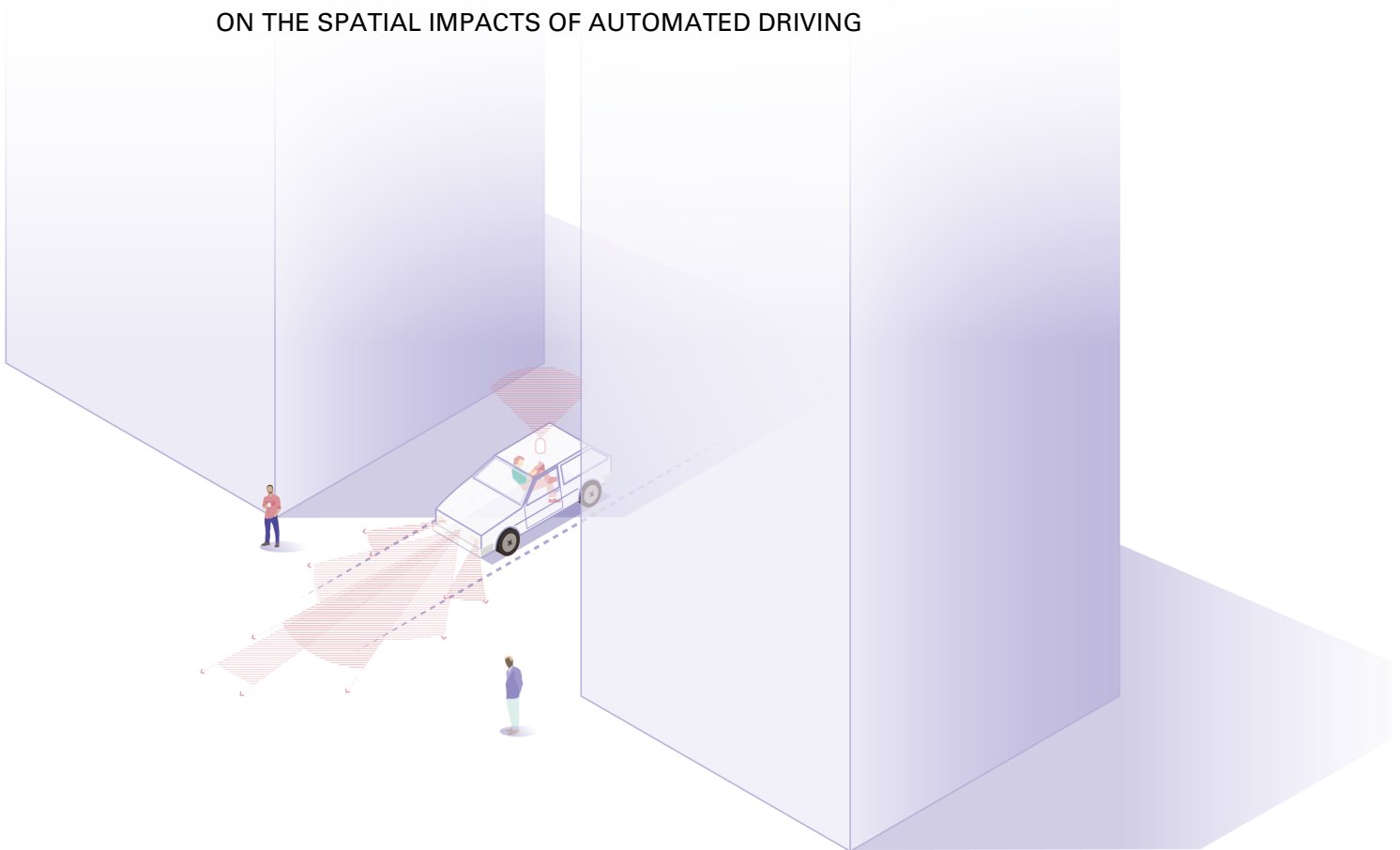


Master Thesis
Delft University of Technology
Faculty of Civil Engineering
Department of Transport & Planning

AUTOMATED DRIVING: DRIVING URBAN DEVELOPMENT?

AN INTEGRATED MODELLING AND RESEARCH-BY-DESIGN APPROACH
ON THE SPATIAL IMPACTS OF AUTOMATED DRIVING



Martijn L. Hollestelle
March 2018

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ON THE SPATIAL IMPACTS OF AUTOMATED DRIVING

By

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In partial fulfilment of the requirements for the degree of

Master of Science

In Civil Engineering

At the Delft University of Technology

To be publically defended on Wednesday March 21, 2018 at 16:00

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PREFACE

This thesis is the graduation work to conclude my Civil Engineering Master at the Delft University of Technology. This thesis has been part of a larger context of a research which also included my graduation for my other Master in Architecture, Urbanism and Building science, track Urbanism which I obtained in October 2017. 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 leads to better understandings and solutions in urban planning problems. The fundamental differences between both works is that this report aims at understanding the spatial impacts of automated driving from a transportation science perspective. For the other thesis, the research aim was to find the consequences for using a research approach with computational models regarding urban planning problems.

I would like to thank everybody who contributed to this thesis, in the first place the committee members. Firstly, I would like to express my gratitude towards my daily supervisor Gonalo Correia. I appreciate how we sometimes perfectly levelled on some topics while having fierce debates on others (usually you were right...). It kept me focussed and with my feet on the ground. I am grateful to Egbert Stolk for all our discussions on methods and the urban planning and design field which helped me greatly to obtain a self-conscious attitude within this research and hopefully in the rest of my professional career. Furthermore, I would like to thank Professor Bart van Arem for chairing the committee and for his positive and curious attitude towards the research. Being part of your exploration on the impacts of automated driving was a great motivation for me. Other people that have greatly supported me in this research are Dimitris Milakis, who has been of great support in the initiation phase of this research and Akkelies van Nes, who supported me for the Urbanism research. Special thanks go out to Justin Hogenberg of the Province of Utrecht and Arnout Kwant from Goudappel Coffeng for their support in using the regional transportation model of Utrecht. Additionally, I would like to thank everyone who has provided me with social support during my graduation process. My fellow students of the graduation office and the staff of Transport & Planning provided for a nice working environment. Thanks to my colleagues from Posad Spatial Strategies for the nice break they provided from my thesis every single day I worked in the office. I would like to thank my parents and sister for their unconditional support. *Kiitos* Lotta, for your support and patience at all times.

Martijn Leendert Hollestelle

Delft, March 2018

SUMMARY

Research problem

Automated driving is an emergent technology, propagated to have great impact on cities. It is expected to make travel safer, more efficient and provide solutions for urban mobility problems. For the benefits in terms of travel, distance might become less a factor of consideration in any spatial decision by any decision maker. This means that automated driving can either promote attractive dense cities or facilitate the opposite process of suburbanisation. The aim of this research is to obtain insights in the spatial impacts of automated driving on the broader perspective of the change in urban development. Conventional land-use transportation interaction research focus primarily on the impact of accessibility in the process of urban development as formalised by Wegener and Fürst (1999). This research adds the concept of spatial integration of infrastructure within the environment and the related spatial quality aspects as additional factor in this research problem (Figure 1). Integration relates to all externalities regarding traffic and infrastructure in space, where this research primarily focuses on qualitative aspects.

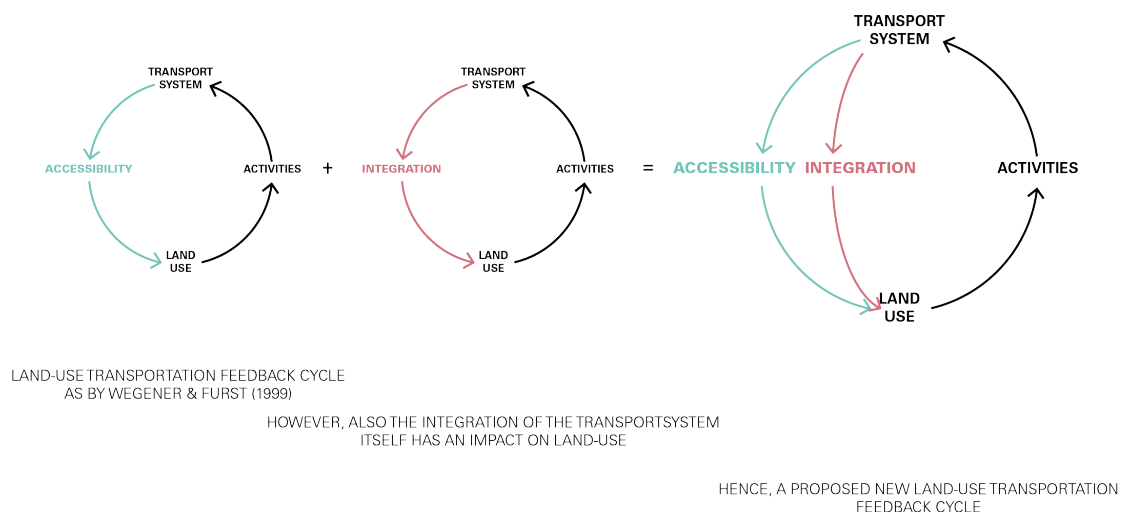


Figure 1: Transportation innovations not only influence land use by means of accessibility. Integration of the transportation system is a determinant. Therefore, the land-use transportation feedback cycle is augmented to a new feedback cycle.

How automated driving will affect cities depends on both development and deployment of the technology itself and on how human agents adapt their behaviour to this technology. Developments in discrete choice modelling and microsimulation allow to acknowledge and evaluate the behaviour of individual decision makers in space and time as driving force in urban change models. As housing is the most prominent land-use function in the built environment (CBS, 2016b), this research scopes towards the residential location choice behaviour by households is modelled in an agent-based model to evaluate urban change and to comply to the paradigm of cities as complex systems: microscopic interaction between urban decision makers drives emergent macroscopic patterns of urban development. The residential location choice depends besides household characteristics on dwelling, neighbourhood and location characteristics (Hunt, McMillan, & Abraham, 1994). The problem entity for this research is conducted by connecting automated driving through these location factors through the concept of accessibility and spatial quality as depicted in Figure 2.

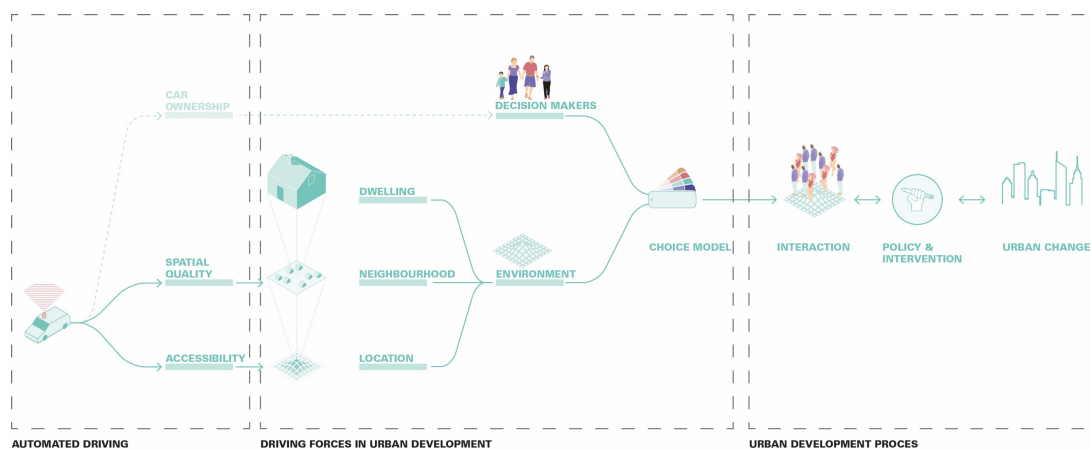


Figure 2: Problem entity for the research. Automated driving is linked to urban development through accessibility and spatial quality effects and through the residential location choice behaviour which is determined as main driving force for urban change processes.

Research approach

A scenario approach is employed to grapple the uncertainty around automated driving and to allow for coherent set of assumptions regarding the development of automated driving. The four distinguished scenarios are summarised in Table 1. All scenarios are studied in conjunction to the current situation (also called the base scenario).

Table 1: Scenarios used in the study.

<i>Scenario 1: Transformation</i> Automated driving develops to an efficient, comfortable shared taxi-bot system with high capacity gains both on the regional roads as on the urban road network. This system is so attractive that it replaces all conventional public transport.	<i>Scenario 2: Growth</i> Automated driving develops to a fully automated system but maintains a private mode of transportation. Technology allows vehicles to drive empty or people without a license. In urban centres, parking is allocated to specific parking zones at the fringes.
<i>Scenario 3: Constraint</i> Automated driving establishes itself but is only allowed on the regional road network. This leads to a modest increase in travel comfort and increase capacity on the highways	<i>Scenario 4: Decline</i> Automated driving develops to full automation but does not lead to capacity increase but to a decrease on the regional road network. No effect on travel comfort. Still replaces all conventional public transport with car travel.

The research is performed through a case study to provide for contextual data. The case study area is the Province of Utrecht, which is chosen for its wide variety of different urban environment and relatively independent urban structure compared to other larger urban regions in the Netherlands. From the problem entity, the three steps that distinguish this research can be derived and further specified:

1. The accessibility effects and underlying principles regarding travel and traffic are examined with VRU, the macroscopic transportation model for the region of Utrecht. Automated driving is evaluated through induced travel demand, change in road capacities and change in value of time. Induced travel demand is assessed through mutation of the existing OD-matrix. Capacity benefits of automated driving are implemented by changing road and intersection capacities. Value of time changes are implemented within the calculation of the travel impedance which provides input for the accessibility calculation;
2. Spatial quality aspects are harder to relate to through conventional methods, hence these are grasped through research-by-design. Network loads from the transportation model as well as the infrastructure requirement according to the scenarios are integrated within the urban environment. As it is not feasible to assess the spatial quality effects on all neighbourhoods and streets in the study area, the effect are examined for different neighbourhood typologies according to ABF Research (2003). For each typology, one zone is chosen as representative to apply the method on. On neighbourhood level, the areas for urban redevelopment are indicated to find the potential for new urban functions. On street level, the street profile and parking requirements are examined by means of redesigning the roads. One arterial road and one residential street has been

considered for each neighbourhood typology. The spatial quality effects on street level are expressed and quantified in housing premiums through hedonic pricing modelling (Luttik, 2000). This allows to evaluate the spatial quality effects in the following research step;

3. The behaviour of the households in the agent-based model is implemented according to the residential location choice model as described by Zondag, de Bok, Geurs, and Molenwijk (2015). For each scenario, the found accessibility and spatial quality findings are evaluated directly as environmental choice attribute of the behavioural model. Scope of the agent-based model is to simulate the change in household density over time. In this case, the simulation runs 10 years in the future from the 2015 base year. The scenarios are presented in comparison to the base scenario.

Research findings

The first research step using the transportation model provides input for the design method in the second step. These both steps in turn provide input for the last research step using the agent-based model. The most important findings in this research are summarised subsequently according to the research steps.

The simulation study using the transportation model found that induced demand by automated driving diminishes the potential capacity gains on the urban road network and manifests in congested roads, leading to higher average travel times in denser urban areas. For bottlenecks on the highway, automated driving proves more beneficial. Whether increased congestion on the urban road network leads to lower accessibility levels, depends largely on the change on value of travel time. Changes in value of travel time have a much larger impact on accessibility values and can supersede the negative aspects of induced travel. When no induced demand occurs, the effects are positive both on average travel time and accessibility. The decreases found in average travel time are relatively small and (around 2%-10%, depending on the scenario) and contribute relatively little to the increase of accessibility levels compared to the assumed value of time reduction (from 0% to 50%). Urban centres and surrounding neighbourhoods benefit most in terms of accessibility when no induced demand occurs nor value of time changes. When both these aspects are considered, the accessibility effects are in favour of rural and remote areas.

From the research-by-design step, conclusions are drawn on the larger neighbourhood scale in terms of urban redevelopment opportunities and on street level regarding spatial quality. The possibilities for new urban functions differ by scenario. The highest transformation potential is found for areas that facilitate large areas of parking or transit hubs. These areas are generally urban centres or surrounding neighbourhoods in larger cities. However, conditions must be met that automated driving replaces transit or valet-parking systems are implemented. In other urban areas, parking solutions are more dispersed because of lower densities, leaving fewer potential for large scale transformation of residential areas. The largest spatial quality benefits on street level can be achieved by diminishing of parking. This can be achieved under a system by which vehicles are shared. In case of private ownerships, it is expected that dwellers still prefer to park their car on the street. Only in areas where

parking policies are enforced, one could consider these spatial benefits. The negative effects of induced demand on the urban road network can have a somewhat negative effect on urban areas. However, urban main roads are not always directly adjacent to dwellings. Most houses are adjacent to streets without through traffic which leaves the negative consequences of induced travel on spatial quality limited for most urban neighbourhoods. Only few neighbourhoods surrounding urban centres, the induced travel might prove unfavourable for streets as the arterial roads might not be able to meet the increase in car traffic as these are never designed for large traffic volumes. Based on the findings, the main conclusion that is drawn that under a scenario where automated driving becomes fully shared, the spatial quality effects are omnipresent in the whole built environment. Under a fully autonomous private system, the spatial quality effects are beneficial for cities but not for smaller villages.

The accessibility findings from the transportation model and the spatial quality findings expressed in housing value premiums under each scenario provide for input of the agent-based model. With this model, the moving behaviour of households is simulated to find changes in household density under the various scenarios. How urban development changes depends on the scenario through which automated driving is evaluated. Three different patterns of urban development have been found in the simulation study:

- An increase of household density in denser urban areas within *scenario 2: Growth*;
- A modest increase of household density in more urban areas in *scenario 1: Transformation* and *scenario 3: Constraint*;
- A decrease of household density in denser urban areas in favour of lower density urban and village characterised environments in *scenario 4: Decline*.

When changes in accessibility or spatial quality are separately simulated, these patterns did not reveal. Instead, all urban development patterns coincided largely with *scenario 4: Decline*. This underpins the emergent properties of the built environment when modelled from the perspective of individual decision makers and their interaction on the housing market.

Conclusions and recommendations

The spatial impacts of automated driving and how accessibility and spatial quality effects impact urban development depends on how automated driving establishes itself as transportation mean. This research found that particularly urban centres are vulnerable to induced travel demand which threatens accessibility levels. This might facilitate the process of suburbanisation. However, when this decrease in accessibility loss is compensated by increased travel comfort and spatial quality gains specifically for those urban areas, the opposite might occur. When the spatial quality benefits cannot be achieved or similar spatial quality benefits occur in all types of neighbourhoods, the change in household density might be lower. Fewer negative effects regarding induced demand will then be in favour of density increase in urban centres.

The research shows that implementing automated driving will not be without challenges. Urban planner and policy makers must be aware of the complications to accommodate induced travel demand in the urban road network. Mass transit seems to remain an important condition for accessibility of

urban centres. Cities which are resilient for a future of automated driving are cities that promote mass transit and sustainable mobility today.

Three different methods which provided input for each other, have been applied in this research. Linking these diverse methods asked for additional assumptions, compromising the resilience of the results. Using an integrated land-use transportation interaction modelling framework would have reduced the number of assumptions needed. However, many residential location choice models nor comprehensive land-use transportation frameworks allow to adequately implement spatial quality factors whilst this research shows that including this provides additional insights and leads to different results. This research illuminates that spatial quality aspects will be a determinant factor in the deployment and impacts of automated driving. Better elaboration on spatial quality aspect within behavioural models can further formalise and reveal the impact of appearance of urban spaces on urban development.

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1 INTRODUCTION

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 human drivers needed. The innovative technology is subject to high expectations to make travel safer, more sustainable and convenient. Therefore, automated driving is considered to provide an adequate answer in contemporary urban problems regarding urbanisation (and corresponding travel and infrastructure related challenges that coincide with this phenomenon). High interest for automated driving can be found among policy makers, popular media, urban planners and within the scientific domain. Most of the research is occupied by the technological aspects of automated driving on vehicle level. Fewer research is available on the impacts of automated driving itself. Research on automated driving focusses primarily on traffic effects and to a smaller extent on behavioural aspects. The impacts on the overall spatial structure have not been assessed from an integral point of view even though the transformative nature of automated driving on the built environment is often proclaimed (Fagnant & Kockelman, 2015; Milakis, van Arem, & van Wee, 2017). The path of development and deployment of automated driving is subject of uncertainty; hence it is crucial from a societal point of view to examine the spatial impacts of automated driving. As automated driving is – like any other technological development – subject to the Collingridge dilemma (Collingridge, 1982), it is of importance to conduct strategic frameworks to steer the impacts of automated driving towards a desired path in the future despite the uncertainty around its actual impacts.

1.2 RESEARCH GOAL

The aim of this research is to build further upon the increasingly available literature on automated driving effects, to *assess the spatial impacts of automated driving from an integral perspective*. Within an integral perspective this research elaborates not on some spatial aspects only, but considers the spatial impacts on urban development in relation to other spatial factors. I.e. this research illuminates *what urban development patterns arise under the emergence of automated driving*. This research links vehicle automation as an innovation on the level of the vehicle itself to the process of urban change.

1.3 RESEARCH APPROACH

For an integral perspective, three different domains are considered: the accessibility domain relating to travel (Figure 1-1), the spatial quality domain relating to infrastructure in space (Figure 1-2) and the domain of urban development (Figure 1-3) on which the changes in land-use and urban form manifest. The prior two domains are important driving forces in this process of urban change, which can be explained through the augmented land-use transportation feedback cycle in Figure 1-4, which this research adapts from Wegener and Fürst (1999, p. vii). Vehicle automation can significantly improve accessibility by reduction of travel cost, time and discomfort. The transportation network allows for spatial dispersion of activities and land-use function in space and time. However, land-use is also dependant on the externalities of infrastructure, hence the integration of the transport system must be added in the feedback cycle to account for spatial quality. If automated driving affects the infrastructure requirements, this can manifest in different land-use patterns as well.

Figure 1-5 provides a graphical representation of the research process and shows how the various research steps are connected to capture the relevant aspects of automated driving for urban change. The various research steps and the structure of the report are further explained below.



Figure 1-1: All travel flows between municipalities in the Netherlands as evaluated by the transport model for the Province of Utrecht.

Figure 1-2: All infrastructure of the Netherlands. By mapping the infrastructure network, also the cities and landscape structures reveal (source data: Kadaster (2016b)).

Figure 1-3: All population centres in the Netherlands (source data: CBS (2014))

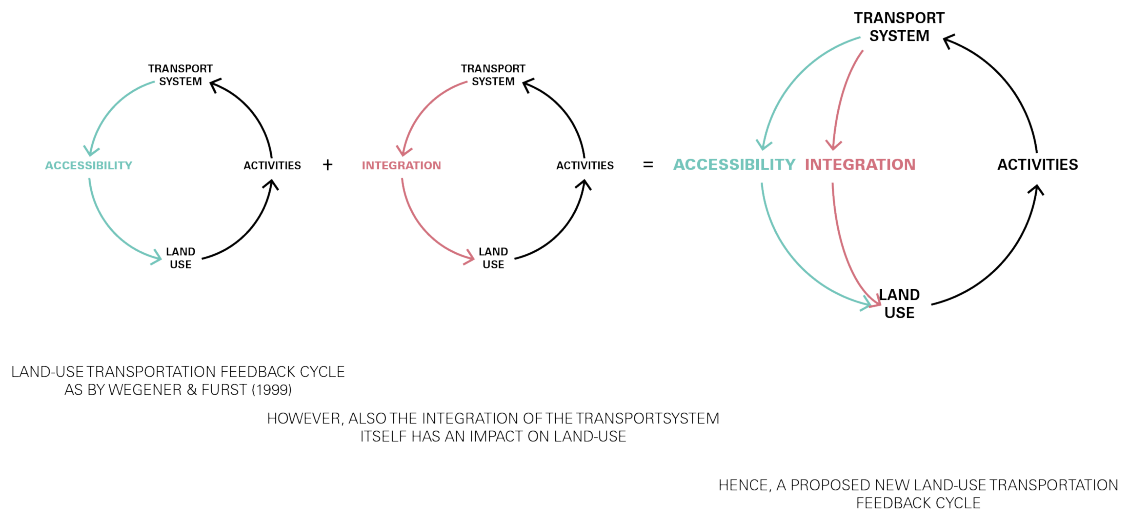


Figure 1-4: Transportation innovations not only influence land use by means of accessibility. Integration of the transportation system is a determinant. Therefore, the land-use transportation feedback cycle is augmented to a new feedback cycle.

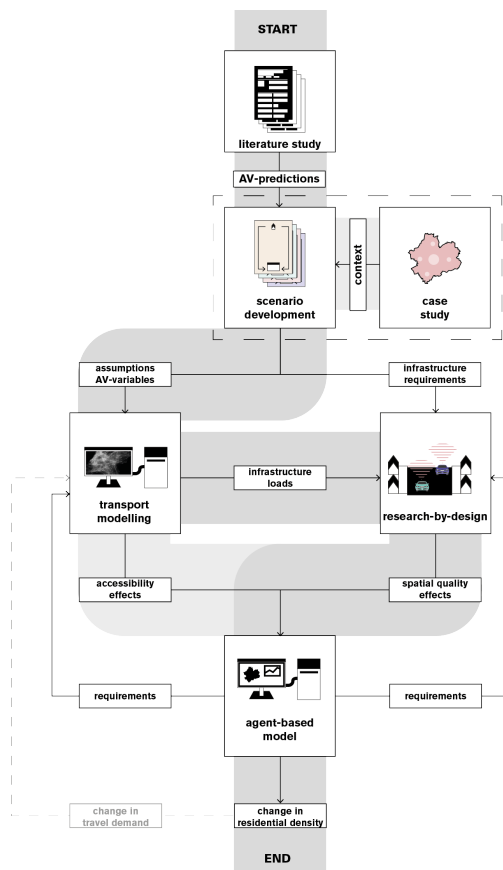


Figure 1-5: Graphical representation of the research process.

1.3.1 RESEARCH CONTEXT

This research studies the spatial impacts of automated driving on urban development from the three domains as prior explained. To justify the wide range of variables that this research problem comprises and acknowledge the relevance of spatial context within the different domains, this research is applied on the case study of the Province of Utrecht. Within this area, a wide range of urban structures is available to be studied and furthermore the area coincides to some extent with the housing market of

the region (Faessen, Gjaltema, & Vijncke, 2011) and its daily urban system Schwanen, Dieleman, and Dijst (2003).

To grapple the uncertainty around automated driving, a scenario approach is employed. Various paths of how automated driving establishes itself as a mode of transportation are assumed. These assumptions range from scenarios that project automated driving as transformative mean of transport to more reserved scenarios. These scenarios allow to adequately justify coherent set of assumptions on which prior research on automated driving impacts is based. Hence, scenarios are an important tool to evaluate the wide range of predictions and findings by scholars within this study.

1.3.2 RESEARCH SCOPE

This research identifies the urban environment as a complex system to acknowledge that the spatial impacts of automated driving are not solely the influence of technological development. Cities manifest phenomena such as self-organisation, nonlinearity and emergent properties. These properties emerge on macroscopic level but are the resultant of microscopic interaction between decision makers (Portugali, 2011, p. 12). The urban environment houses a wide variety of decision makers but this research scopes towards households as most determinant agent in urban development as housing takes the largest share of space in the built environment (Figure 1-6). Empirical research finds that on average jobs follow people instead of the inverse (Hoogstra, Florax, & van Dijk, 2005) and even though urban development also depends on real-estate developers and authorities, the location of construction of houses is still driven or at least strongly influenced by the preference of households (Zondag, 2007, pp. 26-27, 107). The residential location choice generally depends – besides characteristics of the household itself – on three environmental aspects: characteristic of the dwelling, the neighbourhood and the location (Hunt et al., 1994, p. 80). Under the assumptions that dwelling characteristics are not subject to change, the three spatial domains can be perceived through the perspective of the residential location choice. Residential location choice behaviour itself is the driving force of urban development. The accessibility effects relate to the location of neighbourhoods. The characteristics of the neighbourhood bear factors related to the living environment and therefore the spatial quality aspects.

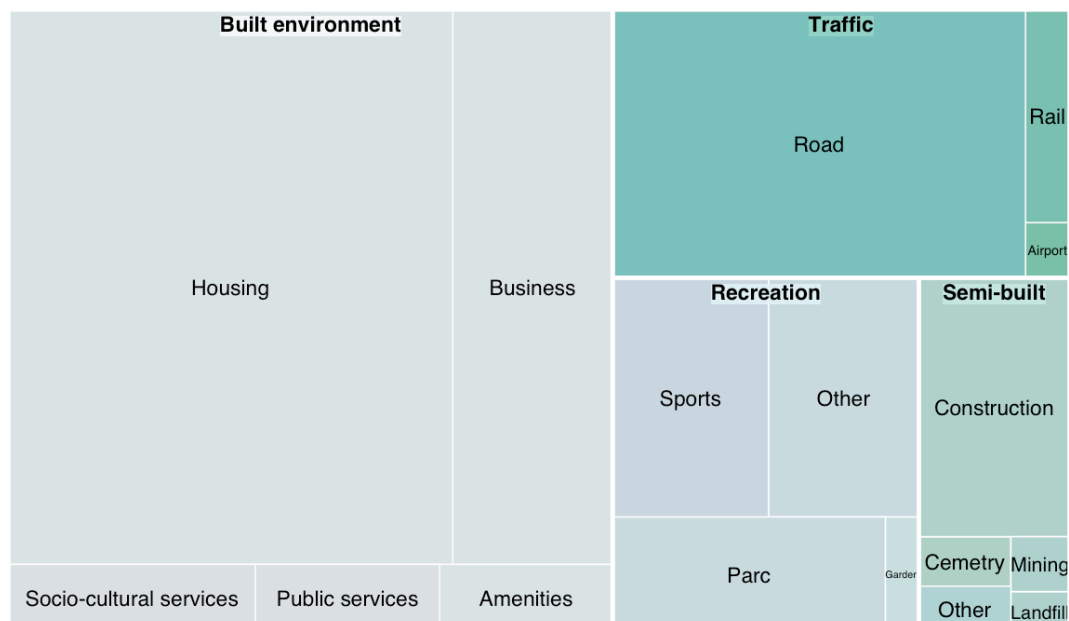


Figure 1-6: Land-use function in the built environment in the Netherlands in 2016 by area (data obtained from CBS (2016b))

1.3.3 RESEARCH PROCESS

The accessibility and spatial quality effects as well as the impact of automated driving on urban development itself are studied for the case study area according to the various scenarios. The accessibility effects of automated driving are examined with the macroscopic transportation model for the Province of Utrecht. Besides accessibility values, the model is also used to obtain network and link conditions. Together with the requirements for automated driving as assumed in the scenarios, the spatial quality effects are examined for various neighbourhood typologies through research-by-design both on the scale level of neighbourhoods and streets. A design methodology is not mainstream within the domain of transportation science. However, this domain has found no suitable methodology to address the spatial quality aspect despite the relevance of this facet within the research problem. By implementing a design methodology, the research can answer to the wide range of variables within the spatial domain such as the societal context in which urban interventions are implemented (Wachs, 1985, p. xiv). The results are later quantified with the help of hedonic pricing model. The accessibility effects and spatial quality effects are then further assessed for their impact on urban development. A residential location choice model is implemented within an agent-based modelling environment to comply with the paradigm of cities as complex systems. By changing the environmental variables for accessibility and spatial quality aspects according to the scenarios, the different changes in urban development patterns reveal. Ideally, the new urbanisation pattern would provide for input on new travel demand as all aspects are interconnected. However, the iterative nature of the urban development process between all aspects is not considered.

1.4 THESIS OUTLINE

The chapters elaborate on the different sequential research steps. Reading the chapters individually allows to grasp the specific topic topics this research comprises.

Chapter 1 provides the introduction of the research and defines the three different spatial domains from which the impacts of automated driving are approached: the domain of travel (place), integration of infrastructure (space) and urban development. Within this chapter, the scope towards housing and households as driving force in urban form is introduced and the research steps applied in this research are previewed.

Chapter 2 and 3 present literature reviews on respectively urban modelling and automated driving. Automated driving is examined to link the technological development on vehicle level to the process of urban change which has been examined in the chapter before. Chapter 2 elaborates on urban (change) modelling. Various methods are used within this research. However, the accessibility study and the study on the spatial quality aspects can be considered data collection steps to further evaluate the impacts on urban development. From that perspective, the residential location choice is considered the method through which all data is evaluated. Hence such model guides the data collection process. The chapter elaborates on the relevant aspects to formalise residential location choice behaviour within an urban change model.

Chapter 4 presents the research methodology. Based on the findings in the literature review, the problem entity is presented. The problem entity links the emergence of automated driving to the behaviour of households. The problem entity defines the perspective on the research problem and allows to derive the further research steps. The research steps are applied on a specific case study using a scenario approach. The case study and scenarios are considered the context of the research. These are therefore presented in chapter 5, alongside the consideration of data sources specific for the case study and further research steps.

The research application is described in chapter 6 to chapter 8. Chapter 6 describes how the transport model for Utrecht is used to implement automated driving and presents the effects of automated driving on network conditions, travel time and accessibility. Chapter 7 explains the research-by-design approach which is applied to assess the opportunities for urban redevelopment and effects on spatial quality for different neighbourhoods and streets. Chapter 8 describes the agent-based modelling procedure used to evaluate the influence of the findings of earlier research step on the change in household density.

Chapter 9 is the final chapter in this report. This chapter gathers the conclusions from the research application and places them in perspective to findings of other research. The chapter reflects on the methods used and provides recommendations for future research and for urban planners.

2 URBAN MODELLING AND LAND-USE TRANSPORT INTERACTION

The introduction presented three domains by which external developments related to mobility must be considered for an integral understanding on the spatial impacts of automated driving. The aim of this chapter is to examine modelling methods and aspects which allow to integrally evaluate these domains within this research. The first section presents frameworks of urban development and land-use transport interaction (LUTI) to understand how different variables relate to the complex nature of the urban environment. The second section elaborates further how these frameworks can be formalised within a modelling methodology. Urban models explicitly define frameworks quantitatively. The third section explains urban metrics which describe various aspects of urban spaces, places and entities.

2.1 LUTI AND URBAN DEVELOPMENT FRAMEWORKS

When explicitly defining the system of urban development and land-use transport interaction for research purposes, one must be aware of the complex nature of the system one assesses. The built environment is complex in terms of the system itself, as well as the complexity that coincides with intervening in the system through policies or implementation of artefacts. Within urban planning processes, the interaction between various decision makers and other actors is aimed at setting boundaries and depicting the context in which later interventions can steer towards a desired goal in the future (George, 1997; Wachs, 1985, p. xv) (e.g. construction of social housing for equity purposes, infrastructural interventions to enhance accessibility and economic prosperity etc.). Because of the scale, magnitude and complexity of urban planning problems, models are crucial to support and externalise the thinking process (Simon, 1969/1996, p. 153). Urban models are therefore often considered as decision support systems (van Leeuwen & Timmermans, 2006) to grapple the complex nature of the system. By explaining the relation between variables in urban development in relation to the spatial impacts of mobility, the complex nature of the system can be further explained and illustrated.

The interaction between land-use and transportation is often explained by the land-use transport feedback cycle (Figure 2-1) of Wegener and Fürst (1999). The cycle illustrates the twofold character of the system: On one hand, the spatial dispersion of people and activities asks for mobility and therefore

for a transportation network; Whereas on the other hand, the presence of transportation networks do allow for spatial dispersion. 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, often designated for specific activities. However, the impact of the transportation system on land-use is more complex and subject to debate (Wegener & Fürst, 1999): Planners can determine the infrastructure requirements for specific urban development plans. However, the effects infrastructure development on urban development is harder to comprehend.

The cyclic character of the system reveals one of its complex characteristics. Intervening on one aspects triggers a range of changes which are all related through its loop structure, complicating assessment of interventions or finding an optimal solution (Hillier, 2012, p. 472; Klaasen, 2007; Rittel & Webber, 1973). Although Wegener and Fürst (1999) describe the process of land-use transport interaction as a single loop, the process itself relates to a wider range of processes, related to actors and other environmental variables. See Figure 2-2 by Moeckel, Schürmann, and Wegener (2002), which reveals that infrastructure not only influences land-use through the concept of accessibility but also by its externalities such as pollution or spatial claim. Furthermore, travel depends on many other factors related amongst economic development and demographics.

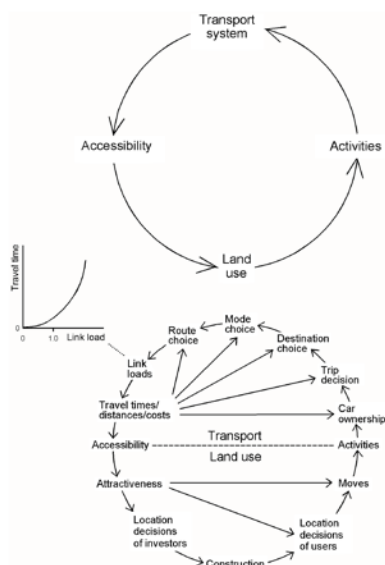


Figure 2-1: The land-use transport feedback cycle (Wegener & Fürst, 1999, p. vii)

... 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
Change of ... causes	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•
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 2-2: Interaction between spatial and mobility related aspects in land use modelling (Moeckel et al. (2002, p. 11))

Comprehensive urban models are formulated to elaborate on the broader processes in urban development and acknowledge the integral role transport and other aspects play within the built environment. Although various models exist, many of these models share common ground by distinguishing the interaction between different decision makers as an important determinant in urban development. Figure 2-3 shows how these decision makers interact through so-called markets (Zondag, 2007, p. 66) which represent the scarcity of spatial components such as land, real-estate or infrastructure capacity. The dynamics of the urban environment are therefore the result of interaction between

different decision makers. This classifies the built environment as a complex system. The built environment bears unpredictable developments triggered by the interaction between the decision makers, because of the large number of decision makers and heterogeneity between these decision makers. Local interaction between decision makers generate patterns of urban development which are hard to predict from a macro-scale perspective (Portugali, 2011, p. 12).

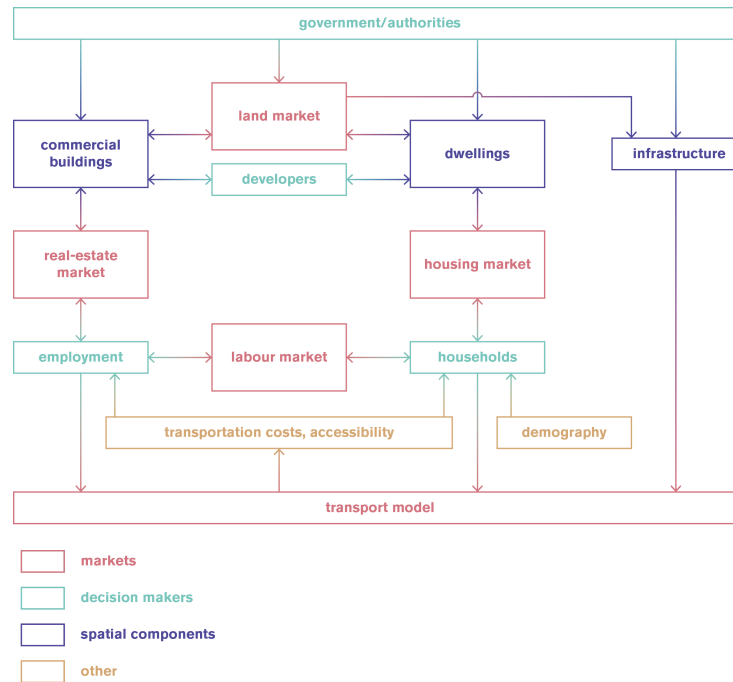


Figure 2-3: General overview of comprehensive urban models. The transport model and the demographic models are considered as exogenous models (adapted from van Nes (2014, p. 9)). The transportation model can be considered a market too.

2.2 URBAN MODELLING

The frameworks and conceptual models for urban development have been formulated in computational models to grapple the complex aspects of the built environment as explained in the prior sections. Models can help to evaluate the interrelation between a wide range of processes and to distinguish the wide range of decision makers. This section explains the development of modelling methodologies for the urban environment and thereafter further explains households as these are considered the most determinant decision maker in the scope of this research.

2.2.1 DEVELOPMENTS IN URBAN MODELLING

Different methodologies exist to model the urban environment. Within this explanation, the most prominent and most determinant methods for the further development of urban modelling are distinguished. This explanation follows the development of urban models as displayed in Figure 2-4. This development shows how urban models transformed from elaborating on the interaction of spatial entities to the interaction and behaviour of decision makers in increasingly higher spatial resolutions.

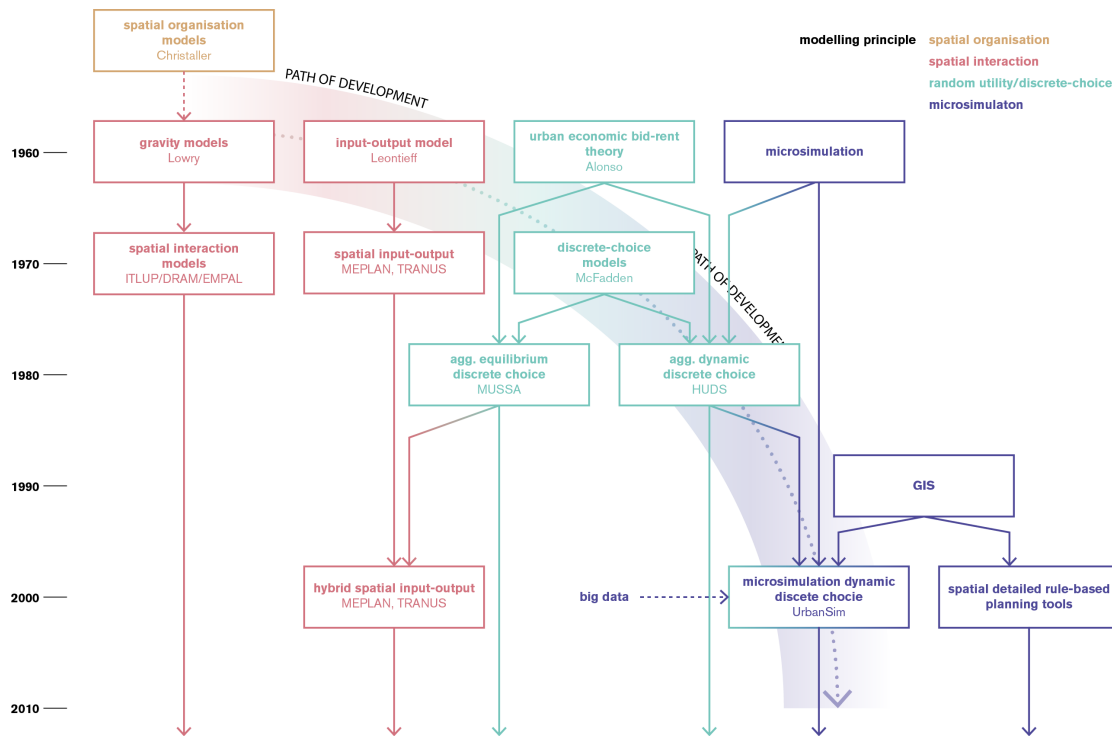


Figure 2-4: Development of urban modelling frameworks (based on Timmermans (2003); Waddell (2014)).

Spatial organisation and spatial interaction models

Theories by e.g. von Thünen (1826) or Christaller (1933) (Figure 2-5) 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. 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): 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. 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 and therefore does not just to the complex character of the urban environment (Wegener & Fürst, 1999, p. 7).

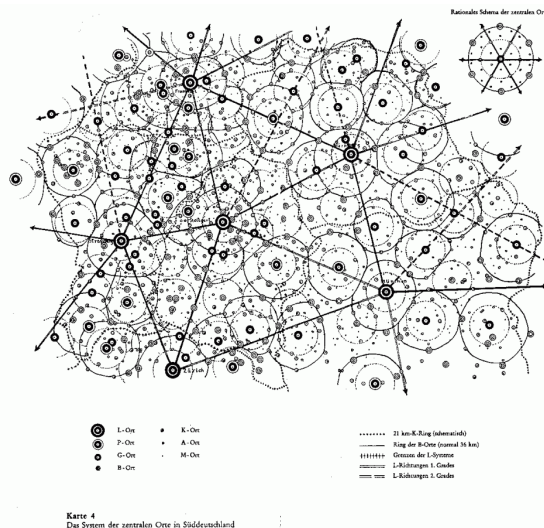


Figure 2-5: Scheme of the central places theory depicted on settlements in southern Germany (Christaller, 1933).

Random utility theory and discrete choice 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. 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). 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.

Today, these choice models are still very important in many transport and land-use models, especially using logit 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. Ortuzar and Willumsen (2011, p. 230) provide an elaborative explanation on discrete choice models in transportation science.

Microsimulation models

Urban models 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 2-3. 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 and solely explore an emergent property from a specific interaction which is best modelled on a macroscopic level. Microsimulation models where decision makers operate within a spatial environment to achieve a certain objective are often classified as agent-

based models. The microscopic approach of agent-based modelling can be favourable when knowledge on macroscopic behaviour is lacking (Borshchev & Filippov, 2004) and in some cases, it is more natural to describe the system based on individual behaviour. This gets to the core principle of agent-based modelling: By modelling microscopic behaviour and interaction, macroscopic patterns emerge (Figure 2-6). Most Meta-LUTI models still rely heavily on discrete choice models (although agent behaviour can be described in many other ways), but are adapted to model choice behaviour in a disaggregated way. 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 2-7.

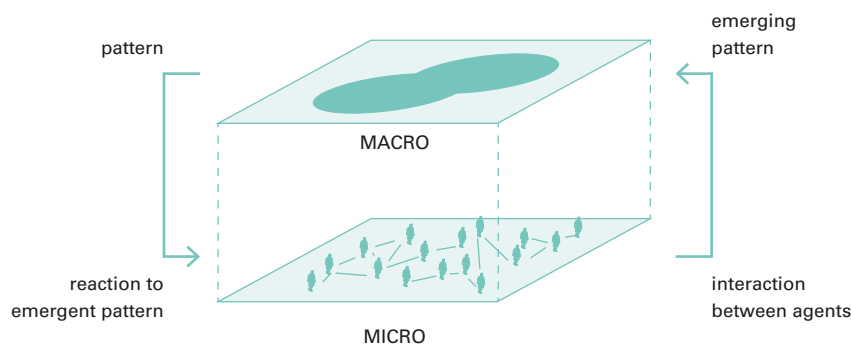


Figure 2-6: Conceptualisation of an agent-based model (adapted from Otter, van der Veen, and de Vriend (2001)).

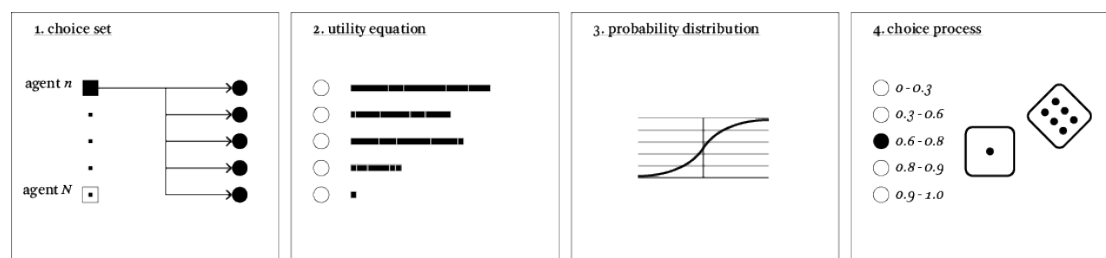


Figure 2-7: Adapting macroscopic discrete choice models to microscopic models (Based on Waddell (2010, p. 169)).

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:

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

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

2.2.2 HOUSEHOLD MOVING BEHAVIOUR

Since the rise of discrete choice models, urban change models increasingly consider the behaviour and interaction of decision makers as driving force in urban change. Since this research scopes towards the residential location choice, models to elaborate on this choice are further explained. A wide range of residential location choice models for households are available. Most of these models are based on random utility discrete choice models. Some of these choice models are conducted to 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, et al. (2015) for TIGRIS XL). Despite different purposes, most of these models consider households as the decision makers (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 categories (Hunt et al., 1994, p. 80; Schirmer, van Eggermond, & Axhausen, 2014) (Figure 2-8):

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

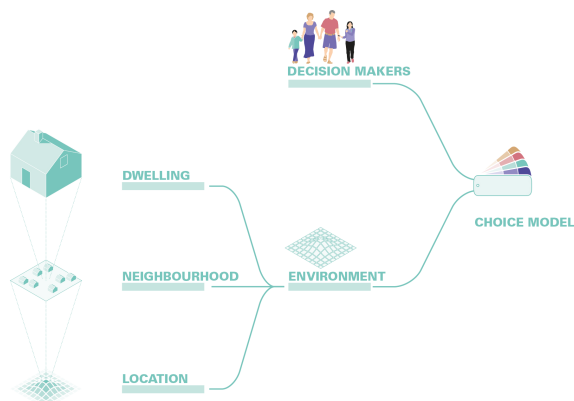


Figure 2-8: Urban form is the result of human behaviour, of which the residential location is a very important behavioural aspect. The residential location choice is based on environmental factors as well as on characteristics of the household itself.

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 (Schirmer et al., 2014, p. 4) or car ownership are considered (Bhat & Guo, 2007, pp. 520-521).

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. 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. 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. Tillemans, Ettema, and van Wee (2006); Wenjia Zhang and Kockelman (2016) on road pricing or congestion).

2.3 URBAN METRICS

The behaviour of the decision makers in urban models evaluates environmental characteristics as decision factors. Within residential location choice models - as explained in the prior subsection - these environmental characteristics relate to the location as well as the characteristics of the spaces. An adequate representation of the environment is therefore an important aspect within urban modelling. Urban models are used to evaluate the transformation of these spatial variables in space and time. Spatial metrics which are introduced as choice attributes in subsection 2.2.2 are further explained in this subsection. However, this section starts first with an elaboration on spatial representation. As microsimulation increasingly allows for higher spatial resolutions, also new possibilities for spatial representation in urban models emerge.

2.3.1 SPATIAL REPRESENTATION

Expressing cities in metrics asks for a data structure to store these metrics. The data need to be structured in such way that it can give a (geo)graphical spatial representation of the urban area(s). The interpretation of the data is therefore a cognitive activity. Figure 2-9 gives an overview of the most common spatial representations. The concentric model (originating from the von Thünen (1826) model) is used to describe a certain variable as a function of the distance to for instance the city centre from a conceptual point of view. Mainstream transportation models represent the environment by a network connecting different zones (Ortuzar & Willumsen, 2011). These zones are classified by neighbourhoods, municipal borders etc. and often the organisation of census data is the main explanation for the shaping of these zones and are therefore less abstract than the concentric zone model. Grid cells are increasingly used in transportation planning and provide a high resolution to use geospatial data (Koomen & Stillwell, 2007, p. 4). This allows for interpretation of finer-scale geography factors and more detailed patterns and morphologies (Batty, 2000, p. 483) detached from administrative boundaries.

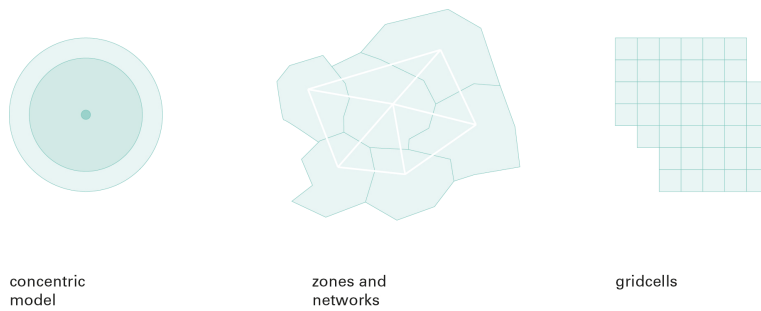


Figure 2-9: Various data structures to spatially represent space by means of urban metrics.

Higher spatial resolutions are not always required to obtain better results. Considering the spatial resolution for a study depends on the scale to which the research problem is applied as well as the key-indicators that are evaluated (Milakis, Cervero, & van Wee, 2015). Large scale variables exert stronger influences on travel behaviour than smaller, neighbourhood scale characteristics (Milakis, Cervero, van Wee, & Maat, 2015; Næss, 2011) but smaller scale variables can give a stronger appearance of the physical appearance of cities and spatial aspects which do not directly relate to travel behaviour (Batty, 2005).

2.3.2 ENVIRONMENTAL METRICS

An urban space 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 e.g. straightforward density values which can be measured directly to advanced (qualitative) indices which provide a more advanced description of an urban entity. Straight forward indicators state for instance density, (land-use) diversity or (network design) Cervero and Kockelman (1997). Depending on what the expression encompasses, the metric can either express urban environments from both a physical or the practical point of view. By combining various more straightforward metrics regarding the urban environment, it becomes possible to interpret the data to obtain more comprehensive insights through hybrid indicators. Examples are for instance the Space matrix by Berghauser Pont and Haupt (2009, p. 118) which provides an indication of the type of building volumes based on floor-space index, ground-space-index, open-space-ratio and buildings layers. Another example which was earlier mentioned in subsection 2.2.2 is the description of neighbourhood typologies by ABF Research (2003) which provides a specific description of neighbourhood environment based on metrics as density, town size, service proximity, building year.

2.3.3 ACCESSIBILITY

Another important metric to describe the urban environment elaborates on places instead of spaces: Accessibility is a key concept to describe the interrelation between dispersion of opportunities and the possibility of reaching these opportunities through the transportation network. Important reasons to examine the accessibility levels of areas is to assess the adequacy or need for (possible) policy plans or infrastructure interventions. Accessibility will be further explained in this subsection as accessibility is an important urban metrics that relates strongly to transportation.

Various ways exist to express accessibility ranging from relatively simple travel time indicators to advanced and more abstract indicators which only become interpretable in relation to accessibility values for other spatial entities. One of the earliest measures to describe accessibility of a place is found in early models similar to the model by von Thünen (1826), using the concept of ‘distance to urban core’. This accessibility indicator seems straight forward, but comprises two aspects that characterise two of the main components of accessibility: the opportunity and the transportation impedance to reach that opportunity. This has been first formalised by Hansen (1959, pp. 73-74), describing accessibility as the potential in a place to opportunities:

$$A_i = \sum_j^n \frac{S_j}{T_{ij}^x}$$

with A_i the accessibility in zone i , S_j the measure of the activities in zone j (e.g. number of jobs, people etc.), T_{ij} the travel time or distance between zone i and j , and x the exponent describing the effect of the travel time or distance between the zones. This accessibility indicator bears both an infrastructural component and a land-use component. However, access to opportunities is not only restricted by spatial dispersion and the design and performance of the transportation network. Geurs and van Wee (2004, p. 128) provide an overview of the various components of accessibility (see Table 2-1), listing also temporal components (e.g. time restrictions, different travel times in different day-times) and an individual component acknowledging the needs and limitation of individuals and their restrictions in space and time.

Table 2-1: 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

Today, a wide range of accessibility indicators is used within practice as well as in research within the academic context. More advanced and heterogeneous expressions for accessibility are applied which comprise more variables and multiple accessibility components. 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. Ideally an accessibility measure would take all these components into account. However, often this is not feasible because of data or computational constraints. Besides providing a classification of accessibility components, Geurs and van Wee (2004) also distinguish a categorisation for accessibility measures as listed in Table 2-2. Infrastructure-based accessibility measures elaborate solely on infrastructure related components as e.g. travel time (loss) or average speed but does not elaborate on any land-use principle. This is however an easily understandable indicator and can prove insightful in land-use dispersion is

limited or implicitly interpreted. Location-based accessibility indicators, of which the definition by Hansen (1959) does consider the spatial dispersion of land-use and activities. Person-based accessibility distinguish themselves by taking the spatiotemporal constraints of individual persons into consideration and calculate accessibility levels for individuals instead of for specific locations or for a specific transportation system. Utility-based measures calculate the accessibility of a homogenous group of individuals on a location by taking into account the perceived utility of different travel options (Bhat et al., 2000, p. 31). Many utility-based accessibility indicators are based on random utility theory and therefore calculates the opportunities in the same utility unit as the travel impedance. These type of accessibility indicators are called logsum indicators.

A logsum accessibility indicator for person type i and travel purpose p is often calculated as follows (Geurs, Zondag, de Jong, & de Bok, 2010, p. 387):

$$L_{piz} = \log \left(\sum_j \exp (\mu_p V_{pijz}) \right)$$

with:

- μ_p The logsum coefficient for travel purpose p ;
 V_{zijp} The representative utility of destination j .

From the equation for the representative (observed) utility, one can conclude that this parameter comprises both travel impedance aspects from origin z to destination j , as well as the destination utility (Geurs et al., 2010, p. 387):

$$V_{zijp} = \beta_p T_{zj} + \chi_{ph} \ln(C_{zj}) + \delta_p D_{pj} + \dots$$

with:

- β_p The travel time coefficient;
 T_{zj} The travel time component, aggregated over mode and over time of day;
 χ_{ph} The travel cost coefficient for purpose p and income group h ;
 C_{zj} The travel cost component, aggregated over mode and over time of day;
 δ_p The destination utility coefficient;
 D_{pj} The destination utility component.

There is an important distinction between logsum indicators with other indicators that consider the opportunities in a destination zone. As logsum indicators rely fully on random utility theory, it requires expressing the opportunities in the destination zone D_{pj} in the same utility unit as the (dis)utility of the travel impedance (T_{zj} and C_{zj} in equation above).

Table 2-2: 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 distribution
Location-based	Distance or contour from one place to opportunities or the other way around; the amount of opportunities in distance to a zone	travel time isochrones
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.	Hansen (1959), Ben-Akiva and Bowman (1998)

There is not one defined way to calculate accessibility. Accessibility must be considered a hybrid index which comprises one or more aspects related to land-use, travel and the agents that are moving through this environment. How to calculate accessibility depends therefore strongly on the application (van Wee, 2016). Some of the challenges regarding accessibility studies relate to equity considering the difficulties taking socio-economic data on the level of the individual into consideration. Also multimodal accessibility calculations prove challenges as to how to evaluate the possibility of multiple alternatives.

2.4 CONCLUSIONS AND DISCUSSIONS

Land-use and transport interaction models elaborate primarily on the accessibility aspects of mobility in relation to land-use. Identifying individual choice behaviour as driving force in urban development allows to examine other spatial factors of transportation related to urban development too. Defining cities and urban processes explicitly in models and metrics helps to illuminate the core principles of urban development from an integral perspective. The aim of this research to consider the spatial impacts of automated driving in urban development. Choice behaviour of individual decision makers provide a natural way to describe the system of urban development and relate to all domains considered in this research. By reflecting on the metrics and existing models described in this chapter, one can conclude that travel effects are well integrated within this system through the concept of accessibility. Urban metrics allow to elaborate on various aspects of the urban environment. However, no explicate framework has been described to elaborate on the spatial quality aspects of transportation although some externalities are considered. Depending on how the behaviour of individual decision makers will be described, further considerations are required to adequately elaborate on these aspects.

3 VEHICLE AUTOMATION

Even though automated driving is primarily an innovation on vehicle level, it is propagated to have spatial impacts as well. This chapter explain how vehicle automation relates to the process of urban change. As the development of automated driving is subject to uncertainty, this chapter identifies the factors related to this development which can determine different outcomes in the future. Through a literature review on a wide range of researches on the development and impacts of automated driving, the bandwidth of predictions and deviation in underlying assumptions are explored.

First section of this chapter provides an introduction on the concept of vehicle automation and the most important applications, followed by examination of the deployment which will be of influence on how automated driving establishes in the second section. The third section of this chapter evaluates literature on the impacts of automated driving on travel, infrastructure requirements and other spatial factors. Furthermore, research that elaborates on the spatial impacts of automated driving itself are explained.

3.1 CONCEPT OF VEHICLE AUTOMATION

Various concurrent definitions such as self-driving car, autonomous vehicle or automated vehicle are used regarding vehicle automation. This research uses the terminology of automated vehicle/vehicle automation and elaborates both on automation of the driving task itself and the ability to connect vehicles with other vehicles or the environment through sensors and communication system (Figure 3-1). When either one of these aspects is present, this research considers these vehicles autonomous vehicles or connected vehicles. Another trend that can be distinguished within the automotive sector is electrification. This aspect is not considered in this study as this is mostly beneficial in terms of environmental and energy related aspects and not in terms of travel efficiency and concepts or comfort.

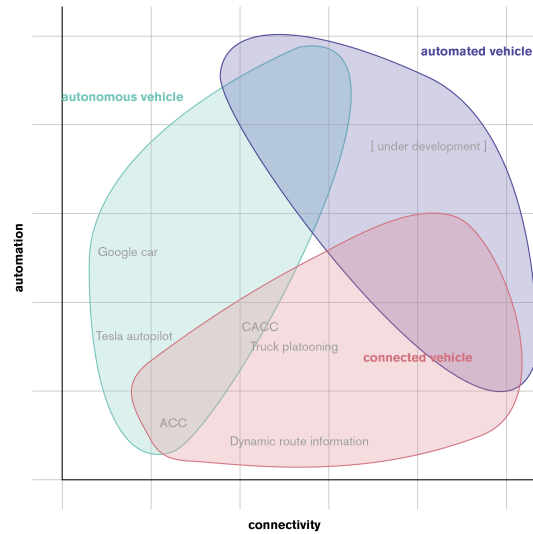


Figure 3-1: Automated driving is the technology where automation of the driving task and connecting vehicles with other vehicles and the data is brought together.

Within automation of the driving task, different stages of automation can be distinguished. 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. Since the levels of automated driving are under constant revision and different classifications are used, this research concludes on the three incremental types of automation as listed below and depicted in Figure 3-2 instead of following a classification of levels:

1. None: the human driver performs all driving tasks;
2. Partly automation: vehicles only substitute specific driver tasks (e.g. adaptive cruise control);
3. Conditional automation: cars perform more tasks, but the driver has still a responsibility in monitoring the environment or perform interventions in case of failure;
4. 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.

To what extent computers can substitute human driver tasks, depends not only on the relation artificial agent – human driver– vehicle, but also how the artificial agent is connected with its environment. Qualcomm Technologies (2015) distinguishes four types of vehicle communications (Figure 3-3) which allow to grasp the different aspects of communications between vehicle and environment or other road users:

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

These concepts reveal that automated driving is a technological innovation beyond solely replacing the driving task with a computer. Some of the concepts as listed above do not even necessarily require replacement of the driving task but are already – however sometimes less advanced – available in modern vehicles (e.g. collision avoiding systems (Harding et al., 2014, p. xiv)), or systems are present which allow for monitoring of vehicles without any requirements on vehicle level such as loop detectors embedded within infrastructure. The difference between these innovations and automated driving is found within the abilities of automated driving to allow for bidirectional communication as these vehicles are increasingly equipped with sensors and computers (Swan, 2015, p. 7).

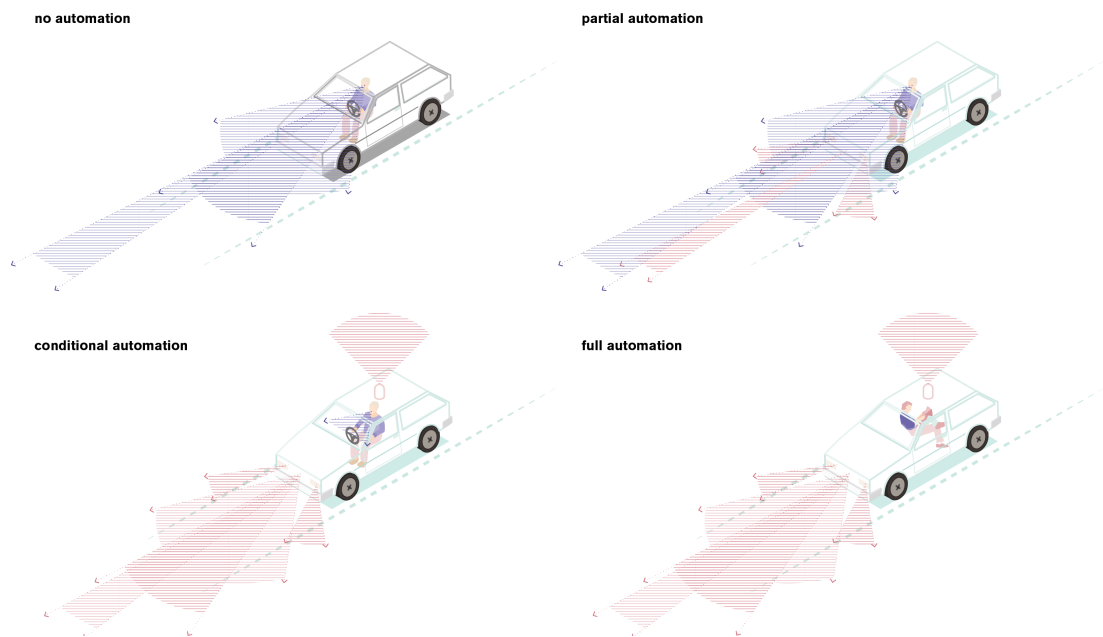


Figure 3-2: Different stages of automation of the driving task can be distinguished, ranging from partial automation where the car take over some of the driving task, to conditional to full automation where the vehicle performs all driving tasks.

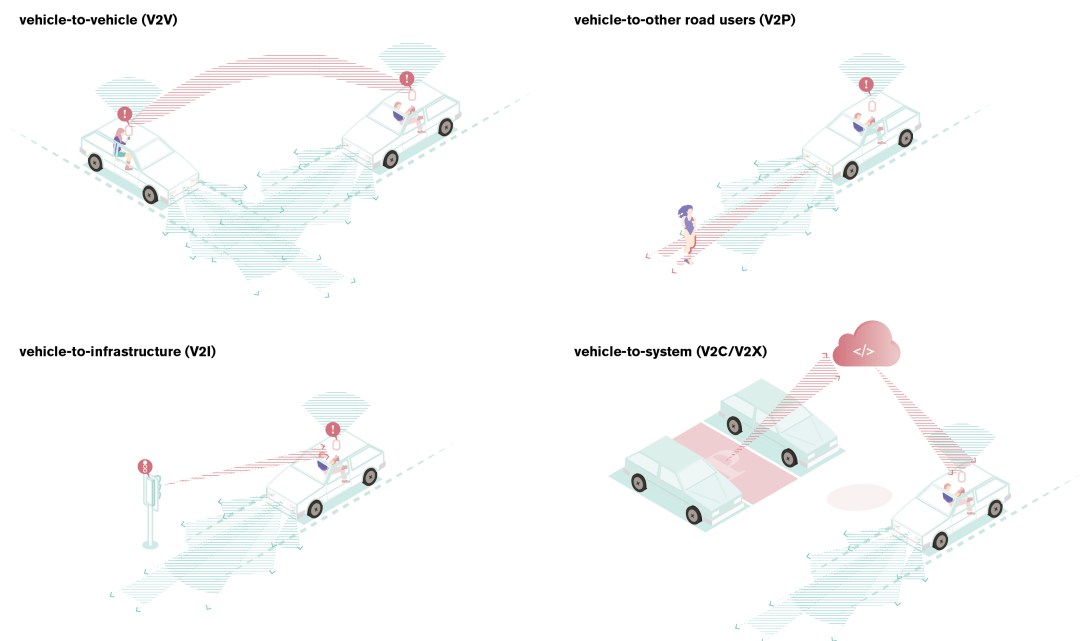


Figure 3-3: Besides automation, increased connectivity of vehicles with other road users, infrastructure and the whole transportation system is part of the automated driving development.

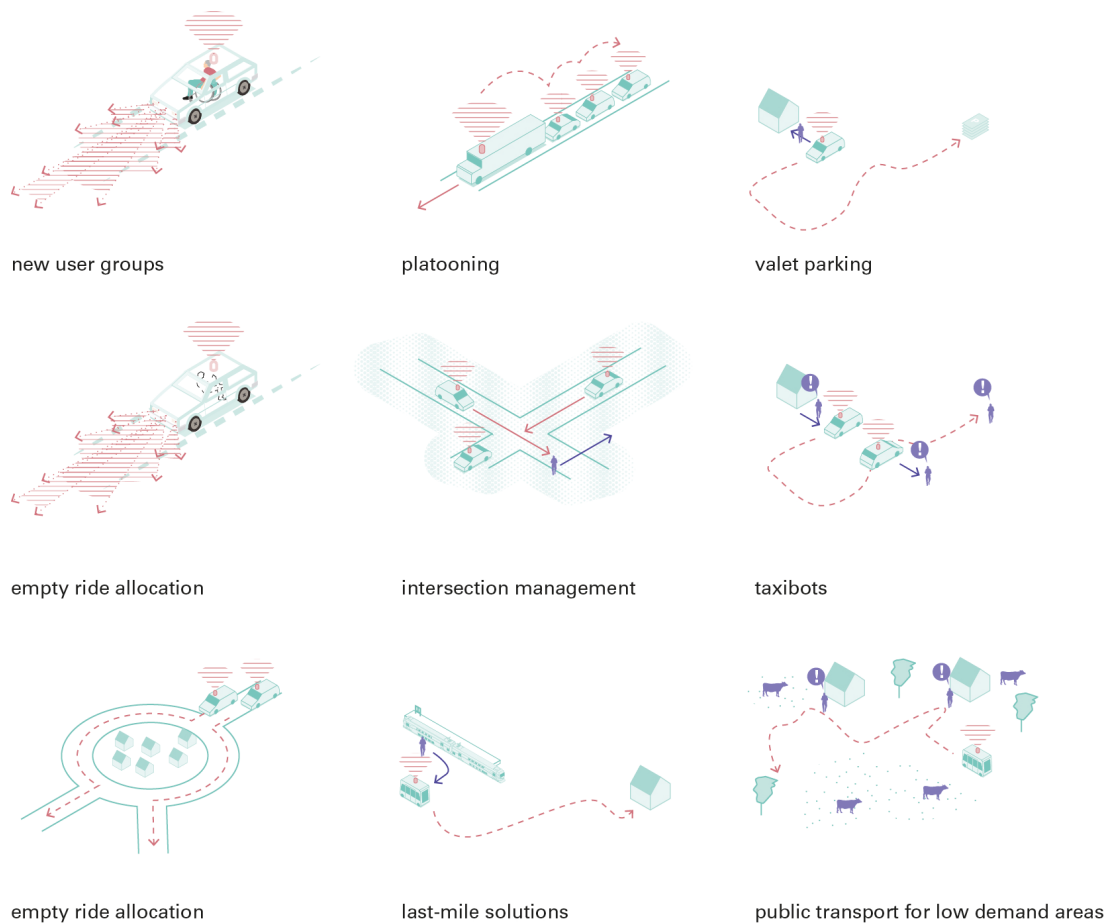


Figure 3-4: Examples of applications of automated driving on various scale levels.

Why automated driving is propagated to be disruptive cannot be solely accounted by automation of the driving task. The examples of connecting possibilities of vehicles already hints on the wide range of applications that automated driving can facilitate (Figure 3-4). Automation of the driving task means that the driver can perform other tasks while driving (Cyganski, Fraedrich, & Lenz, 2014), new-user groups can use automobiles or empty vehicles can relocate themselves to pick-up new passengers (Chen, Kockelman, & Hanna, 2016) or park remotely on a different location (Childress, Nichols, Charlton, & Coe, 2015; Cyganski et al., 2014, p. 5). This cannot only be applied to passenger transport but also to the transportation of cargo (Townsend, 2014, p. 52). Better corporation between vehicles is expected to be beneficial for traffic flows through applications such as platooning or better between-vehicle communication on intersections (e.g. MIT Senseable City Lab (2014)). The latter concept might also be applied on network wide level, resulting in better utilisation of the transportation network through improved traffic management.

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. 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 car fleets often consider such system as a replacement for private transport or as a hybrid form between public and private transportation.

Other 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 influence of automated driving therefore extends the domain of solely the vehicle. Instead, the application of automated driving covers three different scale levels:

- Vehicle level, the possibilities of replacement of the human driver and the applications that emerge from this;
- Microscopic level, applications in relation to traffic and vehicle interaction;
- Macroscopic level, applications on the level of the transportation network itself through new mobility concepts and network wide coordination.

3.2 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. Often there is a phase of high expectations and according to Gartner (2016) autonomous vehicles are just past the highest point of expectancies (Figure 3-6). 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. This uncertainty also manifests in a wide range of predictions about the diffusion of automated driving technology (Figure 3-7), indicating that there is no consensus on this level between and within different fields of expertise. As automated driving must establish within a socio-technical regime, how and if automated driving will prove disruptive for transportation and for the built environment will depend on many factors besides technological development. Besides vehicle elements, other factors relate to current infrastructure and deployment possibilities, cultural and social factors, markets and user practices and regulations and policies (listing aggregated from Geels (2002, p. 1258)). Studies on the impacts of automated driving employ therefore often scenario approaches to grapple the uncertainty around these elements or explicitly assume a specific path of development. Based on the scenario studies on automated driving listed in Table 3-1 one can find that scholars identify following aspect most uncertain yet relevant:

- The development of the technology itself, particularly to what extent automated driving can replace the human driver and which efficiency and comfort benefits coincide with this. This is not only a technological question but also depends on whether individuals are willing to transfer the driving task to an artificial agent. Alongside with the challenges regarding development of technology itself comes the implementation of automated driving within existing infrastructure and interaction with other road users. This might lead to solutions as allowing automated driving only in specific areas, specific highways or specific lanes (Figure 3-5). With this comes the obstacle of potential infrastructure and road network adaptations needed to employ autonomous driving;

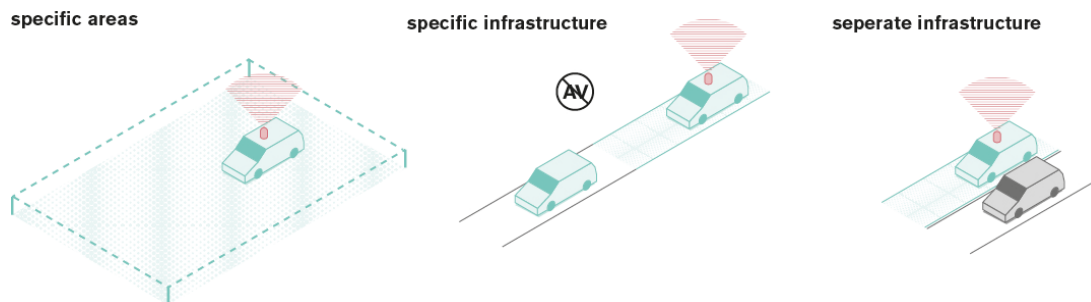


Figure 3-5: Intermediate solutions to allow automated driving in space before automated driving is allowed everywhere.

- A determining factor for the impact of automated driving is if people will be open to sharing vehicles instead of private cars and if parties are able to develop business models to provide this concept in an adequate service.

These two listed components are identified by scholars as most influential factors for how automated driving develops. Yet, there are numerous other factors which might determine the path of development of automated driving. Particularly the domain of policies (e.g. Smith (2012, p. 1142) and ethics (e.g. Bonnefon, Shariff, and Rahwan (2016); Douma and Palodichuk (2012); Glancy (2012)) receive significant attention within literature.

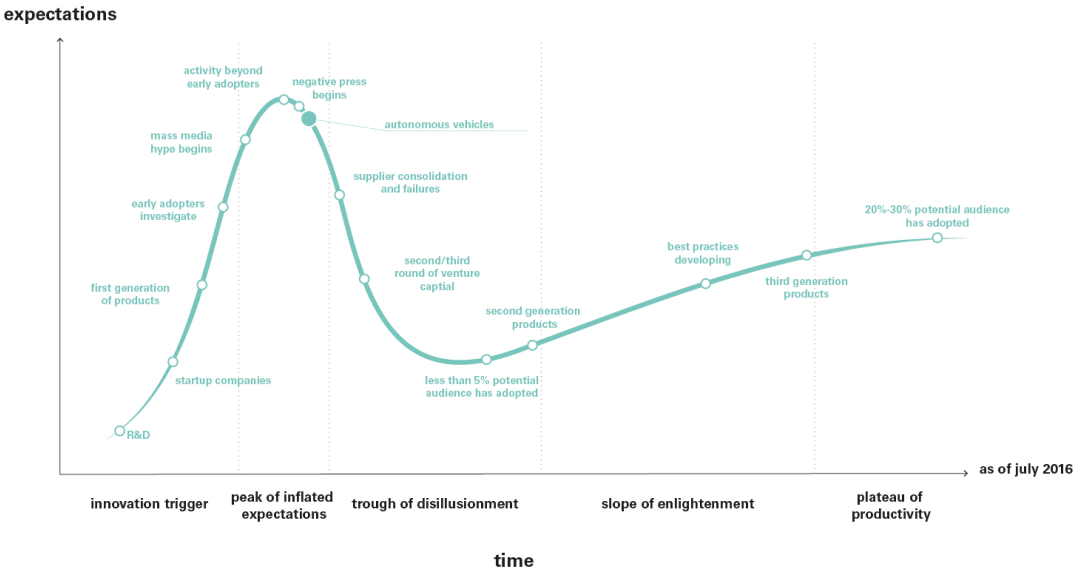


Figure 3-6: According to Gartner (2016), autonomous vehicles are just past the highest point of expectations, but still in the phase of inflated expectations (adapted from Gartner (2016)).

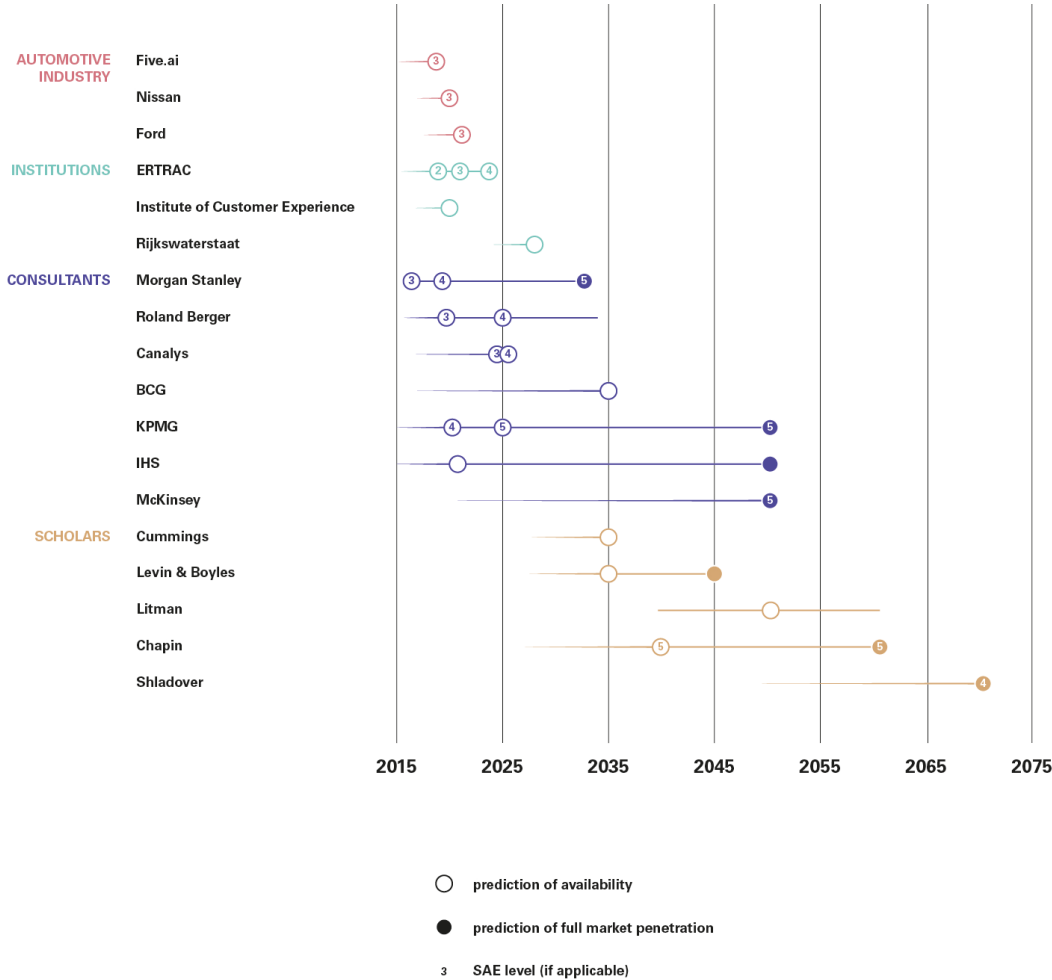


Figure 3-7: Predictions by various fields of expertise on the diffusion of automated vehicles (data derived and interpreted from Alkin (2016); Bernhart et al. (2014); Bertonecello and Wee (2015); Chapin et al. (2016); ERTRAC Task Force (2015); Institute for Customer Experience (2016); KPMG (2015); Krabbendam (2016); Levin and Boyles (2015); Litman (2014); Murphy (2016); Nissan USA (2017); Shanker et al. (2013); Shladover (2016); van der Aa (2016); Wong (2016))

Table 3-1: 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 Stanford (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, Snelder, van Arem, van Wee, and Correia (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, MacKenzie, and Leiby (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	-

3.3 IMPACTS OF AUTOMATED DRIVING

As automated driving has many applications, also the impacts of automated driving are expected to be wide. Within this section, literature on the impacts of automated driving is evaluated based on the three spatial domains as explained in section 1.3 in the introduction. The first domain relates to accessibility and therefore to traffic and travel aspects thus the first two sub-sections examine literature findings on travel demand and behaviour and on traffic aspects. The second domain of integration of infrastructure examines the requirement for infrastructure, vehicle requirements and for street design. The latter domain evaluates literature which conclude on the impacts of automated driving on the urban form itself.

The predictions, findings or assumptions on how much automated driving impacts these domains varies among scholars. The dispersion in predictions can be explained by differences in methodology, data or e.g. case study. However, the underlying assumptions scholars make on the deployment of automated as elaborated on in the prior section also influence the findings. The deployment factors to which automated driving is subject are explained before evaluation of research on automated driving impacts itself.

3.3.1 TRAFFIC ASPECTS

The first section in this chapter introduced applications of automated driving to make travel more efficient and traffic more stable through automated driving and communication between vehicles and between vehicles and infrastructure.

Highway capacity

The largest large of research on traffic aspects of automated driving concerns highways. 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 outer-urban roads of 80%. All these listed researches based on computer simulation to draw conclusions on potential road capacity increase. Considerations regarding these conclusions must be made regarding the theoretical nature of these studies as factors such as heterogeneity in road course, flow direction, vehicle type and lane changing behaviour is not considered. Consequence is that the predictions from these studies show very high potential capacity increases. The experts from the study by Milakis, Snelder, 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.

Urban road network capacity

The urban road network often comprises sequences of short road stretches and intersections. Capacity benefits as found on highways are not likely to incur on the urban road network as intersections are determining in the flow of cars in cities. Intersections for automated vehicles can enhance traffic efficiency by means of V2V communication. MIT Senseable City Lab (2014) 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, Snelder, et al. (2017) is again more reserved and predicts an increase between 2% and 6% depending on the scenario.

3.3.2 TRAVEL BEHAVIOUR

Travel behaviour can be defined as the choices and actions of an individual in relation to travel (Gil, 2016, p. 237). With automation of the driving task, more people might be able to use automobiles and usage can increase because of lower perceived travel impedances. Therefore, this research distinguishes following travel demand aspects in relation to vehicle automation:

- Empty vehicle allocation rides (e.g. to pick-up a passenger or for remote parking);
- Vehicle access of new user groups;
- Change in travel behaviour by change in cost and comfort factors.

Empty vehicle allocation

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 distance to 11% in a theoretical network and 8% in a real situation case study (Fagnant, Kockelman, & Bansal, 2015) in a simulation study for shared vehicles. 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 under a wide range of scenarios with detailed distinctions in different parking policies. This study finds much higher increase in travel distance because empty ride allocation is not accounted for to pick up new passengers but to park the vehicle at designated parking area. Increase in vehicle kilometres by empty vehicles

ranges between ca. 10% if parking is allowed anywhere and more than 50% in case of designated parking areas on specific locations.

New user groups

Another reason for increase in travel 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 et al. (2016) to an increase between 2% and 10%.

Travel comfort and costs factors

Increased travel comfort can lead to an increased number of trips made by cars, or an increase in distance travelled by cars. Travel comfort factors are often monetised in transport modelling through the concept of value of time. When drivers can perform other tasks while in transit (Cyganski et al., 2014; Pflieger, Rang, & Broy, 2016) this can further increase the utility of travel. Therefore, value of time is an important concept to make assumptions on future vehicle usage. Research on the impact of automated driving on value of time is however limited. The expert panel by Milakis, Snelder, et al. (2017) concludes on a reduction of value of time between 15% and 30% under scenarios where automated driving manifests itself partly or fully as transportation mode. Steck, Kolarova, Bahamonde-Birke, Trommer, and Lenz (2017) conducted a stated choice experiment, finding a reduction of value of travel time for commuters of 31% in private autonomous vehicles.

Findings of these studies have not been implemented within researches that evaluate the impact of travel comfort on increase travel. Instead, studies that examine this effect make assumptions under different scenarios. 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 private automated vehicles to study the impacts on mobility and energy impacts. These assumptions are therefore merely a mean to cope with the uncertainty and no actual findings. Childress et al. (2015) take on a similar approach assuming for reductions of 0% and 35%. The assumed change in value of time often coincides with the degree of automation, meaning that higher automation levels result in greater value of time reductions. The mentioned studies evaluate the change in travel behaviour with these assumptions. However, the scenarios considered embody other assumptions as well regarding on for instance roadway capacity. It is therefore not possible to solely derive conclusions on the effect of value of time on travel behaviour.

Studies that do elaborate on various aspects of automated driving to derive conclusions on travel behaviour are e.g. Childress et al. (2015, p. 102), finding changes of respectively 3.6%, 5%, 19.6% and -35.4% in vehicle kilometres travelled (VKT) 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 from 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%.

3.3.3 INFRASTRUCTURE REQUIREMENTS AND INTEGRATION

The efficiency benefits of automated driving do not solely impact traffic and travel behaviour. More efficient use of infrastructure can prove beneficial for the requirements for infrastructure and the externalities that coincide with infrastructure and travel.

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 3-8). 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.

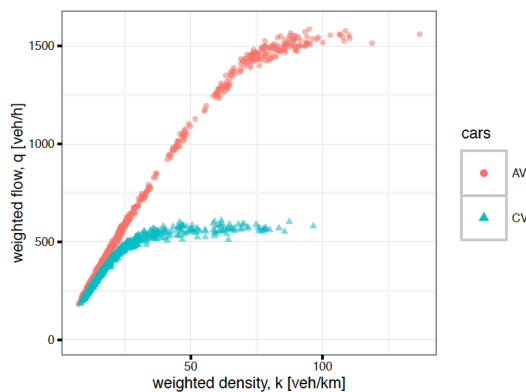


Figure 3-8: Network macroscopic fundamental diagram for automated vehicles (AV) and conventional vehicles (CV) (Ambühl et al., 2016, p. 5).

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.

An alternative for parking would be to use vehicles to pick up new passengers. Automated vehicles can in that case become a system of so-called taxi-bots. This would not lead only to reduction of parking (or making parking obsolete) but would also reduce the number of cars needed. The effect of sharing on the required car fleet to serve travel demand is examined in a few studies (Figure 3-9). 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 for a case study on a hypothetical grid network that one shared automated vehicle can replace eleven conventional cars.

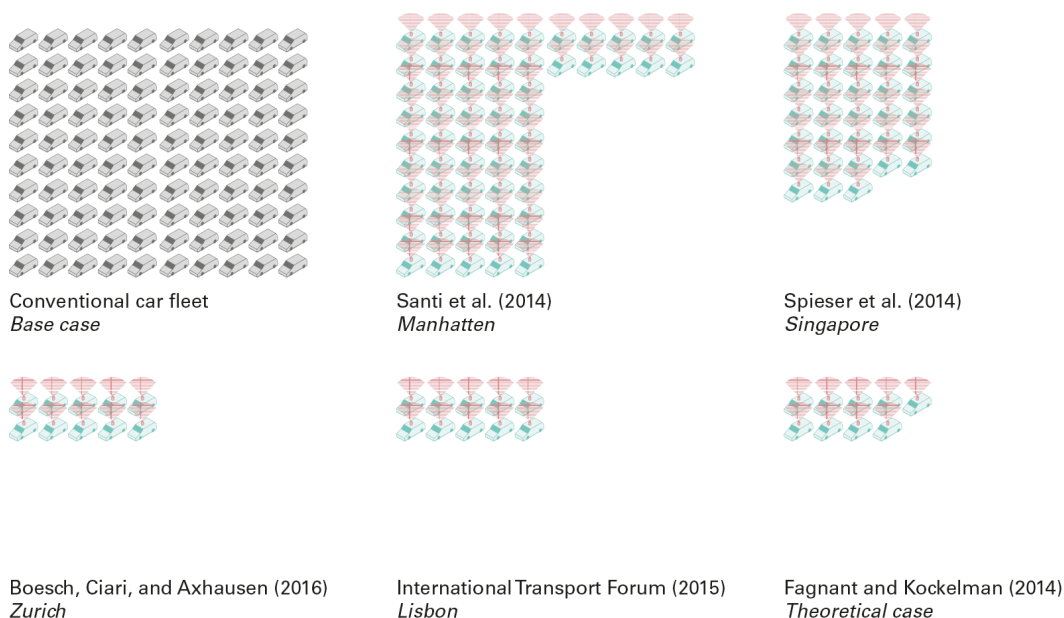


Figure 3-9: Estimated required fleet of automated taxis found in different studies to serve similar mobility levels compared to conventional car fleets (data from Boesch et al. (2016); Fagnant and Kockelman (2014); International Transport Forum (2015); Santi et al. (2014); Spieser et al. (2014)).

Reduction of vehicles, roads and parking spaces can greatly benefit urban spaces. The design of roads and street is covered very limited within scientific research. However, within the urban design practice, it is one of the most covered aspect in the context of vehicles automation. Examples of such

studies are described by Wilson (2016) (Figure 3-10) or by EXCEPT (2017) (Figure 3-11). These designs have a smaller scientific basis and take fewer consideration regarding the current challenges and uncertainties around vehicle automation into account. Instead, these visions are illustrations of the potentials automated vehicles can have in a positive sense on urban spaces.



Figure 3-10: Vision how automated vehicles could help transform sidewalks (Wilson, 2016).

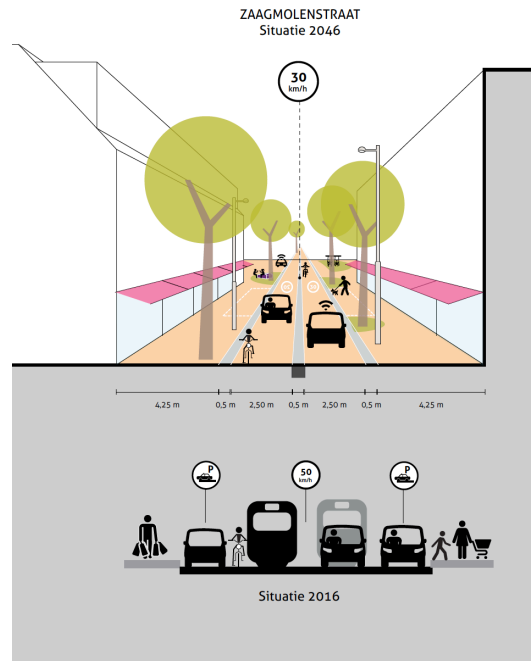


Figure 3-11: Redesign for a street in Rotterdam for a future situation with self-driving cars (EXCEPT, 2017, p. 27).

3.3.4 IMPACTS OF AUTOMATED DRIVING ON URBAN FORM

Some studies have considered multiple aspects of automated driving technology as elaborated on in this section and assess the impacts of automated driving from a spatial perspective and therefore elaborate on the impact of automated driving on urban form. The most comprehensive research the study by Gelauff, Ossokina, and Teulings (2017). Their research uses a spatial equilibrium model to evaluate the change in population dispersion in the Netherlands by increased travel comfort of automated driving and the new opportunities to replace conventional transit solutions. Their most important conclusion was that an increase in travel comfort would lead to people moving to suburban areas. However, if the benefits of automated driving were implemented in public transport systems, the opposite would occur. Zakharenko (2016) investigates the impact from automated driving on a hypothetical concentric city. Because of remote parking solutions, the city centre will generate more economic activity and lower travel costs will lead to the sprawling of the city. Meyer, Becker, Bösch, and Axhausen (2017) do not elaborate on the physical state of the urban environment, but studies the effects of capacity gains and induced demand on accessibility levels in Switzerland, finding decrease in accessibility levels in urban centres and strong increases within the rural areas. Their conclusion is

not on the impact of automated driving on urban form itself but the research hints towards sprawling of urban settlements through the new accessibility patterns that are found.

3.4 CONCLUSIONS AND DISCUSSIONS

Automated driving is a technological innovation that extends beyond vehicle level. Technological development is not the only uncertainty factor in the establishment of automated driving within society and might prove not to be the most determinant factor in the first place. Research shows how automated driving can change traffic, travel, infrastructure and space. The uncertainties around the development of automated driving asks to make assumptions when studying the impacts of automated driving. Many of the researches differentiate various levels of automation and different applications as e.g. shared taxi-bots in scenarios and base different assumptions on the scenarios that are set. The underlying assumptions in these studies are found to have a significant influence on the conclusions of the studies as Figure 3-12 illustrates by showing findings listed in this chapter.

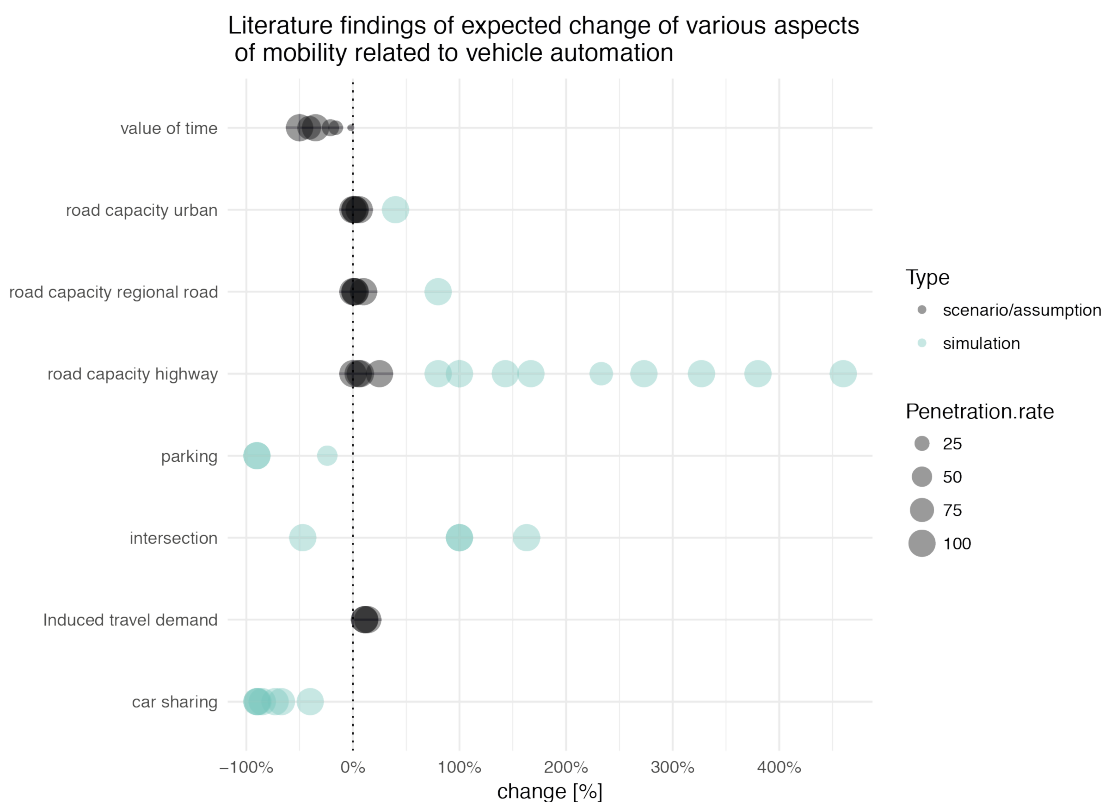


Figure 3-12: Quantitative statements found in the literature review on the impacts of automated vehicles on various aspects related to mobility and the transportation network.

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.

If these findings are projected on the existing research, it reveals that travel and traffic aspects of automated driving are better linked towards research on urban change (processes). The findings regarding the potential spatial quality effects however has not been integrally evaluated in studies that examine the impacts of automated driving on urban form. These studies solely elaborate on the travel and traffic benefits and show findings that hint towards sprawl of urban development. However, the researches on spatial quality benefits show attractive environments that can promote dense urban living. That these findings have not been evaluated within earlier research is understandable for their approaches, which cannot be considered mainstream within the scientific community. However, neglecting these factors might underestimate the impact this can have on urban development processes.

4 RESEARCH METHODOLOGY

This research examines the impacts of automated driving from a spatial perspective by distinguishing the domain of travel and accessibility, infrastructure integration and of urban form. Most research on automated driving focusses solely on traffic or infrastructure aspects. Connecting automated driving to urban development is mostly done by elaborating on accessibility but not on the potential benefits of automated driving for urban spaces. More efficient travel hints towards facilitating urban sprawl whereas the spatial quality effects might promote dense urban living instead. The aim of this research is to illuminate which urban development patterns reveal under the emergence of automated driving, covering both these aspects. This chapter explains the problem entity and the paradigm through which this problem is approached. Based on the defined problem, the research steps are derived and further specified.

4.1 PROBLEM ENTITY

Urban modelling methods increasingly recognise individual decision makers as main driving force in urban development and therefore appeal to the paradigm of cities as complex systems. Within this research, households and their residential location choice are considered the most important factor in urban development for three reasons: housing takes on the largest share of land-use (CBS, 2016b), jobs primarily follow people and not the other way around (Hoogstra et al., 2005) and the development of new housing is for a large share influenced by the preference of households (Zondag, 2007, pp. 26-27, 107). Section 2.2.2 finds that residential location choices depend generally on dwelling, neighbourhood and location characteristics and on characteristics of the household itself (Hunt et al., 1994). By identifying the residential location choice behaviour as driving force in land-use changes automated driving can be linked to the process of urban development through this behaviour: The effect of automated driving can be evaluated through accessibility effects and spatial quality changes in neighbourhoods. Furthermore, car ownership can be considered as a household characteristic. Based on the rationale above, the problem entity is depicted in Figure 4-1.

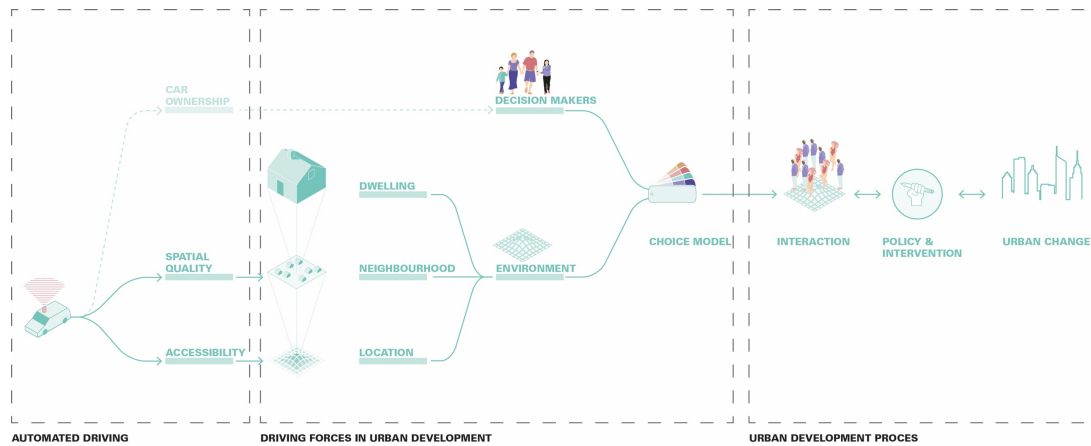


Figure 4-1: Problem entity for the research. Automated driving is linked to urban development through accessibility and spatial quality effects and through the residential location choice behaviour which is determined as main driving force for urban change processes.

The final manifestation of urban change in this research is accounted for by a change in residential densities in urban areas. Automated driving influences this not by primarily changing the behaviour of the households itself but by the characteristics of the environment by which households determine their behaviour. By scoping towards housing and households, other factors and actors in urban development are not considered to narrow down the research and limit the required data. The purpose of this research is not to project an apparent accurate future but reveal the assignments and dynamics that reveal in terms of housing under the emergence of automated driving.

4.2 RESEARCH METHODS

The problem entity in Figure 4-1 reveals the most important research steps for the research. The spatial impacts of automated driving are assessed through the behaviour of individual decision makers to reveal macroscopic urban development patterns. Therefore, it is required to obtain a modelling environment in which the moving behaviour of individual households can be simulated. This behaviour is determined by characteristics of the households and their interaction and by environmental characteristics. Automated driving impacts these characteristics on the realm of spatial quality and accessibility. Hence, three different research and data collection steps can be considered:

- Assessment of the impacts of automated driving on accessibility;
- Assessment of the impacts of automated driving on spatial quality through infrastructure integration;
- Evaluation of the prior findings within a model to study individual household moving behaviour for revealing changes in residential density.

These three steps correspond with the domains which this research distinguishes (see section 1.3). This section explains the methods employed. The research is conducted in the context of uncertainty around the development of automated driving and takes on an integrated spatial perspective to the research problem, hence this research employs a scenario approach and a case study.

Scenario approach

Evaluation of research on automated driving in chapter 3 shows the dispersion of predictions on its impacts. This dispersion is for a large share cause of underlying assumptions within researches on the development and deployment of automated driving technology. To allow this research to build further upon existing research on automated driving and its impact, a scenario approach must be employed to grapple the uncertainty around automated driving. Within the scenarios, coherent developments can be made on how (or if) automated driving establishes itself as transportation mode to later justify coherent assumptions. This allows awareness on underlying assumptions of prior research and exploring the effect of various factors of uncertainty on the research results.

Case study

To allow for a spatial perspective, it is possible to both elaborate on a theoretical case study or a real-world case. A real case is preferred to do justice on the complexity of the spatial context and the rich details in variables this can provide. It is important to make an adequate choice on the specifics and size of the study area and on the spatial resolution. Each urban region has its own specific characteristics based on landscape, geography, culture etc. This complicates deriving general rules from the case specific conclusions and must be taken into consideration when deciding on a case study. Furthermore, it is of importance to choose an urban area of reasonable size with different urban environments - ranging from low density residential to high urban centre areas. Preferably, the case study area consists of at least one or more areas which can be classified as a daily urban system and/or regional housing market. A daily urban system is an “area around a city in which daily commuting takes place” (Sijtsma et al., 2017, p. 20) and often follows boundaries similar to the regional housing market (Faessen et al., 2011; Schwanen et al., 2003). Deciding on the spatial resolution in part depends on data availability but also on the scope. Section 2.3.1 shows that for research on travel behaviour, larger scale metrics prove more relevant. In terms of research with a spatial scope, higher spatial resolutions are usually preferable. As neighbourhood characteristics are relevant attributes in residential choice behaviour, this research aims at the spatial resolution of neighbourhoods. This is also a scale level on which adequate conclusions can be drawn regarding urban development patterns.

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 needs to be evaluated to adequately study the automated driving effects. Hence, a transport model is required to evaluate relevant factors such as travel time (and delay), costs and behaviour on a detailed level and obtain accessibility values.

Spatial quality effects

The qualitative aspects of infrastructure in terms of attractive urban spaces are often neglected within the domain of transportation science. Urban spaces and spatial quality are primarily examined

within the field of urban design. Urban designers play an important role in setting the conditions to shape urban spaces towards a desired goal. Therefore, this research uses a design approach to examine the spatial quality effects of automated driving. It is important to consider two different scale levels. On neighbourhood level, the requirements for large scale infrastructure areas are assessed, finding new options for spatial transformation. On street level, one can elaborate directly on the spatial quality effects itself and the externalities of traffic by examining how much space is required directly for infrastructure and how the additional space available can be used to improve the quality of the streets.

Design-based research methods and engineering-based methods differ in process, goals and models that are used. Therefore, adaptations and considerations must be made to integrate research-by-design within the research process. Within the scientific domain, reproducibility of the results is highly valued whilst the design practice acknowledges the signature of the individual and values originality. The design approach should therefore be very functional, solely elaborating on the functional aspects of infrastructure within the urban environment without very case specific solutions. To obtain a transparent research process, the approach must be consistent and repetitive for all urban spaces. As it is not feasible to assess all urban areas, a classification of neighbourhoods is conducted. For each occurring neighbourhood type, one zone is considered representative. Conclusions drawn from the zone are then assumed similar for all other zones of that typology.

The outcomes of these research steps are in predominantly drawings, giving a qualitative indication of the spatial quality potentials. However, drawings will not directly be compatible with the next research steps. On the neighbourhood scale, a qualitative expression of the transformation potential is made. On street level, the results are quantified using hedonic pricing modelling. Hedonic pricing models are used to express how environmental characteristics (amongst others) influence real-estate values

Residential density transformation

By defining residential location choice behaviour by households as the microscopic driving force of urban change, this research formalises this behaviour and the interaction between different households in an agent-based modelling methodology. Agent-based modelling coincides with the paradigm of this research as cities as complex systems and is based around the behaviour of individual decision makers. Furthermore agent-based modelling allows for a high spatial resolution and heterogeneity in decision makers. On these aspects, agent-based modelling distinguishes itself from older or alternative methods in urban modelling as e.g. system dynamics or spatial interaction models. The largest challenge for using agent-based models however, is to accurately define the behaviour of the agents. Therefore, it is important to know how to describe the behaviour of the agents before the data collection process. One can either empirically derive the behaviour of the agents from e.g. survey data or use an existing residential location choice model.

4.3 RESEARCH PROCESS

The methods presented in the prior section allow to evaluate the spatial impacts of automated driving on urban development integrally. The complete research methodology comprises various

methods and research steps to not only illuminate the changes in urban development but also the preceding environmental aspects that drive this process. A graphical representation of the research process is shown in Figure 4-2. To successfully execute the research, it is crucial that data is accurately collected and that the results of the various research steps are compatible. Within this chapter, the research steps are described from a general perspective. Additional challenges regarding data availability and compatibility arise in most researches including this one. For the case in which various research methods are connected, constraints by later research steps can influence research steps earlier in the process.

The report follows the structure of the process in Figure 4-2. Literature on automated driving effects is already evaluated in 3. These findings will provide input for the scenarios which are presented adjacent to the case study area in chapter 5. These two aspects make up the research context from which assumptions and data are derived in later stages of the research. In chapter 6 to 8 the other research steps are sequentially presented according to the research process. The findings from the accessibility and spatial quality effects of automated driving are used in a residential location choice model. This residential location choice model is implemented in the agent-based model to evaluate the effect of the prior findings on household density. How the prior two steps can or must be executed is in part dictated by the used residential location choice model (the model used is by Zondag, de Bok, Geurs, et al. (2015), see subsection 8.1.1). This will be mentioned when occurring in the transportation modelling or research-by-design step. Regarding the transportation modelling step, this will influence how accessibility is calculated. For the research-by-design step, hedonic pricing modelling is used to quantify the findings to be compatible with the model. Furthermore, this research step follows the same neighbourhood classification as the residential location choice model.

Within section 2.1, the cyclic nature of land-use and transportation interaction was introduced. The found outcomes in terms of new urbanisation patterns will lead to new travel demand patterns too. Ideally, this new pattern would provide input again to the prior research steps. The cyclic nature of the system is however not considered for practical reasons and time constraints as the various research methods ask for personal interpretation and judgement which cannot be automated.

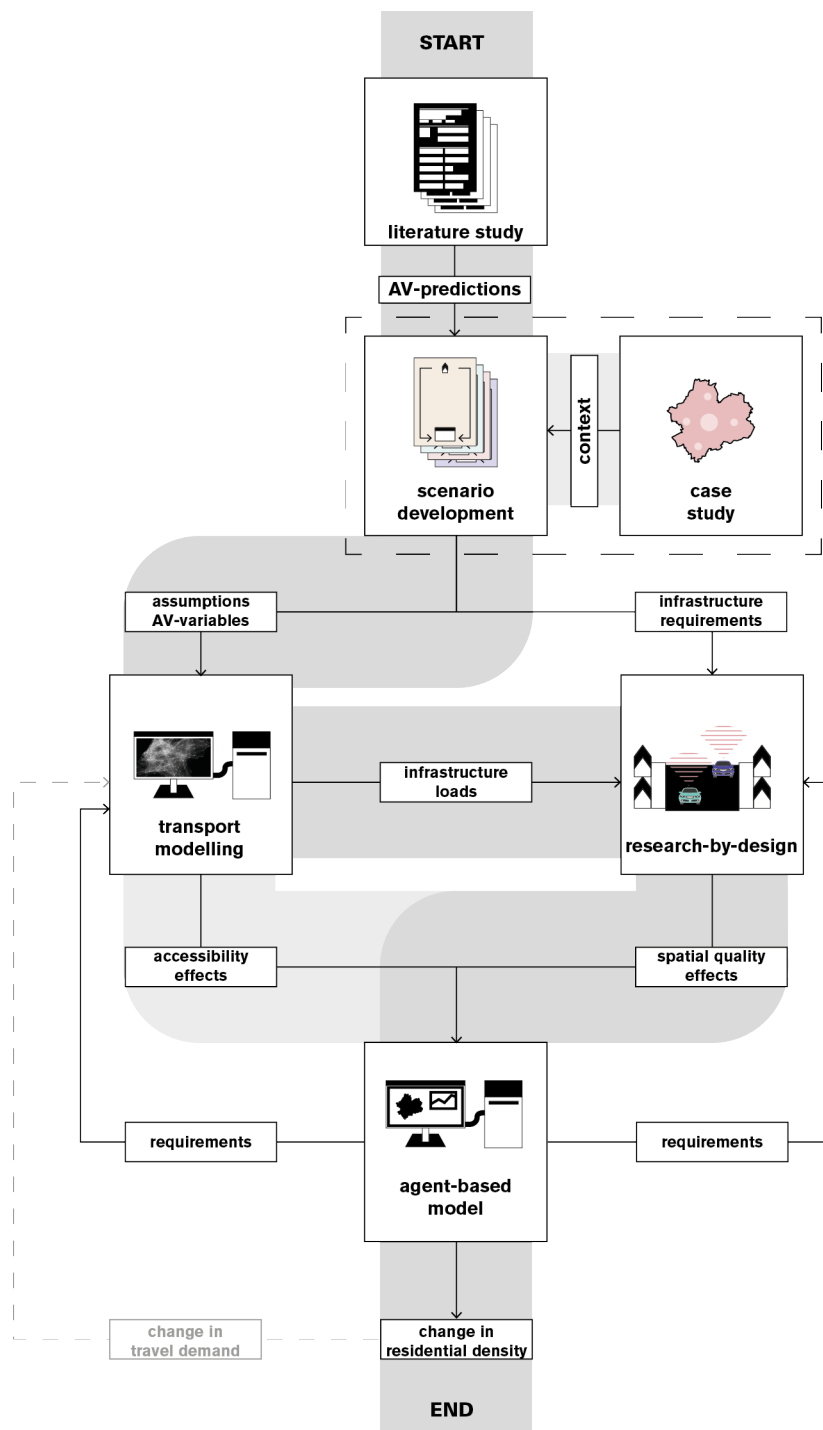


Figure 4-2: Graphical representation of the research process.

5 CASE STUDY AND SCENARIOS

The problem entity as defined in chapter 4 is an abstract representation of the research problem. It is important to state that this research is conducted in a setting of uncertainty around the development and deployment of automated driving. Additionally, 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. Hence a real-world case-study is employed to provide for a real-world data source. This chapter introduces the case study and introduces the scenarios which are used in the remainder of this study.

5.1 CASE STUDY INTRODUCTION

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. The data for the case study is largely derived from open (geospatial) data sources by Statistics Netherlands (CBS) and the Dutch Cadastre (Kadaster). Another important data source for this research is the transportation model for the region of Utrecht (VRU, see subsection 6.1.1). This transport model is made available for this research by the Province of Utrecht.

5.1.1 SYSTEM BOUNDARY AND SPATIAL RESOLUTION

The case study area must comply at least some spatial entity in terms of mobility (a daily urban system) and/or housing market. Faessen et al. (2011) and (Sijtsma et al., 2017) provide a definition of respectively the geographical boundaries of the daily urban system and the housing market around the city of Utrecht. These boundaries align partly with the provincial borders but not completely. VRU however, follows the provincial boundaries. Furthermore, the provincial boundaries for the Province of Utrecht match the definition of the COROP-region (NUTS-3 region (Eurostat, 2017)) for Utrecht. This region also coincides with the nested structure of the residential location choice model used in this study as introduced later in subsection 8.1.1. Therefore, this study sets the system boundary accordingly.

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). Section 2.3 described that higher scale urban variables might be more influential regarding travel behaviour. However, as this research also has a focus on the spatial domain of cities, a *neighbourhood* scale can elaborate better on these effects (Batty, 2000). *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 4-digital postal zones as spatial entities for the modelling study because of the large availability of data on this scale. 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 5-1) are district (in Dutch: *wijk*) and neighbourhood (in Dutch: *buurt*, the terminology is confusing in this case which illustrates the lack of consensus about what neighbourhoods are), both defined by CBS (CBS, 2017c). 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 as defined by CBS (2017c), is because these are differently defined in different towns and cities. 4-digital postal zones are defined more coherent in terms of spatial entities.

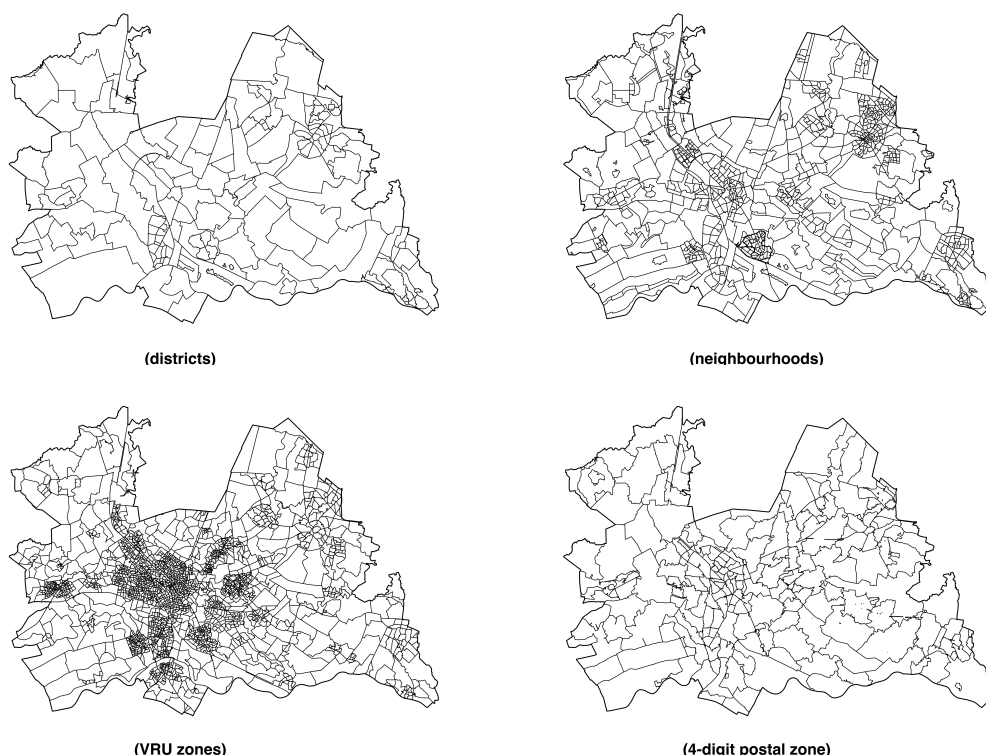


Figure 5-1: Different zone classifications

5.1.2 CASE STUDY AREA CHARACTERISTICS

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 mid-sized cities and rural areas in the east. The area is well connected by highways in all directions and the central railway station of the city of Utrecht is the most important train station within the Netherlands (Figure 5-2). The province housed 1 263 572

inhabitants, divided over 568 152 households in the year 2015 (CBS, 2017b). The most densely populated areas are found in the neighbourhoods of the city centre of Utrecht followed by other towns either surrounding Utrecht and Amersfoort (Figure 5-3). It houses a wide variety in urban environments from different building years (Figure 5-4). 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.

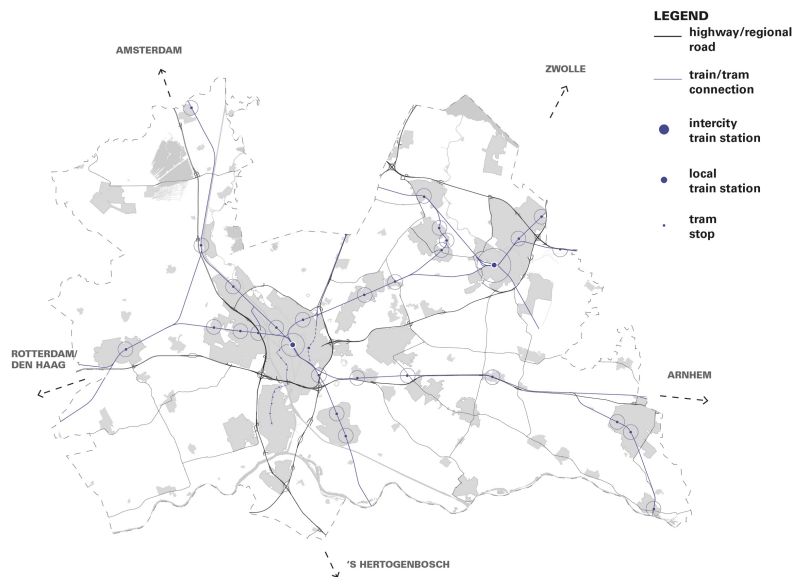


Figure 5-2: Infrastructure network (data derived from Kadaster (2016b))

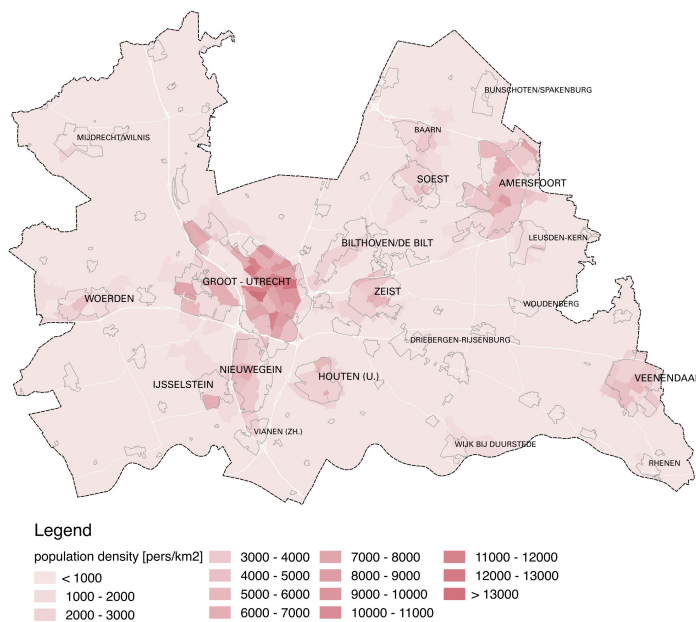


Figure 5-3: Population density (data derived from CBS (2016a))



Figure 5-4: Within the case study area one can find a wide range of different neighbourhoods from different building years. Layout of neighbourhoods is partly the result of how ideal living in that time was perceived. Infrastructure and mobility play a role in this, both in terms of layout as well as location of neighbourhoods (building outlines and year are derived from Kadaster (2016a)).

5.2 SCENARIOS

Many assumptions must be made in this study to grapple uncertainty around vehicle automation. 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 impacts and applications of vehicle automation within the transportation system. 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.

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. 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. The development trends corresponding to the scenarios are depicted in Figure 5-5, 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.

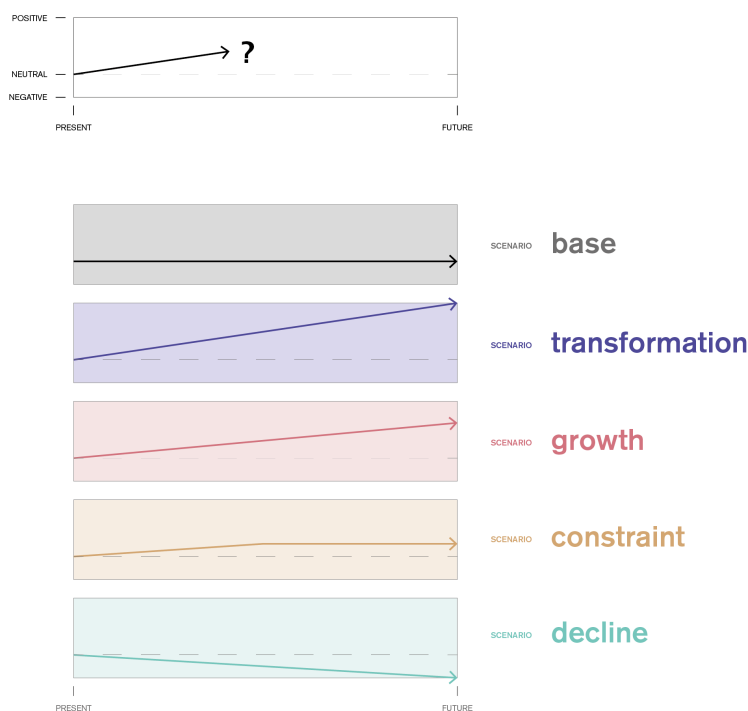
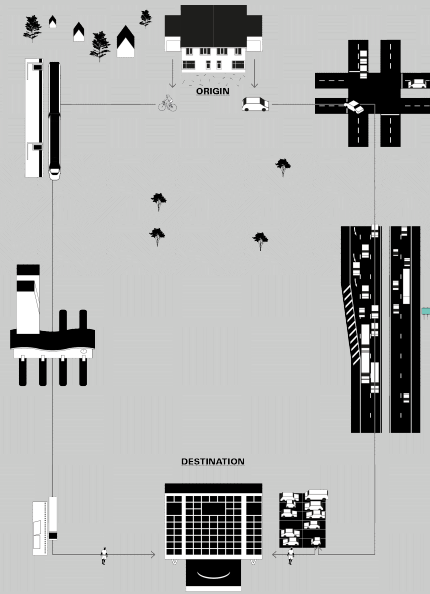


Figure 5-5: Different trajectories for the corresponding scenarios. These are the trends for the trend impact analysis.

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 3. Together with the assumptions per scenario, these are depicted in Table 5-1.

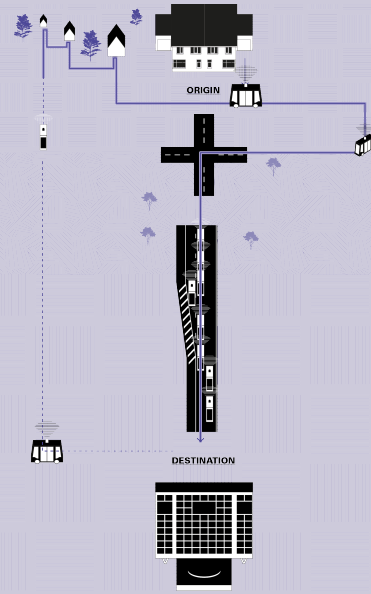
Table 5-1: Variables with corresponding developments considered within the scenarios.

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	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			



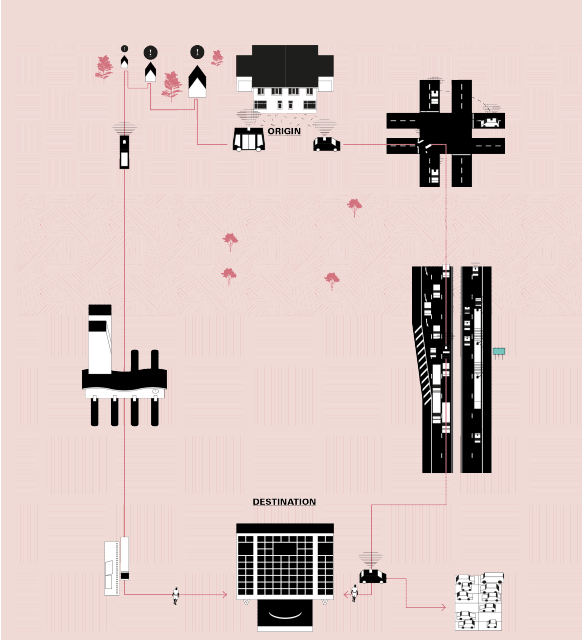
Scenario 0: Base

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

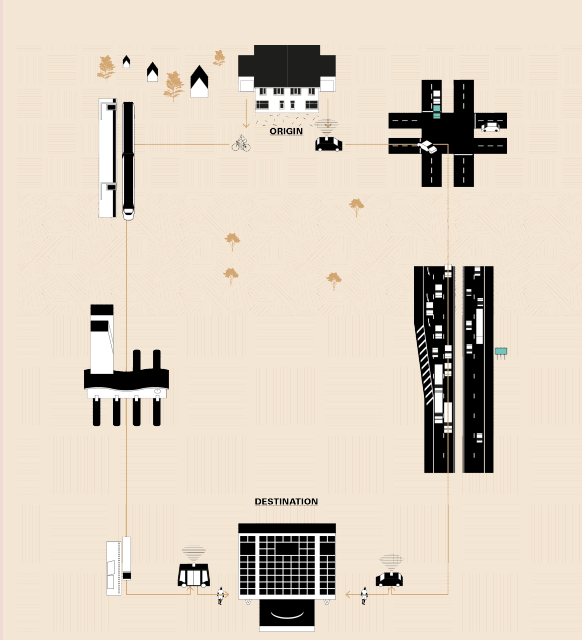
Vehicle automation develops rapidly towards full automation. Driving force behind vehicle automation are technology companies and start-ups. These companies are disrupting the transportation market with new innovative mobility concepts based on sharing demand responsive taxi solutions. The traditional 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.



The diagram for Scenario 2: Growth is set against a light red background with a faint circuit-like pattern. It shows a network of roads connecting various urban elements. At the top, a residential area with houses and trees is connected to a central intersection. Below this, a large industrial or commercial building is shown. To the right, a tall, narrow building represents a transit corridor. At the bottom, a 'DESTINATION' is marked with a large screen and a person. Red lines indicate the flow of traffic and data between these elements, showing a dense, interconnected urban environment.

Scenario 2: Growth

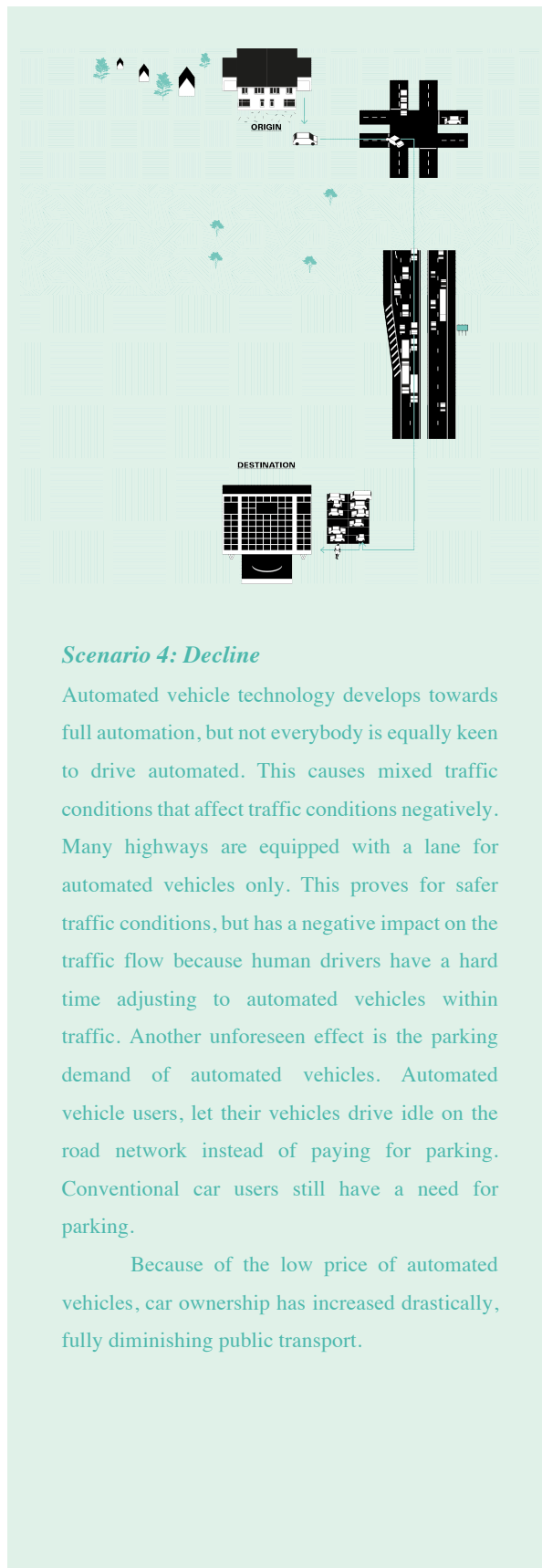
Vehicle automation develops gradually towards full automation. The driving force behind vehicle automation is the conventional car companies. Advanced driver assistance systems gradually develop towards full autopilots, making automated driving in private automobiles mainstream. Protectionism of national 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).



The diagram for Scenario 3: Constraint is set against a light orange background with a faint circuit-like pattern. It shows a network of roads connecting various urban elements. At the top, a residential area with houses and trees is connected to a central intersection. Below this, a large industrial or commercial building is shown. To the right, a tall, narrow building represents a transit corridor. At the bottom, a 'DESTINATION' is marked with a large screen and a person. Orange lines indicate the flow of traffic and data between these elements, showing a less dense, more constrained urban environment compared to Scenario 2.

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 a 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 ACCESSIBILITY AND TRAFFIC EFFECTS OF AUTOMATED DRIVING

This chapter examines the effect of automated driving on traffic and accessibility with the regional transport model of the Province of Utrecht. The accessibility of a location is a consideration factor for households to determine their residential location. Traffic conditions are important indicators for the infrastructure requirements and therefore provide for important input on the spatial quality assessment of automated driving in the next chapter. This chapter start with an evaluation of the regional transport model and how to use it to evaluate the various scenarios of automated driving. Thereafter, the model is used to simulate these scenarios and present the effects of automated driving on traffic and accessibility subsequently.

6.1 AUTOMATED DRIVING AND ACCESSIBILITY MODELLING

This research uses the Verkeersmodel Regio Utrecht (VRU, in English: Transport model region Utrecht) to examine the effects of automated driving on accessibility and traffic. VRU was made available to the author for this research by the Province of Utrecht. It is the only multimodal transport model specifically designed for the case study area. This section elaborates how to use this transportation model for accessibility analysis and how to evaluate automated driving. First step is providing a review of the framework and procedures within VRU. Thereafter, the model framework is further examined for possibilities to obtain accessibility values and implement automated driving. Based on these findings, further assumptions and implementation considerations for each scenario are examined.

6.1.1 INTRODUCTION TO THE VRU FRAMEWORK

VRU is a comprehensive static multimodal four-stage transportation model owned by the Province of Utrecht. The model is integrated in the OmniTRANS macroscopic transport modelling environment (version 6.1.4). In this study, VRU version 3.2 has been used. The model distinguishes various trip purposes, modes, day-times and makes a separation between users with and without car availability. Within the provincial borders, the model shows a high spatial resolution of 2 500 small zones. Outside the provincial border areas, the model comprises another 1 900 centroids with the same socio-economic variables but without geographical border. These centroids gradually become coarser

when the distance from the province increases. Outside national borders, only a few centroids represent countries or larger regions abroad.

Even though VRU classifies as four-stage model, the structure diverges from the classical four-stage model structure. Purpose of these adjustments is for both practical reasons and to obtain more realistic results regarding link loads to improve the functionality of the model for environmental assessment (Goudappel Coffeng, 2013, pp. 18, 38). Figure 6-1 on page 53 shows that VRU differs from conventional four-stage model. Four important differences can be distinguished:

- Travel demand and traffic regarding freight transportation is prior modelled and assigned to the network;
- External travel (with both an origin and destination outside the study area - the province of Utrecht) is added from the regional NRM-West transport model and not internally determined;
- After estimation of origin-destination (OD)-matrices, the results are assessed and adjusted based on travel survey and traffic count data;
- Trip distribution and mode choice are simultaneously determined. This is however not unconventional in transportation models.

The modelling processes that are distinguished within VRU are:

- Trip generation;
- Simultaneous trip distribution and mode choice;
- Trip assignment.

Travel demand is generated externally from OmniTRANS in an encrypted spreadsheet environment using trip-end functions. Each zone has specific socio-economic data which determine the trip generation and attraction. Outcome of the trip generation model is the number of trip-ends by purpose and user type. Trip distribution and assignment are iteratively determined as the trip distribution is influenced by the travel impedance and vice-versa¹. Travel impedance is evaluated through a log-normal distribution function (Figure 6-2 on page 54):

$$F_{mp}(Z_{ijm}) = \alpha_{mp} * \exp(\beta_{mp} * \ln^2(Z_{ijmp} + 1))$$

with:

$F_{mp}(Z_{ijmp})$	The distribution function for mode m and trip purpose p .
α_p, β_p	The cost sensitivity parameters for trip purpose p .
Z_{ijmp}	The travel impedance between zone i and j for mode m and purpose p .

¹ On default, the trip distribution process is run in three iterations. The number of iterations for the assignment process is mode dependant and ranges from one iteration (for the bike) to 30 iterations for car traffic.

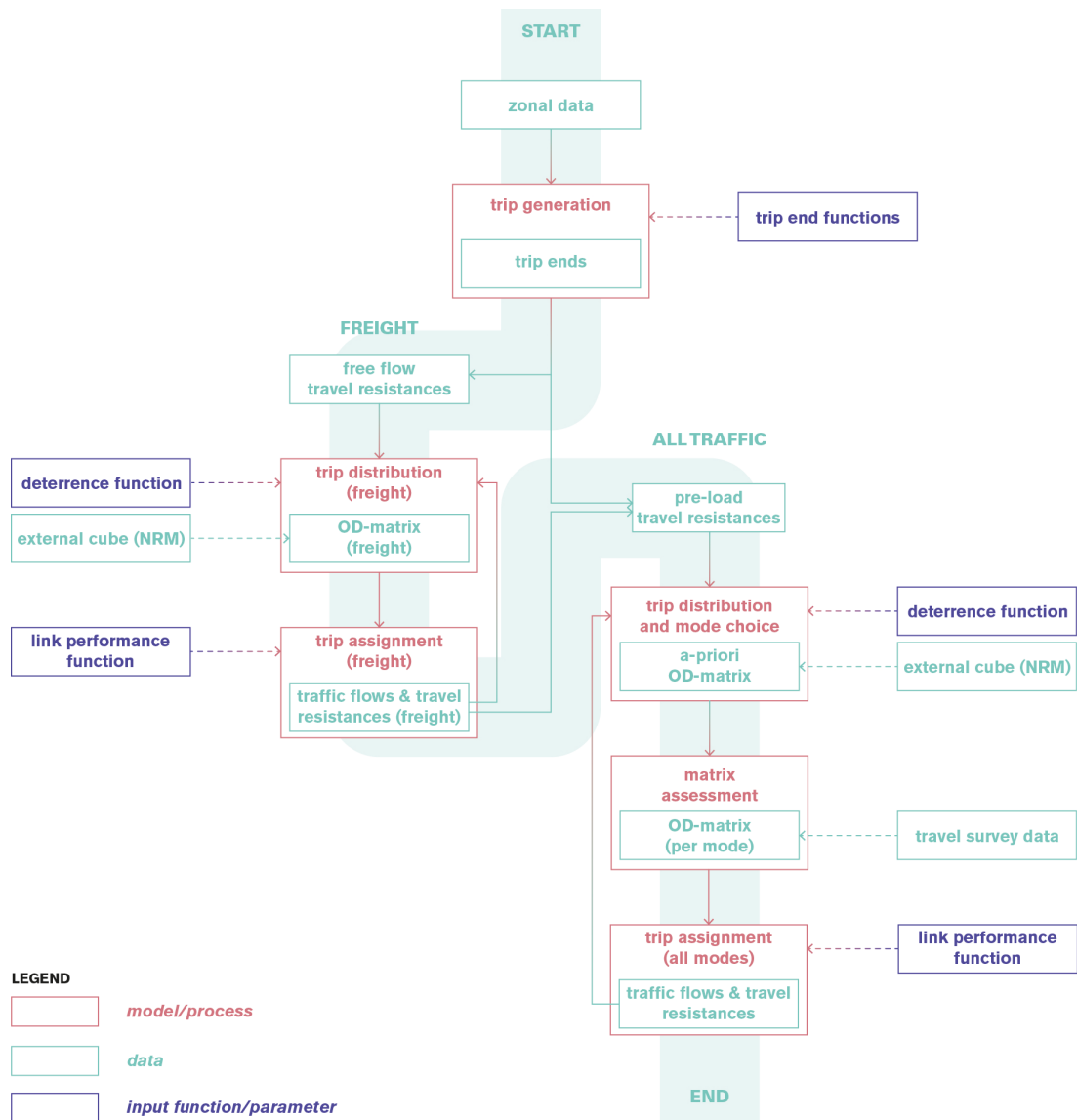


Figure 6-1: The Structure of VRU differs from a theoretical simultaneous trip distribution and mode choice four-stage model as freight is modelled primarily and additional procedures are added to evaluated external traffic and correct the model results to observed travel behaviour.

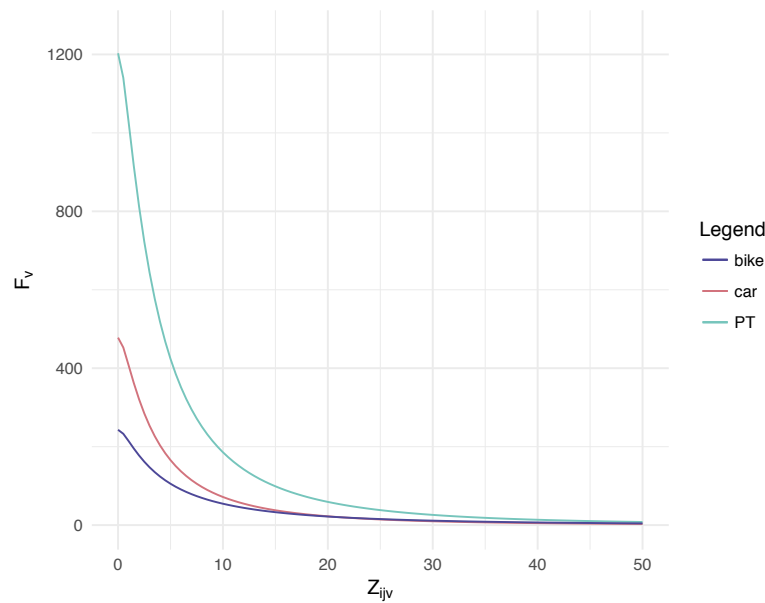


Figure 6-2: Deterrence function per mode for all trip purposes. The diversion of public transport is because VRU produced significantly higher generalised travel costs for the PT mode and the model does not incorporate alternative specific constants in the mode choice process.

The travel impedance Z_{ijmp} is comprised of travel cost, time and comfort factors. For car travel, the impedance is built up by travel time monetised through value of travel time, travel distance costs and optional parking costs and factors related to parking regarding availability (of alternatives). Public transport impedance incorporates time and distance differently. Egress, waiting, transfer and in-vehicle time are all weighted differently and transfers involve travel time penalties. Furthermore, the fare is determined based on various factors considering subscriptions, travel costs compensation by employer or different. For bike usage, monetised travel time is considered only (Goudappel Coffeng, 2013, pp. 31-32). VRU does not incorporate mode specific constants. Instead, the different order of magnitude of the travel costs is evaluated within the deterrence function.

The value from the deterrence function F_{mp} is based on the travel impedance. This value is successively used within a doubly constrained gravity model by which the travel between zones for each mode is determined using the iterative approach by Furness. The outputs are OD-matrices per time of day, per mode and trip purpose.

The OD-matrices are aggregated and assigned to the network within the trip assignment process. In this step, travel time on every link in the network is evaluated with a link performance function (often called BPR curve). Also delays on intersections are modelled within VRU and added to the travel time. Intersection delay factors evaluate 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, p. 11). Based on the travel times on the network, traffic is assigned through a method-of-successive-averaging (MSA assignment, or Volume Averaging).

6.1.2 ACCESSIBILITY MODELLING

No designated functionality exists within VRU for accessibility analysis. Within this study, accessibility is considered as one of the evaluation factors for households in their residential location

choice. The choice behaviour is based on the model by Zondag, de Bok, Geurs, et al. (2015) (decision is elaborated on in section 8.1.1). Therefore, it is important that the outcome of the accessibility calculations in this study coincide with considered components and magnitude to the accessibility indicators used in the given residential location choice model (see also section 2.3.3).

Accessibility indicator

The given choice model is intended to evaluate logsum accessibility indicators but VRU does not provide options to calculate accessibility in a logsum. VRU distributes trips with a (doubly constrained) simultaneous gravity model and therefore needs no computation of the destination utility, whilst this is required to calculate accessibility in a logsum. Therefore, this research chooses to use another utility based accessibility indicator considering the generalized costs of travel and the number of opportunities in a zone. Difference between this indicator and the logsum indicator is that the opportunities are not expressed in the same unit as the travel impedance:

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

with:

A_i	Accessibility in zone i
D_j	Measure for attraction in zone j
F_{ijm}	Distribution function of the travel impedance between zone i and zone j

The decision is made to make no distinction between different user types. Furthermore, the morning peak is considered as the most representative time of day. For this research, the measure for attraction in the destination zone, D_j is set to the number of jobs in zone j , as job accessibility is a suitable proxy to other activity types (Geurs, La Paix, & Van Weperen, 2016, p. 25). To stay closely to the VRU model for accessibility calculation, the number of jobs from the zonal data of VRU is used. These data are supplied by the provincial jobs register (Provincie Utrecht, 2015). Besides the measure for attraction, also an evaluation of the travel impedance between zone i and zone j is required to account for the infrastructure component. The travel impedance Z_{ijmp} is preferably expressed using the aggregated generalised cost of travel between zone i and j - as directly obtained within the transportation model through a skimming procedure. However, this showed to be not possible as the cost skims generated after the final assignment of traffic showed travel costs in a different magnitude than one would expect. This conclusion is drawn from both comparing the outcomes with expected values from the log-normal deterrence functions in the model (Figure 6-2) and from calculating the cost outside of the model environment based on validated travel cost and distance skims:

$$Z_{ijmp} = \alpha * x_{ij} + \beta * t_{ij}$$

with:

α	The value of distance
x_{ij}	The travel distance between zone i and zone j
β	The value of time
t_{ij}	The travel time between zone i and zone j

Furthermore, no multimodal accessibility is considered as the travel impedances of different modes are very divergent and cannot be aggregated within one multimodal impedance. That is because the travel impedances for different modes comprise pseudo costs related to e.g. parking or public transport fees. Therefore, the accessibility calculations evaluated are solely based on car travel without parking costs in the travel impedance. To make sure that the calculated travel impedance indeed coincides with the cost-decay function used within the OD-estimation process of the model, the travel cost distribution of the base scenario has been compared to the cost-decay function with $\alpha_{car,commute} = -0.330$. The comparison shows some deviation between the observed travel-cost distribution and the decay function (Figure 6-3). However, the difference is considered small enough to be satisfactory for the accessibility calculation.

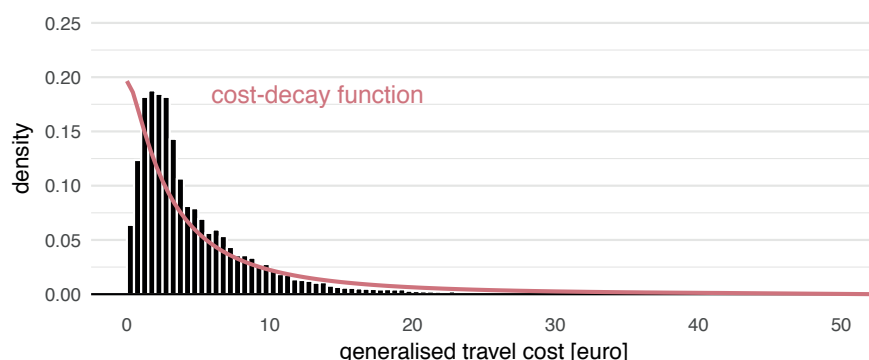
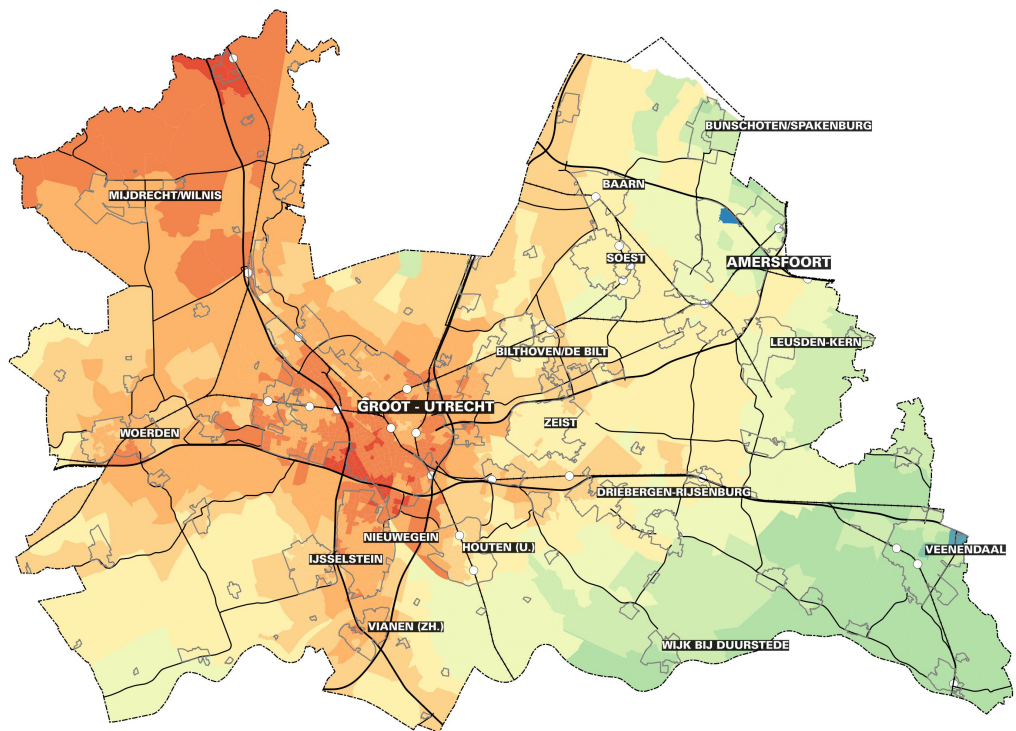


Figure 6-3: Travel cost distribution compared to the cost-decay function for car travel for commuting purposes.

Base accessibility

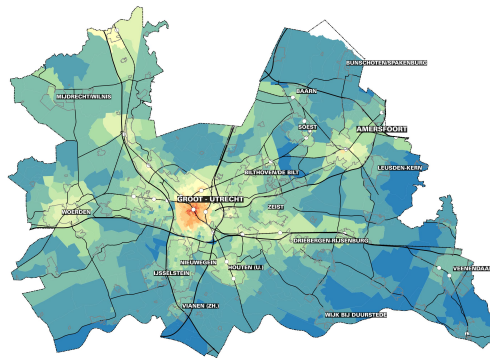
For the base case, the accessibility to jobs by car results in the map in Figure 6-4. Although this map shows only accessibility values within provincial borders, also opportunities outside this area are incorporated. These are however not mapped as the areas outside the border have no geographical boundaries. Accessibility levels in the region are particularly high around the highways surrounding the city of Utrecht and further towards the metropolitan area of Amsterdam which starts just at the border northwest of the province. On a larger scale, the difference between accessibility levels in the east and the west of the province is revealed. The west is part of the Randstad area, comprising the four big cities of the Netherlands, whereas the east is characterised by smaller towns. Furthermore, areas surrounding highway stretches show higher accessibility levels in general. The level of the city scale shows that urban centres have lower accessibility levels because of longer travel times on the urban road network. Accessibility maps (Figure 6-5 and Figure 6-6) for public transport or biking show within those areas accessibility levels are relatively high for these modes.



Legend

accessibility to jobs	600000 - 650000	750000 - 800000	900000 - 950000	1050000 - 1051942
510952 - 550000	650000 - 700000	800000 - 850000	950000 - 1000000	
550000 - 600000	700000 - 750000	850000 - 900000	1000000 - 1050000	

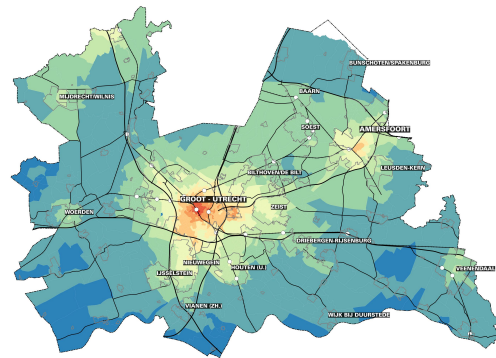
Figure 6-4: Accessibility to jobs in the base scenario.



Legend

accessibility to jobs	15000.0 - 20000.0	30000.0 - 35000.0	45000.0 - 50000.0	60000.0 - 65000.0
6943.7 - 10000.0	20000.0 - 25000.0	35000.0 - 40000.0	50000.0 - 55000.0	65000.0 - 69023.4
10000.0 - 15000.0	25000.0 - 30000.0	40000.0 - 45000.0	55000.0 - 60000.0	

Figure 6-5: Accessibility to jobs by public transportation.



Legend

accessibility to jobs	10000 - 20000	30000 - 40000	50000 - 60000	70000 - 80000
0 - 10000	20000 - 30000	40000 - 50000	60000 - 70000	80000 - 90000
				90000 - 94055

Figure 6-6: Accessibility to jobs by bicycle.

6.1.3 AUTOMATED DRIVING IN VRU

Automated driving has not yet been implemented within VRU. Adaptations or adjustments to the model are required to simulate the effects of the defined automated driving scenarios. Two means to integrate automated driving have been considered. The first is to integrate new automated transportation modes within the model, what asks for re-evaluation of a lot of model parameters and for access to encrypted parts of the model. Therefore, the second option of implementing automated

driving has been applied instead: model parameters are to be altered within the model where possible, to evaluate the various aspects of automated driving. Based on the findings in chapter 3, three different aspects on which the accessibility study must elaborate can be distinguished: induced travel (for various reasons), increased efficiency in traffic and change in travel comfort through value of time.

Induced travel

Two categories of induced travel are considered. The first is a possible increase in number of car trips by new users, empty ride allocation to pick up passengers or for parking allocation (as found in section 3.3.2). A second possible increase is by induced travel because of longer trip lengths because of lower travel impedances because of shorter travel time or higher comfort. The first aspect can solely be incorporated by making adjustment to the existing OD-matrix as the trip-end model is encrypted. Multiplication of the trip-ends before the OD-matrix estimation procedure is not preferred as this procedure comprises additional assessment and adjustment procedures. For the same reason, increase in trip-lengths by lower travel impedances cannot be evaluated (and therefore, value of time changes in relation to induced travel). Hence, the induced travel aspects evaluated in this study are increased trips by new user groups, empty ride allocation for picking up new passengers and by empty ride allocation. Another aspect which relates to induced travel by lower travel impedances is described by Hills (1996), who found that increase in accessibility increases travel too. This is not evaluated as this asks for a cyclic simulation process.

Traffic efficiency

Automated driving is propagated to make traffic more efficient by shorter headways and increased traffic stability. Most research on increased efficiency expresses this is increase in road capacity. VRU can either incorporate this by changing road capacities, PCU-values (passenger car unit) or BPR-function parameters. Prior option is chosen as it allows distinction between inner and outer urban roads and connects well with existing literature on this subject. Another aspect that theoretically can be evaluated is the possibility of improved network wide traffic management. Assigning traffic over the network through a system optimum algorithm instead of the default volume average assignment would emulate this development. However, due to excessive runtimes (in order of magnitude of days) this has not been implemented.

Travel cost factors

Within the approach to implement the scenarios, travel cost factors have no effect on travel demand nor on traffic as time is the only route factor. Value of time has only effect on the final travel impedance which will provide for input of the accessibility calculation as explained in subsection 6.1.2). As the cost factor, changes to value of time is implemented. This will however not result in changes regarding the observed travel within the model.

Network conditions iteratively provide input to the OD-matrix estimation within VRU. The approach to model automated driving in this sub-section does not follow this full procedure (Figure 6-1) for runtime issues, additional procedures within the model and encryptions. Instead, the automated

driving scenarios are evaluated by adjusting the existing OD-matrix from the base case and assign this over the network with different network capacities. Freight is maintained as external demand. The travel and distance skims are obtained and used to calculate accessibility values with different value of travel time according to each scenario. As each scenario comprises a set of multiple coherent assumptions, it might not be directly relatable which assumptions has the strongest influence in observed traffic and accessibility conditions. Therefore, the scenarios are evaluated in two steps: consecutively the simulations are executed without and with induced demand. The approach to model automated driving is graphically displayed in Figure 6-7.

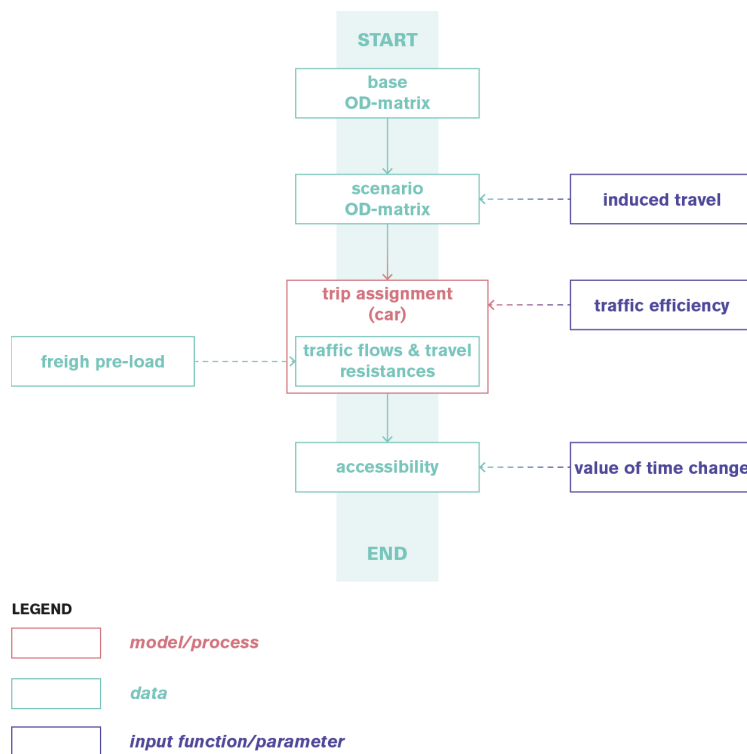


Figure 6-7: Modelling procedure to evaluate the automated driving scenarios in VRU.

6.1.4 SCENARIO PARAMETER DERIVATION

Before the scenarios can be implemented within VRU, one must derive the required parameter values and adjustments to implement according to each scenario. Table 6-1 lists the aspects along with corresponding chosen parameter values per scenario. The assumptions for each scenario are justified below Table 6-1.

Table 6-1: Parameters assumed per scenario.

		Scenario			
Aspect		1. Transformation	2. Growth	3. Constraint	4. Decline
Induced travel	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 directed to designated parking zones	N/A	N/A
Traffic efficiency	Outer-urban roads	+ 100%	+40%	+40%	-20%
	Inner-urban roads	+ 50%	+20%	+0%	+0%
	Intersection delay	All 0.1	All 0.25	+0%	+0%
Travel cost factors	Value of time (all purposes)	-35%	-50%	-15%	+0%

Scenario 1: Transformation

In this scenario, automated driving develops to a fully automated shared vehicle system which replaces both public transport as well as conventional car travel. All travellers have access to automated vehicles and therefore all trips prior made using public transport are now made with the shared vehicle fleet. The OD-matrix for public transport of the base scenario is added to the OD-matrix for car travel to incorporate the induced travel by new user groups:

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

with:

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

Consequence of a shared fleet is that vehicles might drive empty to pick up new passengers. Studies find that around 10 percent of all vehicle kilometres are expected to be empty under such system (Fagnant & Kockelman, 2014, p. 12; Fagnant et al., 2015, p. 105; Santi et al., 2014, p. 13292). These studies however elaborate on dense urban areas. The study by Boesch et al. (2016) raises suspicion that this number might be higher areas with lower densities because – in particular in the morning peak – the spatial dispersion of the origins of trips (the residential location) is higher. Therefore, induced

demand by empty ride allocation in this scenario is set to 20%, with the final OD-matrix for this scenario being:

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

Induced travel for external parking is not considered in this scenario.

The assumption is that V2V-communication sensors are equipped in every vehicle. Hence higher road capacities can be achieved. Yet, the same concern remains towards theoretical studies as stated in subsection 3.3.1. 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 still 100% on outer-urban roads and 50% on inner-urban roads is assumed. Intersection delay factors are reduced to 0.1. This is lower than the lowest delay factor of intersections within VRU by default. This is done to almost fully diminish intersection delay.

Regarding value of time, a decrease of 35% is assumed. This coincides closely with the found scenarios by Milakis, Snelder, et al. (2017, scenario "AV.in bloom") and Childress et al. (2015, p. 101).

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 but owning a driving license is not required to operate a vehicle. Induced demand of 10% by new user groups is assumed based on Harper et al. (2016, p. 8); Sivak and Schoettle (2015); Wadud et al. (2016, p. 10) with no change in travel pattern:

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

Induced demand by empty ride allocation is mostly accounted for by allocation rides between family members. For a privately owned automated vehicle within a household, Correia and van Arem (2016, p. 85) find the magnitude of empty ride allocation caused by automated vehicles of around 10 percent. For this scenario, this value is followed but adjusted to opposite direction of the existing travel demand pattern:

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

Induced travel by parking is not based on earlier literature findings. Instead, the choice is made to assign all arrivals in areas where parking policies are in force to designated parking areas. These areas are either existing park-and-ride facilities of the specific town. In case of towns without park-and-ride facilities, an area is assumed on the fringe of the town. The new OD-matrix is constructed as follows:

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

with:

- P Zones with a parking policy
- Q Designated parking areas

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

The largest decrease in value of time is assumed in this scenario as private mobility is characterised by the lowest values of time of all modes within VRU. The most radical *assumed* decrease in value of time found in literature is a decrease of 50% by Gucwa (2014). This scenario follows Gucwa (2014) under the assumption that travellers perceive more comfort in their own vehicle than in a shared vehicle.

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. 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.

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%. This scenario uses a 15% (round off from 16%) decrease in value of time to differ from the value of time changes in other scenarios.

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.

Just as in the transformation scenario, public transport travel is assigned to the road network:

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

Furthermore, the same percentage of induced travel by empty ride allocation is assumed as for scenario 2: growth:

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

Additionally, this scenario assumes that mixed-traffic of automated and conventional vehicles leads to a capacity decrease of 20% on highways.

6.2 LINK LOADS AND NETWORK CONDITIONS

The primary purpose of this chapter is to obtain accessibility values. However, also the traffic conditions provide input for later steps in this research. Furthermore, examination of the traffic conditions helps to understand the underlying factors that influence the changes in accessibility. Within this section, congestion on the network and its effects on travel time are examined for each scenario. For each scenario, congested roads are identified through mapping the IC-values on the network (IC-value is the intensity on a link divided by its capacity) alongside evaluation of the travel time distribution. The maps in this section are redrawn from the original plots obtained in OmniTRANS for readability purposes. The original plots can be found in appendix A.

All scenarios are compared to the base scenario. In the current situation, VRU shows no significant congestion by IC-values greater than 1 in urban areas. On the highways, congestion occurs on some parts of the A1 and A2 highways, plus on the A27 (Figure 6-8) near Amelisweerd and around Bilthoven. Some of these congested road sections are also known to be strongly congested in the real situation (VID Nederland B.V., 2016).



Figure 6-8: Roads with IC-value >1 for the base scenario, morning peak

Table 6-2 and Figure 6-9 - Figure 6-12 on page 65 show how the various scenarios of automated driving influence the travel times. For these data and plots, only trips within the provincial borders are considered. It reveals that automated driving has a positive effect on mean travel time under most scenarios when no induced demand is considered. The reduction in travel time ranges between 2 and 10 percent under the scenarios which assume capacity gains on the network. The negative scenario (*scenario 4: Decline*), shows an increase in travel time of 2.5 percent which can be accounted for by the 20 percent highway capacity reduction which is assumed. When additional travel is assigned to the road network, the average travel times increase considerably. This illustrates that the potential induced

demand counterbalances the traffic efficiency gains. When including induced travel into the simulations, mean travel times increase in a range of 24 to almost 70 percent.

Figure 6-13 - Figure 6-16 on page 66 show the most congested roads under these scenarios with induced travel. In both the first and second scenario, congestion on the highway network largely diminishes. However, congestion now primarily appears on the urban road network of the City of Utrecht. In the first scenario (Figure 6-13, where public transport gets replaced by a taxi-bot service) primary reason for this is that the city centre of Utrecht today attracts a lot of travel by public transportation. All this travel demand is now assigned over the road network. In the second scenario (Figure 6-14), the congested roads are in opposite direction towards the external parking facilities. Within *scenario 3: Decline*, no induced travel has been assumed. The assumed capacity increase on outer-urban roads has limited effect on mean travel time, but results in fewer to none congested roads (Figure 6-15). In case of strong induced demand where public transportation is assigned to the network without capacity gains (*scenario 4: Decline*), similar congestion patterns occur on the urban road network compared to *scenario 1: Transformation*. However, as no road capacity gains are assumed, also the highway network becomes heavily congested (Figure 6-16).

The analysis shows that the challenges regarding automated driving traffic primarily manifest itself on the urban road network and not on highways. Particularly when induced travel demand is high, the urban road network of larger cities as Utrecht (which generates a lot of attraction in the morning) might face congestion despite increased traffic efficiency.

Table 6-2: Mean travel time for all car travel within the Province of Utrecht for each scenario.

Scenario	Mean travel time [min:sec]	
	Without induced demand	With induced demand
0. Base	11:48 (ref.)	
1. Transformation	10:39 (-9.8%)	14:43 (+24%)
2. Growth	10:55 (-7.5%)	19:24 (+64%)
3. Constraint	11:35 (-1.9%)	
4. Decline	12:06 (+2.5%)	20:00 (+69.5%)

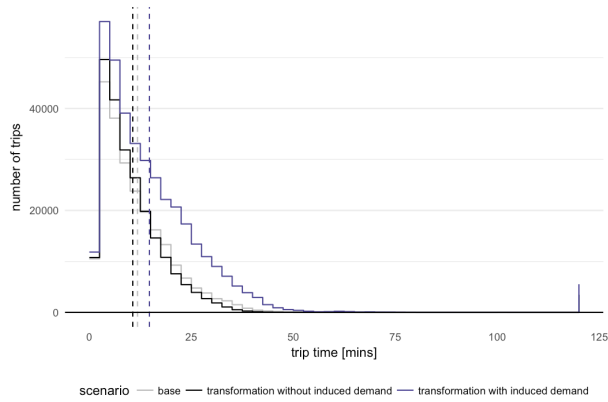


Figure 6-9: Travel time distribution of car travel for *Scenario 1: Transformation*.

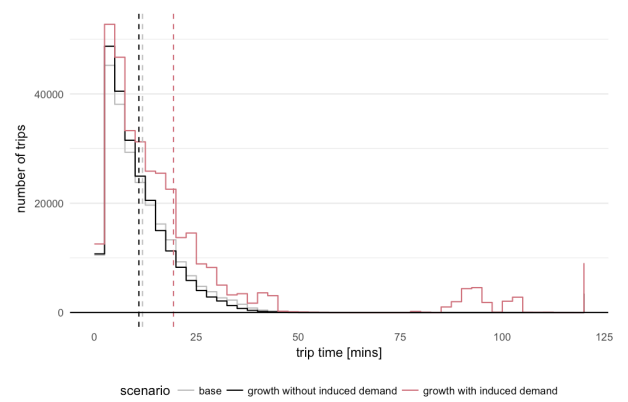


Figure 6-10: Travel time distribution of car travel for *Scenario 2: Growth*.

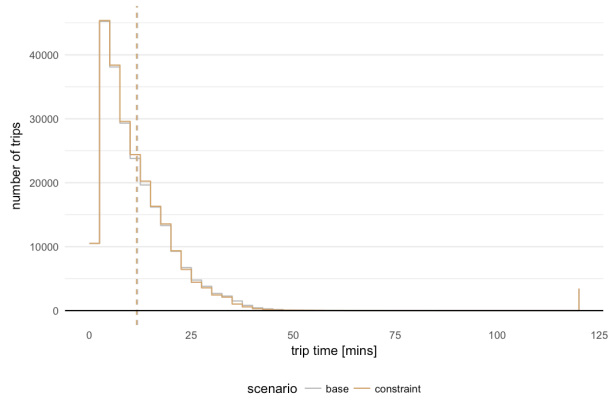


Figure 6-11: Travel time distribution of car travel for *Scenario 3: Constraint*.

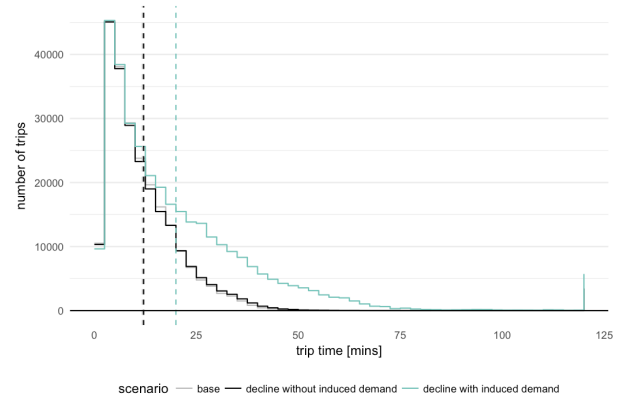


Figure 6-12: Travel time distribution of car travel for *Scenario 4: Decline*.

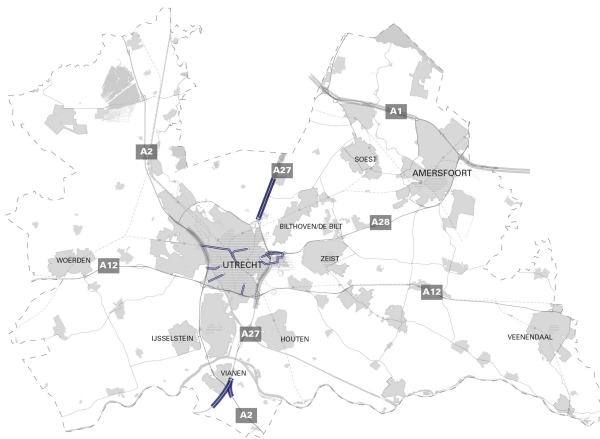


Figure 6-13: Roads with IC-values > 1 for *scenario 1: Transformation* (with induced travel demand).



Figure 6-14: Roads with IC-values > 1 for *scenario 2: Growth* (with induced travel demand).

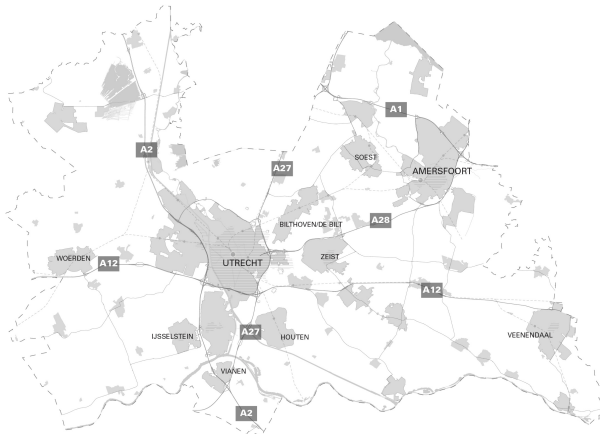


Figure 6-15: Roads with IC-values > 1 for *scenario 3: Constraint*.



Figure 6-16: Roads with IC-values > 1 for *scenario 4: Decline* (with induced travel demand).

6.3 ACCESSIBILITY EFFECTS

Accessibility values can be calculated as explained in section 6.1.2, based on the travel times and distances on the network between zones and the dispersion of jobs over the zones. The accessibility effects per scenario are compared to the base scenario (Figure 6-4). As the prior section elaborating on traffic and travel effects, also for the study of the accessibility effect each scenario has been evaluated both with and without induced demand. Furthermore, by calculating the travel impedance, it is possible to evaluate the effect of value of time changes without running additional simulations (Figure 6-17).

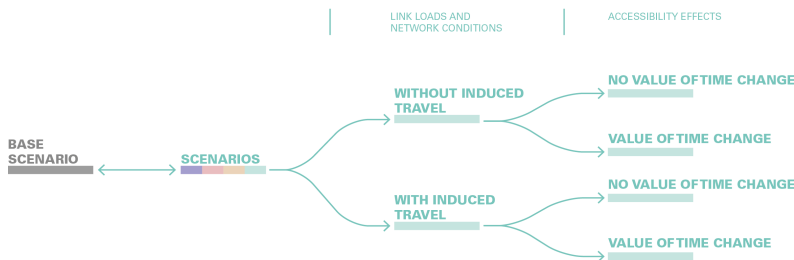


Figure 6-17: The accessibility effects are examined with and without induced travel demand and with and without value of time changes.

Figure 6-18 depicts the distribution of relative accessibility changes for all zones within the province of Utrecht through all combinations possible combinations per scenario. Before interpreting the accessibility findings from a spatial perspective in Figure 6-19, this presentation of the results allows to identify the influence of the various assumptions and factors on the general change in accessibility. The largest influence on accessibility is the change in value of time. Although the traffic and travel effects show significant changes in average trip time, time factors only make up a part of the travel impedance. For the same reason, the negative effects of travel time by induced travel on accessibility are of smaller magnitude than the percentage change in average travel time as found in Table 6-2. A decrease in value of time can outweigh the negative effects of induced travel on accessibility values.

Maps of the relative change in accessibility under the various scenarios in Figure 6-19 show which areas are most subject to change in accessibility. The representation of the data is first explained before elaborating on the contents of the figure itself. Lighter colours represent the left-hand side of the distribution of the relative change in accessibility, the darker colours show the right-hand side of the distribution of relative change in accessibility. The distributions are unique for each map and are already explained in Figure 6-18. If a similar scale for various scenarios (and therefore maps) is applied, one is not able to distinguish spatial differences within a scenario, whilst this is the aim of Figure 6-19.

The maps reveal is that in the case of positive scenario (i.e. *scenario 1: Transformation*, *scenario 2: Growth* and *scenario 3: Constraint*), areas around the city of Utrecht and Amersfoort - the two largest cities - profit more in terms of accessibility than the lower urban areas when no induced demand or travel of time reduction is assumed. However, when induced demand is evaluated, the areas outside the built environment show the strongest relative increase in accessibility (or smallest decrease, depending if value of time change is evaluated). When scenarios are evaluated within a group with induced demand or a group with no induced demand, the influence of solely value of time changes can be examined. When the value of travel time reduces, these benefits appear stronger in the areas which can be characterised as less urban. This reveals particularly when no induced demand is assigned to the

network. A probable explanation is that travel time takes up a larger share of the travel impedance for those areas.

When observing the emergent patterns of change in accessibility, the *transformation* and *growth* scenarios show strong resemblance. This can be explained because both scenarios show similar areas where congestion occurs when induced demand is assigned. The *constraint* scenario has no induced demand but assumes, as the prior two mentioned scenarios, a positive capacity increase on the outer-urban road network. This shows a similar direction of emergent changes, however distributed more homogenously over the areas. The *decline* scenario, which takes on negative assumptions on road capacity shows an opposite pattern when no induced demand is assumed. The west of the province shows a relatively smaller decrease in accessibility than the east. When induced demand is evaluated, a similar pattern emerges compared to the *growth* and *decline* scenario: congested roads because of additional car travel to the large urban centres has a negative effect on accessibility in these areas.

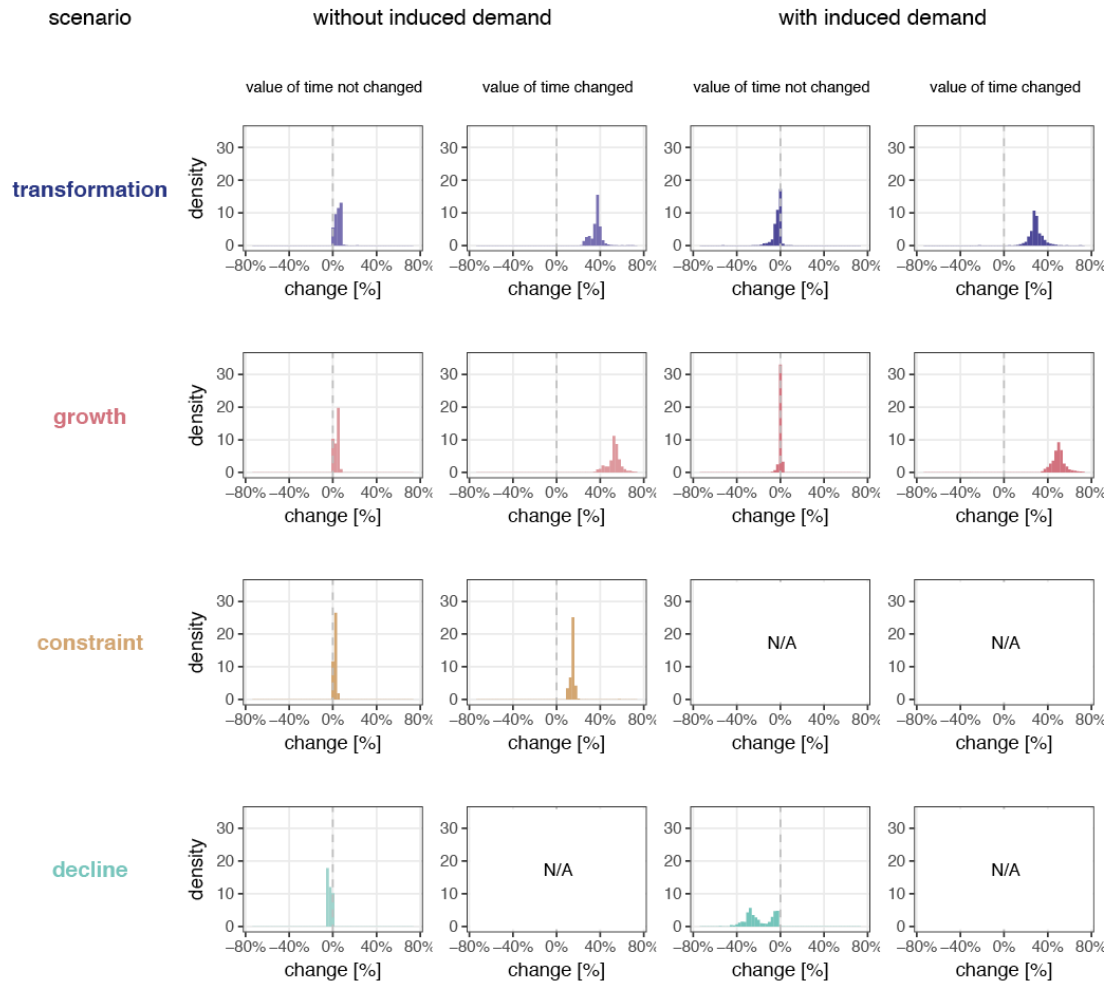


Figure 6-18: Distribution of relative changes in accessibility for each scenario compared to the base scenario, with or without induced demand and with or without value of time changes.

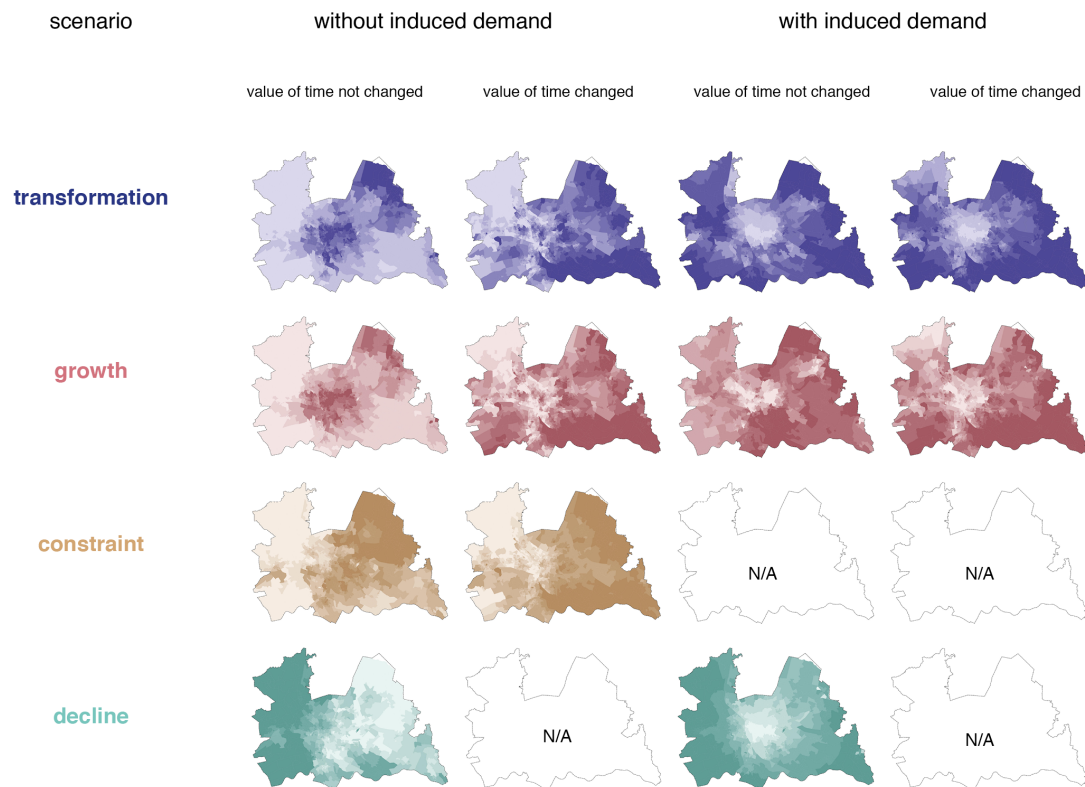


Figure 6-19: Relative change in accessibility compared to the base scenario accessibility. Lighter colours represent the left-hand side of the distribution of the relative change in accessibility, the darker colours show the right-hand side of the distribution of relative change in accessibility (see also Figure 6-18).

6.4 CONCLUSIONS AND DISCUSSIONS

Automated driving can have a significant effect on accessibility and travel depending on scenarios and factors taken into consideration. Increased capacity on the regional road network can lead to a strong reduction of the bottlenecks and average travel time can reduce to around 10 percent. This is however when the amount of car travel is assumed to stay similar. When induced travel occurs because of new users, empty ride allocation or because automated vehicles replace mass transit, the benefits on travel time diminish and change to a strong increase in average travel time. This loss of time occurs primarily on the urban road network. Urban centres attract a lot of travel and the estimated capacity gains of the urban road network is not able to facilitate the increase in travel demand.

The challenges for the urban road network also reveal by examination of the accessibility effects. When no induced demand occurs, particularly the urban centres benefit from automated driving. However, when additional travel demand is added, these gains are mostly diminished in favour of areas outside the built environment. Calculation of the accessibility values of the areas reveals that the changes in travel time account for a modest share in the change of accessibility whereas changes in value of time contribute much stronger to the change in accessibility. Value of time changes are mostly beneficial for areas outside urban centres.

One aspect that has not been evaluated is the induced travel in terms of trip length because of lower travel impedances. For elaborating on this aspect, elasticities for this effect are unknown. However, with the knowledge that higher accessibility levels lead to more travel and vice versa and that induced demand lead to lower accessibility levels, some balancing effects towards the accessibility effects can be expected. Another aspect that has not been considered is a potential change in the actual cost of travel in terms of distance costs. One can expect that this has significant impact on the results as also the changes in value of time show large influence on the final accessibility change.

7 SPATIAL QUALITY EFFECTS OF AUTOMATED DRIVING

To obtain the spatial quality effects of automated driving, a research-by-design approach is employed. Based on input from the scenarios and the infrastructure loads obtained from the transportation model, new designs and potential developments for neighbourhoods and streets are examined by means of drawing and mapping. This is considered a conventional approach within the domain of urban design but not within the field of transportation science and urban modelling. Therefore, this section first elaborates further on the urban design approach and how this can be integrated within the process of this research. Urban design processes are very strongly related to the urban context. As it is too labour intensive to evaluate all urban spaces and neighbourhoods, a classification of neighbourhoods is followed on which general assumptions are based. The classification of these neighbourhoods is further explained in the second section. This research step distinguishes two scale levels within the urban design approach. The first scale is the neighbourhood scale. Section three examines the potentials for urban transformation on the larger scale and uses the findings to reason down to the street level in section four.

7.1 URBAN DESIGN APPROACH

The benefits of automated driving to make urban spaces more attractive has primarily been examined within urban design practices. Within the scientific domain, the aspect has been underexposed or not integrally evaluated with other spatial aspects of automated driving. In this research however, spatial quality is considered as an important link between traffic and the process of urban development. This section explains why a research-by-design approach is used to integrate the spatial quality aspects within this research and how this is done.

Design-based research methods and engineering-based methods differ in process, goals and models that are used. Engineering relates towards the scientific domain whereas design relates stronger towards the arts and humanities (Cross, 2007; Hillier, Musgrove, & O'Sullivan, 1972/1984; Portugali, 2011, p. 9; Snow, 1959/1965). Scientific research is strongly aimed at reproducibility whilst design is often 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.

Within urban planning problems, the frame of factual data comprises spatial constraints and requirements. However, also societal values which must be incorporated within this domain (Wachs, 1985) (e.g. creating inclusive spaces, attractive spaces for specific users). Whilst engineering studies often explicitly define the (simplified) system one examines, design practices embrace the wide variety of variables in a more holistic approach. This also manifests in the methods employed. Engineering methods are increasingly computational models by which externalised processes evaluate large datasets and the relationship between variables in explicitly defined systems (Epstein, 2008). Design methods are often more visual by nature and have a stronger and more interactive relation with the designer/researcher.

Computational models are not able to project the final manifestation of urban spaces as urban development is influenced by human values, choices and democratic processes. Urban designers have an important role in these processes by showing the consequences of different choices and setting the boundaries to steer towards a desired path in the future (George, 1997, p. 148). As these processes have no optimum solution (Klaasen, 2007; Rittel & Webber, 1973), design thinking is often iterative by nature and is led by intuition and the narrative (Lawson, 1979, p. 59).

The spatial quality effects regarding infrastructure integration and automated driving are studied using design thinking. By following an urban design approach, the factors which play a role in the manifestation of urban spaces can be evaluated. It is inherent to urban design thinking that personal interpretation has to some extent a role within this process. Therefore, a modest and repetitive design approach is employed to limit the influence of the signature of the individual (in this case the author) and maintain reproducibility of the results. In practice this means that the urban spaces are perceived from a very practical point of view by solely elaborating on the relation between space and infrastructure requirements. Other factors regarding the social domain or any other trend are neglected and design solutions are mostly found within conventional means. The approach will be executed as repetitive as possible for the considered areas under each scenario.

Two different scale levels are considered: the neighbourhood scale and the street scale. On neighbourhood level, the requirements for large scale infrastructure areas are assessed to find new options for spatial transformation. On street level, one can elaborate directly on the spatial quality effects itself and the externalities of traffic by examining how much space is required directly for infrastructure and how the additional space available can be used to improve the quality of the streets. The scenarios provide information how the neighbourhoods can transform for new urban functions. This information is used together with outcomes from the transportation on how streets can be transformed under each scenario. An estimation can be made on the spatial quality effects of automated driving for neighbourhoods and streets based on these findings. The outcomes of these research steps are in predominantly drawings. However, drawings will not directly be compatible with the next research steps. On the neighbourhood scale, a qualitative expression of the transformation potential is made. On street level, the results are quantified using hedonic pricing modelling. Hedonic pricing

models are used to express how environmental characteristics (amongst others) influence real-estate values (Bateman, Day, Lake, & Lovett, 2001). The process is schematically depicted in Figure 7-1.

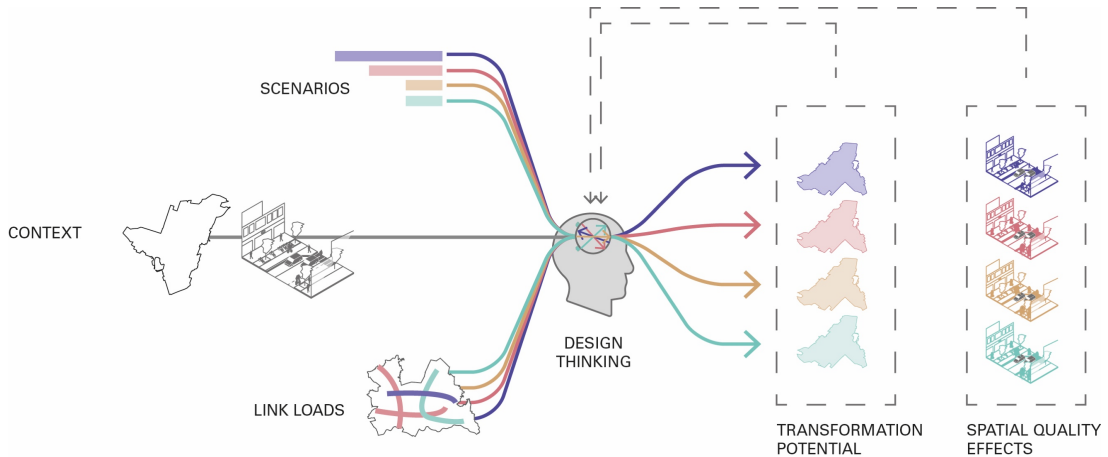


Figure 7-1: The transport system requirements and the travel demand on the infrastructure for each scenario is implemented in the neighbourhoods and streets to enhance quality of the urban space.

As it is not possible to apply a design study for all urban spaces within the case study area, this research classifies neighbourhoods based on different typologies. Examples of such typologies explained as hybrid urban metrics earlier in this report (see subsection 2.3.2). For this research step, the neighbourhood classification by ABF Research (2003) used. It provides a wide array of typologies and is compatible with the residential location choice model used later in this study (see section 8.1.1). Of each typology, one entity is chosen. The chosen zone is considered representative for all spatial entities of the similar class. On those entities, one can apply the design method. The classification and selection process is further explained in the following section.

7.2 NEIGHBOURHOOD CLASSIFICATION AND SELECTION

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) as introduced in 2.3.2. For each typology, one representative zone is considered. Although these typologies give a qualitative description of the neighbourhood, the classification itself is based on quantitative data. The typology classification distinguishes a wide range of different neighbourhood typologies. Furthermore, the typologies coincide with input for the residential location choice model used in the following chapter and must therefore be obtained at some point in this study. A geospatial algorithm has been constructed to classify the neighbourhoods. This section explains the different characteristics of the neighbourhoods and by which data sources the algorithm classifies the neighbourhoods. Thereafter, a representative zone of each typology is chosen to apply the design methodology on.

Official details on the classification of the neighbourhoods are not publically available. However, the publications by Zandbelt&vandenBerg (2009) and ABF Research (2003) provide enough information (summarised in Table 7-1) to construct a deterministic geospatial algorithm to classify the neighbourhoods accordingly. The constructed algorithm classifies zones based on 4-digit postal zones. When a zone covers both built area (as defined by CBS (2014)) and unbuilt area, the zone is split. The town size is determined based on CBS (2014) which provides data on the number of inhabitants in a

built entity. Large towns are set to a population over 200 000 inhabitants. Towns are set between 50 000 and 200 000 inhabitants. Small towns and villages are chosen for populations under 50 000 inhabitants. It is not required to further specify small towns and villages. Based on Kadaster (2016a), the distributions in building year and building function are derived. Amongst these functions also housing is considered. This allows to approximate housing density in the zone. To derive the density of the housing area itself, this data is augmented with land-use cover data from CBS (2012). The decision is made to make no distinction between different rural typologies. This research deviates for this typology from the official classification which distinguishes two types of rural areas based on their distance to a large urban centre (ABF Research, 2003, p. 4). This however is not related to the physical appearance of the area and therefore neglected. Furthermore, an additional neighbourhood typology called ‘work’ is added to classify mono-functional employment areas. Zones with a land-cover of over 80% related to employment or industry according to CBS (2012) are labelled as work areas.

Table 7-1: 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	-	Mostly employment	-	-	-

The algorithm evaluates the data and deterministically generates the map in Figure 7-3 by classifying all zones according to the disaggregated typologies. Pictures of the neighbourhood typologies found in the case study area are displayed in Figure 7-2 for illustration purposes. Only a

small number of zones cannot be classified. The outcome of the constructed algorithm cannot be fully validated. However, from comparison with a map of a smaller part of the case study area showing the aggregated typologies in Faessen et al. (2011, p. 13) and based on interpretation of the qualitative descriptions available compared to the actual situation, it is considered accurate for this study. 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 7-4.

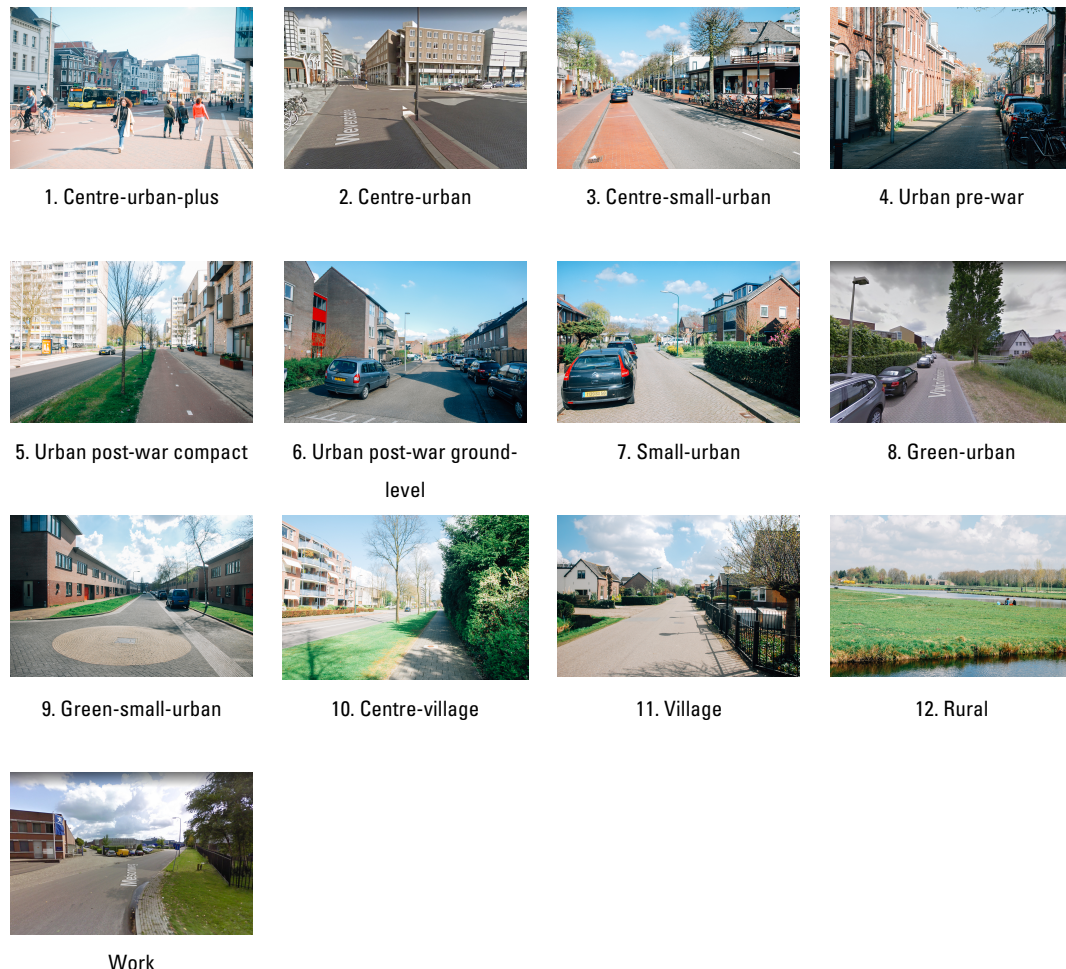


Figure 7-2: Examples of the neighbourhood typologies. (Images for centre-urban, green-urban and work are courtesy of Google Inc.. All other photos are by the author.)

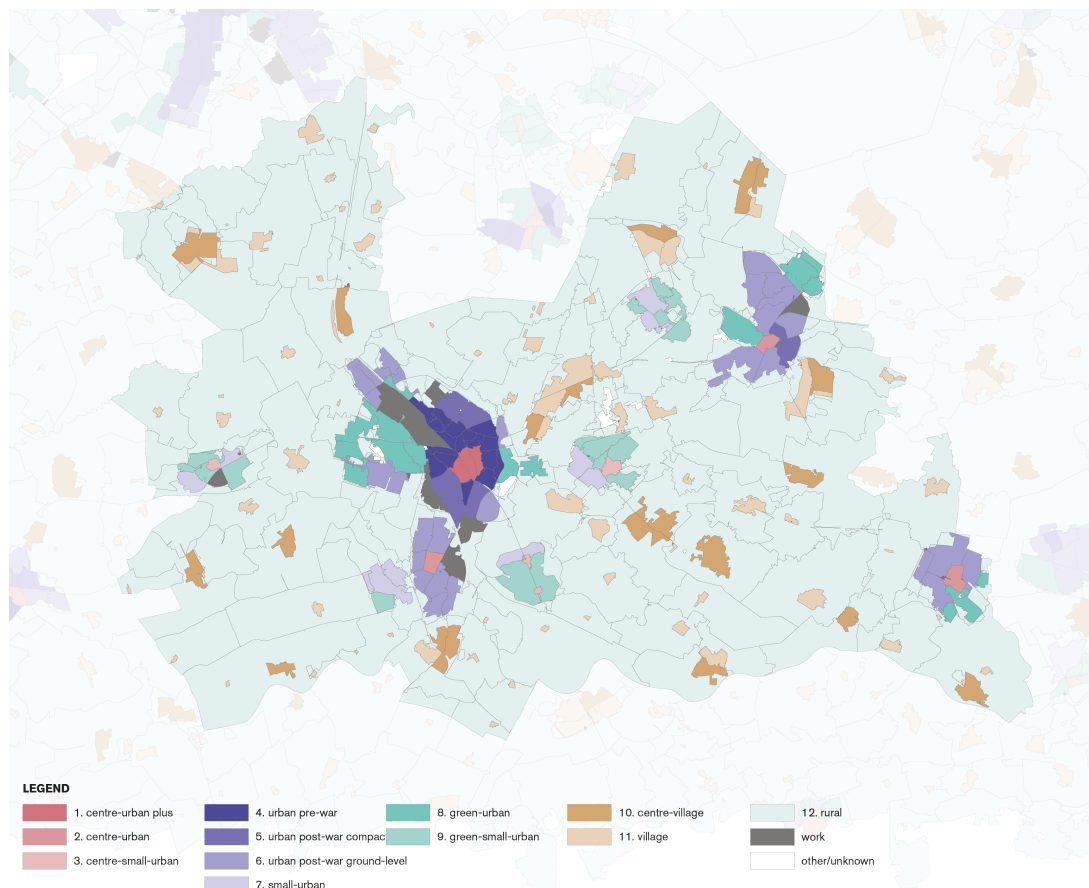


Figure 7-3: Neighbourhood types according to the ABF Research (2003) classification.

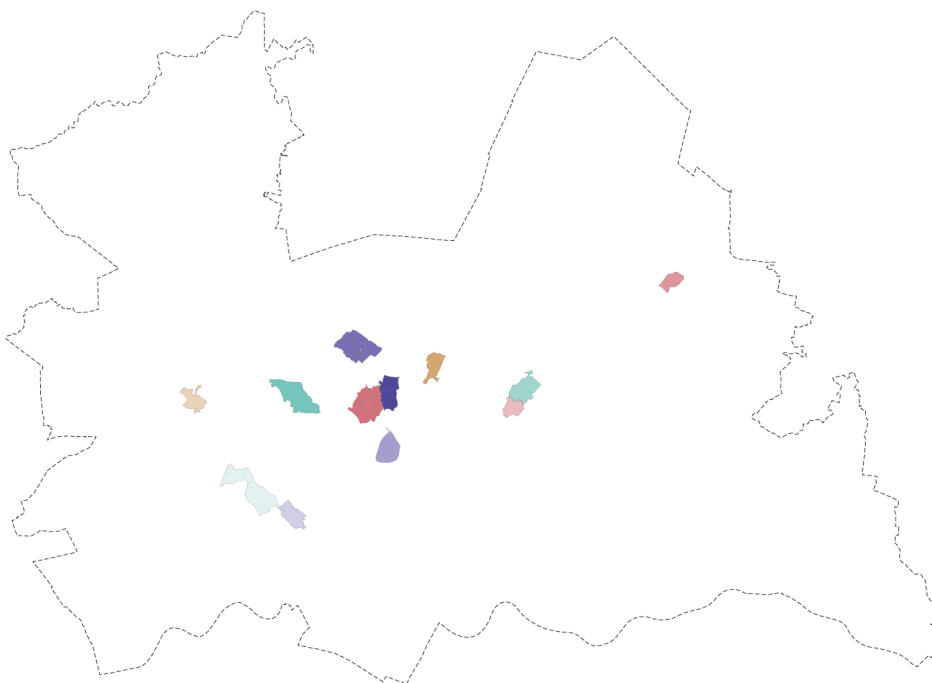


Figure 7-4: Selection of the neighbourhoods that are used to further assess the urban quality effects of automated driving. Each zone or group of zones represents one neighbourhood typology.

7.3 TRANSFORMATION POTENTIAL ON NEIGHBOURHOOD LEVEL

The transformation potential is expressed on the neighbourhood level by mapping both areas with possibilities for new urban developments and areas where conflicts might occur regarding infrastructure requirements and externalities. The approach to the examination of the transformation potential on the neighbourhood scale is first further explained. Thereafter the most important findings are presented.

7.3.1 APPROACH

The mapping procedure is done on the maps in Figure 7-6 and Figure 7-7. Data for the maps is derived from Kadaster (2016a, 2016c); Provincie Utrecht (2016). The maps show how all infrastructure aspects are integrated within the urban environment and therefore provide a good underlayer to map the areas for transformation and conflicts.

The choice to leave the expression to the level of a potential change is chosen because what might happen to the areas is subject to many factors. To illustrate this, the photo manipulation in Figure 7-5 is made, showing different new land-use functions for the Utrecht station area. The outcomes depend on a wide range of variables and political choices beyond the scope of this research. Therefore, the decision is made to solely express the transformation potential qualitatively according to the scoring in Table 7-2. These findings are not explicitly further evaluated in the research, but allow for interpretation of the results. Furthermore, the analysis of neighbourhood level provides for input of the spatial quality assessment on street level.

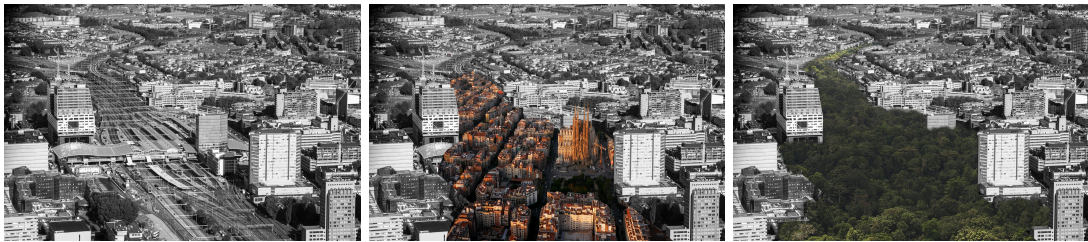


Figure 7-5: Different new land-use possibilities emerge for the Utrecht Central Station area if public transport happens to become obsolete. What land-use function is best, should not primarily be answered by a model study. Instead, a model study should provide for insights to citizens, designers and policy makers to answer that question based on a broader range of evaluation criteria.

AUTOMATED DRIVING: DRIVING URBAN DEVELOPMENT?

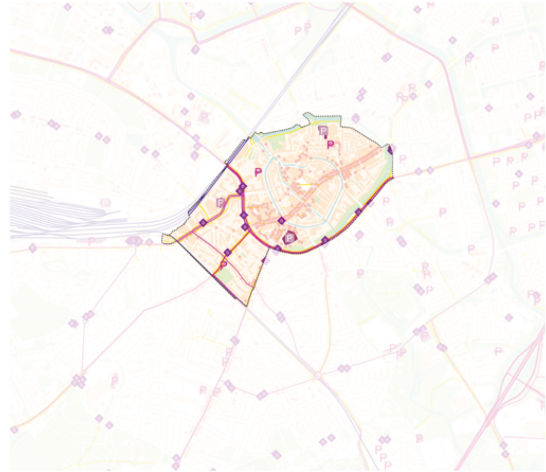
Table 7-2: Evaluation criteria for assessment of the transformation potential for neighbourhoods.

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.

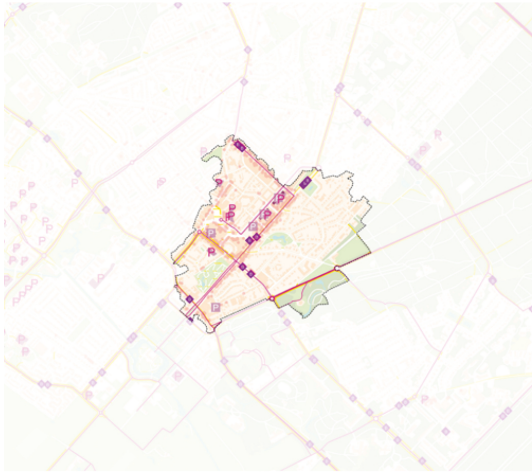
1. Centre urban plus



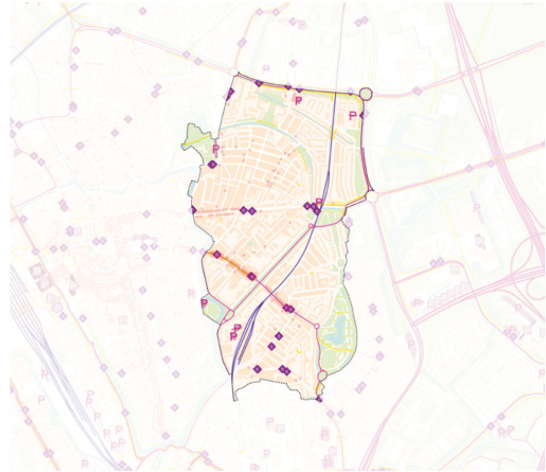
2. Centre urban



3. Centre small-urban



4. Urban pre-war



5. urban post-war compact



6. urban post-war ground-level



Figure 7-6: Maps of current infrastructure integrated within the urban environment in each example zone.

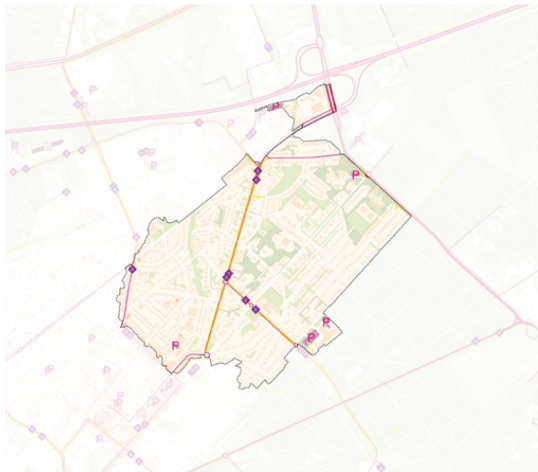
7. Small-urban



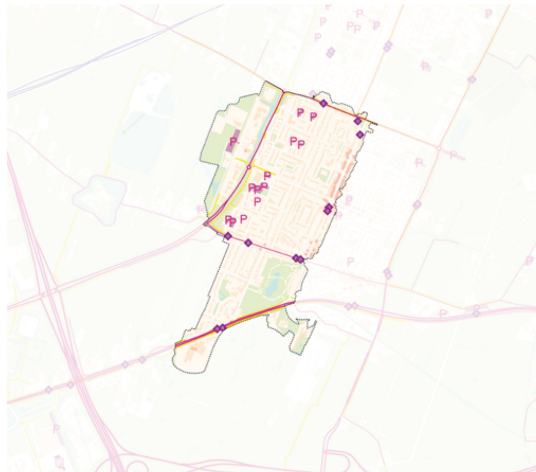
8. Green urban



9. Green small-urban



10. Centre village



11. Village



12. Rural



Figure 7-7: Maps of current infrastructure integrated within the urban environment in each example zone.

7.3.2 FINDINGS

The mapping exercise is applied to all maps for each scenario and thereafter conclusions are drawn on the transformation potential. The result is 48 maps, which are all depicted in Appendix B. The derived transformation potential of each neighbourhood type under each scenario is displayed in Figure 7-8. The figure reveals that the transformation potential is higher in some neighbourhoods than others. Most important findings regarding these differences are explained based on examples from the analysis.

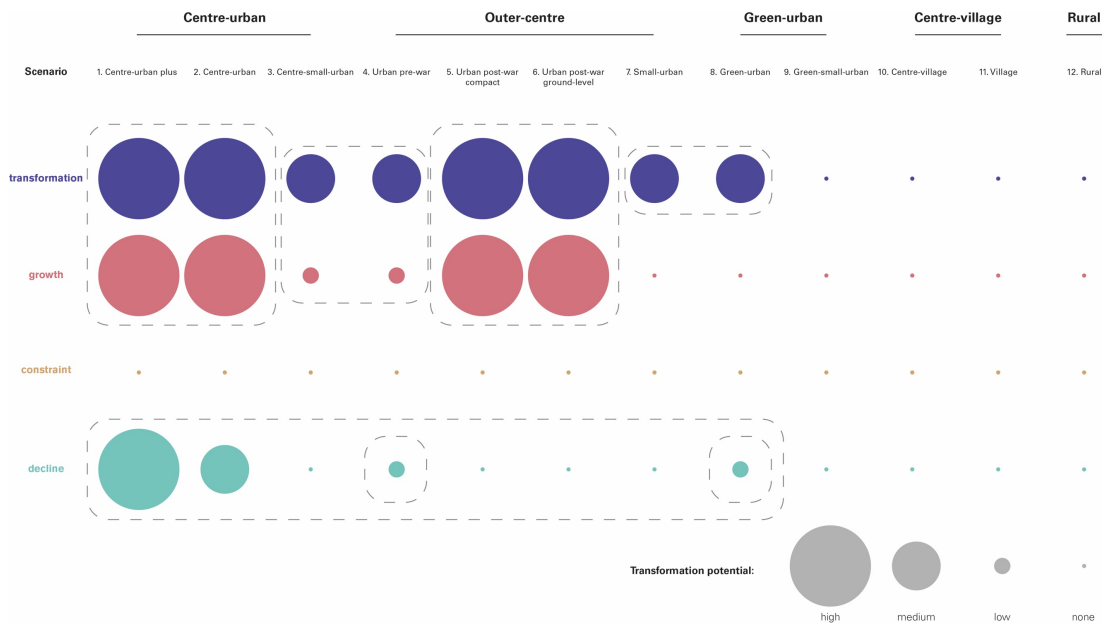


Figure 7-8: Transformation potential per neighbourhood type under the corresponding scenarios. The circled findings are grouped and similar conclusions can be drawn. These are therefore also explained in these groups.

Several neighbourhood typologies show a transformation potential under various scenarios. No transformation potential has been found under the constraint scenario or for some lower urban, village and rural neighbourhoods. For the *scenario 3: Constraint*, no transformation potential has been found for the apparent reason that this scenario only assumes capacity benefits on the highway. This means that within neighbourhoods, no changes are expected regarding infrastructure nodes, parking facilities or network structures. This also relates to the absence of transformation potential for neighbourhood typologies 9 to 12. These areas are (mostly) residential areas of lower dwelling density. Access to public transportation is mostly provided by bus stops and larger parking areas are often will integrated within the urban fabric.

Dense urban centres are often characterised by station areas and large scale parking facilities. In contrast to lower density residential areas as described above. Under scenarios that allow for remote parking or make parking obsolete there is potential to rethink parking areas. Urban parking garages make a large spatial claim even though some of these parking areas are integrated within parking garages (sometimes underground). The pressure of various spatial claims in urban areas allows to reconsider these parking facilities for new functions or passenger drop-on/drop-off areas. When mass transit in its current form gets replaced by disaggregated automated driving solutions, large areas of

stations and surrounding infrastructure must be reconsidered for new urban functions (see earlier example in Figure 7-5). Figure 7-9 on page 85 shows the areas for potential urban transformation for the city centre of Utrecht, which is characterised as a centre-urban plus neighbourhood. The considered areas make up a large share of the urban area and because of the high urban environment, the transformation potentials are considered significant under *scenario 1: Transformation*, *scenario 2: Growth* and *scenario 4: Decline*. However, as the transportation modelling study reveals, the load on some roads in the network will increase under various scenarios because of additional traffic movements. This asks for upscaling of some links or other solutions. This will be further elaborated on in the next section. With the same rationale, the transformation potential for the neighbourhood typology centre-urban is derived based on examination of the city centre of Amersfoort. Under the *scenario 4: Decline*, the transformation potential is set to moderate as the station area takes on a less prominent and smaller place within the area.

Other areas where high transformation potential has been found are the urban post-war compact and urban post-war land-based neighbourhoods (number 5 and 6) under *scenario 1: Transformation* and *scenario 2: Growth* (Figure 7-10 on page 86). On a smaller scale regarding parking, these areas are far from similar. The post-war compact neighbourhoods have a very segregated land-use where large scale parking areas are alternated by large post-war functional dwellings. Land-based neighbourhoods on the other hand are characterised by small-scale parking areas integrated within the urban fabric. However, regarding integration of infrastructure, an important similarity reveals: larger infrastructure is separated from dwelling areas by green areas and structures (Figure 7-11 on page 88). Under the various scenarios, these links can meet travel demand. The green structures are not intensively used. Under the assumption that the externalities of car travel reduce, these green areas can be either improved to attractive green urban spaces or used for new urban development. As the urban post-war compact neighbourhoods are characterised by large scale parking areas within the urban fabric, these allow for new land-use functions as well under *scenario 1: Transformation*.

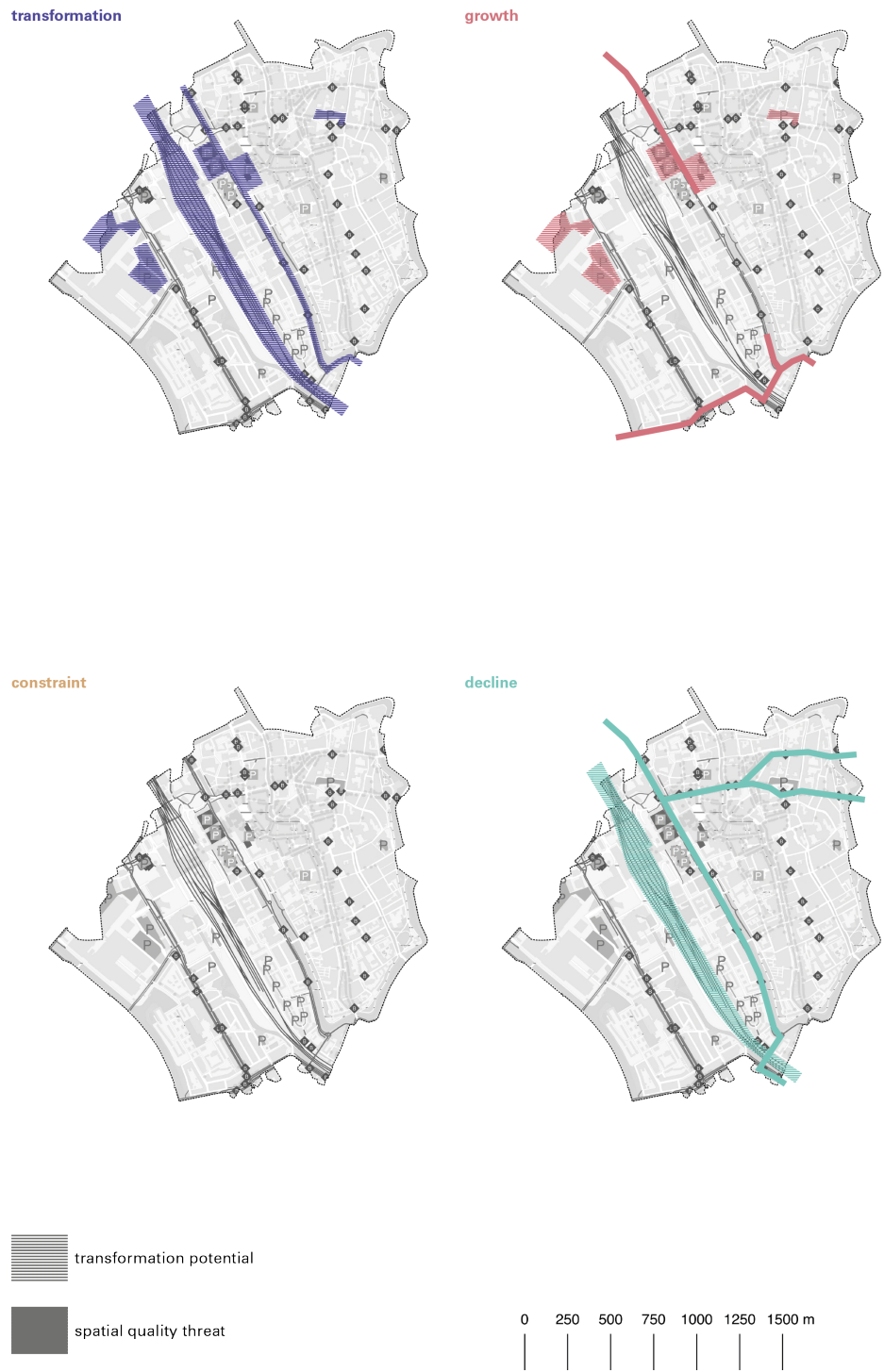


Figure 7-9: Transformation potentials mapped for the city centre of Utrecht (urban-centre-plus typology) under the four scenarios.



Figure 7-10: Urban post-war compact (top) and urban post-war land-based (bottom) neighbourhoods are characterised by infrastructure integrated within green structures. If external factors of travel reduce, those factors can be reconsidered.



Figure 7-11: In urban post-war compact and land-based neighbourhoods, larger infrastructure is integrated within green structures to separate this from dwelling areas. Because of the barrier of the surrounding infrastructure, these areas are often not used. Reduced externalities by car travel provides an opportunity to redevelop or revitalise these spaces. Picture taken at the Carnegiedreef, Overvecht, Utrecht.

For other urban areas, the transformation potential is less profound. For the neighbourhood typologies centre-small-urban, urban pre-war and green-urban, some redevelopment potentials can be identified for areas regarding parking. Urban pre-war areas are often adjacent to urban centres and therefore usually know some parking policy. In these areas, remote parking can prove beneficial. The similar conclusion can be drawn for small centre-urban neighbourhoods as e.g. the city centre of Zeist. Therefore, these areas are characterised by a modest transformation potential under *scenario 1: Transformation* and low under *scenario 2: Growth*. The distinction between the scenarios is based on the negative consequences for the arterial roads in these areas caused by remote parking in the growth scenario. For green-urban areas, the transformation potential depends largely on the building year of the neighbourhood. Pre-war green urban neighbourhoods have often on street parking. In more recent green-urban neighbourhoods as Leidsche Rijn in Utrecht, parking is in some areas concentrated on larger areas within the neighbourhoods. These areas might be reconsidered under *scenario 1: Transformation*. However, since these areas are small and surrounded by green, the potential for urban transformations is still considered low.

The findings show how urban transformation can be facilitated by automated driving under the various scenarios through the maps in Appendix B. Subsection 3.3.3 presented images by urban design practices on the spatial quality aspects of automated driving. These images show denser urban areas and this part of the study finds the highest potential for transformation in similar areas. Especially in urban centres characterised by large parking buildings and areas and train station areas, new possibilities for urban development emerge. Furthermore, this study finds that the areas which are characterised by infrastructure integrated within green areas might be reconsidered, all under the assumption that the externalities of infrastructure reduce. All the examples elaborate on the possibilities that automated driving facilitates. One must however realise that automated driving is not always the sole requirements. There are always several other measures possible to facilitate large scale urban transformation, also related to infrastructure investments. Traffic calming, diminishing of parking can all be facilitated by other factors than automated driving. However, the emergence of automated driving can be an important consideration within such processes.

7.4 SPATIAL QUALITY EFFECTS ON STREET LEVEL

The prior section 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 6 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. This section examines the potential benefits for streets based on the obtained network loads and requirements derived from the scenarios.

7.4.1 APPROACH

Two road types are considered for the examination of the spatial quality effects on street level: arterial roads and streets (roads with only local traffic and no defined function for through traffic). For

each example of a neighbourhood typology distinguished in section 7.2, one representative arterial road and one local street is 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 7-12. 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.

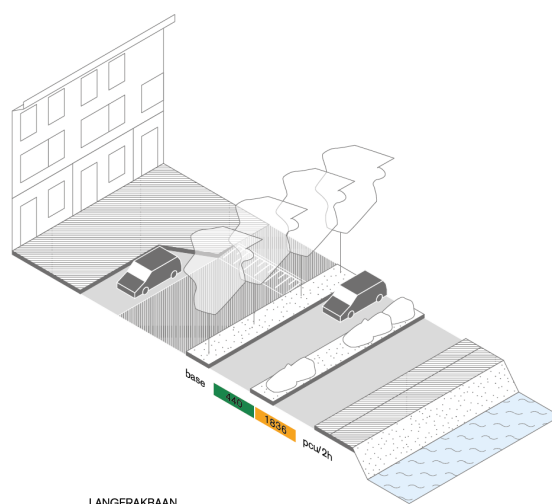


Figure 7-12: The spatial quality effects are investigated by 10-meter road stretches isometric sections.

The prior design step elaborated on the neighbourhood scale and derived the findings in qualitative expressions with the purpose to indicate the potentials for urban redevelopment. This design step on the street scale elaborates on the actual spatial quality effects which provide input to the residential location choice model for the agent-based model used in the next chapter. This requires expressing the findings in a quantitative unit. The residential location choice model chosen for this study in section 8.1.1 provides no choice attribute that relates directly to spatial quality aspects. However on street level, increased attractiveness manifests itself in increase in value of property (Crompton, 2001). Average housing price is a considered choice attribute within the model (Zondag, de Bok, Geurs, et al., 2015). By means of hedonic pricing models, the various influences of property values can be estimated (Nicholls, 2004). The spatial quality effects are therefore expressed using hedonic pricing modelling.

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 et al., 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 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. 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 the weighted average of 0.2 times the premium from arterial road plus 0.8 times the premium of the streets.

7.4.2 FINDINGS

The described approach has been applied to all neighbourhood typologies for both an arterial road and street. The calculated spatial quality premiums for each neighbourhood typology under each scenario are depicted in Figure 7-13. These calculations are based on a total of 88 drawings which are depicted in Appendix C. Most important findings are explained based on examples from the analysis. The explanation will indicate as much as possible to which other roads and street similar conclusions can be drawn.



Figure 7-13: Spatial quality premium per neighbourhood type under the corresponding scenarios.

Residential streets

In many road types under various scenarios, no spatial quality premiums on housing value have been found. Although the potential of fewer infrastructure required to facilitate traffic spark imagination, no significant potential is found for many streets to enhance spatial quality. Most important reason is that traffic demand is already low in many residential streets. The street lay-out itself does not offer possibilities to further decrease space required for automobiles except for the diminishment of parking places (Figure 7-14, the example is given for small-urban, green-small-urban and village typologies, but applies as well for most post-war and lower density residential neighbourhoods). This must however be facilitated in the scenario and can in turn lead to higher demands in other roads. These gains only emerge in residential areas under *scenario 1: Transformation*, as residential areas hardly know restrictive parking policies. In many cases, parking is done on private property. Many streets in urban centres are occupied with on-street parking despite the presence of parking garages. Therefore, also these streets show significant spatial quality benefits under *scenario 1: Transformation* and *scenario 2: Growth* by the possibility to relocate parking elsewhere (Figure 7-15).

As the differences regarding automated driving between *scenario 3: Constraint* and the current situation are small, no potential benefits for spatial quality are found in this scenario for any street. For *scenario 4: Decline* a similar rationale applies. Streets have no arterial traffic function, leaving it relatively unharmed from induced demand effects. For the urban pre-war typology, this does however not apply. These areas are characterised by relatively narrow roads which provide access to the urban centres. These roads are – as also found in section 6.2 – not always able to meet the induced travel. In the case of *scenario 4: Decline*, additional traffic has been found on residential streets to avoid congested roads. As this scenario does not allow diminish parking, this is considered as a significant threat for spatial quality on these streets. Similar effect has also been observed in *scenario 1: Transformation* and *scenario 2: Growth*. However, as these scenarios allow for parking allocation, these scenarios can still provide for an increase in spatial quality.

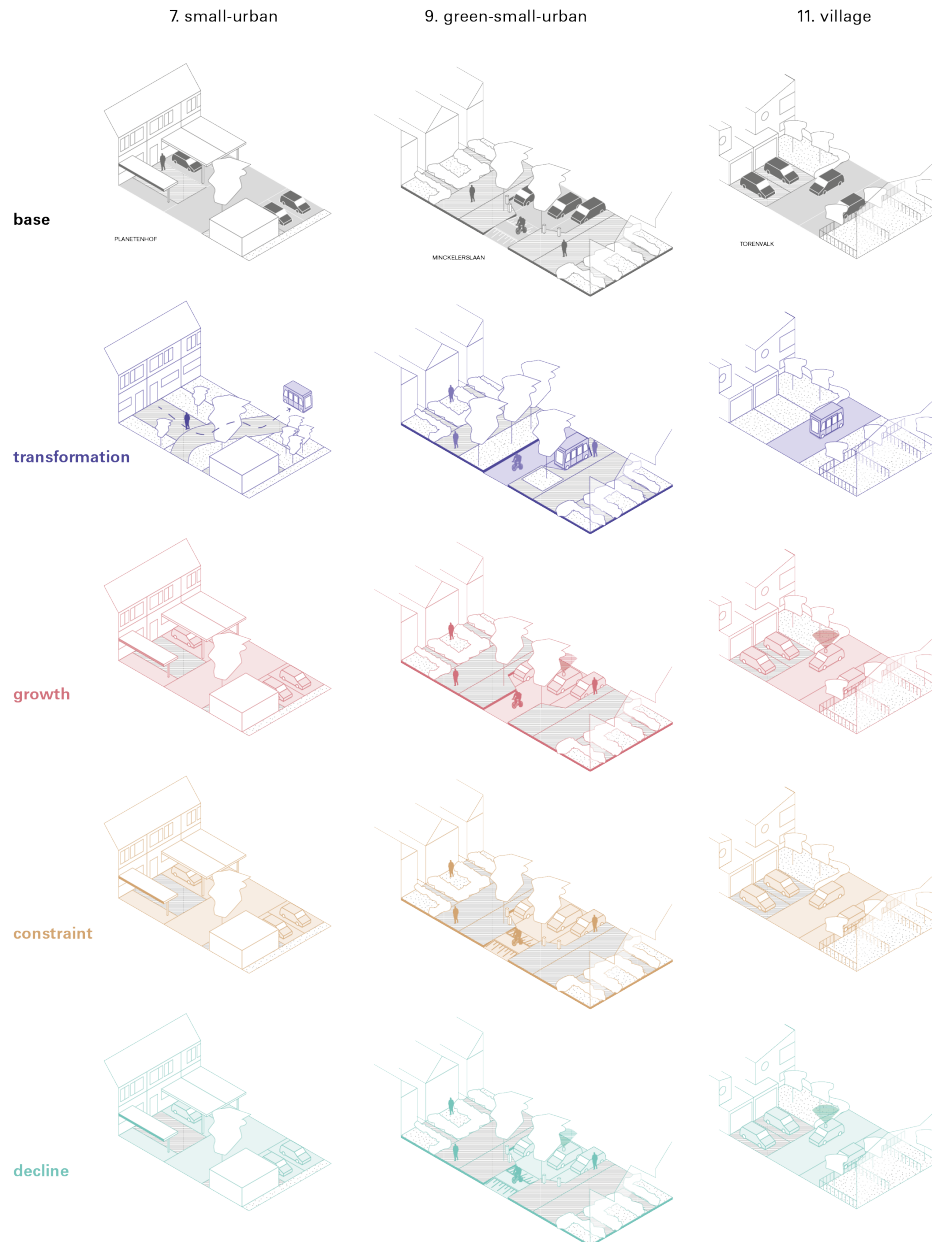


Figure 7-14: Many residential streets have limited potential to reduce the amount of infrastructure. However, diminishing or parking allows for possibilities to enhance spatial quality.

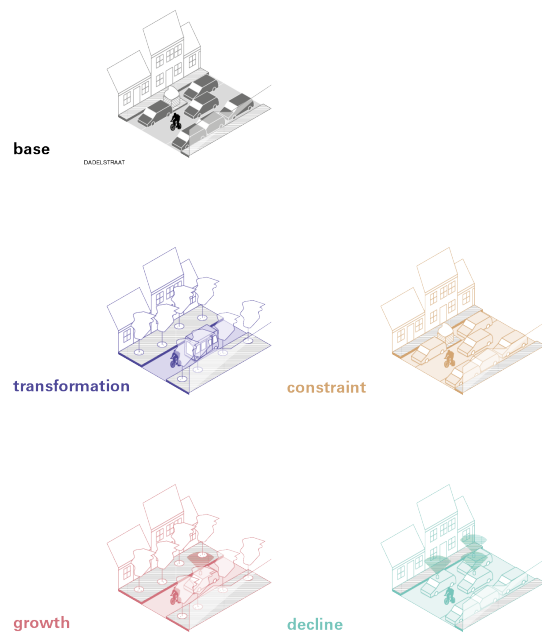


Figure 7-15: Residential streets might face negative effects of induced travel demand. The reduction of parking under *scenario 1: Transformation* and *scenario 2: Growth* can balance these effects. However, under *scenario 4: Decline* the effects are considered a threat for spatial quality.

Arterial roads

Compared to streets, arterial roads are more specifically designed to facilitate traffic flows instead of merely providing access to houses. The potential for improved spatial quality differs between various archetypes of arterial roads.

Section 6.2 found that induced travel demand can prove challenging for the urban road network of the city of Utrecht under *scenario 1: Transformation*, *scenario 2: Growth* and *scenario 4: Decline*. This does however not necessarily mean that spatial quality itself is under threat in these cases. For example, the Catharijnesingel (Figure 7-16 - left) in the centre-urban-plus environment in Utrecht 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 arterial road which is considered in Amersfoort as representative for the urban-centre neighbourhood typology (Figure 7-16 - right), the spatial quality effects are found to be larger because this street is not yet transformed to an urban boulevard as the Catharijnesingel in Utrecht. A design intervention which has been drawn in the isometric section for both prior mentioned examples to make a distinction between the number of lanes in both sections. Under *scenario 2: Growth*, one can observe a large difference between the flows in the different directions. This is accounted for by the induced travel to remote parking locations, hence an opposite direction can likely be observed in the evening peak. A possible design intervention to maintain an attractive street profile could be the usage of dynamic infrastructure. Dynamic lanes could potentially be implemented as separating objects might become unnecessary, if automated driving can meet expectations regarding traffic safety. These

examples show that automated driving is not necessarily a requirement to make roads more attractive. Some roads can be considered already well designed. This is not only illustrated by the example of the Catharijnesingel but also by the arterial roads found in the urban pre-war and urban post-war compact neighbourhood typologies.

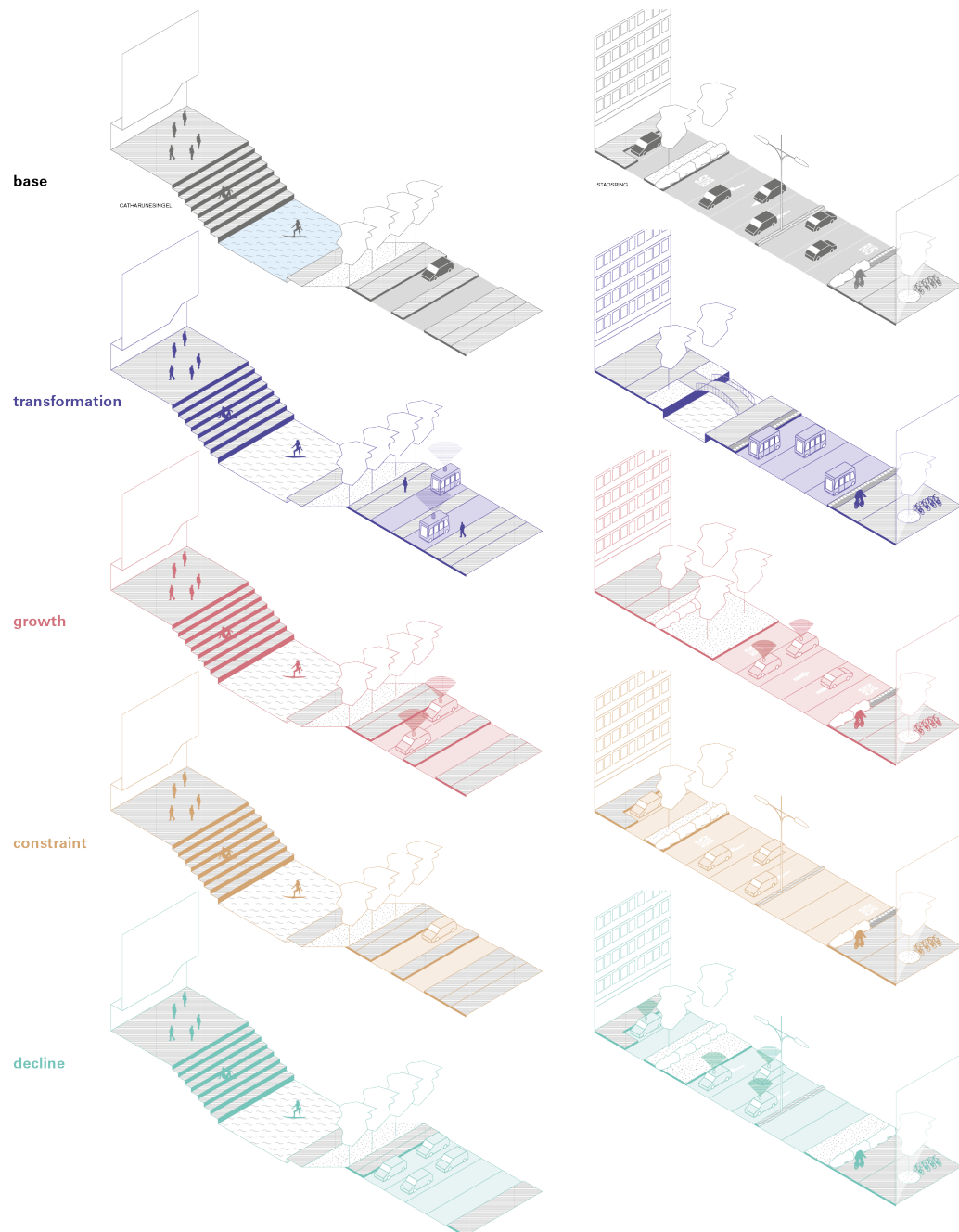


Figure 7-16: Spatial quality analysis for Catharijnesingel, Utrecht (left) and Stadsring, Amersfoort (right).

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. 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 for every case 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 *scenario 1: Transformation*. The analysis finds this difference between the example street for the small-urban neighbourhoods and green-urban neighbourhoods. In the small-urban neighbourhood, one can characterise the arterial roads as intensively used whereas in the green-urban neighbourhood, traffic on the roads was found to be much lower and therefore merging the two roads is considered feasible (Figure 7-17) under *scenario 1: Transformation* and *scenario 2: Growth*.

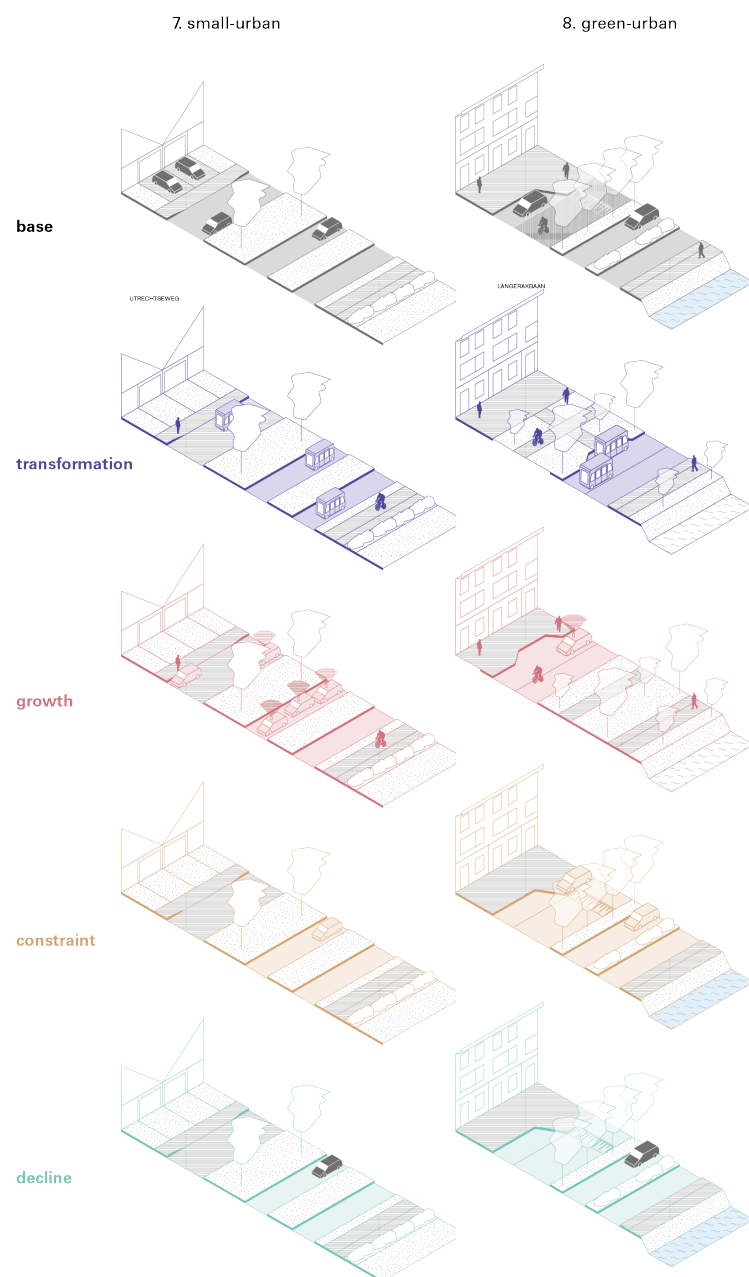


Figure 7-17: Whether a parallel road structure can be reduced to a single road depends on the traffic volume on the respective roads.

The spatial quality effects of automated driving for urban spaces are in terms of streets mostly related to the diminishing of parking. In terms of the functionality of streets for handling traffic, there is no significant benefit found for many residential streets. For roads that have a distinct traffic function, most significant benefits can be found when there is a possibility to reduce the number of lanes. In some cases, roads are already well integrated and therefore do not provide for much room of improvement.

7.5 CONCLUSIONS AND DISCUSSIONS

In this chapter, the transformation potential and spatial quality effects of automated driving have been examined on neighbourhood and street level. By performing a design exercise, a better sense of the location can be developed within the research process. The large number of drawings obtained show that different areas ask for different solutions. Based on specific findings, general conclusions are drawn for this study. Within practice, each area should be considered uniquely to grapple the wide range of variables that matter in the specific urban context.

First design step started with indicating the transformation potential of neighbourhoods for new functions. These expressions have been made qualitatively and provide insight in which areas the best opportunities arise for new urban redevelopment under various scenarios. The second step indicated the spatial quality effects on street level and quantifying these in housing value premiums. Overlapping the transformation potential and the spatial quality increases gains reveal where the largest potential for urban change can be expected. This depends strongly on the scenarios. Within the *scenario 1: Transformation*, significant changes can be expected in all urban areas, whereas in *scenario 2: Growth* a stronger focus on larger urban towns can be observed. For *scenario 3: Constraint*, 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 *scenario 4: Decline*, most significant changes are expected within the urban centres, in this case the city of Utrecht. 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.

8 RESIDENTIAL DENSITY TRANSFORMATION

In the prior two chapters, insights are obtained on the accessibility and spatial quality effects of automated driving. Based on these understandings, a knowledge basis is built on how automated driving can change urban spaces and the importance of place. However, to fully comprehend the spatial impact of automated driving on urban development itself, 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. Instead, the goal is the reveal new directions of 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 agent-based modelling. The first section describes the agent-based model itself and the process of constructing and implementing the model. The second section describes how the model can be used for the experiment. The third section presents the results from the experiment.

8.1 MODEL FORMULATION AND IMPLEMENTATION

Purpose of the model is to simulate the moving behaviour of households through space and time and observe how this behaviour changes under the various scenarios for automated driving. The model of the agents needs to be formulated and implemented within a modelling environment. The behaviour of the agents depends on characteristics of the agents themselves as well as the variables of the environment. This section describes all these facets and corresponding data collection process, followed by a description of its implementation within the used modelling toolkit.

8.1.1 BEHAVIOURAL MODEL

One of the crucial 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 with the benefit to have some additional control over the variables used within the model. Estimating a model (an obtaining data for estimation) is however a time-consuming process and therefore this research is limited to using an existing residential location choice model. Studies by e.g. Hunt et al. (1994) or Schirmer et al. (2014) list 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. Models derived from data for other countries than the Netherlands are not favoured since housing is a cultural phenomenon (Rapoort, 2000). Hence, choosing 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 8-1 based on criteria regarding ease of implementation and suitability for the study purpose. Based on this evaluation, the residential location choice model as described in Zondag, de Bok, Geurs, et al. (2015) and applied within TIGRIS XL is considered most suitable: the 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 and for its good documentation available.

Table 8-1: 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 implementation	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 <i>distance</i> considered	Difficult, only commute <i>distance</i> 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 readily 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

The residential location choice model by Zondag, de Bok, Geurs, et al. (2015) is also explained in the documentation for the TIGRIS XL national land-use model of the Netherlands by Zondag, de Bok, Willigers, et al. (2015). The residential location choice model describes the moving behaviour in two different decisions: the move-or-stay decision and the actual location choice. In between these two

procedures, two additional steps are implemented. After the move-or-stay decision, the number of vacant dwellings can be determined. The actual residential location choice is part of an iterative procedure which also incorporates the interaction between households on the housing market. The decisions that household make are determined by characteristics of the households and various environmental variables. The full modelling procedure from the perspective of the household is depicted in Figure 8-1. A description of the residential location choice model, based on Zondag, de Bok, Willigers, et al. (2015), is given in Appendix D.

Regarding the area which the case study in this research covers, this study allows to simplify the existing behavioural model. The actual residential location choice is modelled through a nested logit model by which each nest represents a COROP-region. As the parameters to adequately implement the nested logit model are not available, the Province of Utrecht – which coincides with a COROP-region – is considered one closed system. This means that households cannot leave the province but also that new households cannot enter the province either.

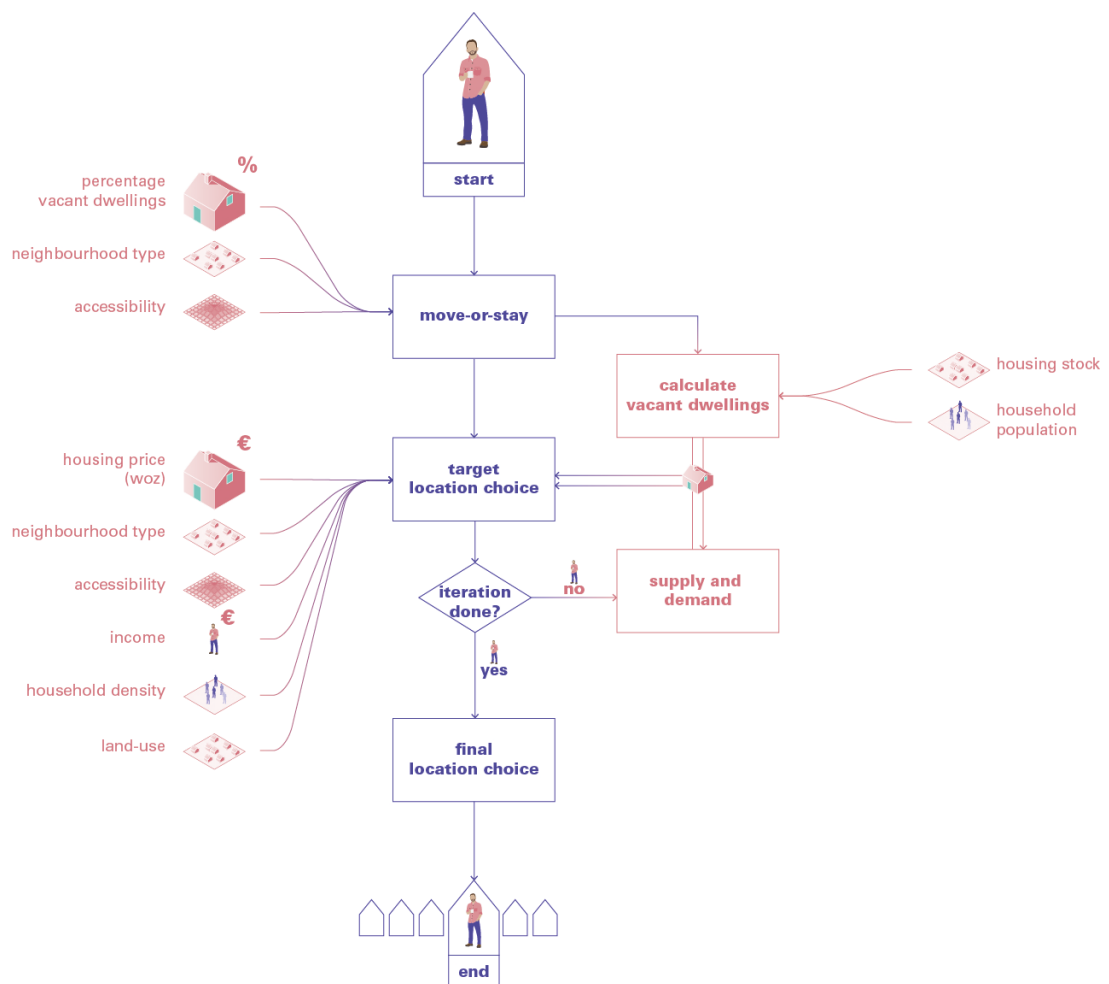


Figure 8-1: Model structure of the residential location choice process.

8.1.2 SYNTHETIC POPULATION

The TIGRIS XL model distinguishes 13 different household types which must be created based on synthetic data or simplifications. It is relevant to elaborate on heterogeneity in decision makers because different households have different moving behaviour. Over time, population is subject to

demographic changes. This has been excluded from the simulation study. 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 8-2 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 (Woononderzoek Nederland). 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 8-2):

- 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.

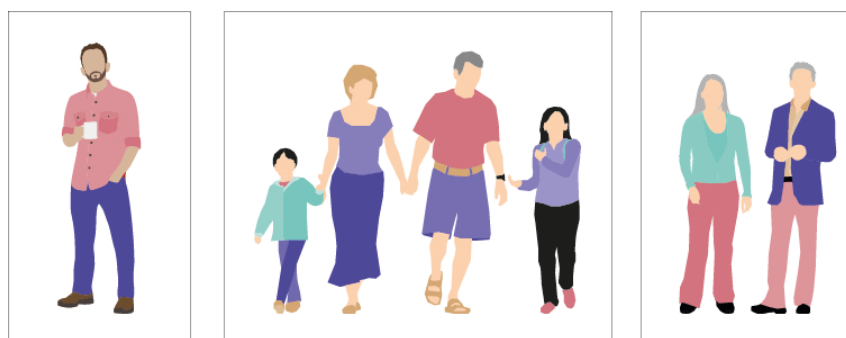


Figure 8-2: Distinguished households

Table 8-2: 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%
							$\Sigma = 100\%$

8.1.3 ENVIRONMENTAL VARIABLES

The residential location choice model describes the weight of different environmental variables in the location choice of different household types. One can distinguish the following groups of environmental parameters:

- Travel resistance between the origin zone and the potential new location;
- Characteristics of the housing environment;
- Socioeconomic variables;
- Housing stock and vacancy variables;
- Accessibility of the location.

These parameters are either evaluated within the move-or-stay decision, the actual residential location choice or both. An explanation is provided below which describes how the environmental variables are obtained and implemented.

Travel resistances

To account for the fact that most moving happens in relative proximity of the origin zone, the resistance between the current zones a household resides and a potential new zone is a significant factor. The behavioural model considers two travel resistances simultaneously. One is the inverse of the travel distance to the candidate zone. The other travel resistance factor is the logsum of the generalised travel

costs between the two zones. The logsum of accessibility between the origin zone and candidate zone is calculated as follows (Pieters, Ruijs, Willigers, & Zondag, 2015, p. 15):

$$LS_{i,j}^{moving} = \ln \left(\sum_m e^{V_{i,j,m}} \right)$$

with:

$V_{i,j,m}$ Utility of the generalised travel cost

Where:

$$V_{i,j,m} = \alpha_m + \beta * Z_{i,j,m}$$

with:

α_m Mode specific constant

β Generalised cost parameter

$Z_{i,j,m}$ The generalised travel cost in euros

The generalised travel costs are obtained from the transportation simulations in VRU. As it proved hard to obtain generalised travel costs for public transportation, the decision is made to only consider car travel. This is no problem under the assumption that the car always provides a lower travel impedance. Having multiple alternatives is not considered in this logsum calculation as no it has no scale parameter μ : the logsum travel resistance is only determined by the most attractive alternative. The equation can be rewritten as follows:

$$LS_{i,j}^{moving} = V_{i,j,m}$$

for car travel, $\alpha_m = -1.669$, $\beta = -0.1727$ regardless of the mode (Pieters et al., 2015, p. 15).

Characteristics of the housing environment

The housing environment is described by environmental variables. Within the choice behaviour, the neighbourhood typology as well as several land-use are evaluated. The neighbourhood typologies are classified according to the aggregated typology classes by ABF Research (2003) which have already been obtained for its disaggregated counterparts in section 7.2. These can therefore be aggregated accordingly and implemented. The neighbourhood typology is evaluated in the utility function as a percentage of the area in the zone. Zones that have been classified as work areas or which have not been able to get a classification from the algorithm used in this study, have not been incorporated in the simulation study as these are considered to have limited to no housing stock. This is more adequate than just than neglecting these typologies in the utility function as the urban peripheral neighbourhood typology is the reference value of the choice model. Areas for work or undetermined areas would be evaluated as urban peripheral areas.

Other land-use which is evaluated regarding housing environment is the area of facilitating services, employment area and water area. Land cover data is available through CBS (2012): land-uses

retail & restauration, public services and cultural services account for facilitating services. Business areas are classified as work related functions.

Socioeconomic variables

Socioeconomic variables for population density (CBS, 2016a), housing value (CBS, 2016c) and average household income (CBS, 2017a) are readily available. Household income will not be evaluated even though the residential location choice model has estimated coefficients for this. It is not possible to associate income data to the synthetic population. Furthermore, the role the average household income plays in the residential location choice is small. Housing value is used as a $t=0$ value and will transform over time in the housing market. Some data is missing regarding average housing price in the area. The areas where housing value is unknown are all areas with a very low housing stock. The housing value is therefore unknown due to privacy reasons. For the case when the area concerns mostly the work typology, this is not considered a problem since these areas are simplified to areas with no housing stock and are therefore not considered in the simulation study. The other areas concern all a rural typology. For these areas, the housing value of a neighbouring rural zone is taken as housing value.

As the scope of the model is to study the transitions in population density, this is a considerable variable. However, the decision makers in this model are households. As subsection 8.1.2 on the synthetic population shows, the household type with children does not specify the exact number of children. Therefore, the average households size of family plus children is calculated under the assumption that every other household is respectively the size of one or two persons. The average size (and therefore considered representative size) of a household with children is 3.8 persons. One could consider this number high.

Housing stock and housing vacancy

No public dataset is available for the Netherlands that accurately describes the actual housing stock. 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 other factors). 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). This assumption leads to some areas where the housing stock sometimes surpasses the number of households or vice versa. This is not necessarily a problem. The equation to calculate vacant dwellings elaborates on the average number of households per dwelling. Nevertheless, values that show a very deviant occupancy rate are further examined to validate the accuracy of the combined datasets. Deviant occupancy rates are considered <0.6 households per dwellings or >1.4 households per dwelling. Based on assessment of the specific context of the zone, a decision is made whether values should be altered. In most cases, the deviant values can be explained

by the presence of a significant number of recreational houses. In that case, the number of dwellings is subtracted from the housing stock to match the population. In two specific cases, the zones largely comprised a refugee centre. Refugees are not considered part of the housing market. Therefore, the households in the areas are reduced to match the number of dwellings. A few areas showing high dwelling occupancy were subject to new housing development. Housing stock has been increased in those zones to match the number of households.

Accessibility value

The accessibility value to which households in this simulation model are sensitive is the accessibility for the trip purpose other within 10 km of the dwelling zone i . Reasoning for the latter is that accessibility primarily plays a large role in moving within the existing housing market. Furthermore local households have more knowledge on local accessibility differences (Zondag, de Bok, Willigers, et al., 2015, pp. 67-68).

There are some challenges to implement the right accessibility values within the model as this study uses another transport model than the model which is intended to use for obtaining the accessibility indicator. There is no data available indicating the order of magnitude of the intended accessibility indicator. Furthermore, it is not possible to calculate accessibility to trip purpose other with VRU as it is unknown which opportunities comprise trip purpose other. Only reference available that gives some insights is de Bok (2007, p. 95), displaying logsum accessibility for commuting trips ranging from <7.5 to >12.0 and logsum accessibility for business trips ranging from <6.5 to >8.0 . When using VRU to calculate accessibility for commuting trips, values ranging from $5.1e+4$ to $11e+4$ are obtained. Although different order of magnitude, the ratio between higher and lower values is somewhat similar making it possible to use a scaling factor. When calculating accessibility within a Euclidean distance of 10 km, this ratio does not occur (Figure 8-3). However, the pattern on map remains similar. Based on Geurs et al. (2016, p. 25), citing Ahlfeldt (2011) and Helling (1998), it is justified to consider job accessibility as a suitable proxy to other activity types.

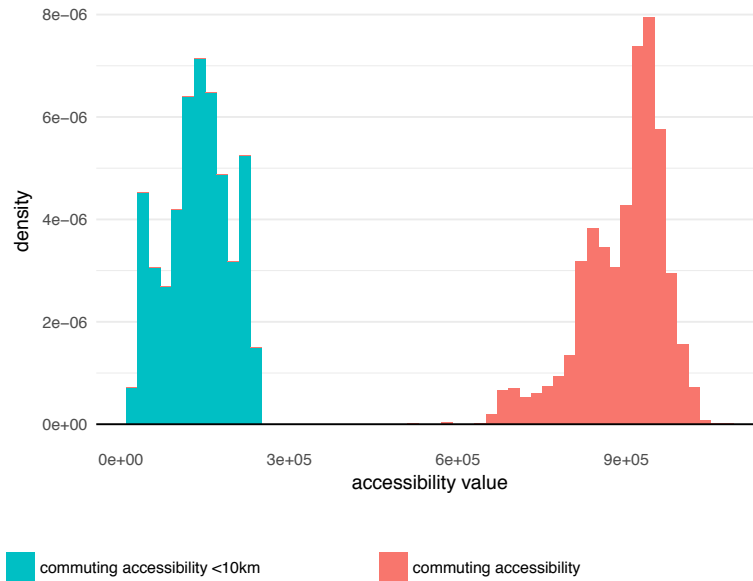


Figure 8-3: Accessibility distribution for zones in the Province of Utrecht calculated to all opportunities and to opportunities within 10 km range.

Based on the available information it is not possible to make an estimation how accessibility for trip purpose other differs from accessibility for trip purpose commute, the decision is made to assume similar accessibility values. The scaling procedure from the accessibility values from VRU towards the residential location choice model is based on the difference between the different commuting accessibility values. The range from the LMS logsum accessibility depicted in de Bok (2007, p. 95) is assumed 7.5 – 15 and the accessibility in VRU $5e+5$ – $10e+5$, resulting in a scaling factor of $1.5e-5$. This means that the accessibility values evaluated in the model are low and possibly inaccurate. This is not expected to significantly change the outcome of the simulations as accessibility plays a modest role in the residential location choice (Zondag, de Bok, Geurs, et al., 2015, p. 124). Furthermore, the accessibility effects of automated driving are also evaluated within the moving resistance between zones (see top of this subsection).

8.1.4 MODEL IMPLEMENTATION

The agent-based residential location choice simulation model is constructed within NetLogo (Wilensky, 2003) (Figure 8-4). 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.

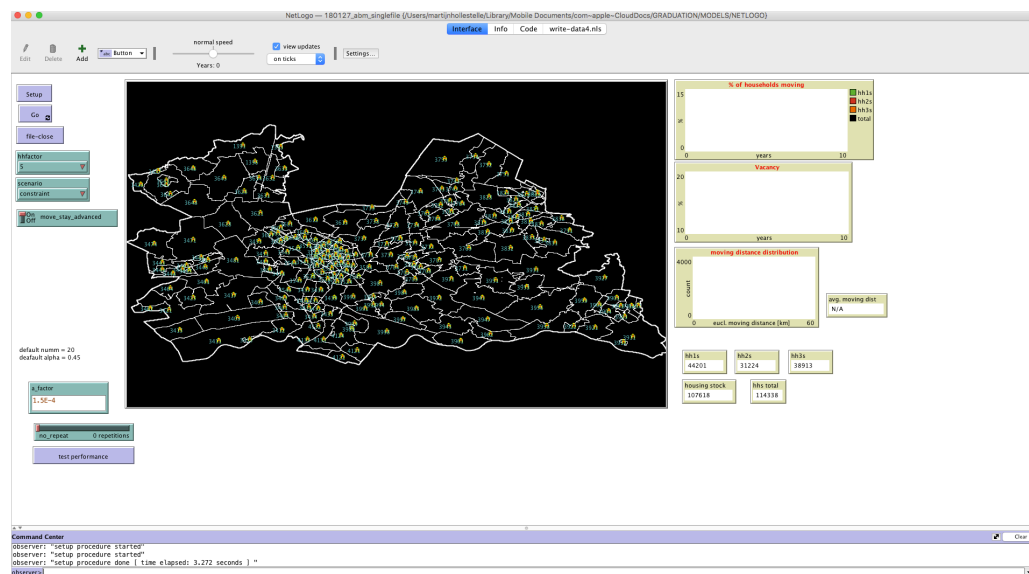


Figure 8-4: GUI of the residential location choice model in NetLogo 6.0.2.

The model is implemented as described in this section with some adjustments and additional considerations. To reduce runtimes, the model does not simulate all the households. Instead, a household factor HF is integrated. Considering the stochastic nature of the events within the model, many replications of the simulations are necessary. Therefore, short runtimes are desired. The stochasticity within the behaviour is implemented using Monte Carlo simulations. Another consideration made regarding runtime is the number of iterations on the housing market. Supply and demand is balanced within a balancing factor. The balancing factor decreases the attractiveness of a zone if the number of households choosing a specific zone as candidate to move towards exceeds the number of vacant dwellings and vice versa. This is an iterative process which has been set to 10 iterations in this model to limit runtimes while still finding balancing factors reach near one values.

8.2 EXPERIMENT SETUP

The agent-based model is used to run experiments in which the development of households in the zones is studied according to each scenario. Within the simulations, the accessibility effects found in chapter 6 and the spatial quality effect found in chapter 7 are implemented. Agent-based models produce a lot of data and bear in the case of the model used in this study, stochastic events. Hence multiple reproductions of each experiment are executed. The main scope of this part of the study is to examine the change in residential density – specifically household density – under the various scenarios of automated driving.

8.2.1 SIMULATION INDICATORS

Agent-based models do not provide for an optimal solution but are used to study the performance of a system under various scenarios. For the case of this research, the influence of various automated driving solutions on household density is assessed. The base scenario without any form of automated driving is considered the reference. The other scenarios are compared in relation to the base scenario. As explained in the prior section, the model is designed to let multiple households be represented by one agent using household factor HF . Based on some hands-on experimenting with the model, a

household factor $HF = 5$ is chosen as this is the lowest factor by which the model runs stable. With $HF = 5$, the model environment is inhabited by over 114 000 agents. The change in household density is expressed by the following equation:

$$\Delta HD_{t,scenario} = \frac{H_{t,scenario} - H_{t,base}}{A_z}$$

with:

$\Delta HD_{t,scenario}$	The change in household density
$H_{t,scenario}$	The number of households in a zone in a scenario
A_z	The area of zone z

This indicator focuses on the absolute difference rather than the relative difference. The reason for an absolute indicator is that this better resembles the new challenges regarding spatial impacts of urban development. To illustrate; when some additional households settle in a low-density zone the relative change can be very high whilst the change in density is only modest to low. Similarly, when a significant number of new households arrives in a high-density zone, the increase might seem modest from a relative perspective.

The model distinguishes various types of households primarily to obtain a more representative behaviour of the whole population. This choice also allows to elaborate on the transformation of household density, specified by household type. This is however not considered for simplicity sake as this would lead to additional simulations as different samples of random variables must be considered.

The time steps of the model are per year but this study takes a forecast to ten years in the future from the base year. The reason to take a ten-year time horizon is because the response duration of residential mobility is estimated to be between five to ten years according to Wegener, Gnad, and Vannahme (1986, p. 4). The ten-year horizon has therefore no relation to any predictions regarding the deployment time of automated driving. The impacts are modelled from $t = 0$.

8.2.2 MODEL VALIDATION

Due to time constraint and data limitations, the model has not been calibrated. A mean to calibrate the model would be to adjust the transformation of household density in the model to census data. This would however, prove for a very time intensive simulation process of parameter sweeping. Reason for the constructed model to show deviant results would primarily lay in the data collection process. For the data collection process, this researched has attempted to make sure the input data follows the requirements for the model as accurate as possible. Regarding the accessibility indicator, limited data was available to make sure the right conversion has been made between the values obtained in VRU and the data required by the choice model. An assumption has been made as described in subsection 8.1.3. Another point of consideration lies in the land-use parameters which are expressed in square meters. for the behavioural model the sensitivity for these parameters is estimated for LMS zones which are on average 3 times larger than the 4-digit postal zones which are used for this study.

Validating the model to obtain insight in how realistic it performs can be done by assessment of the distribution of moving distances. The distribution of moving distances provided by Feijten and Visser (2005, p. 79) (Figure 8-5), gives an indicator on at least some part of the behaviour of the agents. Comparing the moving distance to a model simulation run of 10 years with base scenario variables in Figure 8-6 shows that the constructed model deviates from the observed moving behaviour by Feijten and Visser (2005, p. 79). Although the curves resemble is shape, the simulation model shows a higher share of moving over lower distances. As the province is modelled as a closed system, no moving distances over 75 kilometres can be observed. The absence of possibilities to move further distances is in part an explanation for the higher observed share of shorter distances. Furthermore, one can conclude that the model is over-sensitive to moving resistances to alternatives.

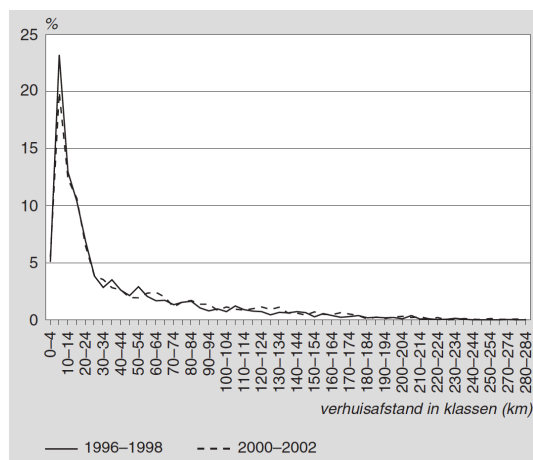


Figure 8-5: Distribution of moving distance in kilometres for 1996-1998 and 2000-2002 as observed in the Netherlands (Feijten & Visser, 2005, p. 79).

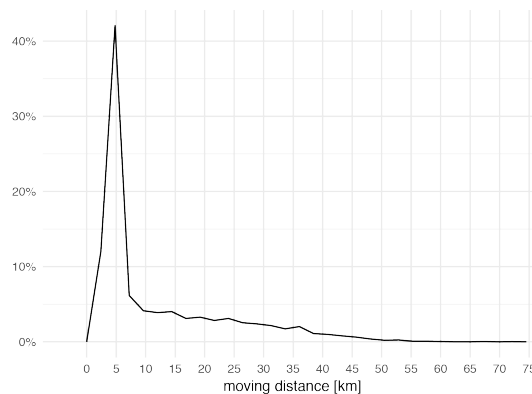


Figure 8-6: Distribution of moving distance as observed in the constructed agent-based model for the base scenario.

8.2.3 BASE SCENARIO

At the starting year of the simulation (the year 2015), the household density is found as depicted in Figure 8-7. Highest densities are found in the city centre of Utrecht and its surrounding neighbourhoods. Some surrounding towns and cities show higher densities as well, particularly within the centre areas. When running the simulation to ten years in the future, changes in household density can be observed (Figure 8-8). This means that the base scenario does not sustain as an equilibrium compared to the base year. Most striking change that can be observed is the change in household density in the urban centre of Utrecht and in the city centre of Woerden. The dataset to describe the environment, shows a relatively high number of families per dwelling in those areas and the model compensates for that. The similar reasoning applies for the areas which show a very high increase in population density, the city centres of Houten and Veenendaal and Tuindorp, Utrecht show a relatively low dwelling occupancy whilst offering an urban neighbourhood typology. It seems that most of these profound differences can be explained from the perspective of average dwelling occupancy. Another difference that appears is that some areas outside the built environment show a modest increase in density whilst other areas show a small decrease. Main difference within these areas is that the areas

that show a decrease are mostly rural areas, whereas the areas that show an increase have a larger share of village area within the zone.

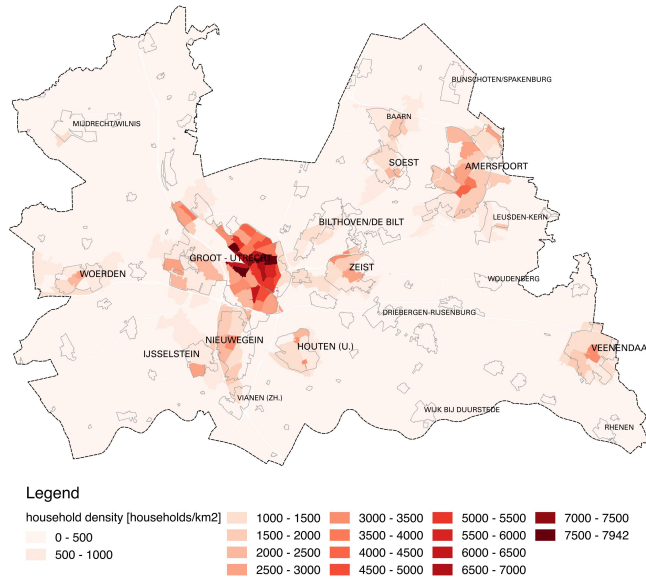


Figure 8-7: Household density at the start of the simulation (t = 0).

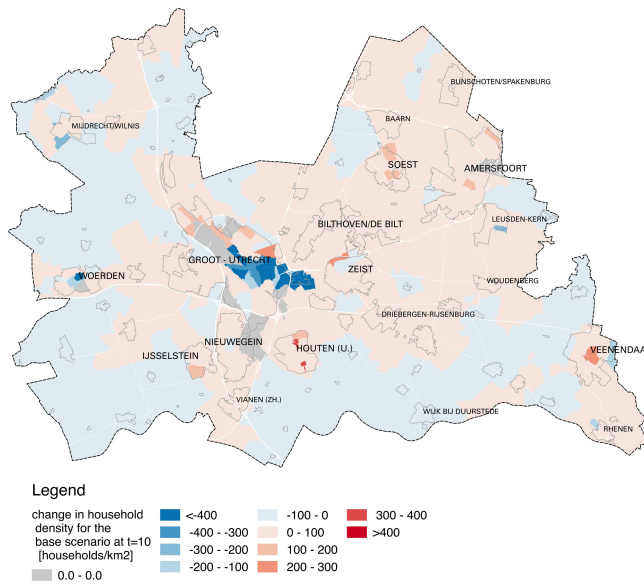


Figure 8-8: Change in household density for the base scenario at t=10 years compared to t=0.

8.2.4 NUMBER OF SIMULATIONS

The simulation results are derived from the change in number of households in a zone between different scenario. Both the outcomes of the base scenario (which serves as a reference) as well as the scenario runs are normally distributed random variables as the results are subject to stochastic events simulated using Monte Carlo simulation. To draw conclusions on the difference between the results, the distribution of difference between two normal distributions must be obtained. This means that for each zone the difference $X = X_2 - X_1$ following a Normal distribution with $\mu = \mu_2 - \mu_1$ and variance $\sigma^2 = \sigma_1^2 + \sigma_2^2$.

To guarantee statistical validity of the results, the goal has been set to have a 95% confidence interval of no more than 25 households/km² deviation for each zone. Based on data of a first test run with $N = 20$ for each scenario, the desired sample size is calculated using the following equation.

$$N'_z \geq t_{\frac{1}{2}\alpha, N-1}^2 \left(1 + \frac{1}{2}\xi^2\right) \frac{X_{s,z}}{X_{d,z}}$$

with:

N'_z	The desired sample size for zone z
$t_{\frac{1}{2}\alpha, N-1}$	The test value, for this case $t_{0.975, 19} = 2.093$
ξ	Test specific parameter, $\xi = 0$ applies as results concern averages
X_s	The standard deviation of the sample run
X_d	The accepted deviation, in this case $X_d = (25/HF)A_z$

Based on these findings, the required number of simulations $N' = 64$ is found to meet the statistical validity of the results for each zone. The choice has been made to run each scenario simulation 75 times. The requirements for statistical validity are met for all zones.

8.3 RESULTS

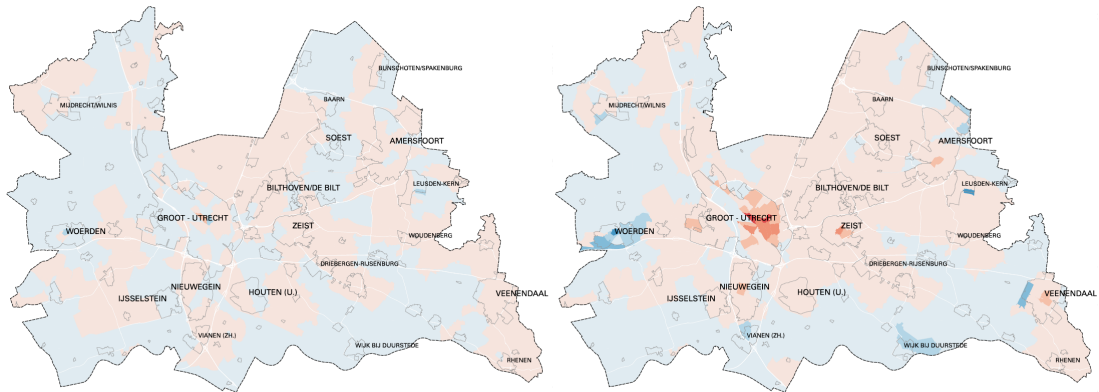
This section presents the results of the simulation study. The first subsection describes the observed changes in urbanisation patterns. The second subsection elaborates on the role of accessibility and spatial quality on these findings to further understand the principles behind the observed differences.

8.3.1 SCENARIO RESULTS

The results per scenario are elaborated in comparison to the change in the base scenario (see subsection 8.2.3). Within these simulations, the accessibility effects found in chapter 6 and the spatial quality effect found in chapter 7 are implemented. The results are explained based on the maps of change in household density in Figure 8-9 and in the plots in Figure 8-10, distinguishing the various neighbourhood typologies.

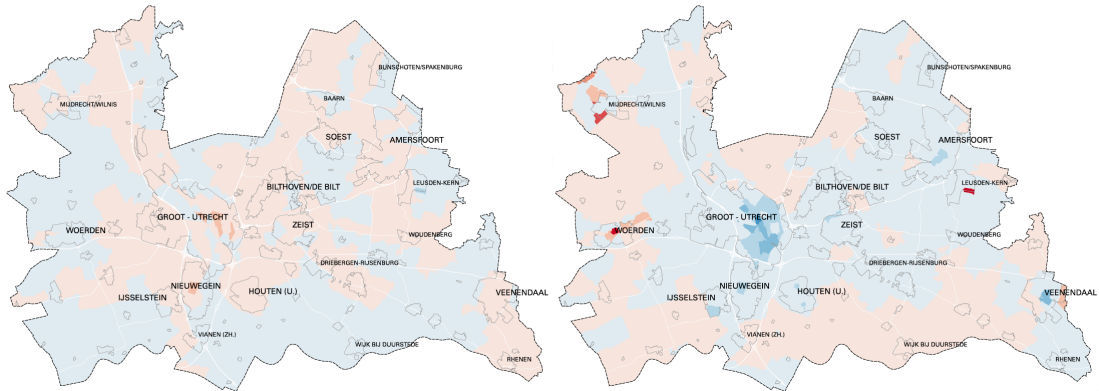
For *scenario 1: Transformation*, no distinct pattern can be recognised from the image except that the changes in household density are rather modest and somewhat homogenous. Elaboration of the results from the perspective of neighbourhood typology shows a similar image. *Scenario 2: Growth* shows a more distinct change in urbanisation pattern compared to the first scenario. Areas that show a strong increase in households are in the urban centre and surrounding neighbourhoods of the city of Utrecht. Furthermore, the centres of Amersfoort and Zeist show a similar increase. A modest increase can be observed in the urban centres of Nieuwegein and Veenendaal as well. The other larger town in the study area, Woerden, shows however a decline in population. The change in household density that reveals in *scenario 3: Constraint* shows a similar pattern as *scenario 1: Transformation* with the small differences that the prior scenario shows slightly higher preference for higher urban environments compared to the latter. *Scenario 4: Decline* – which explores a negative perspective on automated

driving – shows a different pattern. Most towns and cities show a decrease of population in their urban centres and for the case of the city of Utrecht, also in the neighbourhoods surrounding the centre in favour of rural areas.



scenario 1: Transformation

scenario 2: Growth



scenario 3: Constraint

scenario 4: Decline

Legend

change in household density compared to base scenario at t=10 [households/km ²]	■ -200 - -150	■ -150 - -100	■ -100 - -50	■ -50 - 0	■ 0 - 50	■ 50 - 100	■ 100 - 150	■ 150 - 200	■ >200
	■ <-200								

Figure 8-9: Change in household density for each scenario compared to the base scenario at t = 10 years.

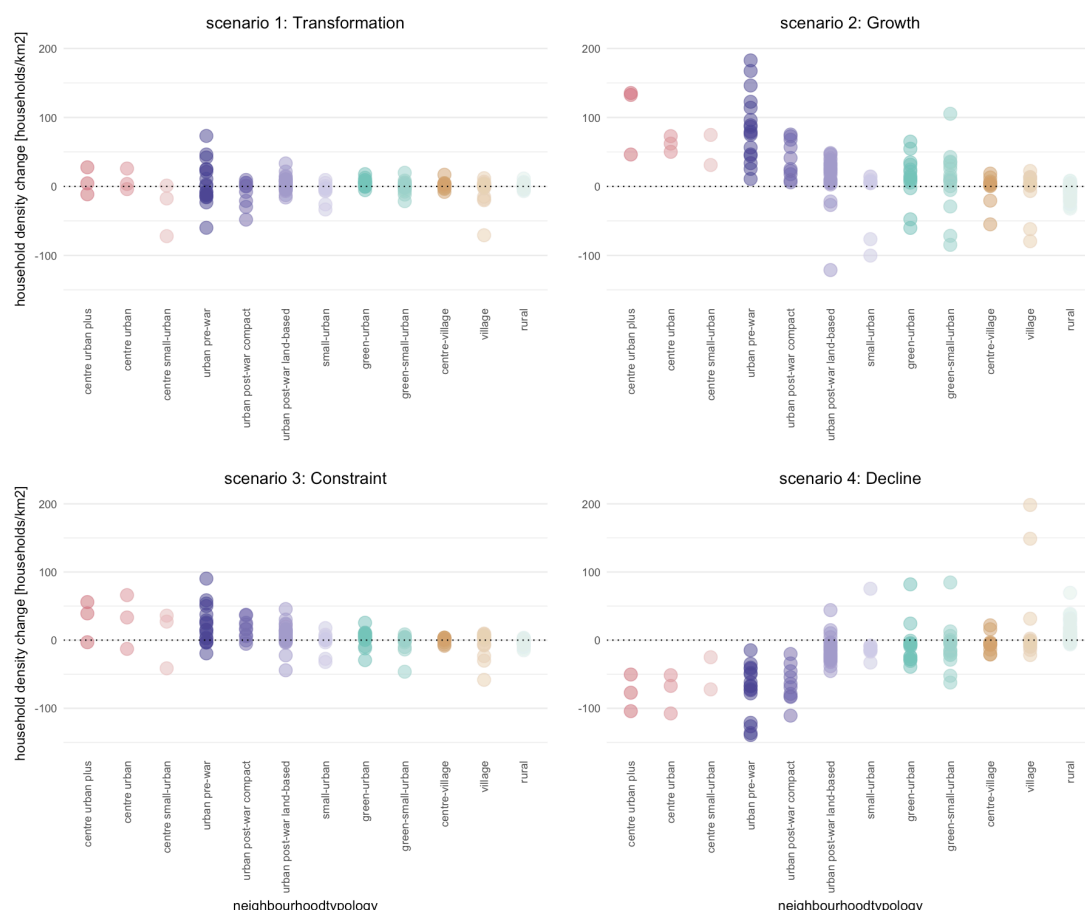


Figure 8-10: Change in household density by neighbourhood typology for each scenario compared to the base scenario at $t = 10$ years.

8.3.2 INFLUENCE OF ACCESSIBILITY AND SPATIAL QUALITY

The prior subsection presented the changes in household density under each scenario. Both accessibility effects and spatial quality effects are evaluated simultaneously within each scenario. To further examine the role of each individual aspect on the results, the scenarios have also been simulated by only evaluating one aspect at a time, leaving the other aspect the same value as in the base case. One must take an important consideration regarding agent-based modelling into consideration regarding the complex system it simulates. Purpose of agent-based models is to reveal emergent properties which cannot be predicted beforehand. The results of the simulations of solely spatial quality or accessibility effects are therefore not merely two parts comprising the outcome as presented in the prior subsection.

The results of the simulations are surprising in the sense that all runs show similar findings which strongly coincide with the findings of *scenario 4: Decline* as explained in the prior subsection. This indicates that the combination of factors show a stronger influence on the system than when considered individually. Furthermore, this illustrates that many other factors are important for the system regarding other variables and interaction on the housing market.

Therefore, it proves more adequate to elaborate on the results from the simulations in the prior subsection to understand the influence of the both considered aspects with disclaimer the unpredictable character of the system. The observed changes in density in *scenario 1: Transformation* and *scenario 3: Constraint* are much smaller than in the other two scenarios. Regarding the first scenario, one must

conclude that the spatial quality effects are equal over all neighbourhood typologies but the rural typology, giving no specific typologies a comparative increased utility over other zones. The accessibility effects are beneficial for all zones. *Scenario 3: Constraint* is similar in respect that no specific urban areas are more subject to change both in accessibility and spatial quality than other areas. Within *scenario 2: Growth*, most spatial quality benefits are found in the larger urban centres. This scenario also shows an increase in population in these areas. Within *scenario 4: Decline*, the spatial quality effects of automated driving do not occur for these areas and accessibility values decrease in most areas. In this scenario, this leads to an increase of population in lower density urban areas.

8.4 CONCLUSIONS AND DISCUSSIONS

By using an agent-based model to simulate the moving behaviour of households in space and time, both the accessibility effects and spatial quality of automated driving are synthesised to reveal changes in urban development. How urban development changes is subject to the scenario through which automated driving is evaluated. Three different patterns of urban development have been found in the simulation study:

- An increase of households in denser urban areas within *scenario 2: Growth*;
- A modest increase of households in more urban areas in *scenario 1: Transformation* and *scenario 3: Constraint*;
- A decrease in denser urban areas in favour of lower density urban and village characterised environments in *scenario 4: Decline*.

Most of the found differences relate to the relation between different types of urban areas. No large pattern revealed on the scale of the whole province (e.g. a shift from west to east). This can be partly explained to the fact that the spatial quality effects found in the prior study were assigned to neighbourhood typologies which are equally distributed over the study area. Furthermore, as the accessibility effects are evaluated with an indicator of accessibility to opportunities within 10 kilometres, the effect to move further or closer away from large centres of opportunities because of accessibility changes is small. The spatial quality effects are implemented within the model environment through premiums on the average housing value. It is important to state that even though housing value explains some quality aspect of an area, the average housing price was evaluated as a negative indicator (minus sign for the weight value) within the choice behaviour of the households.

Elaboration on the results show the difficulty of the individual aspects on the final outcomes. This emphasises once more the complex nature of the urban environment as a system. Taking spatial quality into consideration (through housing value premiums) besides accessibility shows however, that different results are found compared to solely taking accessibility effects into consideration.

Most comprehensive land-use and transport interaction models have a coupling between a transportation model and a land-use model. Within this research, no coupling has been established between the transportation model used in chapter 6 and the agent-based model used in this chapter due to complications to make coupling operational and for runtime concerns. However, it is possible to elaborate on how the results would change if a coupling was established. Within *scenario 1:*

Transformation and *scenario 3: Constraint*, the change in density is modest. This leads to the suspicion that the travel demand will remain similar. However, *scenario 2: Growth* and *scenario 4: Decline* show stronger changes in density, leading to changes in travel demand. Higher density leads to higher travel demand and therefore higher probability for congested roads. The opposite applies for lower density. Therefore, one can expect that coupling might to some extent reduce the final change in density.

Another aspect that is not considered within the model is the real-estate market. The availability of dwellings is one of the most determinant factors within the behaviour of the agents. Transformation of the housing stock is expected – no matter how strict the real-estate market is regulated – to follow to some extent the preferences of the households (Zondag, 2007, pp. 26-27, 107). What this would mean, is that the increase in density of households would to some extent be facilitated by the real-estate market (with some time-delay). As the number of available dwellings would increase, showing also an increase in population within those areas that already show an increase in households. Naturally, new dwellings are also restricted to available spaces for new housing development. Taking the urban development potential defined in section 7.3 could therefore provide for indications of potential change and for direction of the new plans. The transformation potential examination showed the largest opportunities for urban development in urban centres.

This chapter shows that various factors and aspects in automated driving can lead to different changes in urban development. However, by using a comprehensive agent-based model, also the complexity of the built environment as a system reveals. This illustrates the challenges to make accurate and meaningful predictions about the *exact* impact of automated driving under various scenarios. Using a model is an attempt to make the system one evaluates explicit and to illuminate the core dynamics of the system. This chapter learns that considering both spatial quality and accessibility effects together leads to different results than elaborating on single aspects. The case of automated driving relates to a wide range of other factors in terms of urban development and environmental variables.

9 FINDINGS AND DISCUSSIONS

The aim of this research is to obtain insights in the spatial impacts of automated driving from the broader perspective of urban development. Hence, this study elaborated on two important aspects on the relation of land-use and transportation: the concept of travel and accessibility and the concept of spatial integration of infrastructure in the environment in terms of spatial quality. This research distinguishes household moving behaviour as one of the most important driving forces within urban development. The perspective of residential location choice behaviour provided for the perspective and guided the data collection process.

This chapter concludes on the findings from this research and discusses further on the methods and the results used within this research. The first section discusses the findings on the topic of urban development and the second section elaborates on the underlying aspects of accessibility and spatial quality. Within these sections, most important conclusions are presented. The findings will be compared in the third section to other research on spatial impacts of automated driving. Section four discusses the research approach and reflects on the approach in perspective to the nature of the problem. Section five and six provide recommendations for future research and for urban planners.

9.1 FINDINGS ON URBAN DEVELOPMENT

Within the approach, findings on the accessibility effects and on the spatial quality aspects of automated driving form the fundamentals which generate the change in urban development patterns. These are environmental variables on which households base their residing choice. The urban development changes have been studied by evaluating the change in household density.

Different scenarios on the deployment of automated driving show different results in terms of urban development. Under the condition that automated driving deploys as an efficient private mode of transportation (allowing for benefits as empty ride allocation for parking, in this research *scenario 2: Growth*), it can support an increase of population density of around 200 households/km² in urban centres and surrounding urban neighbourhoods. Population density in suburban housing environments decrease in that case. Under a scenario where automated driving develops similarly but without positive benefits of external parking or capacity gains (*scenario 4: Decline*) the opposite pattern revealed: A reduction of household density of around 100 – 200 households/km² is found within the urban centres and surrounding neighbourhoods in favour of the rural village and greener low density urban areas. The

two other scenarios - one assuming a fully autonomous shared vehicle system (replacing mass transit, *scenario 1: Transformation*) and one assuming automated driving only allowed on the highway (*scenario 3: Constraint*) – showed less profound changes in urban development.

The scenarios show different outcomes because different changes in accessibility and spatial quality have been evaluated. However, difference in input variables alone is not enough to fully explain the differences between the scenarios. The findings in density changes do not necessarily occur in the zones which show the largest changes in utility for households to reside. This leads to the conclusion that automated driving has an influence on urban development, yet that other dynamics in the system are more determinant on the outcome. Because of the interaction between the agents in the model, emergent patterns reveal which do not directly relate to automated driving. Automated driving can be therefore considered as a driving force in urban development as it leads to changes in household density. However, other variables and processes are more determinant within the process of urban development: in the case of this simulation study, the interaction between households on the housing market. It is therefore hard to determine the impact of separate factors of automated driving on the outcome without understanding its effect on other variables. Nonetheless, this research shows that considering spatial quality aspects within the research problem leads to different outcomes that solely elaborating on accessibility in terms of land-use transport interaction.

9.2 FINDINGS ON ACCESSIBILITY AND SPATIAL QUALITY

Three of the four scenarios incorporated an increase of car travel under automated driving. Assigning OD-matrices with this induced demand onto the road network revealed congested roads on the urban road network, despite the assumed capacity increase on urban roads. Under assumed capacity increase on the highway, congested bottlenecks disappeared regardless of induced travel. Induced travel on the urban road network leads to an increase of average travel time and therefore shows no positive impact on accessibility levels when no change in value of travel time is incorporated within the accessibility calculation. This applies especially for the largest city in the case study area, the city of Utrecht. Potential reductions in value of travel time by increased travel comfort in automated vehicles, improves accessibility values stronger than the travel time benefits by capacity and efficiency gains. The decreases found in average travel time when no induced demand occurs are relatively small and (around 2%-10%, depending on the scenario) and contribute relatively little to the increase of accessibility levels compared to the assumed value of time reduction (from 0% to 50%). Value of time changes have such strong impact on the final accessibility values that this can overrule the negative effects of induced travel.

Regarding spatial quality effects, the largest potential for large scale transformation is in areas which are occupied by larger infrastructure links, nodes or parking facilities. This is mostly limited to denser urban areas. On the street level, the reduction of parking places leads to the highest increase of spatial quality. However, these benefits come with the drawback of induced travel. Parking can be diminished either by remote parking solutions or by replacing private cars with a shared vehicle system (for this research under the assumption that such system also replaces conventional public transport).

In both cases, this leads to additional travel and to more congestion on the urban road network and this is a dilemma to take into consideration (Figure 9-1).

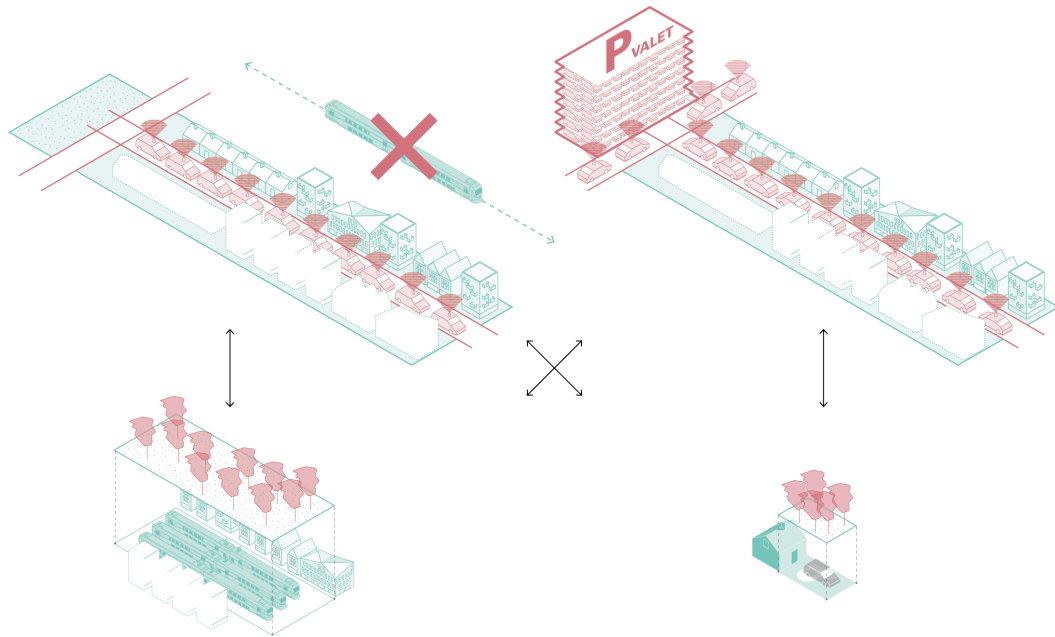


Figure 9-1: Spatial quality benefits come with the challenges of induced travel on the urban road network.

The possibilities to make urban spaces more attractive by the reduction of infrastructure is (besides reduction of parking) limited. The number of streets with only one lane (per direction or in total), make up the largest majority of streets. Many of the streets primary purpose is to provide access to a dwelling rather than to provide large traffic flows. For these arterial streets, more benefits on spatial quality exist when these roads do not suffer from the negative effects of induced car travel. Which areas profit most in increased spatial quality depends on the scenario. In a fully shared system, parking diminishes, and therefore all urban areas can profit. In terms of a valet parking system, this research assumed this most likely for areas which currently enforce a parking policy. Usually these are denser urban neighbourhoods. In that case, mostly urban centres profit. The effects on spatial quality were limited under other scenarios.

9.3 FINDINGS IN RELATION TO OTHER RESEARCH

Few research is done on the spatial impacts of automated driving from a holistic perspective. Nevertheless, some researches which elaborate on this topic were found and examined in section 3.3. When results of this study are compared to the found literature, some similarities reveal whereas also some contradictory findings are discovered.

This study found that induced travel demand is not beneficial for road network and accessibility of urban areas despite potential capacity increase. This coincides with the findings of Meyer et al. (2017). What this research contributes to knowledge on accessibility effects of automated driving is that value of travel time changes can cause still a positive increase on accessibility levels in those areas.

Zakharenko (2016) found that density in urban cores can increase because of diminishing of parking which allows for more economic activity but that subsequently reduced travel cost would also facilitate urban sprawl. This research found that automated driving can facilitate denser urban areas as

well. However not from the perspective of increased economic activity in the urban core but from increased spatial quality (in comparative advantage over other urban areas). This research does not make such strong statement on sprawling as such effect has not been observed this clear. This can be explained from the approach. Zakharenko (2016) approaches the problem from an urban economics perspective on a typical American-style city and allowed within his modelling study to erect new dwellings. This research only elaborated on the existing housing stock and acknowledges the strict housing policy culture in the Netherlands.

Gelauff et al. (2017) had a similar scope for their research: examine the change in population in areas in the Netherlands under vehicle automation. Their finding - which only elaborate on travel aspects - that automation within private vehicles would lead to people leaving cities, has not been found in all scenarios evaluated within this study. Instead, the contrary occurred. Showing only a decrease in households in the city for a scenario where accessibility levels decreased. The explanation should be found in the difference between how the studies obtained accessibility indicators. Gelauff et al. (2017, pp. 9-10) assumed travel time reduction as a factor of the current travel times whereas this study used a transportation model and found that not the same factor of reduction applies for each trip. Even though urban areas have fewer advantages of the capacity gains or automated driving, the value of time factor largely compensates this effect. Therefore, only a similar pattern was found in the scenario where no value of travel time change was assumed.

9.4 DISCUSSION ON THE METHODOLOGY

The research problem has been interpreted through the paradigm of cities as complex systems by which microscopic interaction between decision makers generates macroscopic changes in the built environment. After examination of the accessibility effects of automated driving with the help of a transportation model and examination of the spatial quality effects through research-by-design, this paradigm has been formalised through agent-based modelling.

This research can be characterised in three stages with three different methods, linked to each other (Figure 9-2). This allowed to approach the problem of the spatial impacts of automated driving from a broader perspective but was also one of the challenging factors. Within the connections between the various methods, additional assumptions were needed. This has therefore proved the weakness of this approach as it is difficult to make the findings of one part of the research compatible with sequential research steps. Two challenges arose when linking the research steps. The first challenge was to express the accessibility indicator evaluated by the households in the location choice in the right magnitude. It is hard to know for sure if the assumptions meet this requirement. The reason that made this coupling challenging coupling, was that the behavioural model for the agents did not coincide with used the transport model. Furthermore, implementing spatial quality aspects within the behavioural model of the households was done through housing premiums, whilst other spatial quality related choice attributes within a behavioural model might have proved more comprehensive. However, for this no adequate literature or existing comprehensive choice model which can be easily incorporated. One could overcome the compatibility problem for accessibility by using an integrated land-use and transport model instead of using one transport model and implementing another behavioural model which is not

calibrated for this transport model. This however does not solve the issues regarding the implementation of spatial quality aspects. What this research shows is that spatial quality has an influence on the outcomes of the model study when evaluated through property value. This stressed the need for location choice models that elaborate better on spatial quality aspects to reach out to professions occupied with shaping urban spaces.

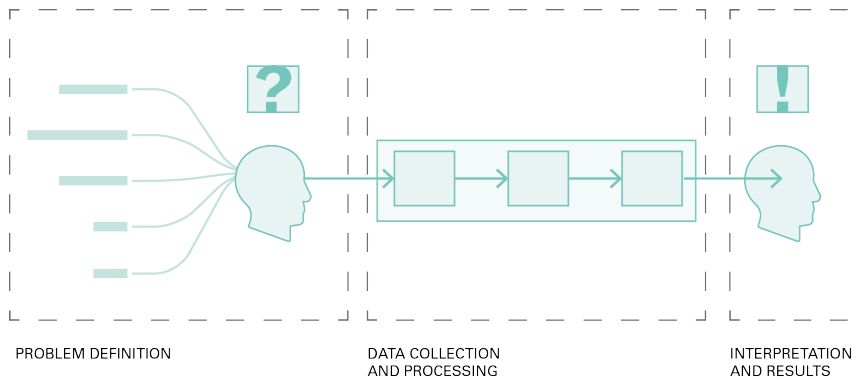


Figure 9-2: Steps within an integrated research process.

Using agent-based modelling proved an appealing method to approach the problem. Describing the system from the perspective of individual behaviour is a natural way to describe the system. Disregarding the actual agent-based model made and used for this study, the perspective of individual decision makers was very important in guiding the data collection process. The largest challenge for using agent-based models is to accurately describe the behaviour of the agents. For this research, this meant that only a few existing choice models could be considered. A strictly defined choice model helps to guide the data collection process and therefore dictates the exact requirements of the input data. These conditions cannot always be met without assumptions or because of missing data, making the research process less resilient. Estimating a choice model specific for this study would have helped to overcome the difficulties regarding the data collection but would have a large impact on the research in terms of time needed. Furthermore, the estimation process of behavioural models is also subject to data availability and uncertainty. Nevertheless agent-based modelling is a suitable method to comprehend cities as complex systems and allows to comprehend the various aspects of automated driving from the perspective of human decision makers. This research proved that the complex nature of the system can be incorporated within the study whilst focussing on a few aspects only.

Regarding the outcomes of the agent-based model itself, it shows that building a model that performs realistically requires a thorough data collection, calibration and validation process. A fully calibrated and validated not been achieved in this study. Nonetheless, the model showed different urban development paths under various scenarios which not necessarily coincided with patterns from the input data. This shows that the impacts of automated driving coincide with a larger dynamic system. Designing the model as such that also the other processes are analysed can help to understand automated driving in relation to these processes. In this case, these processes relate to the interaction of the housing market. The availability of housing is a determinant factor in the developments that emerges from the agent-based modelling study. Evaluating how the real-estate market responds to this change in housing locations of households would allow to further study the effects on urban form and would allow to find

more deviant results from the current situation. However, as the response time of the real-estate market to residential mobility is a certain number of years, it is recommended to evaluate the change in urban development further in the future than the ten years that have been considered without dwelling stock transformation.

Having access to VRU for this research was invaluable. Having a comprehensive transportation model for this research allowed to invest the accessibility effects of automated driving from a broad perspective. Implementing automated driving based on literature findings in a macroscopic transport model was a straight forward method and is less research intensive compared to using a macroscopic model. One can therefore conclude that using VRU was adequate for this research. One aspect that provided some obstacles was the encryption of some part of the model. However, through thorough examination of the model and correspondence with people who manage the model helped largely to overcome this difficulty.

Using design thinking within this research enabled elaboration on underexposed aspects and was therefore an important method to obtain conclusions. However, adjusting design thinking to integrate within a modelling study was challenging. This has been mentioned before in terms of compatibility. However, also the design act itself was different from conventional research-by-design. Design thinking is often led by intuition. Performing a repetitive design task and simultaneously attempt to report the process as transparent as possible is *counterintuitive* in that matter. One of the motivations of this research was to obtain better insights in the impact of automated driving using both engineering and design based methods. This research illustrates this, but also reveals that challenges in relation to the scientific domain in terms of reproduction of the results and personal judgement remain.

Context to this research was given by a scenario approach and a case study. The scenario approach allowed to make coherent assumptions and therefore managed to derive conclusions on the development of automated driving for these specific paths. This allows to project a concise image on the impact of automated driving under various scenarios, comprising multiple factors. This has however complicated to derive conclusions on various assumptions within each scenario. Considering to runtime issues of the simulation models, this was a suitable solution. If more time would have been available, it would have contributed the conclusions of the research to better specify the impact of each assumption on the development of automated driving through sensitivity analysis.

The case study area was a valuable input for specific contextual data. Both the wide array of neighbourhood typologies provided and the hierarchy of urban settlements within the province allowed for many spatial aspects to elaborate on. Using another case study might have led to different results. The province of Utrecht, and particularly the city of Utrecht is very well connected through public transport and this might be one of the explanations of the negative impact of induced demand when public transport is assigned to the roads. In urban areas with different mode shares, other results might occur. Another consideration to be made is that the system boundary of the study was limited to the provincial borders and considered a closed system, meaning that the larger scale urban development processes have not been observed.

9.5 RECOMMENDATIONS FOR FUTURE RESEARCH

The comprehensive scope of this research leaves room for improvements and other variables to relate to. Various other aspects related to vehicle automation, can be further examined, other methodologies can be applied to the problem and assumptions could be further specified. Hence a list of possible recommendations is identified to improve or specify the research approach:

- This study states that cities are complex systems and that these systems manifest phenomena such as self-organisation. One example of this self-organising ability would be that households adapt their residing location to network conditions. No feedback was integrated between the land-use modelling and transportation modelling procedure. It would be worthwhile investigating the impact of coupling and interaction between the transportation and the land-use model.
- This research made no statement on when automated driving will manifest itself. Instead, the research was based on data primarily from 2015. It is very likely that automated driving will establish only in the further future. Assessing the results from this study in relation to observed trends (e.g. aging society, e-commerce) could further specify the context in which the urban assignments around automated driving arise.
- As the case of automated driving is an urban planning problem, the model study should be presented to policy makers and planners to investigate what policy and design responses occur based on the observed effects. By elaborating on potential measures, the research can relate to the broader socio-technical regime that automated driving compels.
- Spatial quality aspects should be considered a significant factor within the assessment of automated driving on urban change. Formalising spatial quality aspects within behavioural models as evaluation factors would allow to more explicitly incorporate these factors within the research.
- Many simplifications have been made in this research to make the results compatible or due to time constraints. Contemporary urban models distinguish a wide array of different decision makers. Furthermore, these models increasingly evaluate accessibility measure from person based and temporal components. This research showed the emergent properties of the system it simulates. The emergent properties can be driven by many factors. This is an important explanation why some urban models are increasingly more detailed (e.g. UrbanSim). This research could be a blueprint on how to evaluate the spatial impacts of automated driving on all these facets in a broader modelling approach.

9.6 RECOMMENDATIONS FOR URBAN PLANNERS

Whereas some sources (especially within popular media and in practice) propagate the benefits or threads of automated driving. This research had a neutral position towards vehicle automation. Nevertheless, this research provides adequate insights to make recommendations to urban planners on how to conduct spatial strategies to act on the emergence of automated driving:

- No scenario for automated driving used in this study is without implementation challenges despite all potential efficiency, safety and comfort gains of automated driving. This study shows that induced demand can be negative for the urban road network. Automated vehicles remain on road cars just as conventional vehicles and mass transit solutions will always be a requirement for accessible urban centres. Urban planners and policy makers are therefore urged to keep investing in mass transit services.
- Although diminishing of parking on streets and replace it by a valet-parking system to the fringes of the city can be a solution to make urban areas attractive, the consequences for the urban road network are negative. This means that one should be careful with speculating and planning for such a system. Parking should be preferably accommodated locally to prevent strong increase in vehicle kilometres in cities.
- The availability of housing and the housing market are of larger influence on urban development than automated vehicles. Therefore, the key to attractive urban environments lies in the development of urban neighbourhoods that facilitate sustainable mobility behaviour involving active mobility, public transport and car sharing. On latter aspect, automated driving might contribute. However, it is by no means a requirement.
- The study showed that when public transport becomes obsolete, large public transport nodes provide for large areas for urban redevelopment. The same applies for large inner-urban parking areas when parking is allocated differently. One important question is what to do in these new areas. From an urban planning perspective in connection to transportation, this research proposes the development of high quality high urban housing areas which promote sustainable travel behaviour as induced car travel is a serious threat for the urban road network. If large scale urban housing can diminish the need for car travel (automated or not), urban quality will improve. This notion coincides strongly with current popular planning paradigms. Hence, this research supports this paradigm and will not participate in promoting automated driving itself as a solution for attractive urban environments or urban mobility problems.

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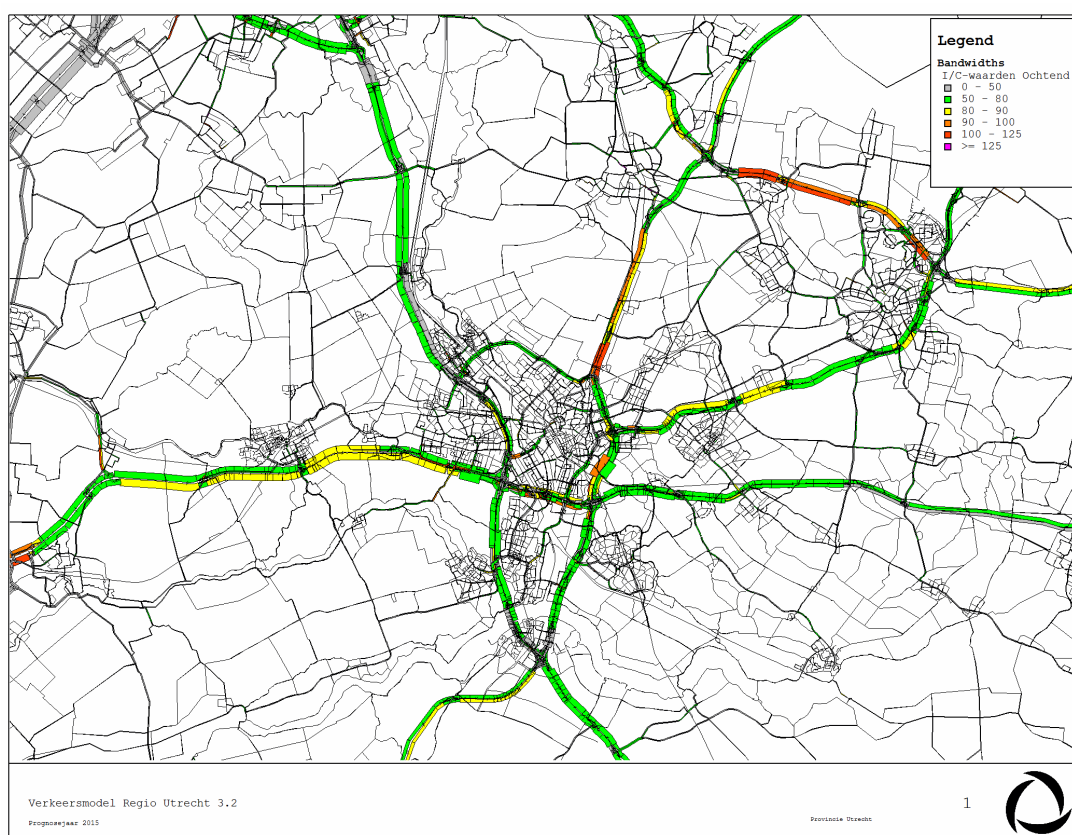
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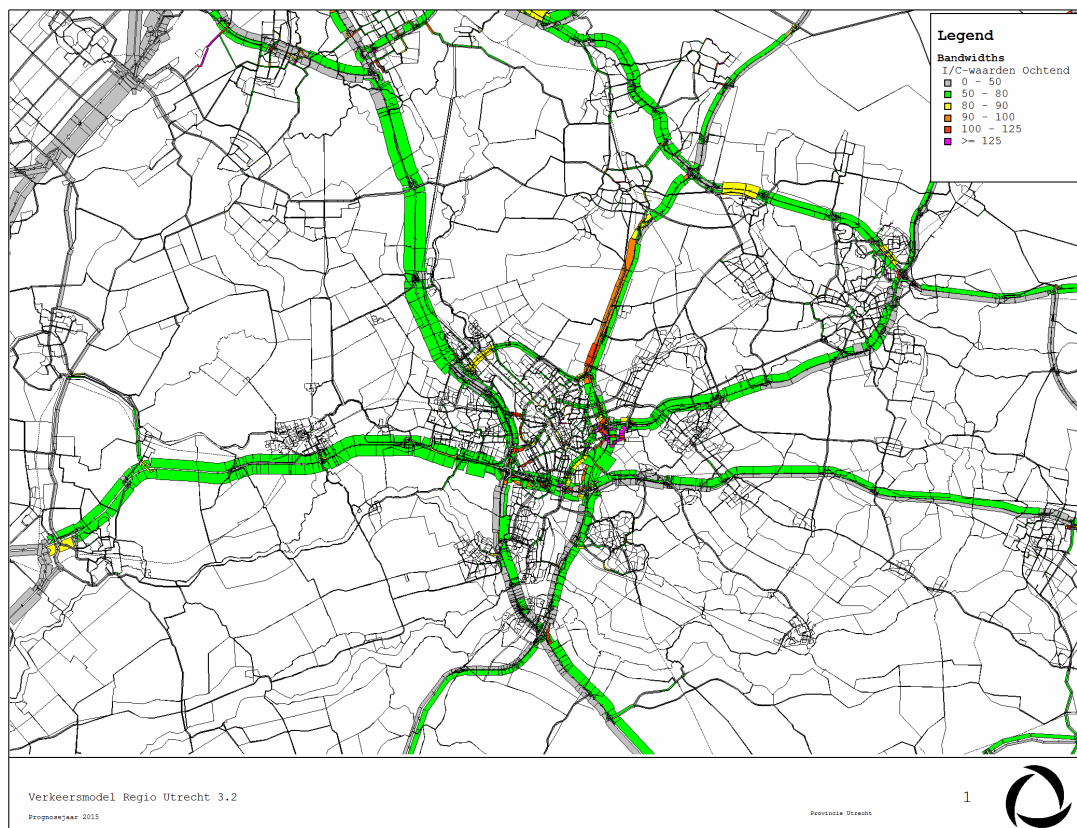
A IC-PLOTS PER SCENARIO



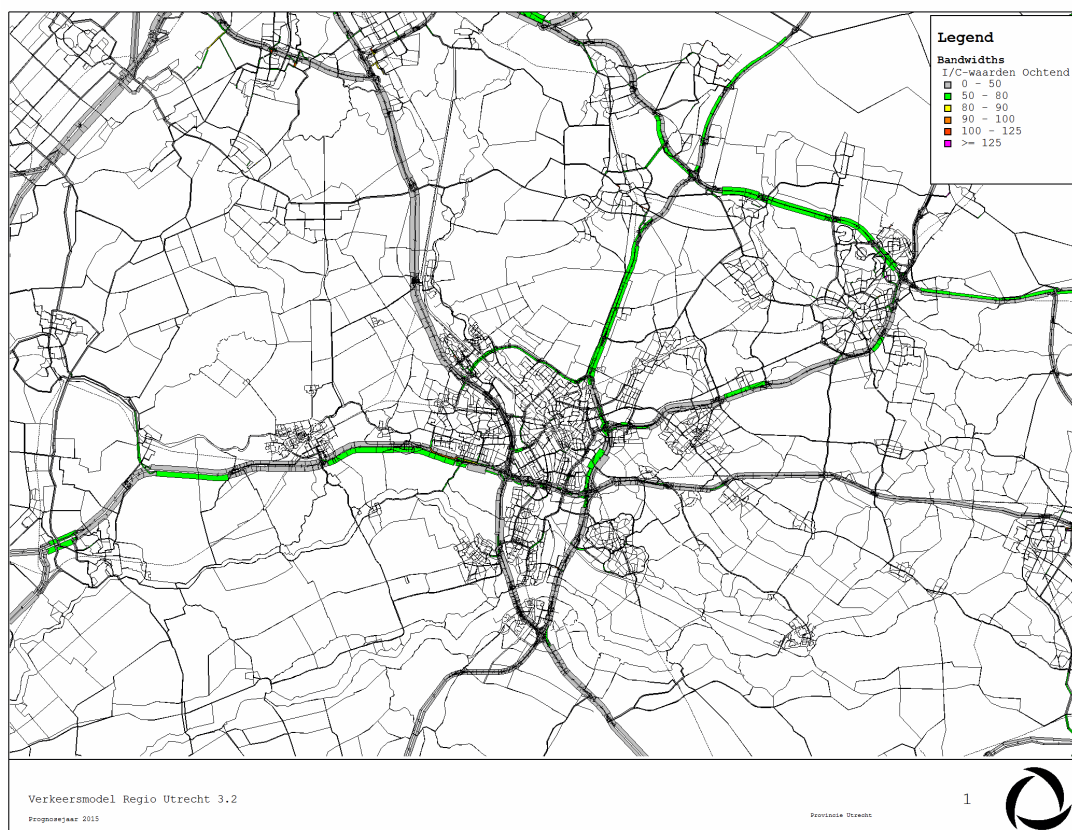
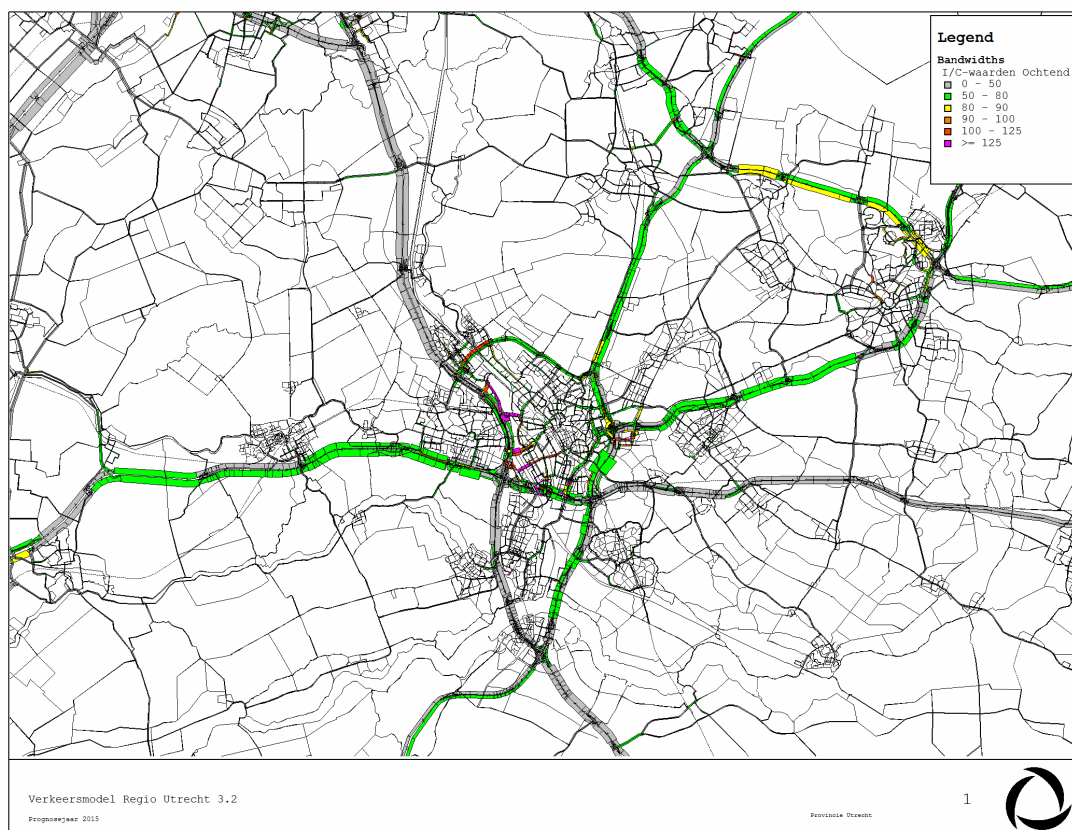
Appendix figure A-1: IC-plot for scenario 0: Base.

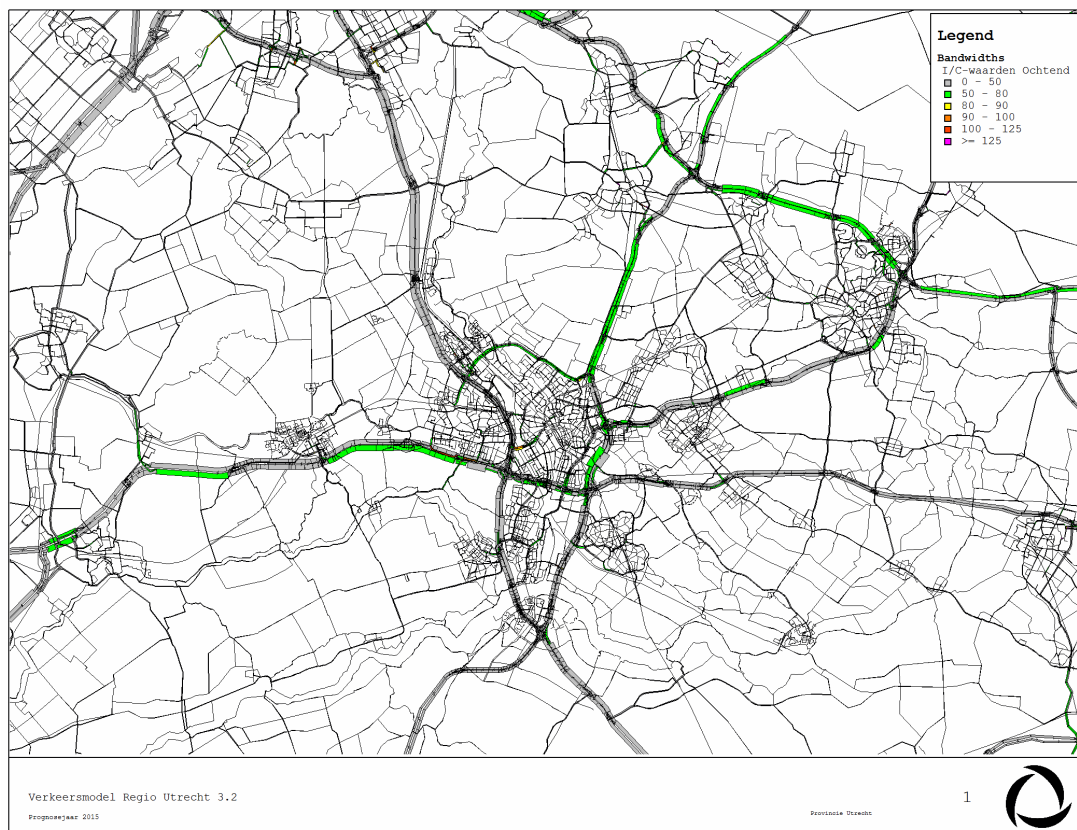


Appendix figure A-2: IC-plot for *scenario 1: Transformation* (without induced travel demand).

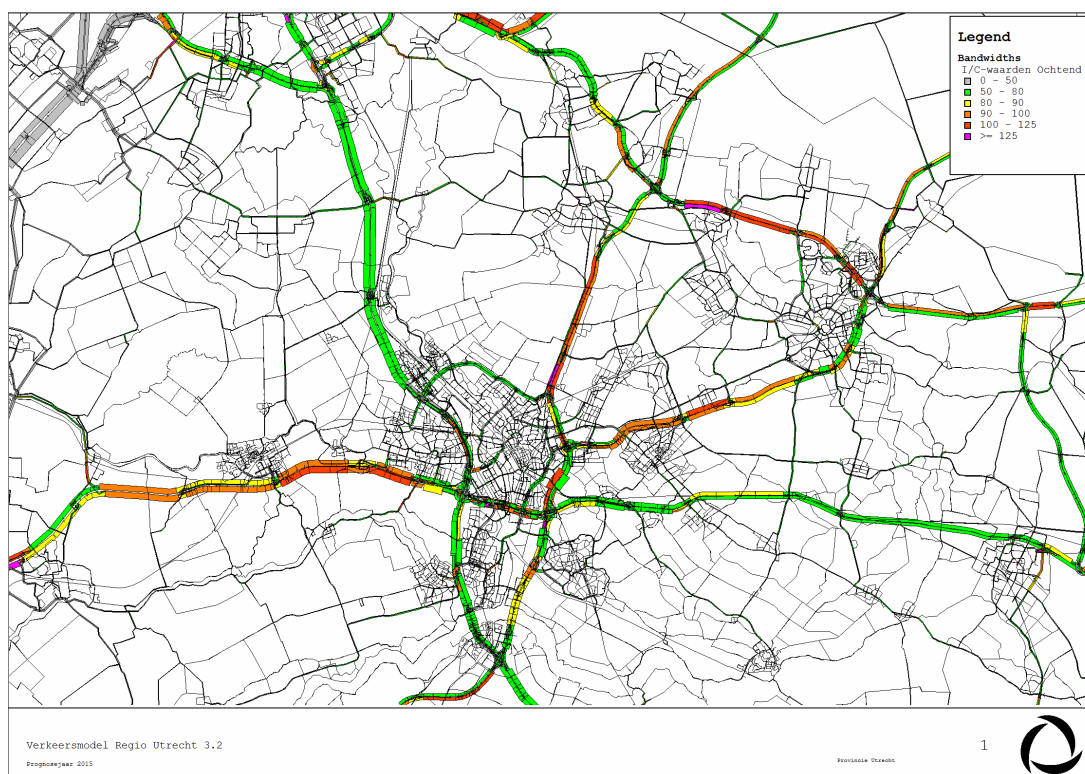


Appendix figure A-3: IC-plot for *scenario 1: Transformation* (with induced travel demand).

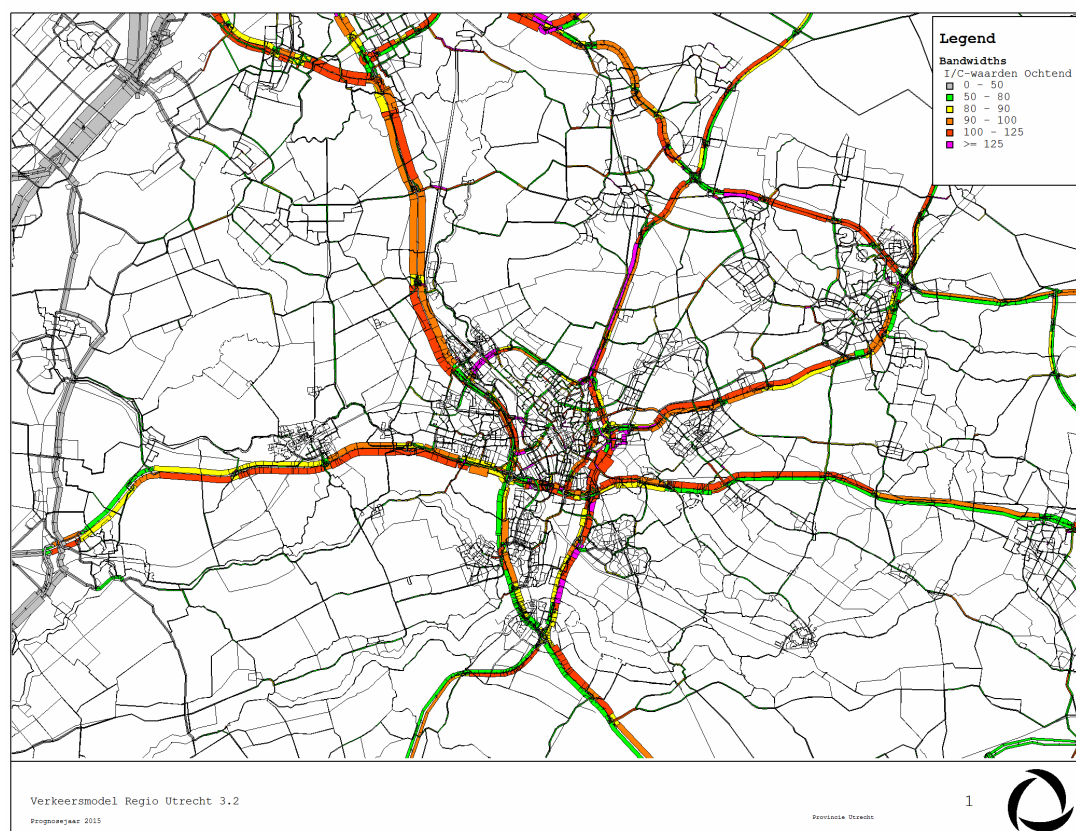
Appendix figure A-4: IC-plot for *scenario 2: Growth* (without induced travel demand).Appendix figure A-5: IC-plot for *scenario 2: Growth* (with induced travel demand).



Appendix figure A-6: IC-plot for *scenario 3: Constraint*



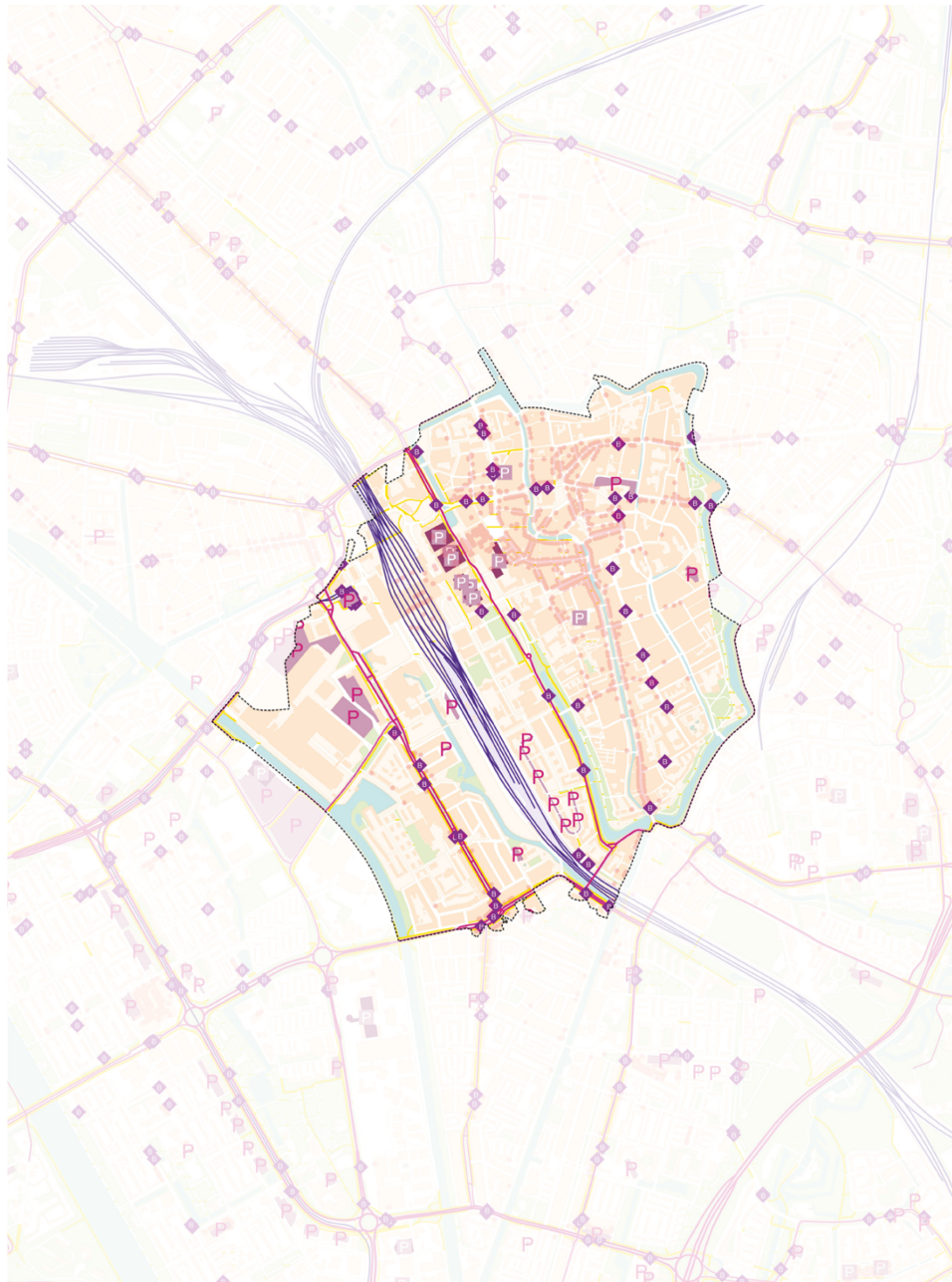
Appendix figure A-7: IC-plot for *scenario 4: Decline* (without induced travel demand).



Appendix figure A-8: IC-plot for *scenario 4: Decline* (with induced travel demand).

B URBAN TRANSFORMATION POTENTIAL MAPS

B.1 CENTRE-URBAN-PLUS



typology:
place:
#dwellings:
#employment buildings:
#amenity buildings:
% < 1940:
% 1940-1970:
% 1970-1990:
% > 1990:
dwelling density:

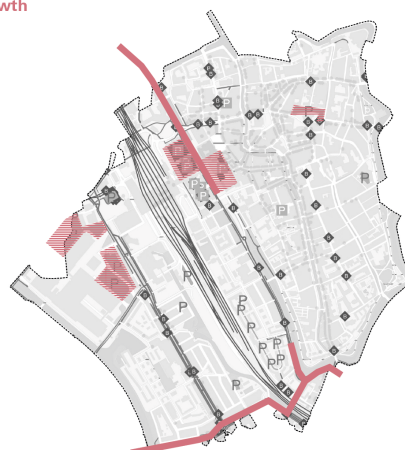
1. centrum stedelijk plus
Groot - Utrecht
12015
3032
1950
56.5 %
3.9 %
19.4 %
20.2 %
382 dwellings/ha

0 250 500 750 1000 1250 1500 m

transformation



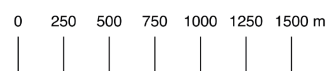
growth



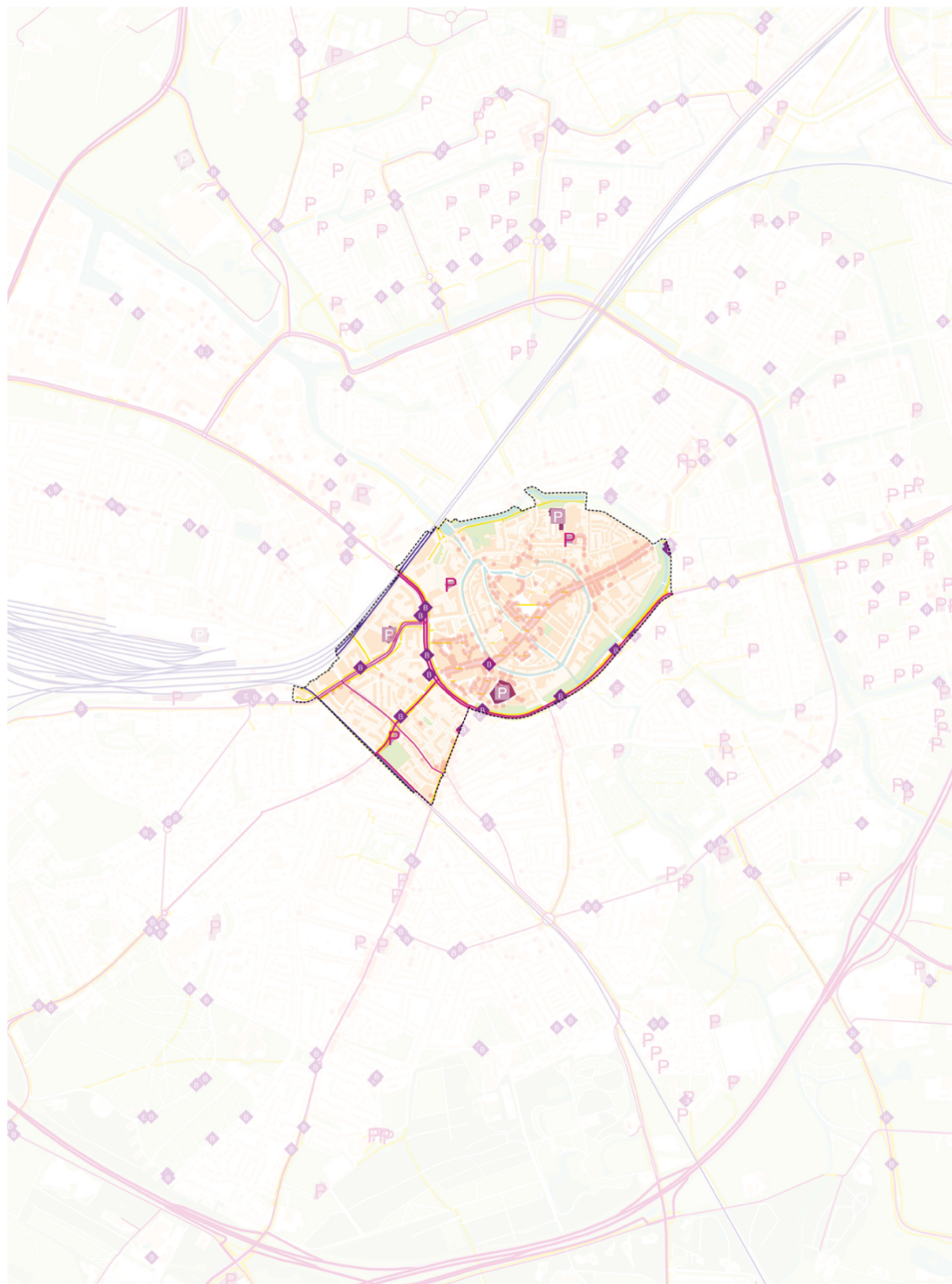
constraint



decline

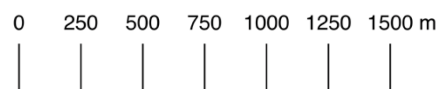


B.2 CENTRE-URBAN

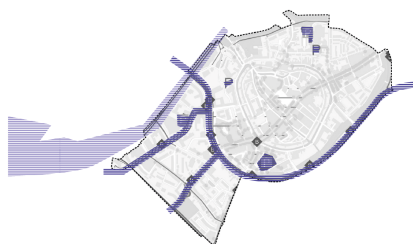


typology:
place:
#dwellings:
#employment buildings:
#amenity buildings:
% < 1940:
% 1940-1970:
% 1970-1990:
% > 1990:
dwelling density:

2. centrum stedelijk
Amersfoort
3761
355
668
44 %
4.9 %
28.1 %
23.1 %
38.2 dwellings/ha



transformation



growth



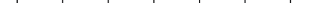
constraint



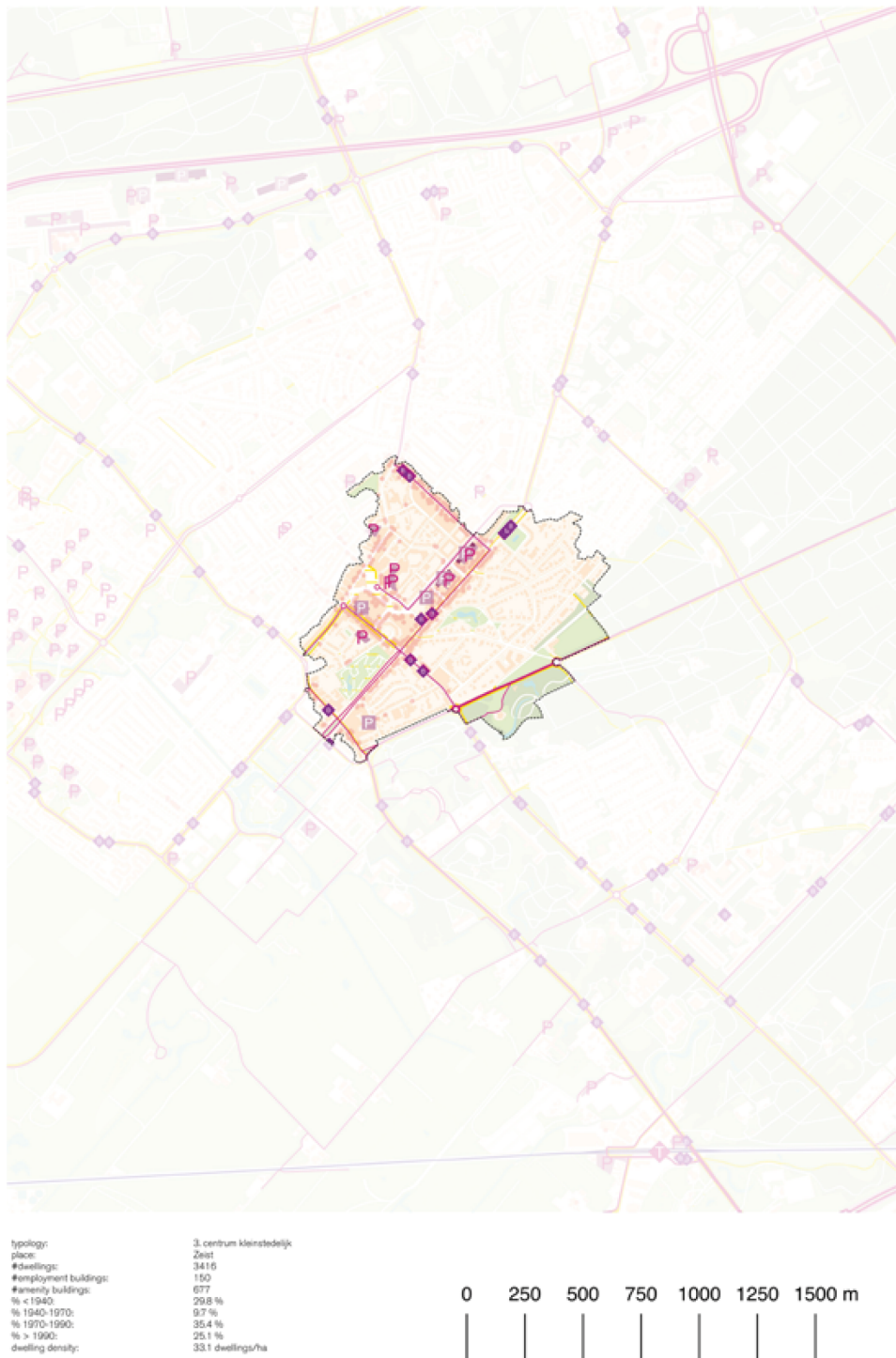
decline

 transformation potential spatial quality threat

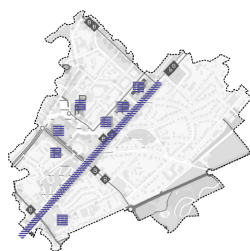
0 250 500 750 1000 1250 1500 m



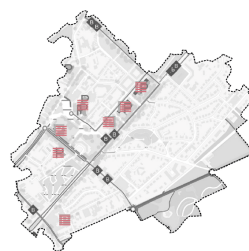
B.3 CENTRE-SMALL-URBAN



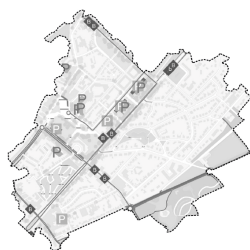
transformation



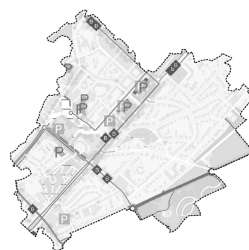
growth



constraint



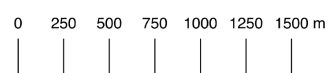
decline



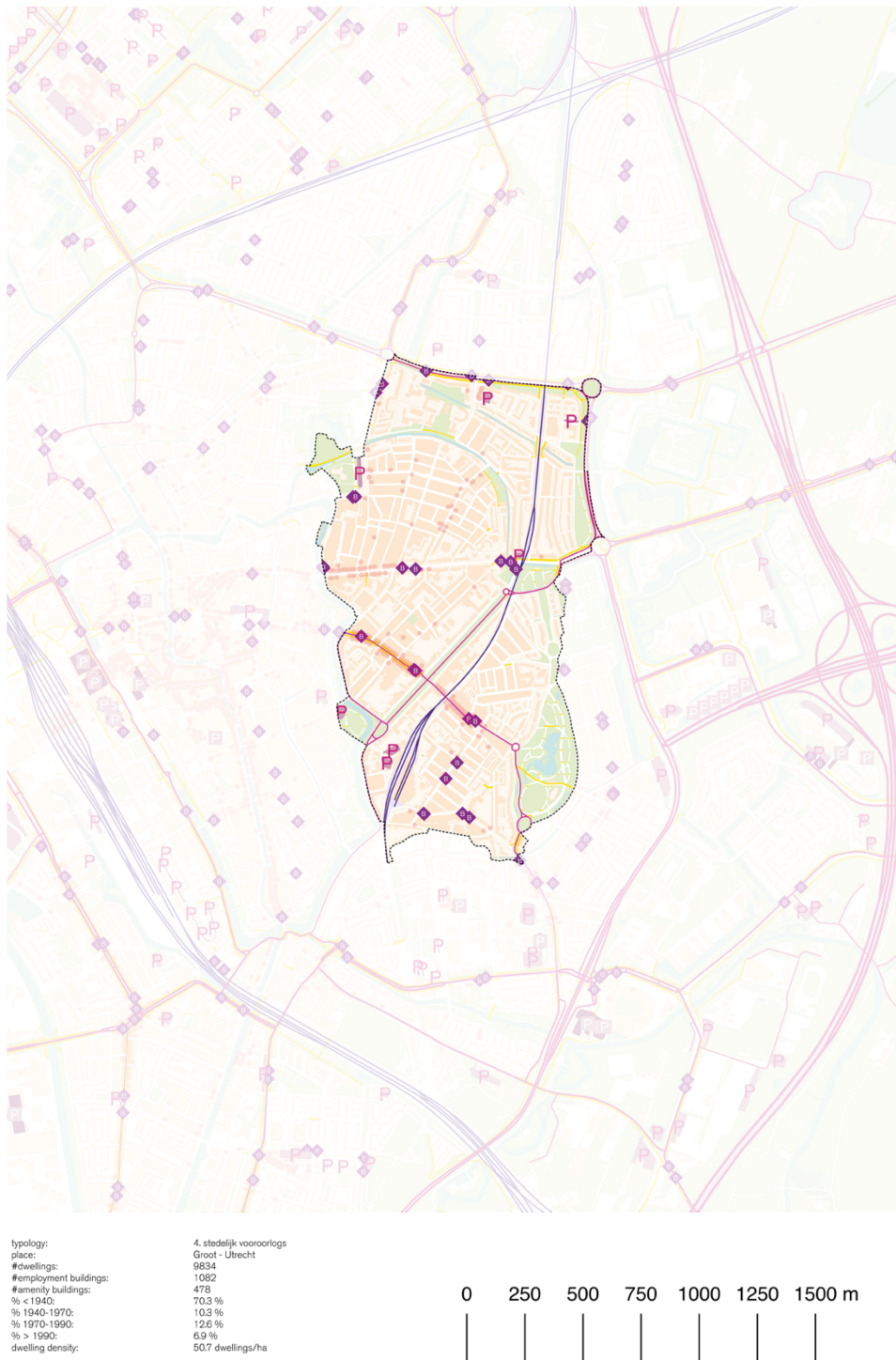
transformation potential



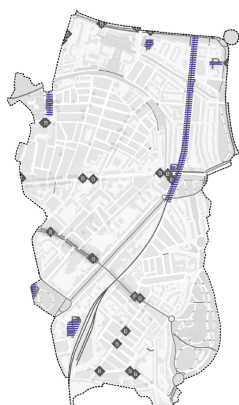
spatial quality threat



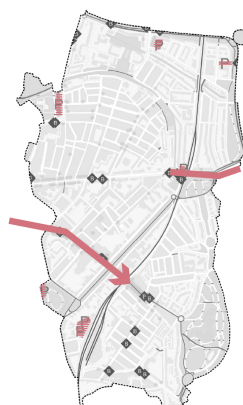
B.4 URBAN PRE-WAR



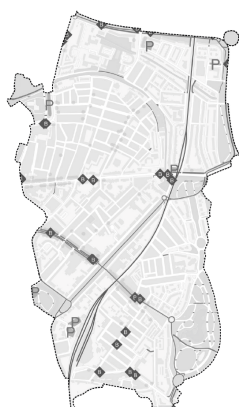
transformation



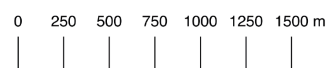
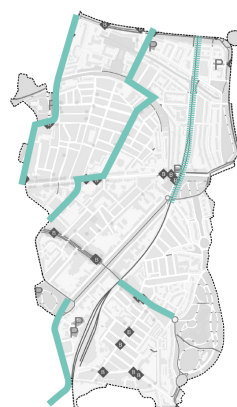
growth



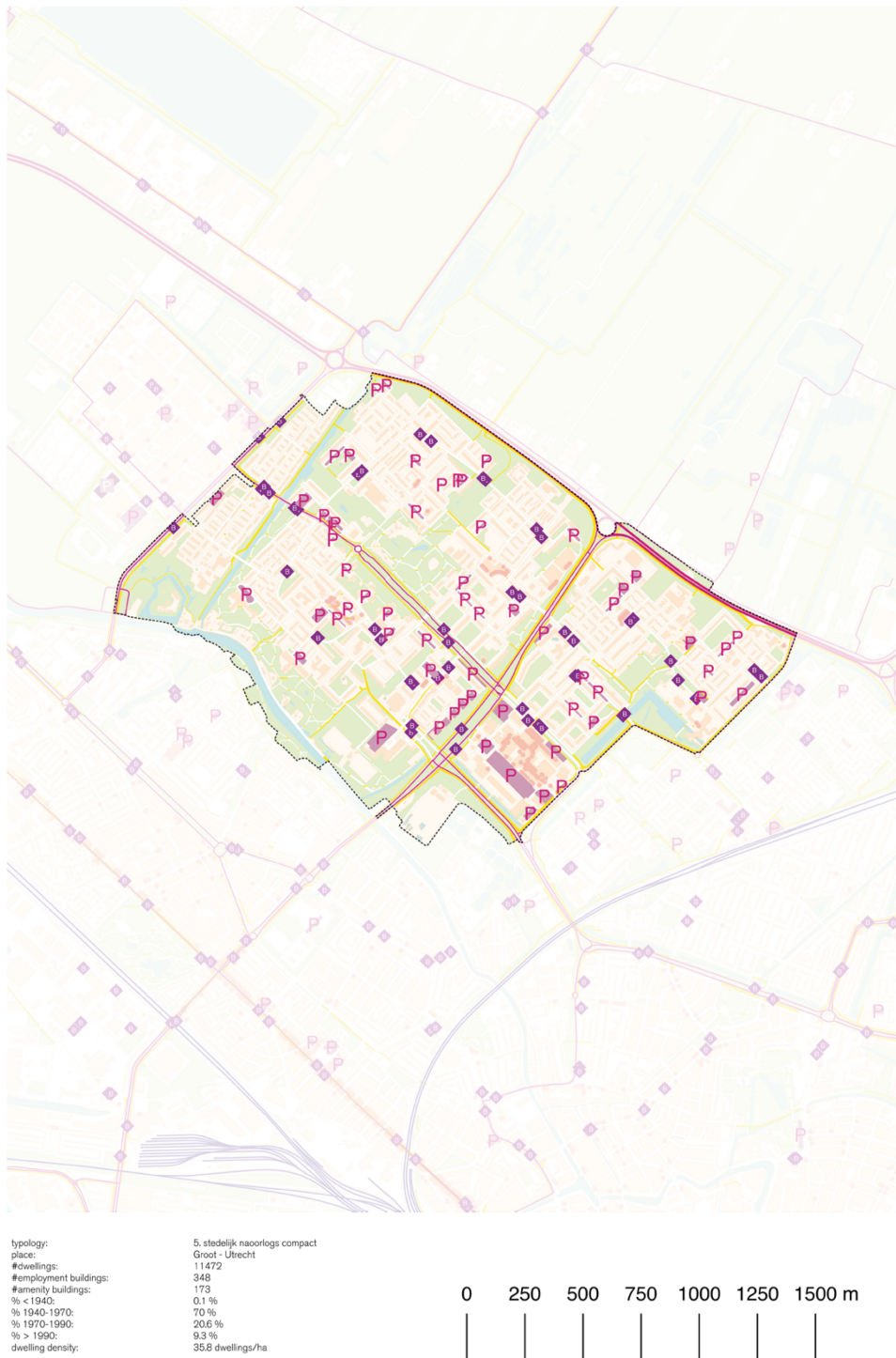
constraint



decline



B.5 URBAN POST-WAR COMPACT



transformation



growth



constraint



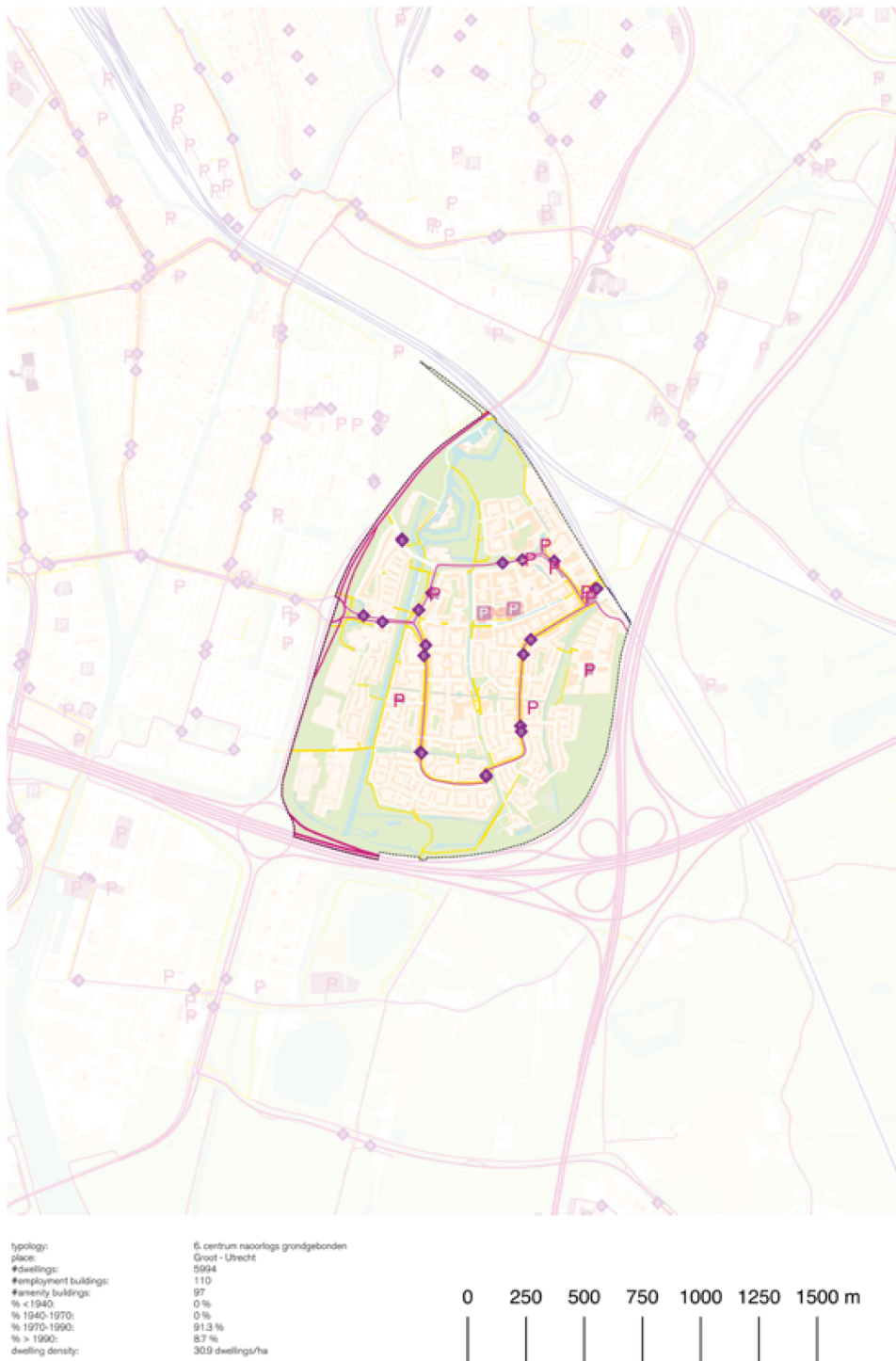
decline



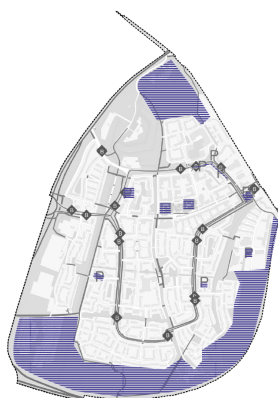
spatial quality threat

0 250 500 750 1000 1250 1500 m

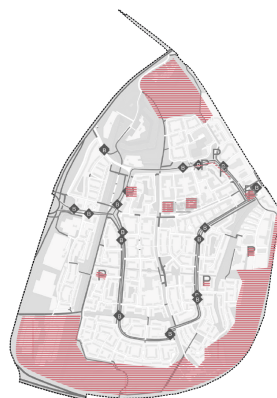
B.6 URBAN POST-WAR GROUND-LEVEL



transformation



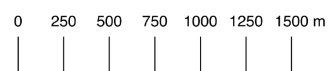
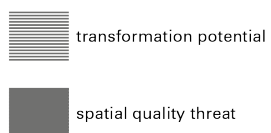
growth



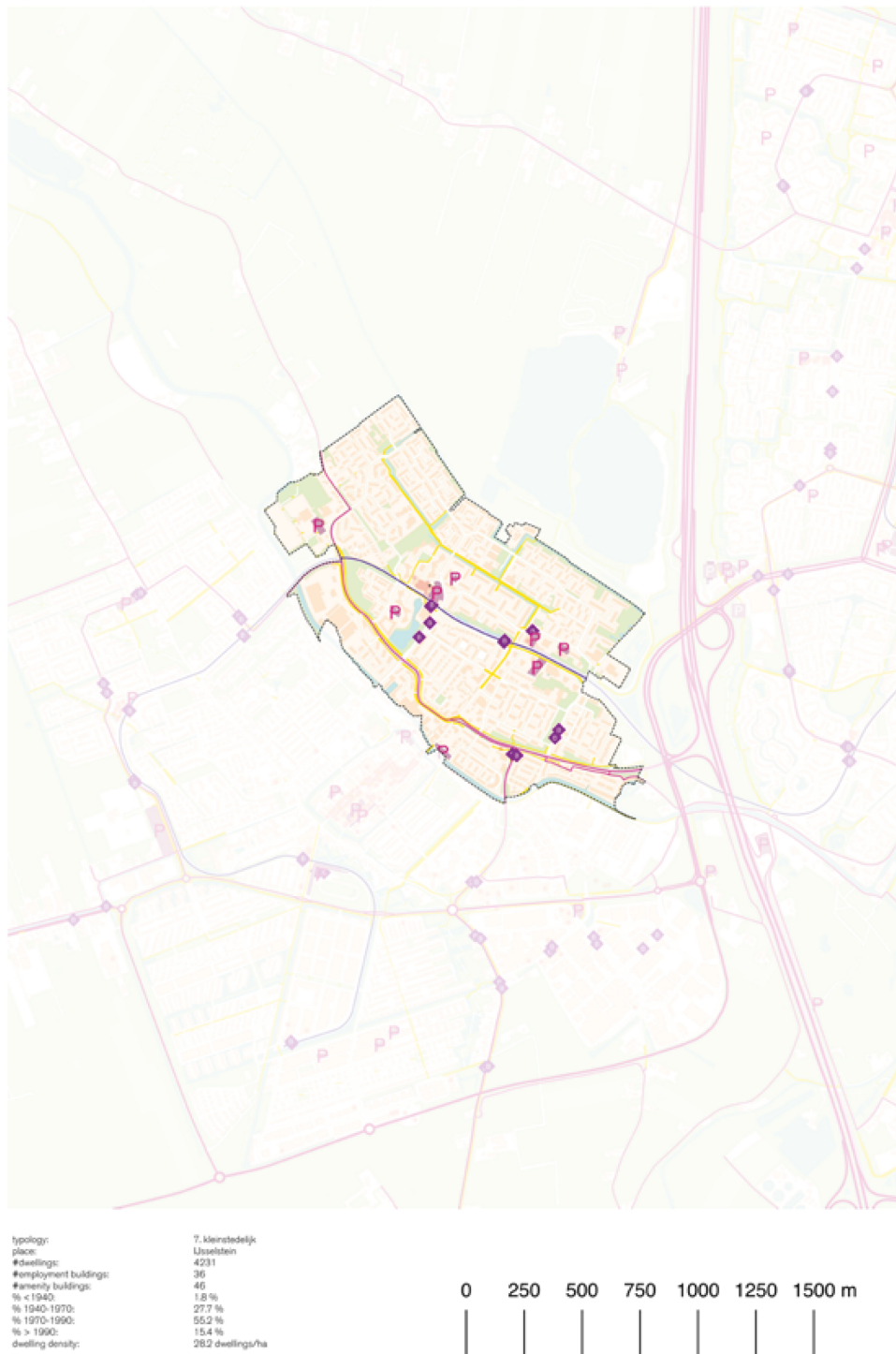
constraint



decline



B.7 SMALL-URBAN



transformation



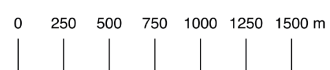
growth



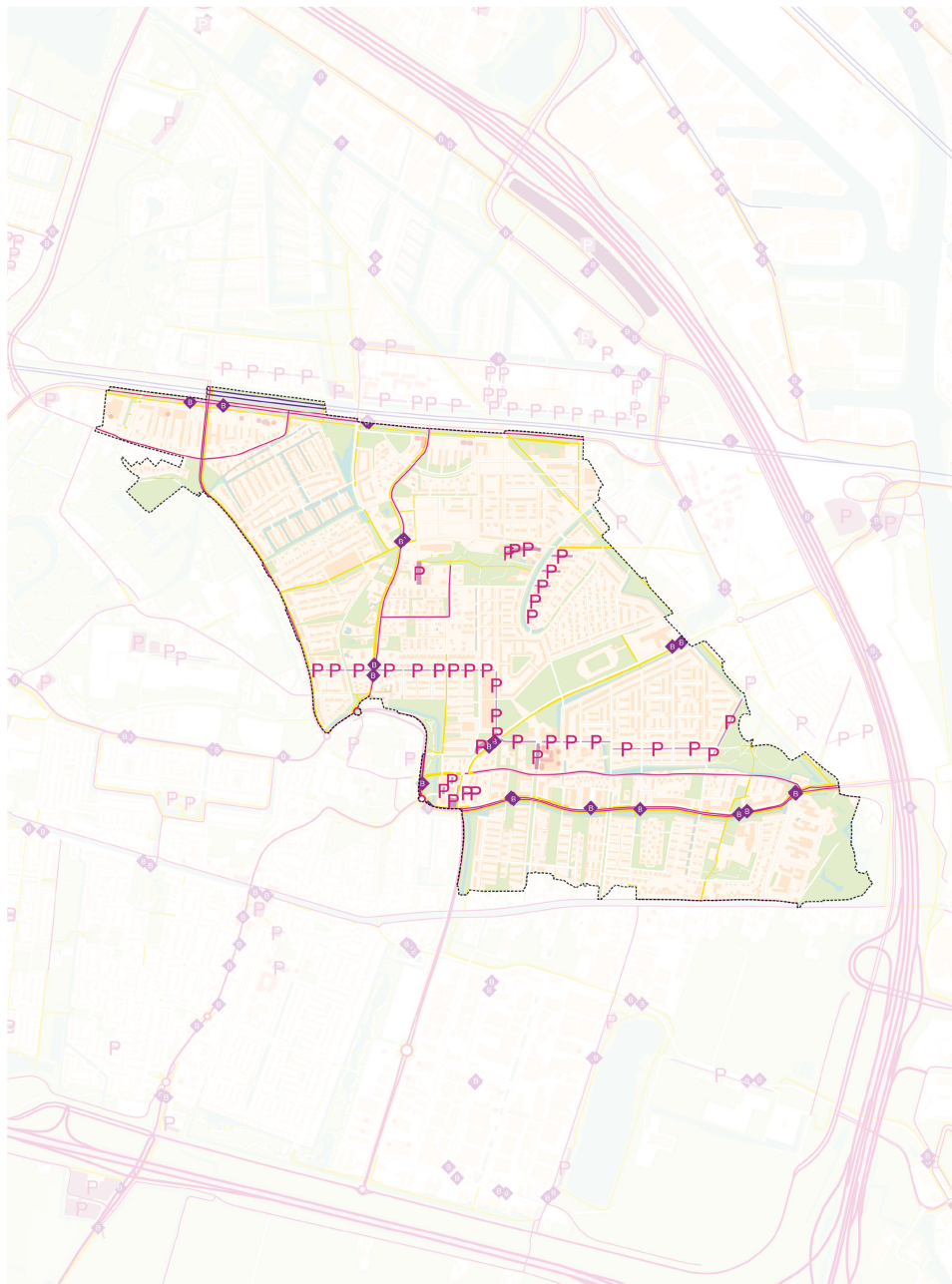
constraint



decline



B.8 GREEN-URBAN



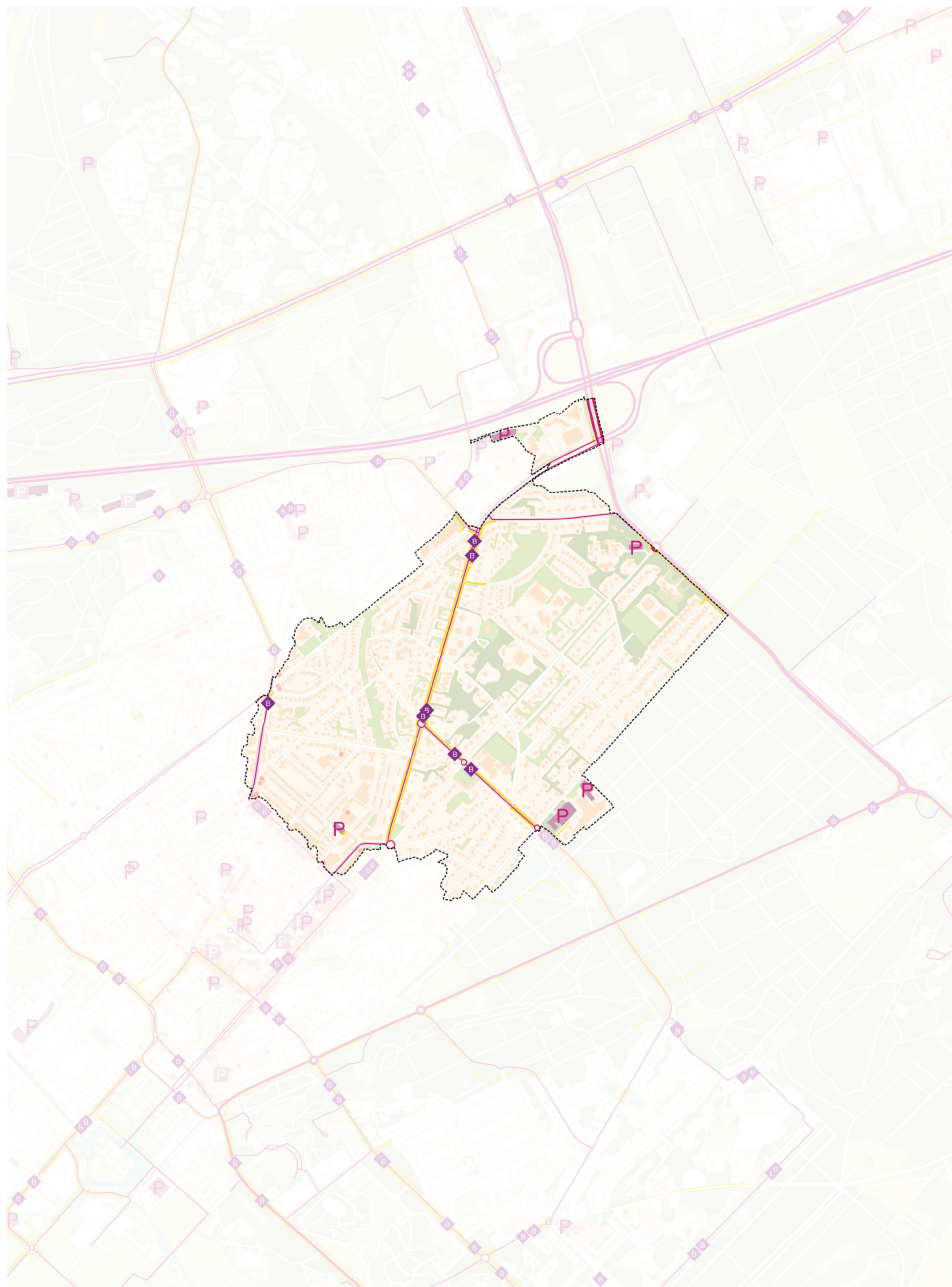
typology:
place:
#dwellings:
#employment buildings:
#amenity buildings:
% < 1940:
% 1940-1970:
% 1970-1990:
% > 1990:
dwelling density:

8. groen-stedelijk
Groot - Utrecht
7853
216
162
1.6 %
0.4 %
0.5 %
97.4 %
24.9 dwellings/ha

0 250 500 750 1000 1250 1500 m



B.9 GREEN-SMALL-URBAN



typology:	9 groen-kleinstedelijk
place:	Zeist
#dwellings:	2281
#employment buildings:	116
#amenity buildings:	41
% < 1940:	46.8 %
% 1940-1970:	19.1 %
% 1970-1990:	0.0 %
% > 1990:	27.5 %
dwelling density:	11.6 dwellings/ha

0 250 500 750 1000 1250 1500 m

transformation



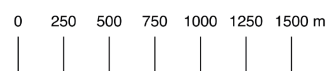
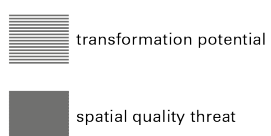
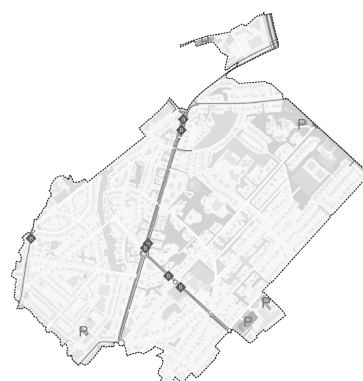
growth



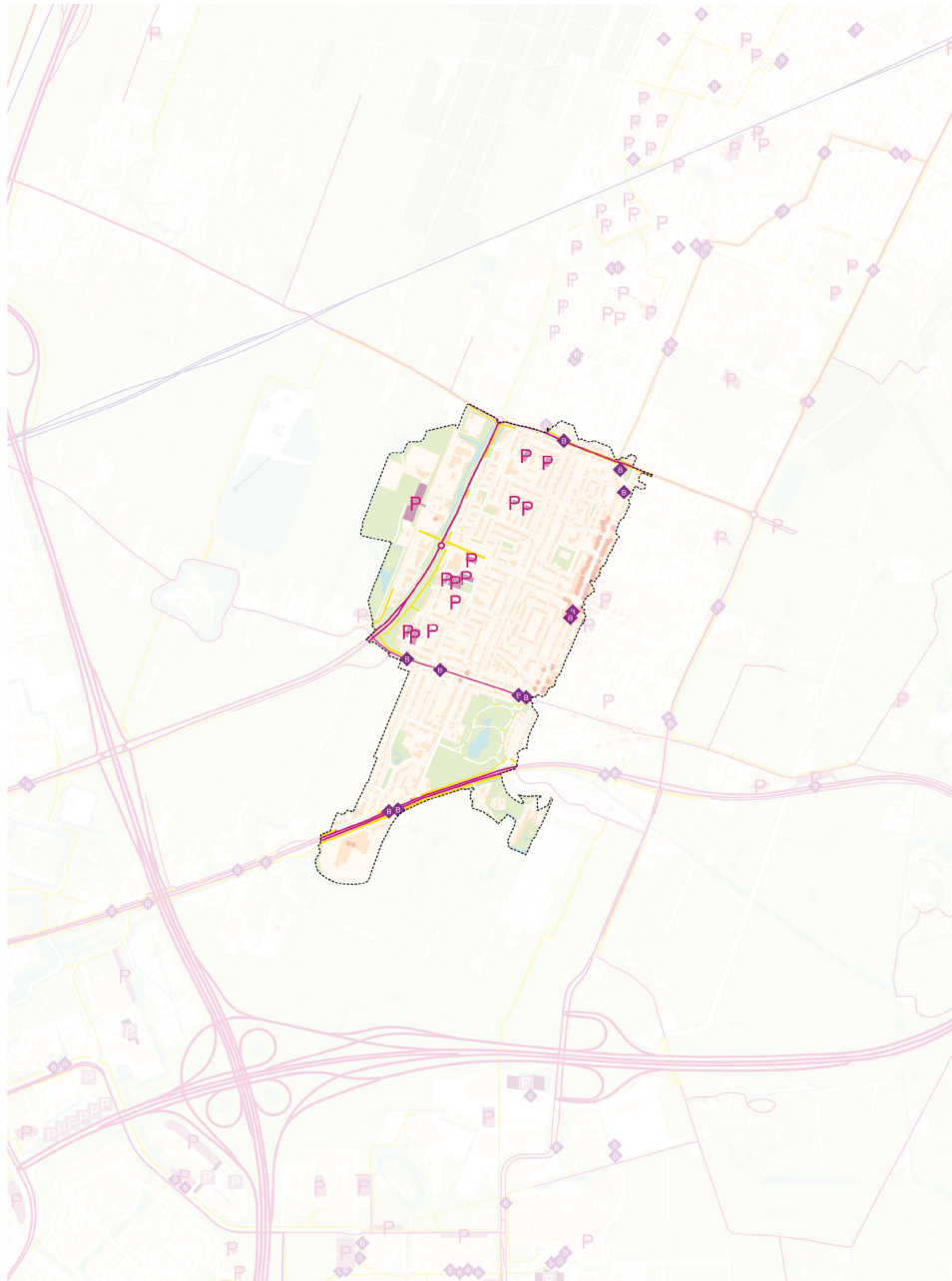
constraint



decline



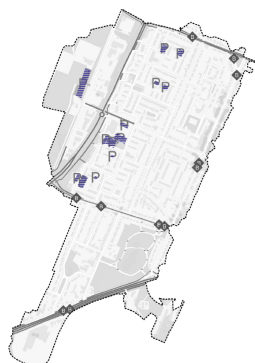
B.10 CENTRE-VILLAGE



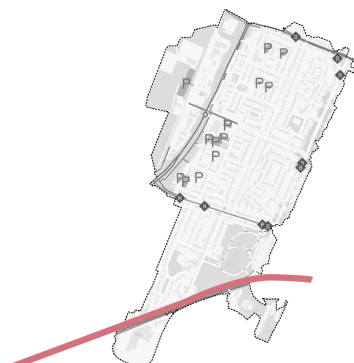
typology:	10. centrum-dorps
place:	Blithoven/De Bilt
#dwellings:	2648
#employment buildings:	48
#amenity buildings:	175
% < 1940:	27.8 %
% 1940-1970:	38.8 %
% 1970-1990:	20.8 %
% > 1990:	12.6 %
dwelling density:	20.3 dwellings/ha

0 250 500 750 1000 1250 1500 m

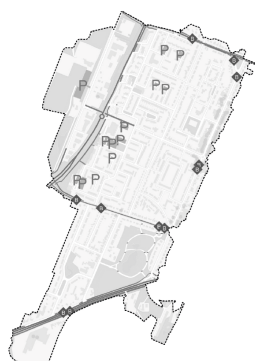
transformation



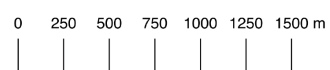
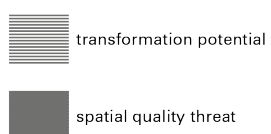
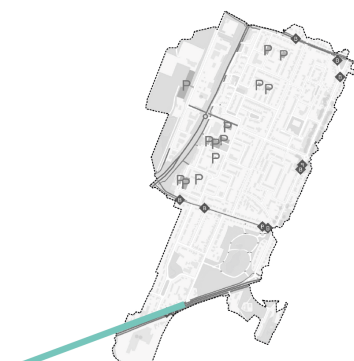
growth



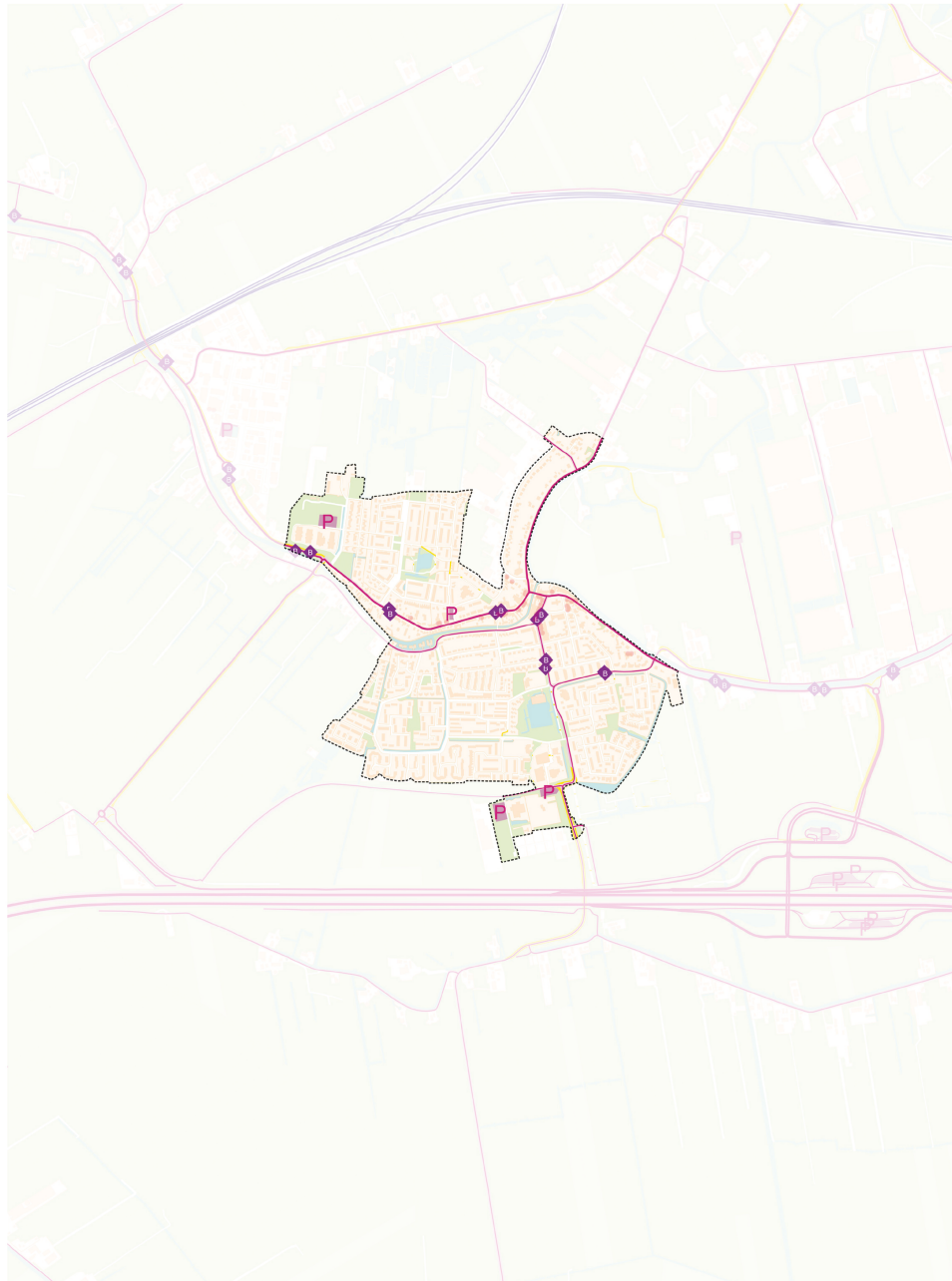
constraint



decline



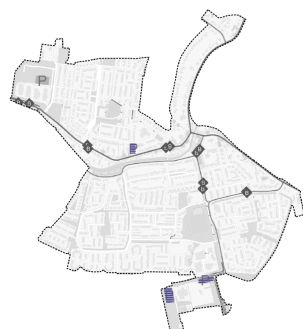
B.11 VILLAGE



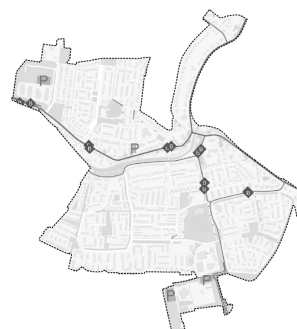
typology:	11, dorps
place:	Harmelen
#dwellings:	2892
#employment buildings:	33
#amenity buildings:	64
% < 1940:	63 %
% 1940-1970:	31.4 %
% 1970-1990:	46.2 %
% > 1990:	16.1 %
dwelling density:	22.1 dwellings/ha

0 250 500 750 1000 1250 1500 m

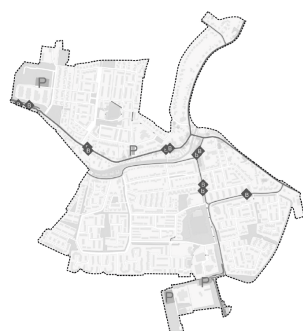
transformation



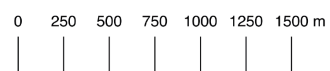
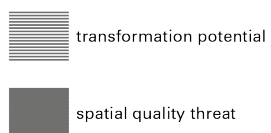
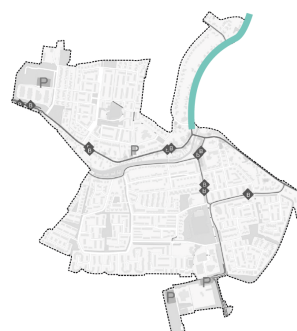
growth



constraint



decline



B.12 RURAL



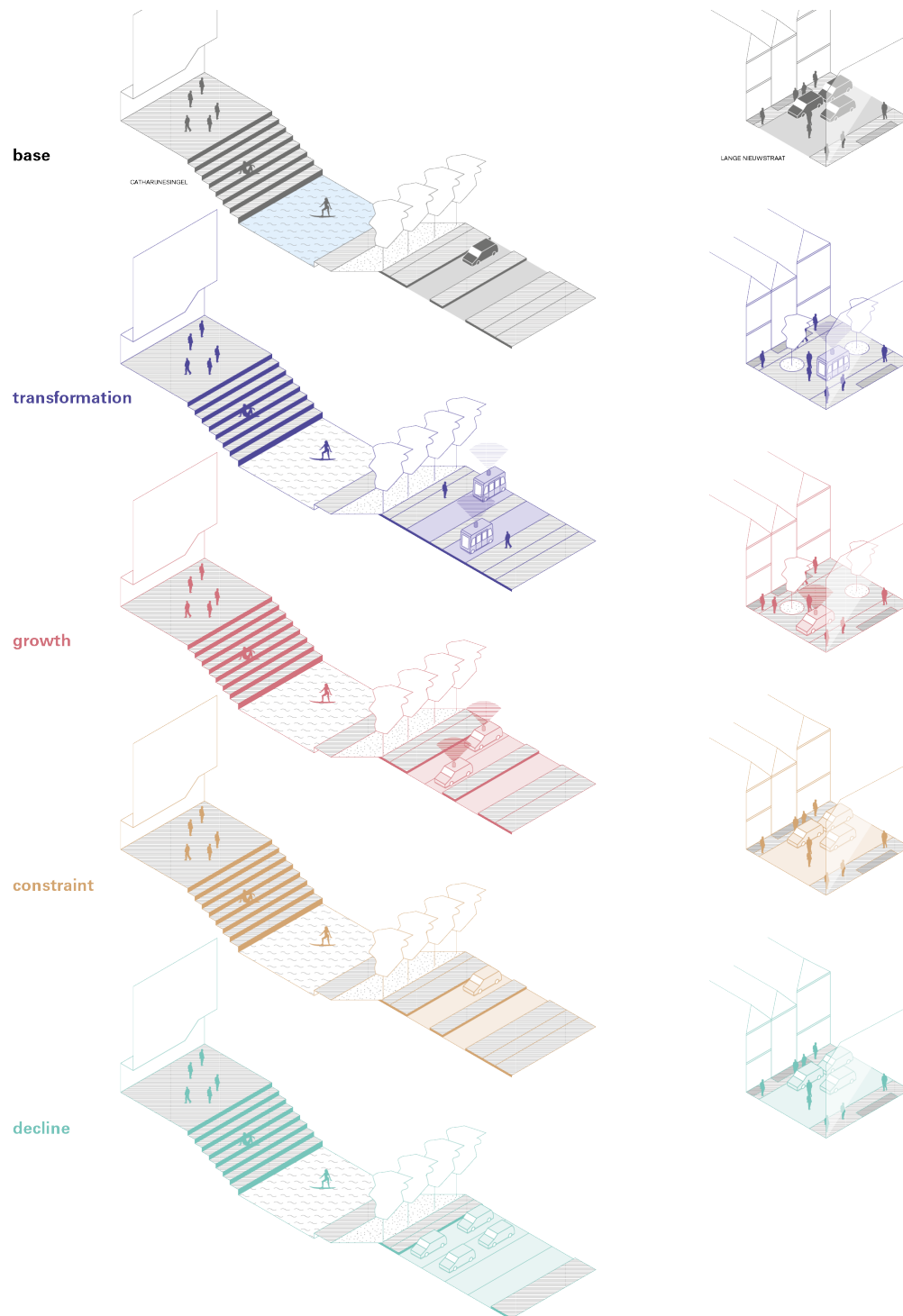
typology: 12. landelijk
 place:
 #dwellings: 111
 #employment buildings: 37
 #amenity buildings: 2
 % < 1940: 37.3 %
 % 1940-1970: 24.5 %
 % 1970-1990: 13.6 %
 % > 1990: 24.5 %
 dwelling density: 0.3 dwellings/ha

0 250 500 750 1000 1250 1500 m



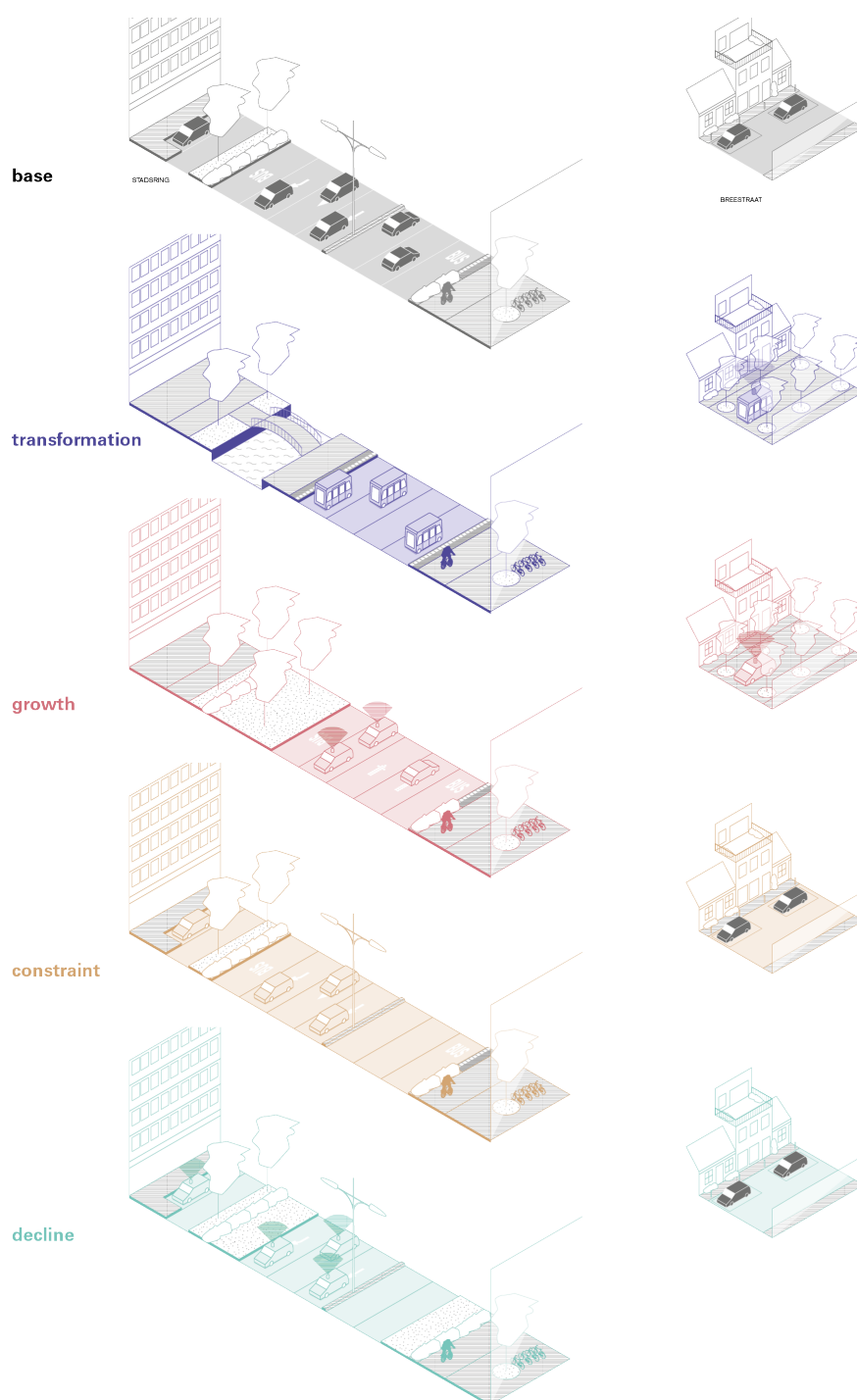
C SPATIAL QUALITY ASSESSMENT DRAWINGS

C.1 CENTRE-URBAN-PLUS



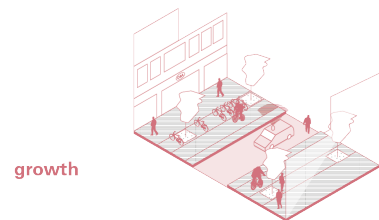
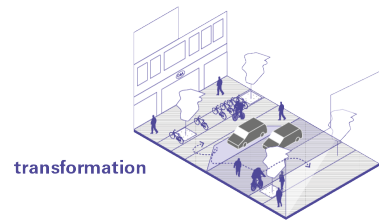
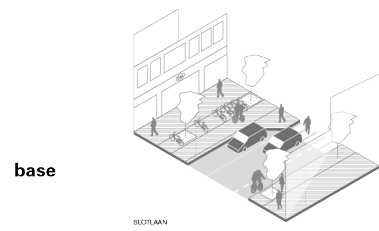
Appendix figure C-1: Road and street section for neighbourhood typology 1. Centre-urban-plus.

C.2 CENTRE-URBAN



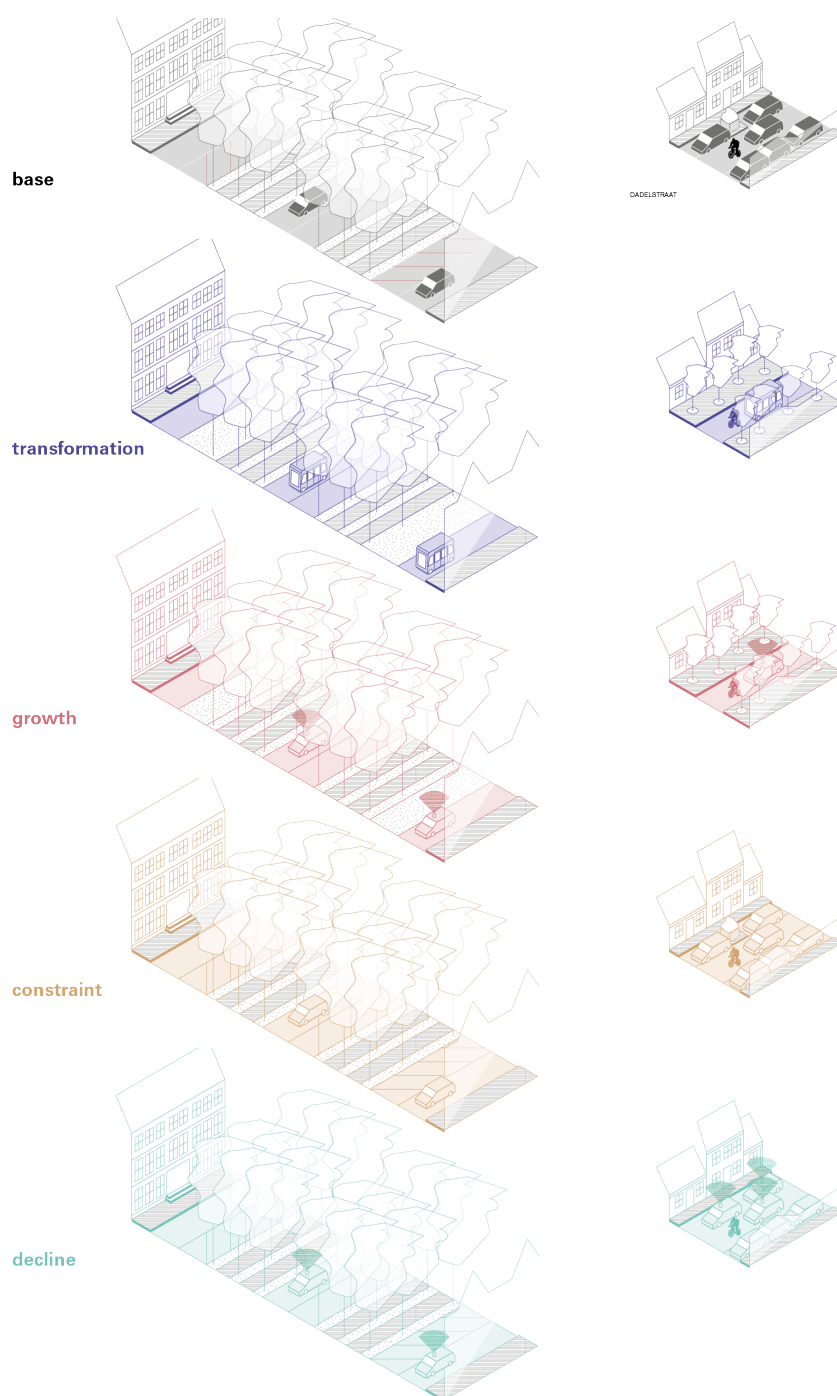
Appendix figure C-2: Road and street section for neighbourhood typology 2. Centre-urban.

C.3 CENTRE-SMALL URBAN



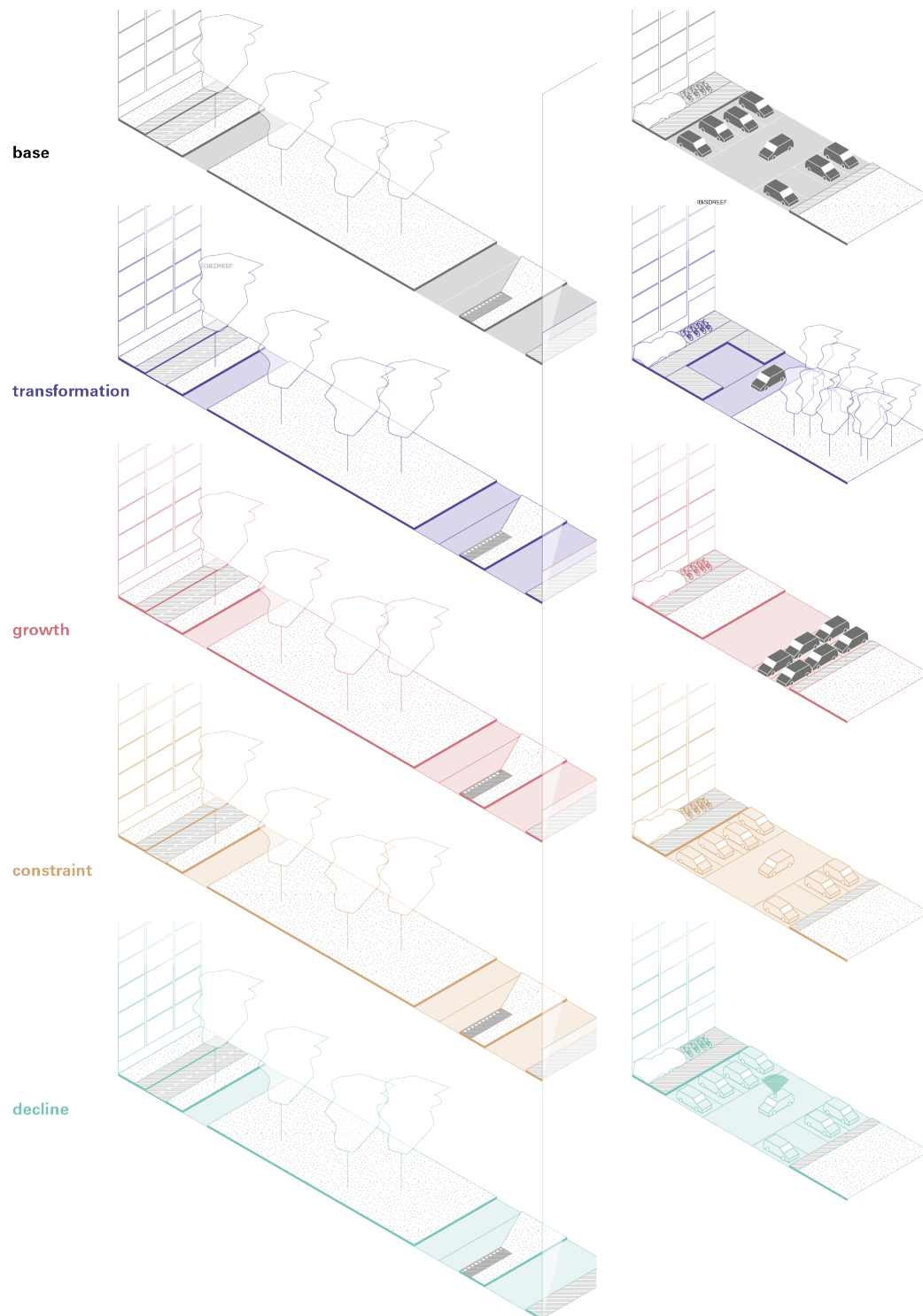
Appendix figure C-3: Road for neighbourhood typology 3. Centre-small-urban. No representative street has been found. Therefore, the street from typology 2 has been considered.

C.4 URBAN PRE-WAR



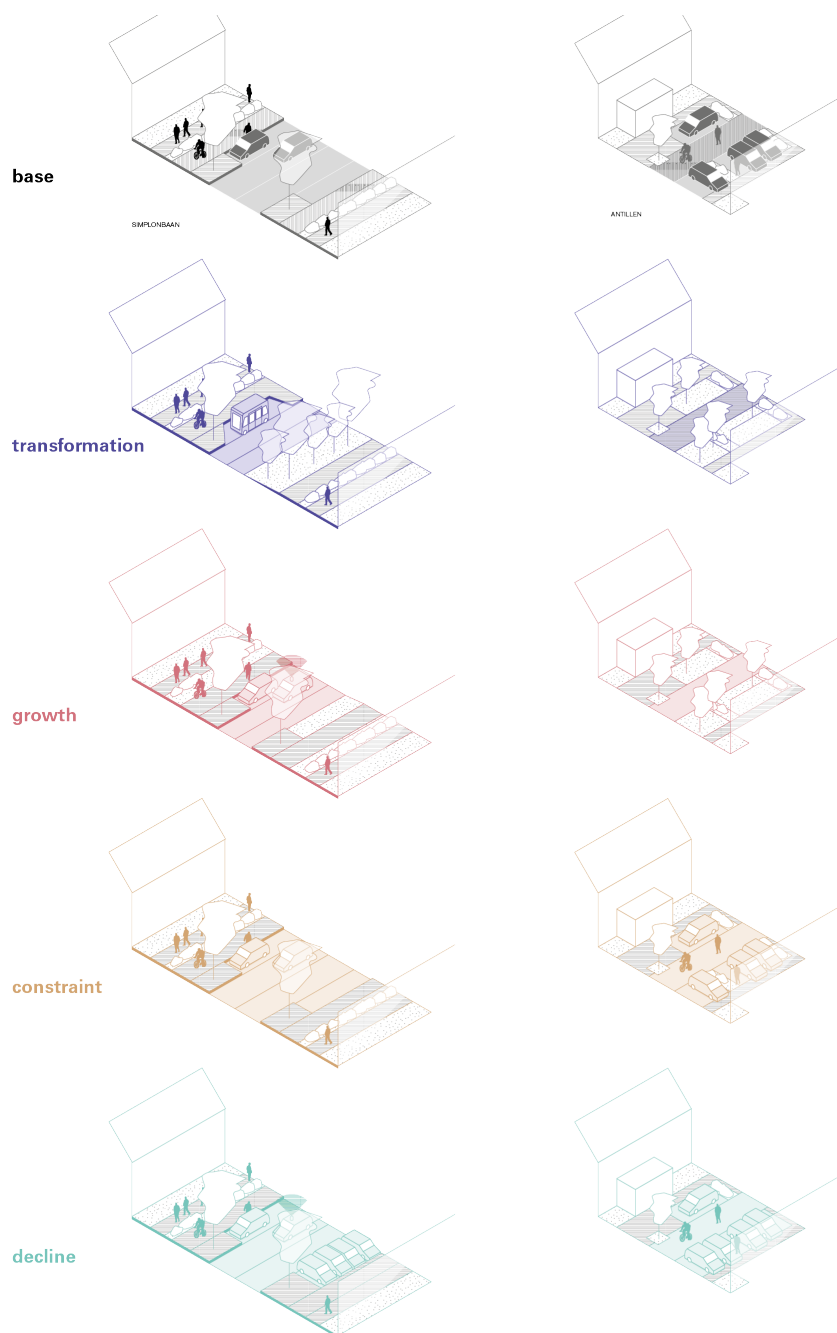
Appendix figure C-4: Road and street section for neighbourhood typology 4. Urban pre-war.

C.5 URBAN POST-WAR COMPACT



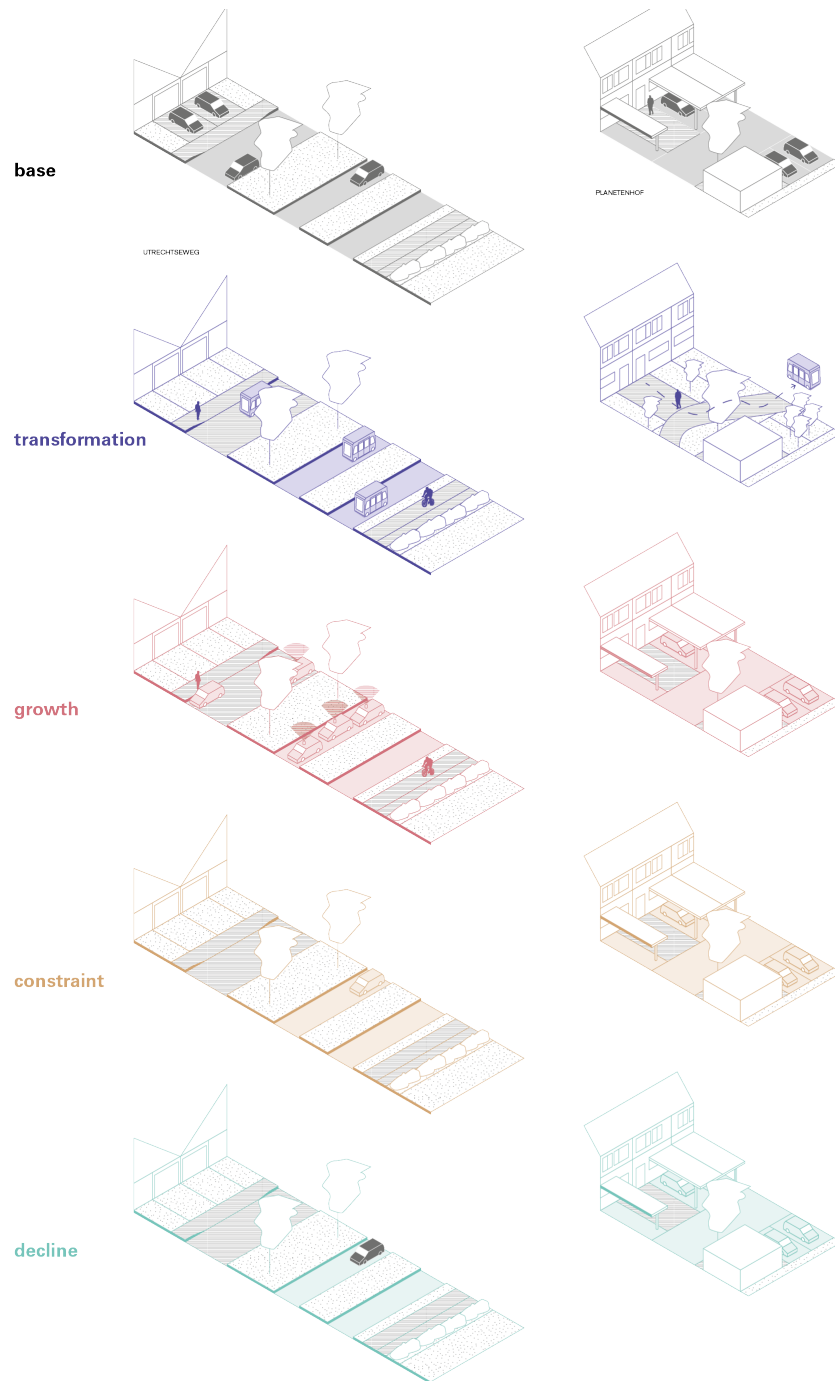
Appendix figure C-5: Road and street section for neighbourhood typology 5. Urban post-war compact.

C.6 URBAN POST-WAR GROUND-LEVEL



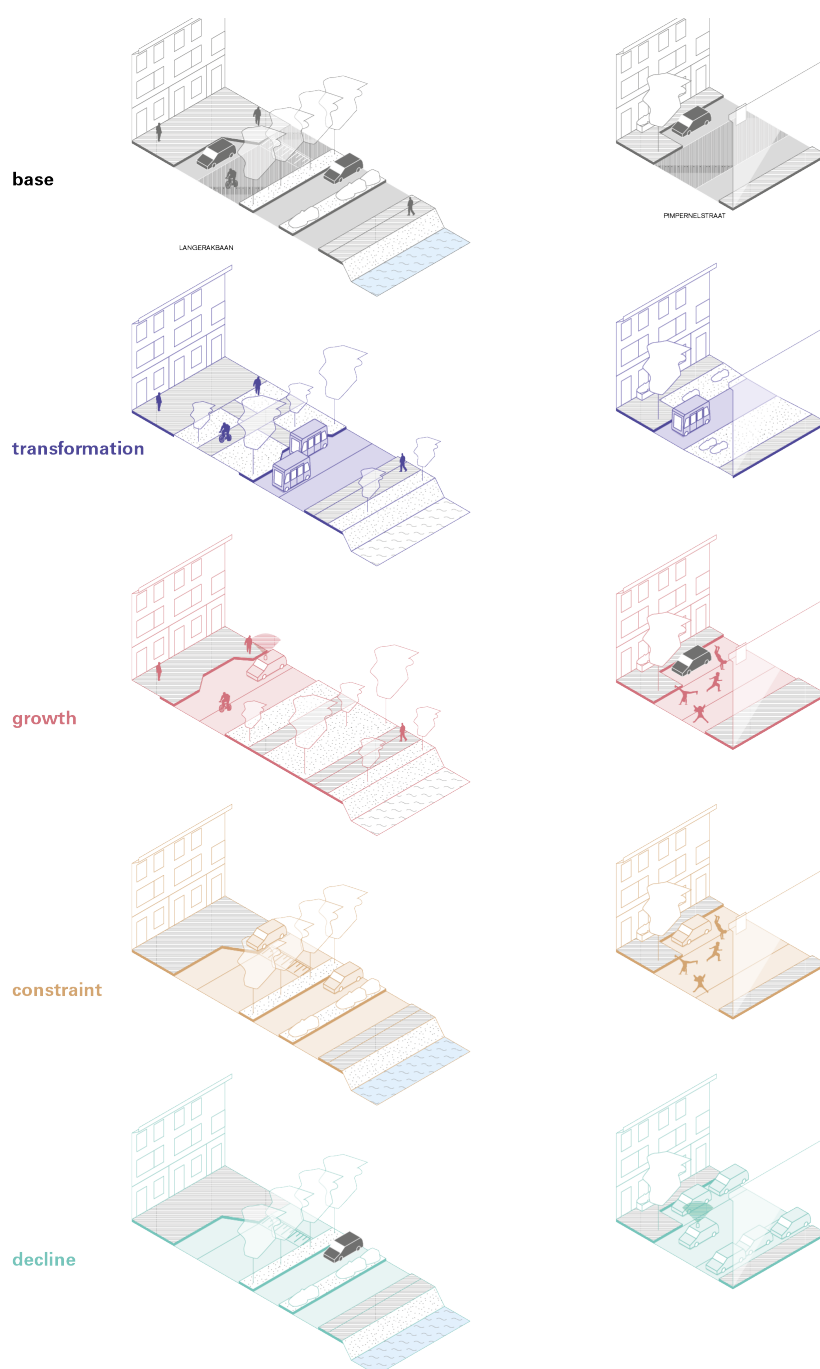
Appendix figure C-6: Road and street section for neighbourhood typology 6. Urban post-war ground-level.

C.7 SMALL-URBAN



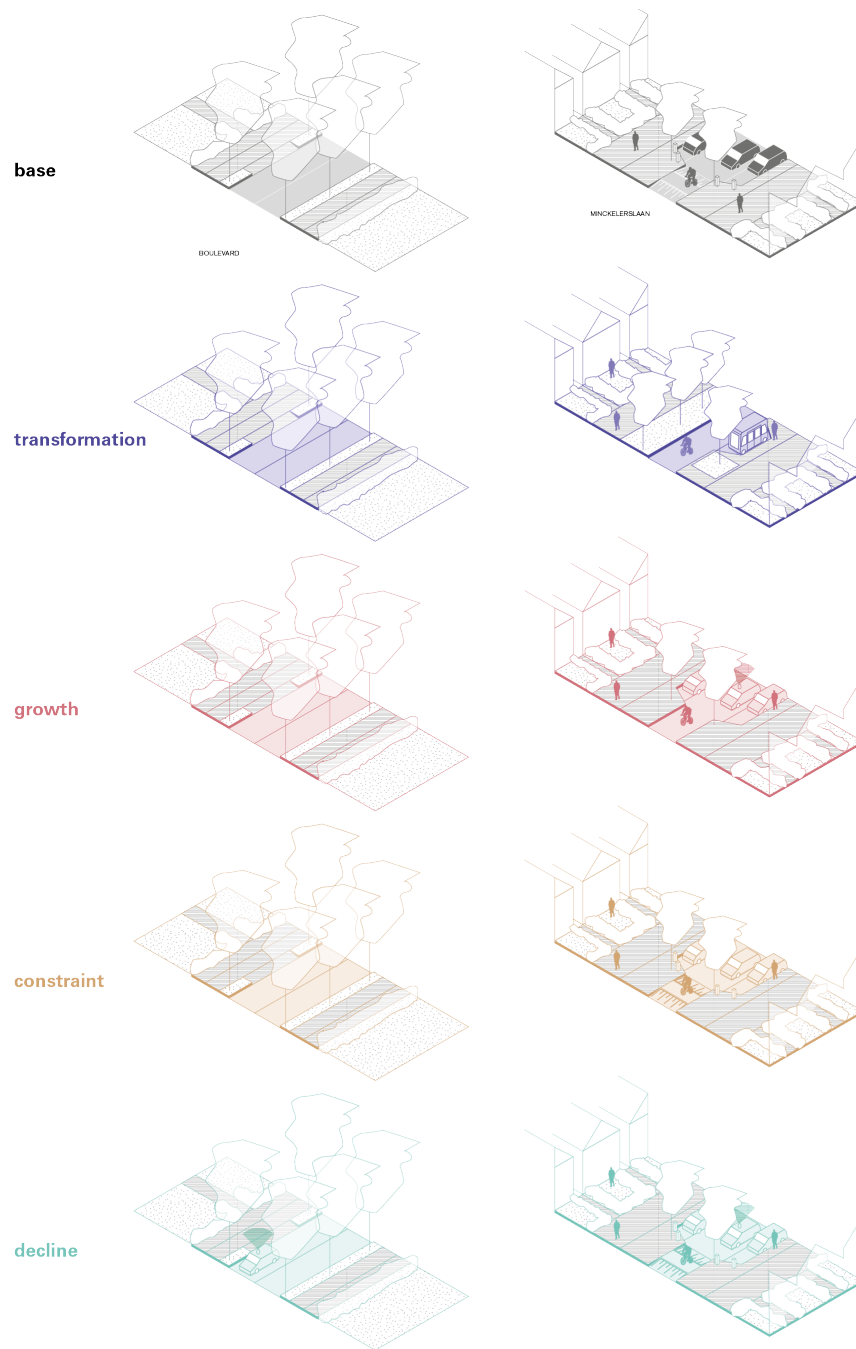
Appendix figure C-7: Road and street section for neighbourhood typology 7. Small-urban.

C.8 GREEN-URBAN



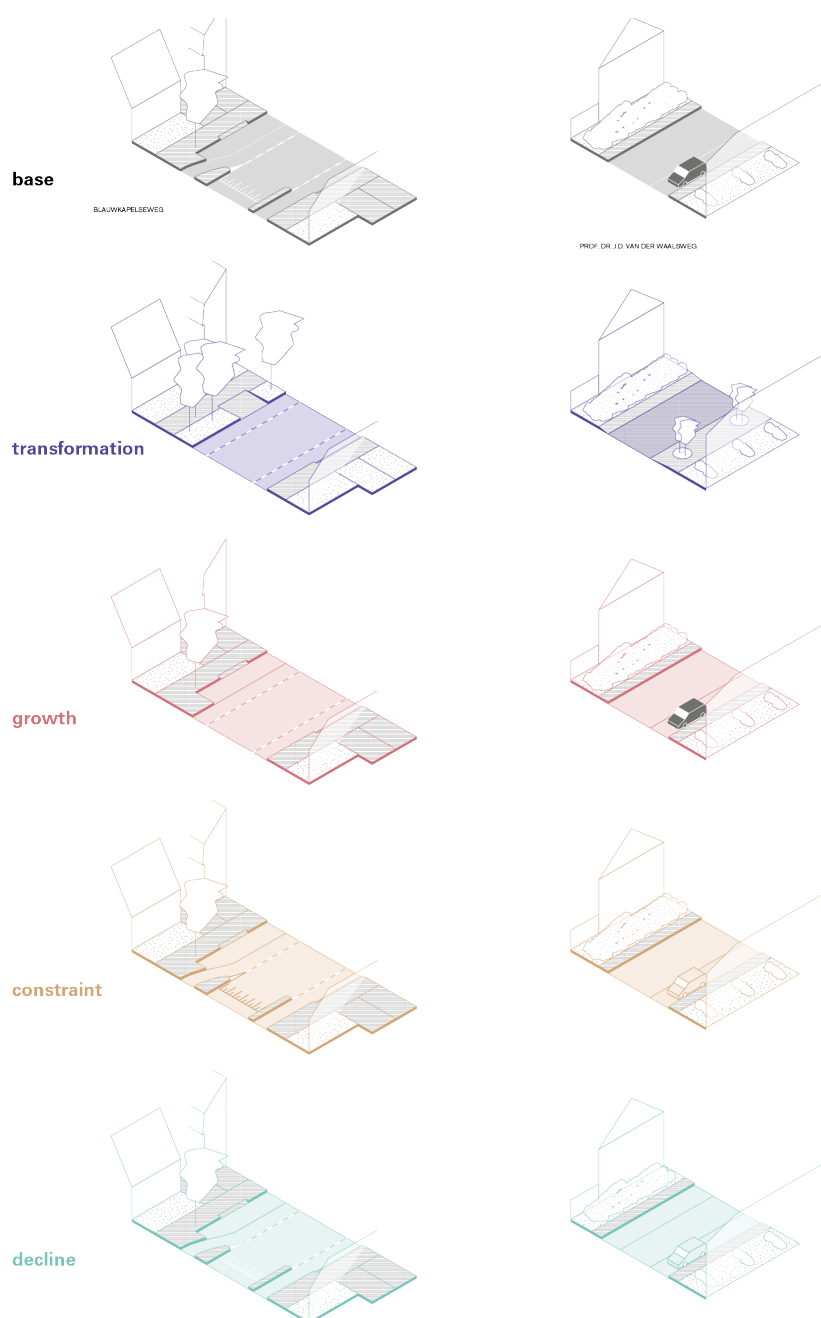
Appendix figure C-8: Road and street section for neighbourhood typology 8. Green-urban.

C.9 GREEN-SMALL-URBAN



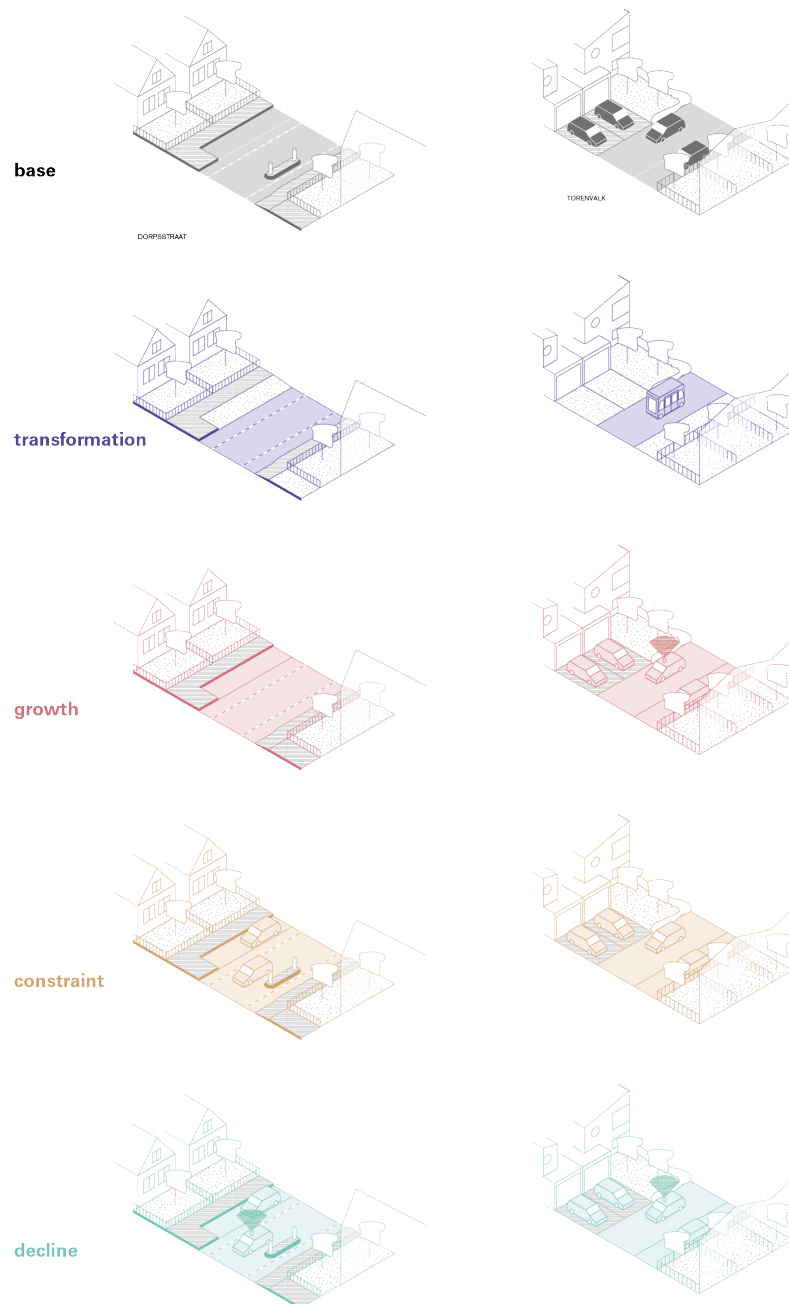
Appendix figure C-9: Road and street section for neighbourhood typology 9. Green-small-urban

C.10 CENTRE-VILLAGE



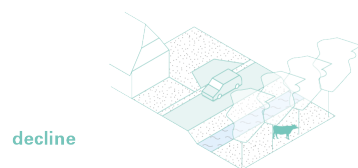
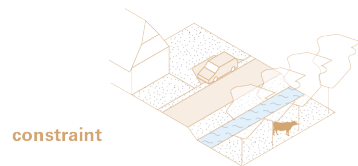
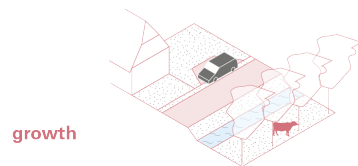
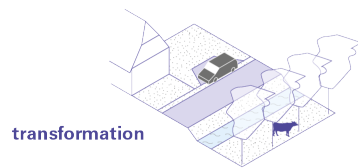
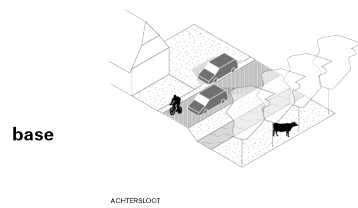
Appendix figure C-10: Road and street section for neighbourhood typology 10. Centre-village.

C.11 VILLAGE



Appendix figure C-11: Road and street section for neighbourhood typology 11. Village

C.12 RURAL



Appendix figure C-12: Road section for neighbourhood typology 12. Rural. There are no streets found for this typology.

D RESIDENTIAL LOCATION CHOICE MODEL

The final location choice is the result of four different procedures which are described based on Zondag, de Bok, Willigers, et al. (2015):

- 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
- Housing market interaction: incorporating the supply and demand and calculating the actual area to move to.

D.1 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:

$$V_{z,h,t}(stay) = \bar{\alpha}_h * \bar{X}_{z,t}$$

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 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.

Table 1: Explanatory variables of the move-stay decision (adapted from Zondag, de Bok, Geurs, et al. (2015, pp. 118, 120), Zondag, de Bok, Willigers, et al. (2015, p. 61)).

Type of variable	Variable	Unit
Model specific	Alternative specific constant for stay alternative	0/1 dummy
	% of zone peripheral urban area (ref.)	Percentage
	% of zone village area	Percentage
Environmental	% of zone city centre area	Percentage
	% of zone peripheral low urban density	Percentage
	% of zone in rural area	Percentage
Socioeconomic	% vacant dwellings	Percentage

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

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

with:

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

D.2 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:

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

with:

VD Number of vacant dwellings
 D Number of dwellings in a zone
 H Number of households in a zone

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:

$$P_{z1,h,t}(z2) = \frac{VD_{z2,t} * \exp(\bar{\alpha}_h * \bar{X}_{z1 \rightarrow z2,t} + \bar{\beta}_h * \bar{X}_{z2,t})}{\sum_{z2 \in r} (VD_{z2,t} * \exp(\bar{\alpha}_h * \bar{X}_{z1 \rightarrow z2,t} + \bar{\beta}_h * \bar{X}_{z2,t}))}$$

with:

P	The probability of choosing zone $z2$
X	Attributes for the location choice alternative
α, β	Sensitivity parameters
$z1$	Origin zone
$z2$	Candidate zone

The attributes that comprise the utility calculation are displayed in Table 2.

Table 2: Explanatory variables of residential location choice (adapted from Zondag, de Bok, Geurs, et al. (2015, pp. 118, 120), Zondag, de Bok, Willigers, et al. (2015, p. 65)).

Type of variable	Variable	Unit
Model specific	Alternative specific constant for origin zone	0/1 dummy
	Average dwelling price in zone (woz)	Euros
Socioeconomic	Population density	Pop/m ²
	No. of vacant dwellings	Dwellings/zone
	Average yearly income of a household	Euros/year
	% of zone peripheral urban area (ref.)	Percentage
Environmental	% 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
	Inverse distance for intraregional relocations	km ⁻¹
	Accessibility to alternative	Logsum
	Accessibility for trip purpose other for location within 10 km	Logsum

Housing market interaction

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
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	Final value for balancing factor, limited between 0.99 and 1.01