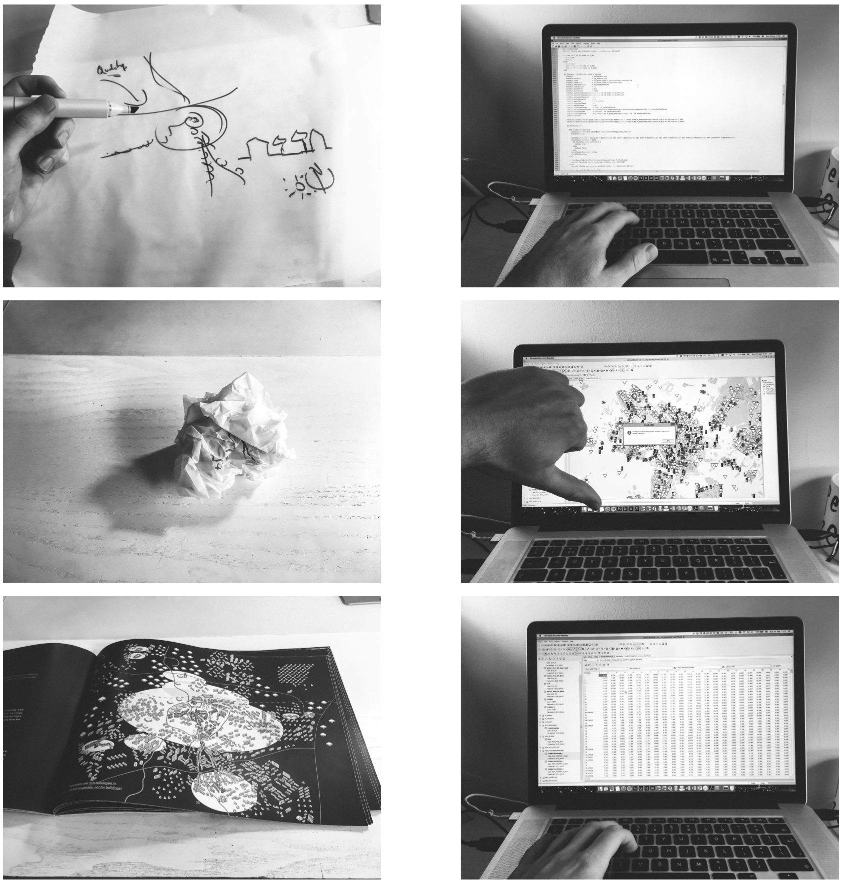
12.2 EVALUATION OF THE PROCESS

Using computational models in urban planning and design is challenging. It asks the researcher to learn a lot of theories, programming languages and computer programmes. Making a computational method operational is a design process itself. Within a design process, the solution is always part of the iterative process and therefore the relation with the context is something that keeps the researcher involved with the actual study topic. Within a computational modelling research, the iteration process is not related to the solution but to the method itself (Figure 12-1).

I started this research with the idea that I would be able to use a model within an iterative design process. However, due to errors, data incompatibility, long runtimes and any other problem people using software and programme languages face this full iteration process has never been reached. The method became an obsession and up to a month before submission of this report I have made attempts to get the method working. This has compromised other research steps. By taking on a holistic approach together with models, the modelling process becomes increasingly complex. Together with a case study relating to automated driving everything became more difficult. Next time, I would take on a case under a less hypothetical context. This would allow for more time and energy to focus on the aspects of an integrated research methodology.

I was always charmed by the optimism by which design takes on urban challenges. Through an engineering approach I might have become more sceptical and have been thinking more in limitations. To put plans into actions, design can prove for great inspiration. However, some questions are of such challenge that design alone cannot answer questions.

If I would have accepted earlier that it would not have been feasible to construct a fully operational model, I might have derived the similar conclusions earlier in the process and provide more efforts in the development of the strategy and design. This is a price a pay for considering the model construction process as a design itself. In that sense, I feel slight disappointment about that I have not been able to show a final design on the level I wanted and could. However, the topics I grasped in this research have led me to more uncharted territory than a conventional research might have done. I am thankful for all the insights obtained and I am eager and curious to use this insights in the future.



Prototyping

Rejection

Result

Figure 12-1: The iterative process of design (left) and the iterative process of engineering (right).

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APPENDIXES

A NEIGHBOURHOOD SPATIAL QUALITY ASSESSMENT DRAWINGS