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# Transport Networks, Land Use and Travel Behaviour: a Long Term Investigation

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**Delft University of Technology**

# Transport Networks, Land Use and Travel Behaviour: a Long Term Investigation

**Proefschrift**

ter verkrijging van de graad van doctor

aan de Technische Universiteit Delft,

op gezag van de Rector Magnificus Prof.ir. K.C.A.M. Luyben,

voorzitter van het College voor Promoties,

in het openbaar te verdedigen op

woensdag 24 mei 2017 om 12:30 uur

door

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Cover photo: Roel Hemkes

Printed in the Netherlands

*Dedicated to*

*Nasrollah and Ziba*

# Preface

The present work would not have been possible without the support of many who helped me in one way or the other. I would like to thank first and foremost my supervisors at TU Delft. My promoter Prof. Bert van Wee, you inspired me with your vast knowledge, critical thinking and the ability to address a wide range of subjects. You stand and feel comfortable at the rare point where different strands of knowledge merge. My daily supervisor Dr. Kees Maat, you are an exceptional teacher. You guided me patiently over the course of the PhD a step at a time, you knew when to push me and when to let go so that I would figure out the way. You showed me how to teach. You helped me operationalise and finalise ideas which would never have been possible otherwise.

Furthermore, I am thankful to:

Prof. Vincent Nadin and Prof. Wil Zonneveld who introduced me to OTB and made the start of my PhD possible. Prof. Han Meyer, participating in the IDEA League doctoral school programme under his supervision was one of the highlights of my PhD studies where I met new people, countries and ideas.

NETHUR and TRAIL research schools, which provided me with professional networks in the fields of urban and transport studies and ample opportunities to question, improve and present my research. Conchita van der Stelt who kindly helped with the publication of this thesis.

My many colleagues at OTB and the department of urbanism, especially Evert Meijers, Jan Jacob Trip, Arie Romein, Marjolein Spaans, Erik Louw, Rob Konings, Andreas Faludi, Ekki Kreutzberger, Paul van de Coevering, Andre Ouwehand, Jaap Nieuwenhuis, Roberto Rocco, Ana Maria Fernandez Maldonado and Jorge Gil. I learned a lot from you and enjoyed your company at the coffee corner, lunch time, our research presentations and our outings. My colleague and friend Dominic Stead, you supported me in many ways, it was a pleasure to work with you on the CASUAL project.

My dear friends to whom I owe my social life outside the PhD (and therefore my sanity): Marianne van Dijk, Anna Duarte, Despina Sapoutzi, Rad Haghi, Igor Pessoa, Donya Ahmadi, Nadjla Ghaemi, Soudeh

# Content

# Chapter 1:    Introduction

Many policies depart from the idea that transport infrastructure and land use are interrelated. A large number of studies have investigated this relationship: some have focused on the impact of transport infrastructure on land use, others the reverse, and very few on both. There is also a rich body of literature which examines the role of land use and transport infrastructure in determining travel behaviour. A number of these investigations are long term, but for the most part they have been carried out at a single time point or over short timespans. It is essential to analyse the relationships between transport infrastructure networks, land use and travel behaviour over the long term, as their outcomes only become observable over time. This thesis investigates the relation between transport infrastructure and land use, and the subsequent travel behaviour, in the long term, that is, for periods of more than a decade and longer.

The introduction begins with the historical background of this field, explaining why it is important to investigate the relationship between land use, transport infrastructure and eventually travel behaviour. The following section frames this relationship in a theoretical setting. Section 1.3 summarises the existing literature (see Chapter 2 for the detailed version), resulting in the research gaps and followed by the thesis' main research question. Section 1.4 breaks down this question into sub-questions which are addressed in the four core chapters of this thesis (Chapters 2–5) and briefly explains the scope and method of analysis in each chapter. Sections 1.5 and 1.6 provide an overview of the data used for the empirical analyses and the structure of thesis.

## 1.1.    Transport infrastructure and land use: a mutual relationship over time

Cities are clusters of people and their activities. For urban functions such as the production and consumption of goods, services and information to take place, cities need to be connected, not only from within, but also to one another and the hinterland. Infrastructure networks–including transport, utility and telecommunications–provide the functional connectivity within and between cities and enable the flow of people, goods, and information. Transport networks like rail and road networks are

major physical infrastructures which connect different urban elements and activities, and make the exchange of goods and people possible. A well-connected and efficient transport infrastructure is a prerequisite for cities to function well. Moreover, cities with a high-performing transport infrastructure network in terms of speed, connections and service area, outdo their counterparts with a less efficient infrastructure network.

Over time, transport infrastructures have improved. For instance, horse-drawn carriages were replaced by steam, diesel and electric trams. Moreover, transport modes and their networks have flourished and declined as new transport systems were introduced throughout the course of history (Mom & Filarski, 2008). For instance, barges traveling on waterways were partly replaced by trains on rails, which later had to compete with buses and private automobiles on the road network, before the airplanes and airway networks entered the picture. Transport modes have become increasingly faster, covering larger distances and service areas at a finer scale. At the same time, the pervasive use of private modes, such as the car and bicycle as opposed to train and bus, has become possible.

The constantly upgrading transport infrastructure networks shape land use patterns, i.e., locations where people perform their activities–such as dwellings, offices, social or recreational amenities–and the characteristics of these locations–such as their spatial structure, density or composition. The effect of transport infrastructure on land use, takes places via the concept of "accessibility". New or improved transport infrastructure increases accessibility, which is "the extent to which land-use and transport systems enable (groups of) individuals to reach activities or destinations by means of a (combination of) transport mode(s)" (Geurs & van Wee, 2004, p.128). The rise in accessibility of certain locations makes them more attractive in comparison to others and entails the relocation of activities to the more attractive locations. The concept of accessibility plays an important role in the fields of urban and transport planning and policy making and can be interpreted and measured from various viewpoints (accessibility is explained in more detail in Section 1.2).

Past and present examples of how transport infrastructures have shaped land use via accessibility are abundant. For instance, roads encourage linear developments on the vacant lands along them, railways influence the location choice of a number of industries, or motorway exits and transit nodes attract certain amenities and firms. The critical link between transport infrastructure and land use is traceable over history: from ancient capitals such as Rome, Madrid, London (Neuman & Smith, 2010) and medieval cities such as Amsterdam, which were built upon extensive infrastructures, to contemporary cities, such as Dubai and Singapore which are developed around transport hubs. Transport infrastructure networks and their improvements are believed to have transformed the shape of human settlements from walking cities to car-dependent suburbs. A very marked example is public transport, especially the railway network, which played a critical city-shaping and later decentralising role in the 19th century and at the turn of the 20th century in Europe, and the US (Black, 2003; Mikus, 1966; Smith, 1998). The so-called American "streetcar suburbs", are good examples of the suburban settlements closely related to public transit which emerged during that period (Warner, 1962).

Transport infrastructure networks, together with land use patterns–as well as sociodemographic traits, attitudes and preferences–co-determine people's travel behaviour, that is, the way they use the transport infrastructure networks to connect their activity locations. A historical example is when the emergence of the Dutch railway network encouraged industry to locate in and around the bigger cities. As a result, the labour force relocated closer to its work location and used the railway network to commute (Dijksterhuis, 1984). Nowadays, depending on their residential location and the availability of certain transport modes, people might use the metro for commuting to work, drive the car to the gym using the road network, or use bicycle paths to go for their daily shopping on bicycle.

There exists however, a reverse relation as well: as cities grow and people change their travel behaviour, they demand larger and faster transport infrastructure networks. Thus, new stations are opened on the sites of residential expansions, highways are improved at their bottlenecks and faster trains are introduced to answer the travel demand of a growing population who increasingly wishes to become more mobile. Levinson (2008) refers to this simultaneous process of evolution of land use and transport systems, as well as the deployment of new transport technologies in space and over time, as "co-development".

It is important to know how cities develop as many of them are expected to grow and house more than half of the world's population. A population which is expected to rise progressively (United Nations Department of Economic and Social Affairs, 2014). As a consequence, the existing and future supplies of transport infrastructure networks are to respond to the growing demand for the functional connectivity between urban elements and activities within and between cities. Moreover, the forthcoming developments in cities and their transport infrastructure will occur under conditions where the planet cannot afford to face, and will increasingly have to pay higher costs for negative economic, social and especially environmental consequences such as the rising issues with fossil fuels, greenhouse gas emissions and global warming (Wilson & Piper, 2010).

To understand and plan the development of cities, it is necessary to study the relationships between transport infrastructure networks, land use and travel behaviour. The interrelated changes of these three components could directly and/or indirectly influence the economic, environmental and social performance of cities. For instance, new or improved transport infrastructures impact the environment directly (e.g. through the physical space dedicated to highway and railways). They also affect it indirectly by triggering changes in land use (such as the physical relocation of firms and households) and eventually travel behaviour. Moreover, transport infrastructure can promote economic growth and provide a more equal access to job opportunities (or vice versa). Similarly, transformation of land use, e.g. a conversion from undeveloped to urban land due to the presence of motorways, has environmental consequences. A planned or unplanned increase in population density around transit nodes could decrease ecological footprint and/or cause overcrowding, traffic congestion and safety issues which reduce the livability of cities. Finally, a change in people's travel behaviour, e.g. distance travelled and the mode of travel, due to the provision of new transport infrastructure such as high speed rail or air travel, is directly linked to the consumption of resources and energy, as well as air and noise pollution.

It is important to study the above relationships over a long period of time, because developments in transport infrastructures and land use, are long-term processes which demand long time periods to take place and become observable. Wegener, Gnad, and Vannahme (1986) classify developments in transport infrastructure and land use as "slow" urban processes. These processes, especially transport construction, are considered slow regarding their "response time", as the planning and the acquisition of the necessary capital and permissions for construction is time consuming. Furthermore, their "response duration", i.e., the time during which the response affects the stock, is slow, as it takes years for such projects to be completed. In the case of transport networks, they develop over decades if not centuries (Xie & Levinson, 2011). Being slow also applies to the "response level" of the developments in transport infrastructure and land use. The response level is related to response duration, and indicates the rate of change which affects the physical stock, while taking the size of the affected stock into account. Average replacements in transport infrastructure affect only one to two percent of the existing stock per year (excluding drastic events such as their deconstruction by war) (Wegener et al., 1986). Importantly, changes in land use patterns have very low reversibility. In the case of transport infrastructure networks, their change is almost irreversible. In other words, land use patterns and to a

higher degree, transport infrastructure networks, have long lifespans and are very durable. This is mainly because of their high sunk costs and costs of replacement. This persistence is referred to as the "legacy" effect and is evident in cities which have maintained their size and physical structure over history, regardless of the exogenous shocks to which they have been subjected (Xie & Levinson, 2011). Examples are cities after the WWII bombings, such as Japanese cities (Davis & Weinstein, 2002) or Rotterdam in the Netherlands. Another example is transport infrastructures being re-built at their original locations following their destruction, as in the case of London after the great fire in 1666, due to the prevailing home and lot ownership patterns (Xie & Levinson, 2011). The durability of land use patterns, and to a higher degree transport infrastructure networks, has serious policy implications. An "incorrect" policy could affect developments for decades and even its discontinuation will not guarantee the restoration of the situation to the pre-policy era. It is virtually impossible to reverse the impact of a constructed highway which has severed a historic urban fabric or a natural area.

The primary focus of this thesis is to investigate the relationships between transport infrastructure networks, land use and travel behaviour, in the long term. Here, long term is considered to be more than a decade with the intention of going as far back as data availability allows for. Such long-term investigations are scarce, as most studies have analysed the relations at one moment, or over short time periods which are for the greater part less than a decade (Section 1.3 elaborates further on the existing literature and gaps). In order to truly understand how these components are related, and how the change in one is linked to the change in another, longitudinal approaches are needed. Long-term investigation is the first step towards identifying effective land use and transport policies which can improve the functioning of cities, reduce unwanted environmental, economic and social impacts, and achieve sustainable urban development. While the interplay between transport infrastructure networks, land use and travel behaviour is of interest for various fields, this thesis investigates these relationships from a spatial perspective–rather than social or economic–which focuses on the role of and the effect on land use in specific.

## 1.2. Theoretical framework

The idea that land use and transport infrastructure interact and are interdependent is not new (see for example Hoyt, 1939; Mumford, 1961; Rodrigue, Comtois, & Slack, 2009). Dieleman and Wegener (2004) distinguish three main categories of theories explaining the two-way interaction between transport and land-use. The first category involves technical theories. According to the technical theories which focus on urban mobility systems, it is the technical conditions such as transport technology which guide the form and organisation of urban developments (Hansen, 1959; Wegener & Fürst, 1999). The central premise of these theories is that transport and land use co-develop and co-determine travel behaviour (detailed explanation follows further below). The second category, economic theories, take account of location costs, e.g. for firms or households in addition. They originate in the work of von Thünen (1826) who introduced the bid rent theory, explaining agricultural land rents based on the distance and consequently the transport costs between where goods are produced and the market where they are sold. This theory was further developed by Alonso (1964), Muth (1969), and Mills (1972), and reformulated in a manner that the city and its central business district played the role of the market. The gist of their theory, the monocentric city model, is that access, which is provided by transport systems, is a driver of and capitalised in property and land value. Finally, the third category, social theories, explain how cities are shaped as space is appropriated by individuals or groups (Dieleman & Wegener, 2004). Its theoreticians include scholars like Robert Park and Ernest Burgess from the Chicago School of urban sociology who incorporated evolutionist concepts to explain the development of cities. Qualitative theories of city formation like concentric (Burgess,

1925) and sectoral (Hoyt, 1939) city growth are products of this school of thought. Later on, Hägerstrand (1970) introduced the concept of "time budgets", which operationalised the concept of space appropriation at the individual level.

The chosen theoretical framework for this thesis is the so-called transport land use feedback cycle from the first category of theories (Giuliano, 2004; Meyer & Miller, 2001; Wegener & Fürst, 1999). This model explains the interaction between transport infrastructure and land use, using the concept of accessibility, while taking into account the behavioural aspects. This model is chosen as it explicitly reflects the structuring role of transport infrastructure on land use which is the primary focus of this thesis. Furthermore, it matches the spatial perspective of this work which is specifically interested in the role of and impact on *land use*. The adaptation of this model by Bertolini (2012) is helpful as it presents different response times which are central to this work, as well as potentially influential exogenous factors. The components of the model are defined below:

- Transport infrastructure networks (TINs) provide the connectivity between activities and consist of infrastructure and related transport services. These networks are hierarchical by nature, as certain nodes and links are more important than others, such as  motorway lanes versus residential streets, and intercity railway stations versus tram stops.
- Land use (LU) includes locations (e.g. dwellings, offices, social or recreational amenities) where people perform their activities, as well as the characteristics of these locations, such as their spatial structure, density or composition (e.g. the degree of mix of uses).
- Travel behaviour (TB) is the way people use the transport infrastructure networks to connect their activity locations. For instance trip length, distances, times, durations, travel modes, frequencies, and chaining behaviour.
- Accessibility has different definitions and measurements (e.g. infrastructure/location/ person/utility-based measures) and is based on the field of application and the phenomenon it aims to explain (see for an overview Geurs & van Wee, 2004). This thesis uses the definition of Geurs and van Wee (2004, p.128): "Focusing on passenger transport, we define accessibility as the extent to which land-use and transport systems enable (groups of) individuals to reach activities or destinations by means of a (combination of) transport mode(s)".

The transport land use feedback cycle (Figure 1.1) theorises the complex relationships between transport infrastructure networks, land use and travel behaviour and the exogenous factors which influence them. According to this model, the introduction of a new or improved transport infrastructure improves accessibility, because it lowers the (monetary, time) cost of reaching certain locations. Consequently, more accessible areas become more attractive than others. Land use, which includes the locations of activities (e.g. residences, offices, amenities), redistributes due to the change in accessibility. The change in land use patterns entails changes in activity patterns (e.g. living, working), which occur at and between land uses. Activity patterns are translated into travel behaviour as they take place over the existing transport system. Finally, change in travel behaviour will eventually demand new or improved transport infrastructure.  In short, improvements in the transport infrastructure network increase accessibility, making land more valuable for further development. At the same time, land development generates travel demand and consequently induces the need for infrastructure improvements (Giuliano, 2004).
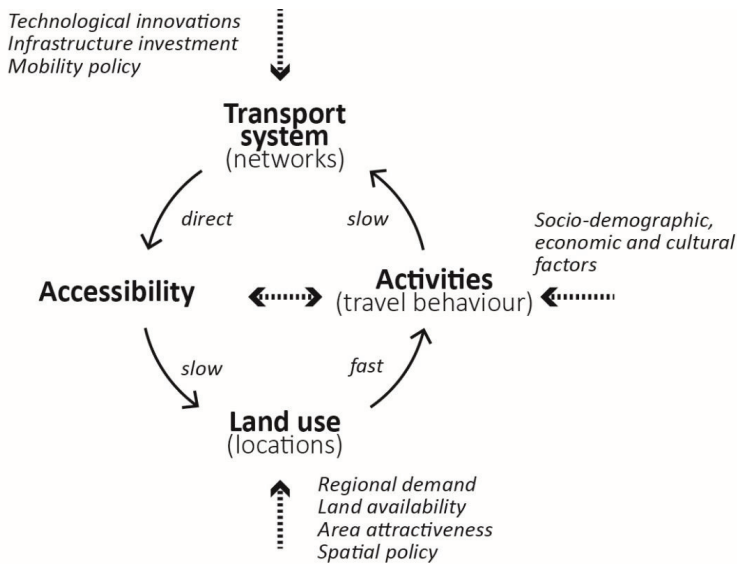
**Figure 1.1. Transport land-use feedback cycle (Wegener & Fürst, 1999; adapted by Bertolini, 2012).**

While the transport land use feedback cycle is a very useful conceptualisation of the relationships between transport infrastructure networks, land use and travel behaviour, investigating these relationships is challenging, due to the following issues:

- It takes time to observe the effect of change in one component of the cycle, on the other components (Giuliano, 2004). Furthermore, response rates vary over time (Bertolini, 2012). For instance, while the introduction of a new train station directly influences accessibility (in the railway network and its vicinity), the succeeding re-adjustment of land use and eventually travel behaviour will occur over longer time periods. In other words, TINs, LU and TB respond to changes in one another with different delays.

- There are various exogenous factors which influence the cycle (the external dashed lines in Figure 1.1) (Knight & Trygg, 1977; Rietveld, 1994). Examples are the emergence of new technologies, policy aims on economic growth, traffic management and sustainability goals. In addition, LU is also influenced by land availability, attractiveness of the location, economic dynamics in the region and spatial policies. Examples of spatial policies are those which aim to curb urban sprawl and guide urban growth by a host of measures encouraging compact, mixed-use development and the use of transit and active transport modes, such as "Concentrated Deconcentration", "Growth Centres" and "Compact City" policies in the Netherlands or the "Smart Growth" approach in North America.

- The effect of the exogenous factors could also differ within various time frames. For instance, the introduction of a subsidy to lower transit fares, might encourage transit use, however its effect could wear off after a couple of years. Furthermore, the synergy between the exogenous factors can affect the interrelationships in various ways. For example, the presence of regional demand, coupled with supportive transport-land use policies could ensure that an upgraded transit network causes significant land use change.

- The impact of one component on the other not only varies over time, but also differs across space and at various spatial levels. Thus, depending on the level of investigation, various

outcomes could be found. For instance, a highway might raise population density in its direct vicinity while draining residents and lowering the population density of areas further away.

- It is hard to isolate the effect of transportation on land use or vice versa, because of the feedback system (Giuliano, 2004). Thus, the problem of endogeneity complicates the analysis. For instance, the emergence of new railways could have been the *reason* behind or the *result* of population growth. The causality could also change over time, for instance, the railways could have initially followed the population and later stimulated its growth.

## 1.3. Previous studies, gaps and the goal of this study

There are extensive research traditions which investigate part of the transport land use feedback cycle, using a variety of methods. These strands of research provide input for various policies aimed at influencing the result of the interactions between the cycle's components, in order to achieve sustainable economic, environmental and social development. The existing literature and the subsequent scientific gaps which are not covered by the current state of the art research are presented below:

1. The majority of existing long-term investigations on the effect of TINs on LU are qualitative or use simple descriptive analyses. The existing long-term research, which covers several decades up to around a century, is mostly interested in the determinants of city formation and growth. However it is mostly in the form of descriptive accounts of the relationships between TINs and land development (or urbanisation patterns) from a historical geography standpoint. Examples of such literature are historical narratives of the evolution of railways and land development in Britain and Ireland (Turnock, 1998), Germany (Roth, 2003), and the Netherlands (Schmal, 2003), or the formation of streetcar oriented developments in Boston (Warner, 1962), Minneapolis and St Paul (Lowry, 1979).

2. There are fewer empirical studies focusing on the spatial outcomes of the relationship between TINs and LU compared to those which focus on the economic outcomes of this relation (examined elsewhere by authors such as Debrezion, Pels, & Rietveld, 2007; Lakshmanan, 2011; Melo, Graham, & Brage-Ardao, 2013). While there exists an increasing number of empirical literature which investigates TINs' effect on LU from a spatial perspective, those which look at this relationship over the long term are still scarce (Kasraian, Maat, Stead, & van Wee, 2016). Furthermore, most attention has been given to car travel and only recently the spatial and economic rail impacts on urban systems have been investigated in a quantitative way (Papa, Pagliara, & Bertolini, 2008). All in all, as the literature review in Chapter 2 concludes, there is a shortage of empirical studies which include and compare the land use impacts of both road and rail. Finally, most of the investigations are uni-directional as they measure the impact of TINs on LU. Only a handful of studies have a bi-directional approach which investigates the impacts of TINs on LU *and vice versa* (LU on TINs) and the leading factor between the two (e.g. King, 2011; Levinson, 2008).

3. The effects of TINs and LU on TB have been investigated by extensive empirical literature (Ewing & Cervero, 2010; Transportation Research Board, 2009). The general hypothesis and summary of the available literature is that the built environment influences travel behaviour through the 5 D's of density, diversity, design, destination accessibility and distance to transit. What is lacking once more, is the long-term perspective. Studies quantifying long-term relations between locations, individual characteristics and travel behaviour are very scarce (Ellder, 2014). The number of long-term studies in this respect has increased in the last decade,

mostly in the form of longitudinal studies which investigate the issue of self-selection (e.g. Cao, Mokhtarian, & Handy, 2009; van de Coevering, Maat, Kroesen, & van Wee, 2016). However, the investigations are still dominated by cross-sectional or short term studies with time spans of just several years.

4.  There is also a lack of investigations at the regional level comprising of several cities. Existing studies have mainly investigated the relationships at a single city region (e.g. King, 2011; Levinson, 2008; Stanilov, 2013). There are a handful of studies which include several city regions, however these regions are treated as separate observations and not in connection with each other (e.g. Baum-Snow, 2007; Duranton & Turner, 2012). Alternatively, studies have investigated the relationships at the level of countries (Alvarez, Franch, & Marti-Henneberg, 2013; Mojica & Marti-Henneberg, 2011), and neighbourhoods, such as the vicinity of (new) transit lines (e.g. Ratner & Goetz, 2013). However, because of the *network* characteristic of transport infrastructures, modification in a certain part of a transport network has implications for accessibility and consequently land use in other locations (Giuliano, 2004). While research at the higher and lower levels are needed, it is important to investigate the relationships at a regional level composed of several cities connected by transport infrastructure, to capture the *network* characteristic of transport infrastructures.

It should be noted that there are also ex ante simulations of land use transport interaction. These models simulate the impacts of land use policies (e.g. zoning, density restrictions) and/or transport policies (e.g. investments in transport systems, imposed taxes and fares) on future land use and transport development patterns and provide decision support for urban planning (for reviews see Acheampong & Silva, 2015; Iacono, Levinson, & El-Geneidy, 2008; Wegener, 2014). However, these studies are outside the scope of this thesis as they are based on assumptions and are not empirical.

This thesis addresses the multiple gaps in the existing scientific literature mentioned above. As mentioned earlier, the central focus of this thesis is to unravel the relations between transport infrastructure networks, land use and travel behaviour (1) in the long term. Furthermore, it investigates these relationships (2) empirically, (3) at a regional level, (4) with a spatial focus on the role of and the effect on land use, while (5) comparing the role of both road and rail networks whenever possible.

## 1.4.    Research questions, study area, scope and methodology

As explained in the previous sections, it is important to investigate the relationships between TINs, LU and TB because of their consequences for the functioning and development of cities. Changes in LU and especially TINs are irreversible processes which will affect the patterns of development for decades to come. Furthermore, it is essential to analyse these relationships over the long term, which in this case is defined as at least a decade, while going back as far as data availability allows for. The reason behind the long-term focus is because the results of the relationships between TINs, LU and TB only become observable in the long run. However, such long-term empirical analysis is largely missing from the existing literature. In specific, empirical investigations into the structuring role of both road and rail networks at the regional scale are scarce. This thesis aims to fill these gaps by answering the following research question, while using the transport land use feedback cycle (explained in Section 1.2) as the point of departure:

*What are the long-term relations between transport infrastructure networks, land use and travel behaviour at the regional level?*

As it is hardly possible to investigate all the relationships in the transport land use feedback cycle in one integral work, specific relationships are modelled separately in the chapters of this thesis. Each of the four core chapters addresses a sub-question of the main research question and focuses on a specific relationship. Chapter 2 uses literature review and Chapters 3–5 apply quantitative empirical analyses as their method of investigation. The empirical analyses are performed on the study area of the Greater Randstad Area.

The Greater Randstad Area is the population and economic core of the Netherlands situated in its west and includes the four major cities of Amsterdam, The Hague, Rotterdam and Utrecht (Figure 1.2). The Randstad is a useful case study for a number of reasons. First, it is a polycentric urban region with a variety of development types including metropolitan areas, medium-sized and small cities, as well as rural areas. Second, the investigated study periods within the time span of 1850 to 2010 display various trends of development in TINs and LU. These trends include the introduction of railway networks in the second half of the 19th century and train-led urbanisation which continued into the first decades of the 20th century, the introduction of the motorway network after WWII accompanied by massive suburbanisation and finally a revival of the railway network since the 1970s which included the introduction of new types of light rail and eventually the high speed rail. Fourth, the Randstad has witnessed the application of various national transport and spatial policies to curb urban sprawl. The "Concentrated Deconcentration" of urban development and the designation of Growth Centres were implemented during the 1970s and early 1980s. During the 1980s, the revival of inner cities was encouraged under the "Compact City" agenda which materialised as the VINEX policy in the 1990s (Maat et al., 2005; Geurs and van Wee, 2006). In the 2000s, the National Spatial Strategy emphasised the concept of "Network Cities" and focused on the definition of a network of cities connected by transport network corridors (Alpkokin, 2012). The Randstad has also witnessed a shift from car dominated transport policies of the 1960s and the 1970s to promoting "sustainable" transport and public transport in the 1990s (Annema and van Wee, 2009; Ministry of Transport, 1990).

While these events are partly specific to the Netherlands, the general trends–i.e., the introduction of the railway network in the second half of the 19th century followed by train-led urbanisation, massive post WWII suburbanisation accompanied by the drastic growth of the road network, the initial focus on the development of the road network which was later changed to the public transport or both, and an array of spatial policies to curb urban sprawl–could be witnessed in many (at least western) countries. In specific, the findings of this thesis could be of interest to other comparable poly-nuclear areas in western countries with saturated development and transport accessibility. Examples are the Ruhr region in Germany, the urbanised part of the Flanders in northern Belgium and San Francisco Bay Area in the US.
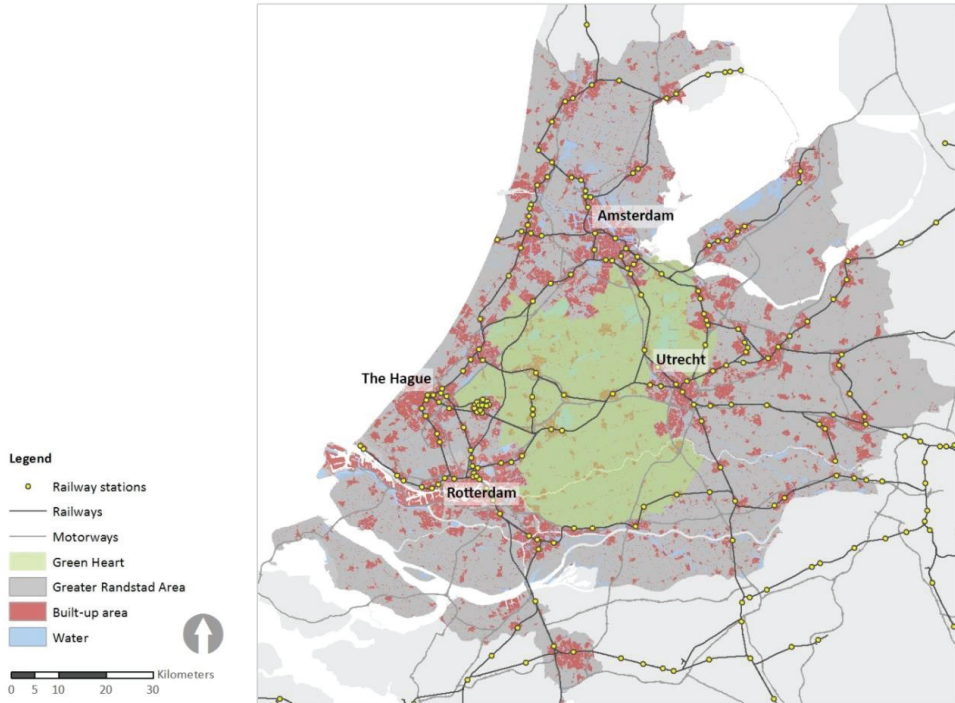
**Figure 1.2. The Greater Randstad Area in 2010.**

The sub-questions and the chapters which have consequently addressed them, as well as their scope of analysis are presented below:

a) *To what extent does the existing empirical literature provide evidence on the long-term relationship between transport infrastructure networks and land use*?

Chapter 2, "Long-term impacts of transport infrastructure networks on land-use change: an international review of empirical studies", addresses this question. This chapter reviews long-term empirical literature from around the world, with time spans ranging from approximately a decade to a century within the period of 1831–2010. It adds to previous literature reviews on the impact of TINs on LU by including (i) recent empirical evidence from studies published since 1995, (ii) on both road and rail, (iii) from different parts of the world, (iv) while focusing on long-term impacts as opposed to short-term impacts. The investigated transport modes are road and rail, with the intention of comparing the roles of private and public transport and adding to previous reviews in the field which have mostly focused on a single transport mode. Examined land use characteristics are (i) density (population/employment), (ii) land cover, and (iii) type of development (residential, office, amenities).

b) *In what way have land use and transport infrastructure developed over the long term in general and in relation to each other? At what time has new transport infrastructure led to new urbanisation or vice versa?*

These questions are addressed in Chapter 3, "Development of rail infrastructure and its impact on urbanisation in the Randstad, the Netherlands". Here the relation between TINs and LU is investigated

from 1850 to 2010. TINs are narrowed down to the railway network (lines and stations). The focus on the railway network is based on its critical historical role soon after its emergence in encouraging urbanisation, which is one of the conclusions drawn from the literature review in Chapter 2. Due to the unavailability of detailed LU data for such an extensive period, it is measured as the amount of urbanisation, that is, the amount of "built-up area" defined as the physical space used for urban functions, including real estate for housing, services, and companies, infrastructure and parks.

c) *To what extent have transport accessibility, proximity to existing urban areas and spatial policies affected the spatial dynamics of urbanisation in the Randstad?*

Chapter 4, "The impact of urban proximity, transport accessibility and policy on urban growth: a longitudinal analysis over five decades", responds to this question. This chapter focuses on the period from 1960 to 2010. The road network including the motorways, their exits and regional roads are added to the investigated TINs besides the rail network, as this period witnesses the introduction and growth of the Dutch motorway network. The investigated LU indicator here is urbanisation (with the same definition as Chapter 3) in terms of the built-up proportion of a 500 m by 500 m grid cell.

Chapters 5, "A pseudo panel analysis of daily distance travelled and its determinants in the Netherlands over three decades", focuses on the following questions:

d) *How has travel behaviour developed over the long term in the Randstad? What is the role of access to transport infrastructure and land use characteristics in its development while controlling for socio-demographic factors?*

Extending the analysis to the right-hand side of the transport land use feedback cycle, this chapter investigates the change in TB in relation to TINs and LU. The study period is exceptionally long for TB studies, covering three decades from the first conducted National Travel Survey in 1979 to 2010. Bicycle travel behaviour is added to that of train and car, regarding its important share in Dutch travel behaviour. The measured TB characteristic is average daily distances travelled by the train, car and bicycle. Similar to the previous chapter, investigated TINs are the rail and road networks. The residential location of respondents is chosen as a proxy for LU after testing for other characteristics such as the amount and the population density of built-up area.

It should be noted that the study area, the Greater Randstad Area, has minor differences in its borders across chapters based on the extent of the available data sources for the investigated time periods. Table 1.1 shows the corresponding chapter for each sub-question. It also provides an overview of the investigated land use characteristics, transport modes, travel behaviour indicators and applied methods per chapter.

The applied methods start with literature review (Chapter 2 and the beginning of Chapter 3), continue with rather simple descriptive analyses and logistic regression (Chapter 3) and end with more complex econometric models for longitudinal data analysis such as Generalised Estimating Equations (GEE) (Chapter 4) and pseudo panel analysis with a hybrid specification (Chapter 5). Each chapter encompasses the detailed account of the applied methods.

**Table 1.1. Overview of chapters.**

| Research Question→ Chapter | Study period | Transport infra. | Land use characteristic | Travel behaviour | Methodology |
|---|---|---|---|---|---|
| a→ Chapter 2 | Ranging from approx. a decade to a century within the period of 1831–2010 | Road & rail | Density (population & employment); land cover; type of development (residential, office, amenities) | — | Literature review of 49 empirical long-term studies form Europe, USA & Eastern Asia |
| b→ Chapter 3 | 1850–2010 | Rail | Urbanisation, measured as the amount of built-up area | — | Review of historical literature; descriptive analysis; logit regression |
| c→ Chapter 4 | 1960–2010 | Road & rail | Proportion of urbanisation, measured as the share of urban land in a 500 m × 500 m grid cell | — | Generalised Estimating Equations (GEE) analysis with logit function |
| d→ Chapter 5 | 1980–2010 | Road & rail | Population density; location within the Randstad (urban core, suburb or rural) | Average daily distance travelled by train, car & bicycle | Pseudo panel analysis with a hybrid specification |

## 1.5.   Data

A substantial amount of time and effort was dedicated to collect various data sources and to create a consistent spatio-temporal dataset. Table 1.2 presents an overview of the data types and sources used in this thesis to represent transport infrastructure, land use, travel behaviour and spatial policies. Detailed explanations of the sources and indicators follow in the chapters.

**Table 1.2. Overview of data types and sources.**

| Indicator | Investigated years and frequency | Source | Type |
|---|---|---|---|
| **Transport infrastructure networks** | | | |
| Railway network (lines and stations) | 1839–2010 (annually) | National railways database (Ministry of Infrastructure and the Environment, 2013); earlier time points were mapped by the author using Sluiter (2002), stationsweb.nl Google OpenStreetMap (OSM) | Vector (lines for railways and points for train stations) |
| Motorway network (lines and exits) | 1980, 1990, 2000 | National historical roads database, Planbureau voor de leefomgeving (PBL); exits mapped by the author | Vector (lines for motorways and points for motorway exits) |
| | 2005, 2010 | National roads database (Ministry of Infrastructure and the Environment); exits mapped by the author | |
| **Land use** | | | |
| Built-up area (i.e., buildings and paved surfaces plus transport infrastructure) | 1850, 1910, 1940 | OverHolland, Delft University of Technology | Vector (polygons) |
| | 1960, 1970, 1980, 1990 | Historical land use maps of the Netherlands (HGN), Alterra, Wageningen University | Raster (cell size: 25 m × 25 m) |
| | 2000, 2010 | Mutatiereeks Bodemgebruik 1996–2010 ("adjusted version" of the Land Use Dataset) by Statistics Netherlands (CBS) & the Netherlands' Cadastre, Land Registry and Mapping Agency (Kadaster) | Vector (polygons) |
| Population | 1980–2010 (every 5 years) | Statistics Netherlands (CBS) | Tables of municipal population (based on the then-existing boundaries) |

| **Travel behaviour** | | |
|---|---|---|
| Old OVG | 1979–1998 (annually) | Travel diary data provided by CBS and Socialdata and reworked by van Goeverden, the Faculty of Civil Engineering, TU Delft, as databases at the trip- and person-level |
| New OVG | 1999–2003 (annually) | |
| MON | 2004–2009 (annually) | |
| OViN | 2010 | |
| **Spatial policies** | 1960–2010 | Vector (polygons) for the boundaries of the Green Heart, Growth Centre municipalities and VINEX locations provided by PBL |

## 1.6.    Structure of the thesis

The remaining chapters of this thesis are organised as follows. Chapter 2 presents the paper "Long-term impacts of transport infrastructure networks on land-use change: an international review of empirical studies", published in the journal of *Transport Reviews*. Chapter 3 encompasses the paper "Development of rail infrastructure and its impact on urbanisation in the Randstad, the Netherlands", published in the *Journal of Transport and Land use*. Chapter 4, titled "The impact of urban proximity, transport accessibility and policy on urban growth: a longitudinal analysis over five decades", is currently under review. Chapter 5 includes the paper "A pseudo panel analysis of daily distance travelled and its determinants in the Netherlands over three decades", which was presented at *Transportation Research Board conference 2017* and is currently in the review process. Finally, Chapter 6 presents the summary of answers to the research questions, a discussion which links the thesis' findings to ongoing worldwide debates, their policy implications and potential generalisability. This chapter closes with recommendations for future research. Please bear with the discrepancies in the reference styles of different chapters due to varying journal requirements.

## Acknowledgements

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# Chapter 2: Long-term impacts of transport infrastructure networks on land-use change: an international review of empirical studies

## Abstract

Improvements in geographical information systems, the wider availability of high-resolution digital data and more sophisticated econometric techniques have all contributed to increasing academic interest and activity in long-term impacts of transport infrastructure networks (TINs) on land use (LU). This paper provides a systematic review of recent empirical evidence from the USA, Europe and East Asia, classified regarding the type of transport infrastructure (road or rail), land-use indicator (land cover, population or employment density, development type) and outcome (significance, relationship's direction) as well as influential exogenous factors. Proximity to the rail network is generally associated with population growth (particularly soon after the development of railway infrastructure), conversion to residential uses and the development of higher residential densities. Meanwhile, proximity to the road network is frequently associated with increases in employment densities as well as the conversion of land to a variety of urban uses including commercial and industrial development. Compared with road infrastructure, the impact of rail infrastructure is often less significant for land cover or population and employment density change. The extent of TINs' impact on LU over time can be explained by the saturation in TIN-related accessibility and land-use development.

*Keywords:* transport infrastructure networks, land-use change, road, rail, long-term impacts.

## 2.1.    Introduction

Land use (LU) and transport infrastructure networks (TINs) are closely interlinked and this is underpinned theoretically in the so-called transport land-use feedback cycle (Figure 2.1). On the one hand, the development of TINs can improve local accessibility and in turn increase the demand for more urban development. On the other hand, the urbanisation of land can result in the growth in local transport movement and an increase in the demand for TINs. Some interactions are direct or relatively rapid, whereas others are more long term in nature. The system is also dynamic (Giuliano, 2004), which means that the left- and right-hand sides need to be considered simultaneously. However, as the cycle represents a market-driven process (we refer to this as an endogenous effect), it is clear that exogenous influences also play a role, such as the emergence of new technologies, policy aims on economic growth, traffic management and sustainability goals. In addition, LU is also influenced by land availability, attractiveness of the location, economic dynamics in the region, and spatial policies. Hence, the TIN-LU relationship is a complex and dynamic process, in which many influences play a role.
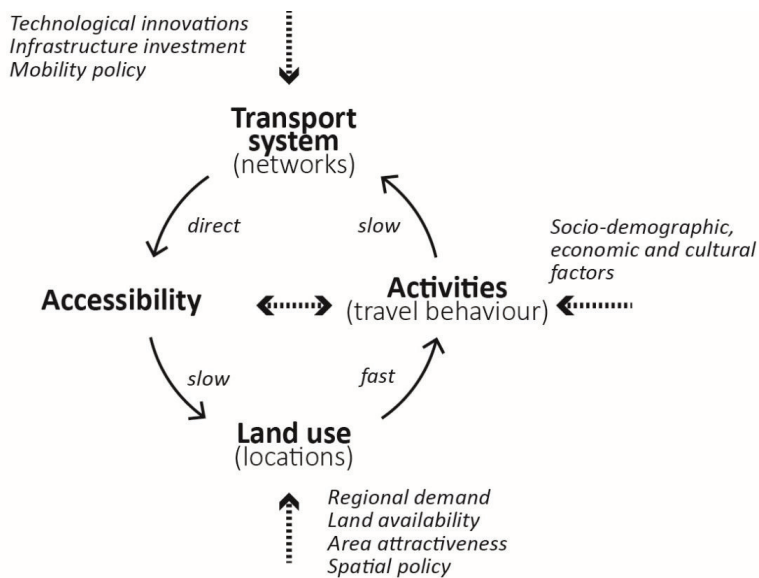


**Figure 2.1. Transport land-use feedback cycle (Wegener & Fürst, 1999; adapted by Bertolini, 2012).**

While certain interactions between LU and TINs (the right-hand side of the figure) have been the subject of several reviews in the past (see e.g. Ewing & Cervero, 2010), investigations of other interactions have been much more limited, especially those that are long term in nature. Very few papers take the full cycle into account, and it is the long-term impact of TINs on LU that is the key focus of this review paper (i.e. the left-hand side of the figure). In reviewing recent empirical literature, this paper considers whether LU development and its magnitude can be explained by TIN development (via accessibility), taking into account that both TIN and LU are also subject to a range of external factors.

A growth in empirical investigations of the long-term impacts of TINs has occurred over recent decades partly due to substantial improvements in the quality and availability of spatial TIN and LU data. It has also been aided by the availability of more sophisticated analytical techniques. For example, more sophisticated geographical information systems (GIS) allow the development and analysis of large,

historical, spatial data sources, which then make it possible to track spatial changes in both TINs and LU more closely over time. High-resolution land-cover data sets derived from remote sensing techniques alongside digitised aerial photos or historic land surveys now provide researchers with a more detailed picture of change. Moreover, the application of econometric models has contributed to methodological improvements, such as instrumental variable estimations, which do not have a long history of application in quantitative studies (Atack, Bateman, Haines, & Margo, 2010). This advance in research methods has resulted in an emerging strand of literature interested in quantifying the long-term impact of TINs on LU or their interaction.

A key contribution of this paper is its focus on longer term impacts of TINS on LU (and vice versa), a wider geography of studies, different types of transport infrastructure (road and rail) and more recent evidence. The paper provides a broader perspective on previous reviews in the field (e.g. Badoe & Miller, 2000; Cervero, Seskin, & Parsons Brinckerhoff Quade & Douglas Inc., 1995; Giuliano, 2004; Knight & Trygg, 1977).

### 2.1.1.  Scope

While the main focus of this paper is the impact of TINs on LU, it also considers the interaction between the two, and whether and when TINs have followed LU development or vice versa. Both mono-directional studies (investigating the impact of TINs on LU) and bi-directional studies (investigating the impacts of TINs on LU and vice versa) are reviewed, with mono-directional studies representing the majority of the sample.

The paper reviews recent empirical studies originating from different parts of the world, which have considered the long-term impacts of TINs, both road and rail infrastructure, on LU. Demographic and spatial LU impacts of TINs, measured by changes in population and employment density, land cover and development type (residential, office, commercial, industrial) are reviewed, whereas economic outcomes measured by economic performance indicators such as the Gross Domestic Product (GDP) and property values are excluded (examined elsewhere by authors such as Banister & Berechman, 2001; Debrezion, Pels, & Rietveld, 2007). The focus on empirical findings means that ex-ante studies on land-use-transport modelling (LUT) are outside the scope of this paper (for an overview see Iacono, Levinson, & El-Geneidy, 2008; Wegener, 2004).

All studies reviewed were published in peer-reviewed journals between 1995 and 2014. Because of the focus on the impacts of networks of transport infrastructure, studies of the impacts of small additions to TINs (e.g. a new metro station) are outside the scope of this review. Only studies with time spans of around a decade or more are included in this review. One reason for reviewing longer-term analyses is that they are more likely to capture the relatively slow development of LUs arising from changes in TINs. Moreover, long-term observations make it possible to compare differences between various stages in history, which provides insights as to whether the LU impact of TINs has changed over time, as authors such as Giuliano (1995) and Cervero et al. (1995) have hypothesised. Evidence from several continents is compared in order to understand whether the results are general or regionally specific. A total of 49 studies were reviewed which originate from several regions across the world: USA (22 studies), Europe (21 studies) and Eastern Asia (6 studies).

The paper is divided into three main parts. Section 2 reviews the basic characteristics of the studies, including the stage in history examined, the time span, interval data frequency, spatial unit(s), study location, data types and indicators. Section 3 summarises the empirical findings of the studies reviewed. Section 4 provides the conclusion, proceeds with a discussion on a scheme which can explain the influence of TINs on LU over time and identifies new directions for future research in the field.

## 2.2.   Study Characteristics

### 2.2.1.   Stage in history, time span and data interval

All articles reviewed in this paper are temporal in nature: they examine data at multiple points in time (i.e. multiple cross-sections). However, the studies vary in terms of three temporal dimensions: (i) the stage in history considered (e.g. the beginning or middle of the railway building era); (ii) the total time span examined (e.g. a decade or a century); and (iii) the frequency of data collected across the total time span (e.g. five or ten year intervals). Figure 2.2 illustrates the variation between the three temporal dimensions in the 49 articles reviewed. The horizontal lines mark the length of the study period, the breaks representing the data intervals. Only the period in which the LU-TIN interactions are considered is depicted in the figure.

In general, the more recent studies, especially from Europe, investigate periods further back in time and with longer time spans, indicating a growing interest in long-term empirical analysis. The growth in long-term studies can partly be explained by advances in GIS techniques as well as the wider availability of high-resolution digital data and more sophisticated econometric techniques. Few studies examine data from earlier than 1950 (16 studies of 49) or consider time spans longer than 50 years (11 studies). The majority of studies (31) only investigate the impact of one type of TIN (i.e. either road or rail) on LU: only a minority (18) investigate both. The studies which go furthest back in time and start in the 19th century focus only on rail networks. Hardly any studies investigate the impacts of road infrastructure before 1950, probably because documenting historical road network evolution is very difficult in comparison to railway lines and stations. While a substantial amount of research has been done on the relation of rail and population change, the long-term role of access to rail in relation to employment and land cover change has not often been considered. Almost all studies on land-cover change span the second half of the 20th century.

Most studies focus on the second half of the 20th century, especially the last few decades (Figure 2.2). Studies which only focus on the impact of new TINs tend to have rather short time spans, such as the before-after impact study of the Bay Area Rapid Transit (BART) (Cervero & Landis, 1997). Studies concerned with urban growth usually look further back in time. Examples are those tracing the role of railways and earlier forms of public transport in population distribution patterns (Koopmans, Rietveld, & Huijg, 2012; Levinson, 2008).

### 2.2.2.   Spatial unit and study area

The commonly used spatial units of analysis are census tracts, districts, municipalities or counties. Finer units of analysis, such as parcels and blocks or point location microdata, are usually aggregated into grid cells. A few studies employ other spatial units than administrative divisions or grid cells. For example, Cervero and Landis (1997) and Bollinger and Ihlanfeldt (1997) examine grid cells and tracts within station catchment areas, that is, a half-mile and quarter-mile ring of the stations. The total area of analysis (i.e. the area covered by all spatial units) in the studies ranges from a whole city region to a whole country. Studies with larger study areas tend to contain larger spatial units.
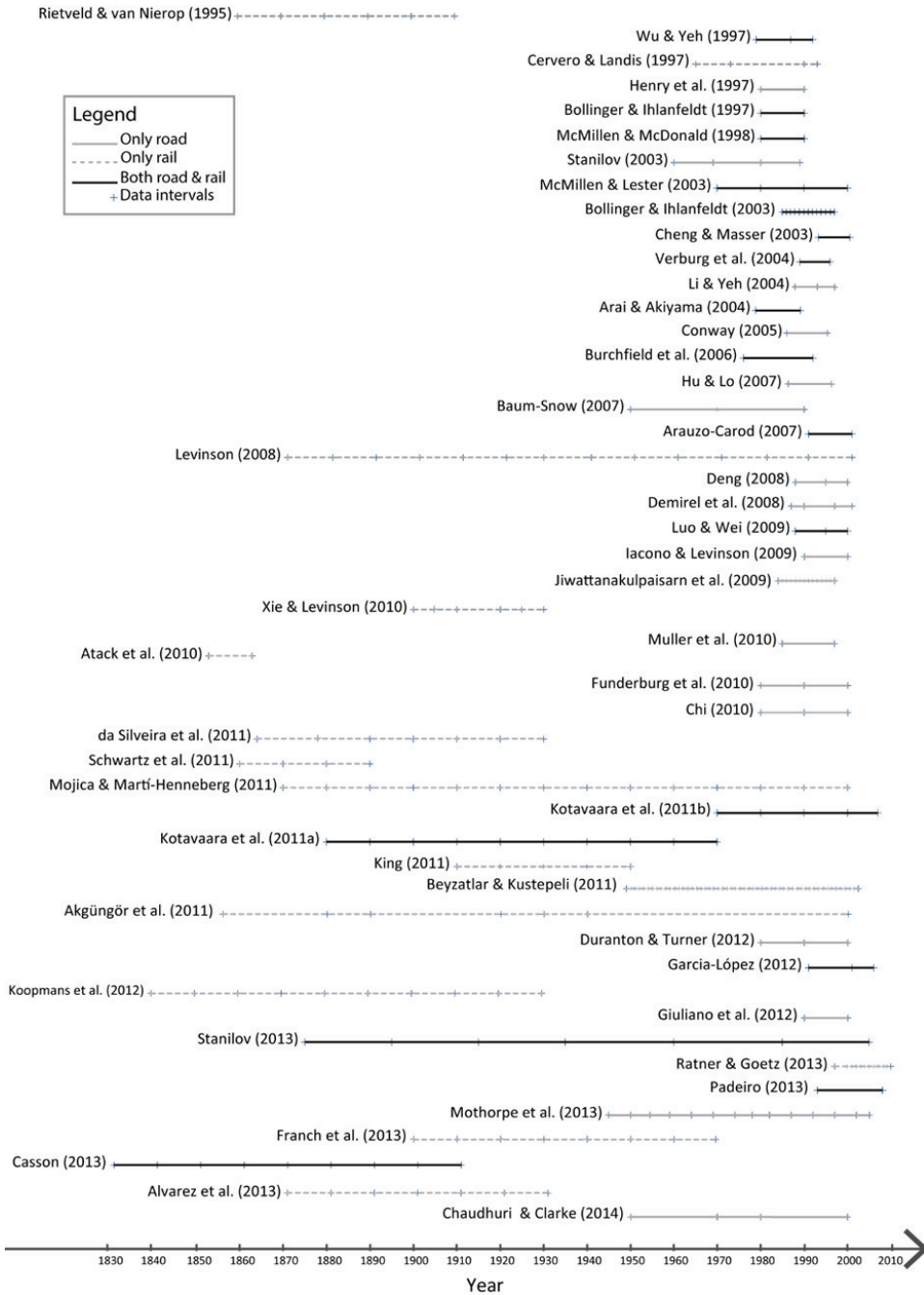
**Figure 2.2. Stage in history, time span and data intervals of the papers reviewed.**

Studies at the regional and intraregional scales often differ in scope. Studies at the regional scale usually seek to demonstrate the effect of TINs on regional land development processes such as urbanisation or regional population/employment growth (and vice versa). The spatial units examined in these studies are often metropolitan areas, frequently across an entire country (e.g. Duranton & Turner, 2012). In terms of their scale and macro-economic approach, they are similar to studies investigating the relationship between transport infrastructure and economic productivity. Intraregional studies, on the other hand, investigate finer spatial units such as parcels and blocks, station areas, census tracts and districts/municipalities, often across a whole city region. These studies are frequently concerned with quantifying the more local changes in employment, residential and commercial densities and land covers within the region as a result of specific transport infrastructure projects.

### 2.2.3.  Data types and indicators

Different data sources and indicators are used to examine LU and transport infrastructure. Most studies use population density as a proxy for LU, particularly those examining earlier stages in history. Some studies use the share of urban land as the indicator for LU development but generally only for the second half of the twentieth century when reliable data became available from satellite images and remote sensing techniques. This type of land- cover data is often available at intervals of five to ten years either as raster (e.g. Demirel, Sertel, Kaya, & Seker, 2008) or manually digitised vectors based on aerial photos (e.g. Stanilov, 2003). In a smaller number of studies, the increase in the proportion of the population living in urban areas (i.e. urbanisation) was used as a proxy for LU change (Atack et al., 2010). Meanwhile, the work of Burchfield, Overman, Puga, and Turner (2006) employed a measure of urban sprawl (i.e. the inverse of compactness of urban development) as an indicator of LU change. In general, studies of the impacts of TIN on LU in Eastern Asia cover more recent time periods, and focus on land-cover change rather than population growth (often due to data availability issues). In these cases, rapid land development combined with high-resolution recent data provides the opportunity to monitor change in detail. Only a few studies employ indicators for development type (residential, office, commercial, industrial) and intensity, using aggregated parcel attributes such as total floorspace. Table 2.1 summarises the characteristics of the studies according to region, TIN type and LU type.

**Table 2.1. Empirical studies of the impact on TIN on LU according to region, TIN type and LU type.**

|  | Region | | | |
|---|---|---|---|---|
|  | **Europe** | **United States** | **Eastern Asia** | **Total per type** |
| **TIN** | | | | |
|     Road | 3 | 12 | 2 | 17 |
|     Rail | 10 | 5 | 0 | 15 |
|     Road and Rail | 8 | 5 | 4 | 17 |
| **LU type** | | | | |
|     Land cover | 6 | 6 | 6 | 18 |
|     Density (population or employment) | 15 | 12 | 0 | 28 |
|     Type of Development | 0 | 3 | 0 | 3 |
| **Total per region** | 21 | 22 | 6 | 49 |

Various transport infrastructure indicators are used to measure the characteristics of transport modes including their length, the number/density of lines/stations and the distance to stations/highway exits. Distance is generally measured from the centroid of the unit of analysis (e.g. tract, municipality or grid cell) to the transport node (station, highway exit). Distances are mostly measured as straight-line (Euclidian) distances, except for a few cases where network distance was calculated (e.g. Giuliano, Redfearn, Agarwal, & He, 2012). Almost all studies use the concept of accessibility to analyse the LU transport interaction. Various measurements of accessibility are used, ranging from simple Euclidian distance to more complex gravity-based indicators. In addition to physical and geographical measures, TIN investment indicators such as (per capita) expenditure on highway improvements have also been used.

## 2.3.    Results of the studies

This section reports the main results of the studies in terms of the impact of rail and road networks on LU. Table 2.2 summarises how many studies found significant results, positive or negative, or varying results with respect to different time intervals or different study areas. Table 2.3 adds more detail by including the study period, region and specific LU characteristics.

**Table 2.2. Summary of the main impacts of infrastructure on LU according to the studies reviewed.**

| Relationship | Studies focusing on road or rail | | Studies focusing on road and rail | |
|---|---|---|---|---|
| | Road | Rail | Road | Rail |
| Non-significant | 1 | 0 | 3 | 5 |
| Positive | 10 | 9 | 10 | 3 |
| Negative | 0 | 0 | 0 | 3 |
| Varying | 6 | 6 | 4 | 4 |

Models used for investigating population or employment change are quite varied. They include OLS, instrumental variable estimates, causality tests, Generalized Additive Models (GAMs) and experimental research designs such as Difference-in-differences. However, those determining land-cover change are quite straightforward, usually using logistic regression to model the probability of land conversion (e.g. from non-urban to urban or from one land type to the other) according to a variety of variables (e.g. Luo & Wei, 2009).

### 2.3.1.   The impact of rail infrastructure on land-use change

The development of railways has played a significant role in the spatial distribution of population in many countries. Akgüngör, Aldemir, Kustepeli, Gulcan, and Tecim (2011) show that population growth along railway routes in Turkey was highly correlated with network development, especially up to 1940. Meanwhile, Beyzatlar and Kuştepeli (2011), who focus on the impacts of rail infrastructure in the second half of the 20th century, conclude that railway length had a short as well as a long-term impact on population density increase. In Portugal, da Silveira, Alves, Lima, Alcantara, and Puig (2011) identify two phases for the impact of railway development on population growth up to 1930. Before 1911, the effect was strong as parishes with railway stations grew faster than those without, but after completion of railway network, it grew weaker. Similar relationships are reported by Mojica and Marti-Henneberg (2011) for France, Spain and Portugal. They report that the urban areas connected to the rail network increased as the railways expanded up to the 1920s and decreased afterwards.

Impacts of railway development on population change can vary substantially across different territories in the same country. According to da Silveira et al. (2011), more affluent regions in Portugal experienced population growth during the early development of the railways, whereas poorer regions experienced depopulation over the same period. Nevertheless, Schwartz, Gregory, and Thevenin (2011), report a positive impact in the less developed parts of south-west France in the 1800s. They also illustrate that railway density was significantly associated with reducing the pace of out-migration in rural areas in Wales and south-west England during the 1870s and 1880s. Looking at a longer period of time for the same region (1871–1931), Alvarez, Franch, and Marti-Henneberg (2013) conclude that parishes most accessible to rail were most likely to experience population growth. Elsewhere in Oxfordshire (UK), Casson (2013) finds negative, positive and no correlation between population growth and three respective waves of railway development (periods between 1831, 1861, 1891 and 1911). He suggests that different results can be related to the trunk lines built in the first and third waves (facilitating interurban traffic between larger cities rather than serving the intermediate towns) versus local lines serving the study area which were built during the second wave.

In a study of Finland, Kotavaara, Antikainen, and Rusanen (2011b) conclude that proximity to railways significantly explained population growth from 1920 to 1970, except for the 1930s, coinciding with a decade of recession. In a separate study, they (2011a) report that travel time to the nearest railway station was significantly related to population growth in 1970s but insignificant for the last decades of the 20th century. In the period 2000–2007, the relationship between proximity to railway station and population growth became significant again, which they explain in terms of major government investments in long-distance transport infrastructure.

For a number of studies, the strength of the relation between rail and population change, as well as its rate, varies across different periods. Rietveld and van Nierop (1995) explain the growth rate of 44 Dutch cities as a consequence of the growth of railways from 1840 to 1890. They note substantial changes in patterns of urban growth from decade to decade and report that the change in number of railway lines entering the cities is a modest but significant explanatory variable for a certain number of decades. The modest impact of rail on population growth is also confirmed by Koopmans et al. (2012) who extend Rietveld and van Nierop's study period by 40 years. Their "relative rail accessibility" indicator and its change (reflecting the change in shortest travel times between municipalities as a result of railway network improvements) show a significant and positive relation with municipal population growth during half a century coinciding with Dutch industrialisation (1880–1930). However, they conclude that this effect is small when compared to urbanisation (operationalised by "relative centrality" indicator which was only influenced by population distribution) and crowding effects (indicated as population density in persons per sq. km). Similarly, Atack et al. (2010) confirm that the role of early railway network in population growth of American Midwest in the 1850s was not significant. However, railways were found to have significantly caused much of the increase in urbanisation, measured as the fraction of a county's population living in urban areas.

At the city-region scale, it is suggested that rail can encourage the depopulation of the core while increasing the population in the periphery. For example, Levinson (2008) reports that additional surface and underground rail stations are linked to the increase of population in the London periphery. Similarly, Garcia-Lopez (2012) finds that improvements in the Barcelona's metropolitan railway network were linked to suburban population growth between 1991 and 2006. In Chicago, McMillen and Lester (2003) conclude that the proximity of a tract to commuter rail stations was associated with higher population density in the period between 1970 and 2000. On the other hand, Bollinger and Ihlanfeldt (1997), report that the location of Atlanta's MARTA (Metropolitan Atlanta Rapid Transit

Authority) rail transit stations was not significantly related to patterns of population growth in the city during the 1980s.

Results on the relation between rail access and employment growth are mixed. For example, Cervero and Landis (1997) show that growth in jobs in relation to BART has been mainly limited to downtown San Fransisco. On the other hand, Bollinger and Ihlanfeldt (1997, 2003) find no rail impact on employment around MARTA's station areas in the last decades of the twentieth century. Meanwhile, significant rail coefficients for employment density are reported around the same period for Chicago, a city with an established rail network (McMillen & Lester, 2003; McMillen & McDonald, 1998).

The indicator of land-cover change has been less frequently investigated than population density in studies of relationships between TINs and LU. The results of studies using indicators of land cover can be quite contradictory. Distance to railway line is reported to have no impact on LU change in Guangzhou from 1979 to 1992 (Wu & Yeh, 1997). Surprisingly, in the case of Nanjing (1988–2000), the proximity to rail is shown to discourage the conversion to urban land. Authors attribute this to the fact that rail does not support within-city displacements but serves "long-distance interurban" commutes (Luo & Wei, 2009). On the other hand, Cervero and Landis (1997) illustrate that LU is significantly more likely to change in the proximity of BART stations.

Evidence was found that rail attracts residential developments. For example, Xie and Levinson (2010) show that the growth of the streetcar network encouraged residential development in the Twin Cities of Minneapolis and St Paul between 1900 and 1930. Cervero and Landis (1997) report that while multi-family housing grew rapidly around 25 BART stations, the major development belongs to non-residential LUs (i.e. commercial, office and industrial), particularly office space in downtown San Francisco. The rise of development (mostly residential but also non-residential such as offices) is also observed in station areas close to Downtown Denver from 1997 to 2010 (Ratner & Goetz, 2013).

### 2.3.2. The impact of road infrastructure on land-use change

Most studies demonstrate that new road infrastructure, especially major road infrastructure, facilitates the relocation of population from the centre to the periphery (i.e. suburbanisation). Examining the impact of interstate highways on suburbanisation of US Metropolitan Statistical Areas between 1950 and 1990, Baum-Snow (2007) reports that the improvements in the highway system attract population along the highways and contribute to the central city's population decline. Meanwhile, Garcia-Lopez (2012) concludes that the proximity to highway exits encouraged suburban population growth in the Barcelona Metropolitan Region between 1991 and 2006. Analysing the effect of roads on the growth of population in 275 Metropolitan Statistical Areas of continental USA between 1980 and 2000, Duranton and Turner (2012) suggest that the increases in the major road stock can explain why some areas experienced higher population growth than others. Chi (2010), examining the effects of highway "expansions" on population change in Wisconsin during the 1980s and 1990s, suggests that highway expansions mostly influenced population increase in suburban areas, thereby strengthening suburbanisation. On the other hand, Henry, Barkley, and Bao (1997) report that the initial stock of highways in 1980 was unrelated with population growth in rural hinterland tracts in South Carolina, Georgia and North Carolina during the 1980s. Meanwhile, McMillen and Lester (2003) contend that population density growth between 1970 and 2000 was lower within a third of a mile of highway interchanges than other locations in the Chicago metropolitan area.

It is generally demonstrated that the road network, especially major road infrastructure, influence employment growth (a few studies, however, did not find this connection). Investigating the relation between highway road networks and employment in 48 contiguous US states between 1984 and 1997,

Jiwattanakulpaisarn, Noland, Graham, and Polak (2009) report that the density of lane-miles of non-local roads significantly explains the variations in employment growth in private sector. They conclude that the presence of an impact and its direction varies depending on the location (within the same state including the highway or all other states), time lag (short- or long-run impact) and type of highway (interstate highways or non-interstate major roads). According to a study by Giuliano et al. (2012), highway network accessibility was significantly related to the growth of employment centres and urban spatial structure in the 1990s in the Los Angeles region. Examining the relation of specific highway improvement projects and employment change in three Californian counties from 1980 to 2000, Funderburg, Nixon, Boarnet, and Ferguson (2010) report that employment growth can be highly variable – both positive and negative. They conclude that the type of highway improvement (e.g. new extensions/connections or expanded capacity) can influence the overall impact on employment change as well as more location-specific characteristics, such as local economic performance or the degree of rurality. In their study of Chicago, McMillen and Lester (2003) report that highways increasingly encouraged employment growth between 1970 and 2000. Meanwhile, Bollinger and Ihlanfeldt (1997, 2003) demonstrate the same positive relation between presence of highways and per capita expenditures on them with employment growth in Atlanta for the periods of 1980–1990 and 1985–1997. Other studies, however, do not find evidence of a significant relation between highways and employment. Henry et al. (1997), for example, conclude that the density of highways in 1980 was not a significant factor in attracting employment growth during the 1980s, and Arauzo-Carod (2007) finds no significant relationship between TINs (road or rail) and the distribution of professional groups of population and workers across the territory.

Studies examining land-cover change conclude that the presence of or the proximity to the road network increases the likelihood of land-cover change in general, and the conversion from non-urban to urban (i.e. urbanisation) in specific. Using satellite images at roughly five year intervals from 1987 to 2001, Demirel et al. (2008) show that the doubling of the road transport network coincides with an increase in urban areas and a decrease of barren and agricultural land in the southeast part of Istanbul Metropolitan Area. The results of Muller, Steinmeier, and Kuchler (2010) suggest that more urban development has taken place near motorway exits in Switzerland than further away, during the period 1985–1997. Mothorpe, Hanson, and Schnier (2013) also report a link between the development of the interstate highway and the growth of urban areas in the counties of Georgia, USA, over the second half of the 20th century.

In Atlanta, Hu and Lo (2007) report that the odds of urban development in close proximity to major roads nearly doubled in comparison to distances of more than one kilometre from the road network. Conway (2005) finds the same significant relation between accessibility to highways, measured as the network distance to the nearest exit, and new urban development in New Jersey between 1986 and 1995. The proximity to the road infrastructure or its density is correlated to urban land development for various studies of China (Cheng & Masser, 2003; X. Z. Deng, Huang, Rozelle, & Uchida, 2008; Li & Yeh, 2004; Wu & Yeh, 1997).

**Table 2.3. Summary of the results of the studies according to transport type and LU variables.**

| Author(s), Year | Time period | Study area | LU | TIN | |
|---|---|---|---|---|---|
| | | | | Road | Rail |
| **Chaudhuri & Clarke (2014)** | 1950–2000 | Friuli-Venezia region, Italy | 1 | + | |
| **Alvarez et al. (2013)** | 1871–1931 | England and Wales, UK | 2 | | +* |
| **Casson (2013)** | 1831–1911 | Oxfordshire, UK | 2 | 0 | –/+ |
| **Franch et al. (2013)** | 1900–1970 | Spain | 2 | | +/– |
| **Padeiro (2013)** | 1993–2008 | Île-de-France region, France | 2 | + | 0 |
| **Ratner & Goetz (2013)** | 1997–2010 | Denver, USA | 3 | | + |
| **Mothorpe et al. (2013)** | 1945–2007 | Georgia, USA | 1 | + | |
| **Stanilov (2013)** | 1875–2005 | West London, UK | 1 | +* | +* |
| **Giuliano et al. (2012)** | 1990–2000 | Los Angeles region, USA | 2 | + | |
| **Koopmans et al. (2012)** | 1840–1930 | the Netherlands | 2 | | + |
| **Garcia-López (2012)** | 1991–2006 | Barcelona Metropolitan Region, Spain | 2 | + | + |
| **Duranton & Turner (2012)** | 1980–2000 | Metropolitan regions, USA | 2 | + | |
| **Akgüngör et al. (2011)** | 1856–2000 | Turkey | 2 | | + |
| **Beyzatlar & Kustepeli (2011)** | 1950–2004 | Turkey | 2 | | + |
| **King (2011)** | 1910–1950 | New York city region, USA | 3 | | + |
| **Kotavaara et al. (2011a)** | 1880–1970 | Finland | 2 | + | + |
| **Kotavaara et al. (2011b)** | 1970–2007 | Finland | 2 | + | + |
| **Mojica & Martí-Henneberg (2011)** | 1870–2000 | France, Spain and Portugal | 2 | | +* |
| **Schwartz et al. (2011)** | 1860–1890 | France and Great Britain | 2 | | + |
| **da Silveira et al. (2011)** | 1864–1930 | Portugal | 2 | | +* |
| **Chi (2010)** | 1980–2000 | Wisconsin state, USA | 2 | + | |
| **Funderburg et al. (2010)** | 1980–2000 | Merced, Orange and Santa Clara counties, California, USA | 2,3 | + | |
| **Atack et al. (2010)** | 1850–1860 | Midwestern states of Indiana, Illinois, Michigan, Ohio, Wisconsin, Iowa and Missouri, USA | 2 | | + |
| **Muller et al. (2010)** | 1985–1997 | Switzerland | 1 | + | |
| **Xie & Levinson (2010)** | 1900–1930 | Minneapolis and St Paul city regions, USA | 3 | | + |

| Study | Period | Location | LU | | |
|---|---|---|---|---|---|
| Jiwattanakulpaisarn et al. (2009) | 1984–1997 | 48 contiguous states, USA | 2 | + | |
| Iacono & Levinson (2009) | 1990–2000 | Twin cities, USA | 1 | + | |
| Luo & Wei (2009) | 1988–2000 | Nanjing, China | 1 | + | − |
| Demirel et al. (2008) | 1987–2001 | Southeast part of Istanbul Metropolitan Area, Turkey | 1 | +* | |
| Deng (2008) | 1988–2000 | China | 1 | + | |
| Levinson (2008) | 1871–2001 | London and Westminister city regions, UK | 2 | | + |
| Arauzo-Carod (2007) | 1991–2001 | Catalonia, Spain | 2 | 0 | 0 |
| Baum-Snow (2007) | 1950–1990 | Metropolitan regions, USA | 2 | + | |
| Hu & Lo (2007) | 1987–1997 | Atlanta region, USA | 1 | + | |
| Burchfield et al. (2006) | 1976–1992 | Entire conterminous United States | 1 | 0 | − |
| Conway (2005) | 1986–1995 | New Jersey, USA | 1 | + | |
| Arai & Akiyama (2004) | 1979–1989 | A suburban district of Tokyo | 1 | + | − |
| Li & Yeh (2004) | 1988–1997 | Pearl river delta, China | 1 | +* | |
| Verburg et al. (2004) | 1989–1996 | the Netherlands | 1 | + | + |
| Cheng & Masser (2003) | 1993–2000 | Wuhan city, China | 1 | + | |

Notes: LU characteristics studied: 1 = land cover; 2 = population/employment density; 3 = type of development (residential, office, commercial, industrial). Relationship between LU and transport: + = positively related; 0 = no relationship; − = negatively related.* A statistical test of significance was not performed; Blank denotes that the TIN type was not investigated.

Wu and Yeh (1997) differentiate between road types and report that the magnitudes and signs of proximity to different road types changed before and after the Chinese land reform in 1987. Before land reform, proximity to inter-city highways located away from the centre increased the probability of land development. After reform, however, proximity to city streets encouraged the development of land, suggesting the attraction of new commercial developments to locations closer to city centres. The impact of the development of the road network on land-cover change varies by location according to studies such as Mothorpe et al. (2013) who suggest that land cover is closely linked to the initial degree of urbanisation. Of their "urban", "rural" and "transition" categories, only the "urban" counties show a significant growth of urban land as a result of interstate highway developments.

Various studies also indicate that highways attract commercial and/or industrial developments (Arai & Akiyama, 2004; Iacono & Levinson, 2009; Muller et al., 2010; Verburg, van Eck, de Nijs, Dijst, & Schot, 2004), while supressing residential development (Cervero & Landis, 1997; Iacono & Levinson, 2009; McMillen & Lester, 2003). Measuring the impact of road network on LU distribution pattern within the suburban areas of Greater Seattle between 1960 and 1990, Stanilov (2003) links the growth of residential and non-residential LUs to "integral accessibility", an index based on access to the regional road network. LUs seeking most regionally accessible locations were commercial, followed by industrial, multi-family, medium-density single-family and finally low-density single-family uses.

### 2.3.3.   The leading factor between transport infrastructure and land use

The number of bi-directional studies, which explore the interaction between LU and TIN, is relatively low in comparison to mono-directional studies of the impact of TIN on LU. According to several bi-directional studies, there is a view that TINs have followed LU, as in the case of early railways which followed the existing population cores (Atack et al., 2010), or the subways which followed the established residential development patterns in New York (King, 2011). Meanwhile, TINs are reported to have led LU in the case of electrified streetcars causing urbanisation in Twin Cities (Xie & Levinson, 2010). However, not all findings are clear-cut. For instance, Jiwattanakulpaisarn et al. (2009) conclude that in the USA, causality between highways and regional employment could have happened in either direction, or Levinson (2008) reports that rail station density and population density were mutually reinforcing in London periphery (Levinson, 2008).

### 2.3.4.   The role of other factors

The impact of TINs on LU (and in general their interaction) depends to a considerable extent on exogenous factors which can influence their supply (Figure 2.1). Major advances in TIN technology such as the emergence of railways or the electrification of tramways have been declared as a major driving force of LU change (e.g. Xie & Levinson, 2010). Infrastructure investments and transport policies influence the supply, but also the usage of TINs. Transport policies result directly in the investment in and the improvement of major TINs. For instance, King (2011) indicates that the subway was initially planned to disperse high residential densities from downtown New York to the outer boroughs. Cervero and Landis (1997) specify that BART was intended to encourage a multi-centred settlement pattern. In terms of LU impact, Kotavaara et al. (2011a) claim that significant investments in the supply of long-haul rail transport in Finland influenced population distribution at a regional level in the 2000s. Furthermore, TINs are financed in a variety of ways which can affect LU decisions to various degrees. For example, the development potential of TINs can be fully exploited when transport developers have real estate interests and/or the legal authority to develop land (Xie & Levinson, 2010). On the other hand, when transport providers are not linked to the land development market and are dependent on fare revenues, only profitable routes within the existing built-up area are likely to be developed, and new TINs are unlikely to lead to new urban expansion (King, 2011).

Similarly, the final impact on LU can depend on exogenous factors influencing its supply. In the absence of regional demand, new TINs are unlikely to stimulate LU change. An example is that of railways encouraging growth in prosperous regions contrary to the lagging ones where they might even discourage further development (da Silveira et al., 2011). Furthermore, the availability of developable land as a prerequisite for TINs' impact is demonstrated (e.g. Cervero & Landis, 1997). Surprisingly, area attractiveness has been mostly overlooked. An exception is Bollinger and Ihlanfeldt (2003) who used crime rates as a proxy for area attractiveness and found that it can repel the positive impact of rail stations on employment. A minority of previous research has attempted to empirically measure the role of spatial policies. From those who have, the majority have focused only on the role of local policies, overlooking regional and national policies. China is an exceptional case where a radical and rapid change from a centrally planned to transitional economy (via economic and land reform) was observed, and its effect on the LU-TIN relationship was measured (Cheng & Masser, 2003; Wu & Yeh, 1997). In most cases, however, policy changes are less radical and more gradual, making it more difficult to quantify their effects. In an attempt to take the gradual change in planning policies into account, Chaudhuri and Clarke (2014) used a quasi-experimental method to determine the role of "political history" ("the combination of regional level government programs and political events affecting urbanization pattern in a region"). They attribute the physical and structural differences

between LU and TINs of two cities in the same region in Italy to the indirect result of various planning policies. The conclusion is that political history affected the LU and road-network changes separately, but not the type of spatial relationship between them.

Finally, in addition to separate transport and spatial policies, there are combined policies targeted at development of transit nodes under the umbrella term "Transit-oriented Development" or TOD policies. The main goal of such policies is to encourage high-density, mixed-use, pedestrian- and bicycle-friendly environments, in combination with improved transit systems to promote transit use (Bertolini, Curtis, & Renne, 2012; Cervero, 2007). Examples include rezoning, density bonuses, marketing of air rights and available excess land around transit nodes combined with level of service improvements, such as higher frequencies or speed. Table 2.4 provides a list of the effects of spatial policies at the regional and local scale measured in the literature. A number of chosen examples demonstrate how they were operationalised and which results were obtained.

**Table 2.4. Effects of TIN and LU policies measured in the reviewed studies.**

| Policy type | Way of measurement | Result |
| --- | --- | --- |
| **LU policies** | | |
| **National/regional government policies** | | |
| Land ownership | Comparison of access indicators before and after the Chinese land reform which allowed land leasing (Wu & Yeh, 1997) | Introduction of land markets to cities changed the role of accessibility in determining type and location of land development |
| Spatial planning | Dummy variable showing whether a municipality belonged to designated New Towns (Padeiro, 2013) | Being part of a New Town exclusively influenced employment growth in municipalities with more than 100 jobs |
| **Local government policies** | | |
| General LU plan, development restrictions | Dummy variable indicating whether a site was planned as built-up or undevelopable area (Cheng & Masser, 2003) | Master planning had limited influence on urban growth due to the rise of market-driven land development |
| Administrative divisions | Percentage of "unincorporated" areas in the urban fringe (Burchfield et al., 2006) | Percentage of land in the urban fringe not subject to municipal planning regulations encouraged sprawl |
| Tax incentives | Dummy variable indicating if tracts were eligible for specific neighbourhood-based property tax abatements (Bollinger & Ihlanfeldt, 2003) | Designation of commercial-industrial enterprise zone, influenced metropolitan distribution of employment |
| Zoning | Minimum lot size allowed by municipal zoning regulations (Conway, 2005) | Not significant in explaining land cover change |

| **Integrated LU/TIN policies** | | |
| --- | --- | --- |
| TOD measures | Introducing an interaction term between transit access variable and station types (designated by Transit Station Area Development Studies) (Bollinger & Ihlanfeldt, 1997) | Only rail stations classified as "mixed-use regional nodes" had an influence on the mix of employment in tracts which contained a portion of their impact area |

## 2.4. Conclusions, discussion and recommendations for future research

### 2.4.1. Conclusions on the effects of transport infrastructure on land-use change

This paper has systematically reviewed the long-term influences of transport infrastructure networks (TINs), both road and rail, on land use (LU). It investigated how LU is likely to change as a result of the development of different TINs over time, and the role of external factors including policies in this respect. Its specific contribution to the field is threefold. First, it provides a synthesis of the most recent empirical evidence from studies published since 1995. Second, it reviews and compares empirical evidence from different parts of the world – USA, Europe and Asia. Third, it focuses specifically on the long-term impacts of TINs on LU, as opposed to short-term impacts.

Proximity to rail is generally considered to have influenced population distribution, especially after the railway network emergence. Exceptional negative effects were reported for lagging regions, trunk lines which were not beneficial to the local study area, or areas which already had a dense rail service for a while. Proximity to rail has also promoted conversion to residential LU and development of higher residential densities. However, findings on its role in increasing employment density are inconclusive, indicating that its success is more dependent on exogenous factors such as complementary policies and area attractiveness, which are mostly favourable in downtown areas.

For the road network, studies generally suggest that the presence of or the proximity to major highways is associated with the conversion to urban land, increases in employment densities and commercial and industrial development. However, this is not always the case for residential uses, suggesting that living in the direct vicinity of motorways could be unattractive.

Of the 19 studies which have examined both access to rail and road networks, almost all of them find lower coefficients or no significance for access to rail compared to the road network, regardless of the study period. However, it should be noted that these studies mostly focus on changes during the second half of the 20th century and onwards, when the rail network is assumed to have lost its initial impact.

Exogenous factors influencing the supply of TINs and LU can determine the result of TINs on LU. Technological innovations, infrastructure investments and mobility policies influence the supply of TINs. In terms of LU, regional demand, land availability, area attractiveness and spatial policy play important roles. While these factors have been mentioned, they have not always been explicitly addressed. This is especially true in the case of area attractiveness and spatial/transport policies.

### 2.4.2. Discussion

Formulating clear-cut conclusions on the impacts of TINs on LU with a focus on their relation over time needs care because of the variety of methods, data sources, spatial and temporal scales, physical

locations and findings (see Deng, 2013 for an extensive review of potential causes behind inconclusive results in the study of TINs' economic impacts which can also be applied to their LU impacts). Nevertheless, a simple scheme for illustrating the relationships over time can be used to summarise the general situation (Table 2.5). The horizontal and vertical axes in the table represent the degree of development of LU and TIN, respectively. In practice, these axes are continuous but are represented in binary form in Table 2.5 for simplicity of presentation.

**Table 2.5. Importance of saturation level of TINs and LU on the impacts of the transport system on LU.**

|  | LU *before* development saturation | LU *after* development saturation |
|---|---|---|
| TIN *before* accessibility saturation | **High impact** if there is demand;<br><br>• TIN is likely to follow the existing LU pattern and lead further development (e.g. early railways/tramways)<br>• TIN can lead if it has significant technological advantage or is successfully applied as a tool to encourage further growth (e.g. highways stimulating growth in undeveloped areas) | **Potential impact**;<br><br>• LU is likely to lead (e.g. mass transit introduced into congested city centres) |
| TIN *after* accessibility saturation | **Potential impact** if LU development constraints are removed;<br><br>• TIN is likely to lead (e.g. encouraging LU developments by relaxing building restrictions in accessible preserved areas/city centres, development of highly accessible brownfield sites, reclamation of land around transport nodes) | **Marginal impact** unless an occurrence of:<br><br>• A substantial change of LU policies (e.g. land leasing in Chinese cities after land reform)<br>• Supportive transport measures (e.g. restrictive parking, road/congestion pricing, fuel tax, reduced fares or increased level of service)<br>• A combination of the above (e.g. increasing service frequencies and higher density development around transport nodes) |

In terms of TINs, there is a threshold after which their accessibility improvement and consequently LU impacts become increasingly marginal (Axhausen, 2008; Giuliano, 2004). This trend can be observed in the case of the impacts of rail on LU, which follows a logistic function. Non-significant coefficients for access to rail variables have been reported at the beginning of the development of the railway network (when the impact has not yet had effect) and in more recent decades (when the impact has worn off). For the period in between, more significant results were reported. In the case of road network, its initial impact is less clear due to the lack of studies which consider the situation before 1950. Nevertheless, the saturation in accessibility provided by the road network is observable in the case of the weakening effect of highway developments after the era of highway building.

Similarly, there is also a development threshold after which LU change (e.g. conversion from non-urban to urban, rise in population density, stock of housing and other buildings) slows down. In other words,

just as land development increases so do constraints for further development. Further TIN improvements are unlikely to yield significant LU changes when there is no space for development, mainly due to the durability of the built-environment and the high costs of demolishing and reconstructing an already developed area. On the whole, the magnitude of TINs' impact on LU depends on the stage of TIN development coinciding with the stage of LU development.

Regarding the leading factor between TINs and LU, the number of bi-directional studies is too small to draw definitive conclusions for the time being. However the findings suggest that the more developed of the two is likely to have the upper hand in leading the other's development, unless a significant advance in transport technology or an effective policy intervention occurs which succeeds in setting a new trend. In other words, whether it is TIN or LU which leads seems to be closely related to the concurrence of TIN and LU saturation stages as well. Table 2.5 indicates the possible leading factors at each stage in addition to the likely extent of LU impact.

### 2.4.3.  Recommendations for future research

Although there are many papers on the relationship between TINs and LU, certain issues have only scarcely been addressed. These issues are reflected in the following recommendations for future research:

- Current literature mainly focuses on direct impacts of TIN development on LU; however, the same developments may also affect other spatial levels, a phenomenon referred to as spatial spillovers. The existence of TINs' impact, its type and significance can vary at different spatial scales. Positive spillover effects emerge from the network behaviour of TINs. For instance, a new highway link not only affects the locations it directly connects, but also influences a wider region by reducing the overall travel cost and increasing the overall accessibility (Giuliano, 2004). Conversely, TIN modifications could also change the comparative advantage of different regions to attract productive resources (e.g. labour force) and entail negative spillover effects (Boarnet, 1998; T. Deng, 2013). An example is a highway increasing employment in the states it directly passes through at the expense of other states (Jiwattanakulpaisarn et al., 2009). Thus, the extent to which TIN investments can redistribute LU changes across jurisdictions and over larger distances calls for closer investigation.
- TINs have impact not only on LU but also on economic (see e.g. Aschauer, 1989; Lakshmanan, 2011; Munnell, 1990), environmental and social domains (Geurs, Boon, & Van Wee, 2009). To assess the overall impact of TINs, these strands of research need to be compared.
- The length of the study (time span) should be long enough to capture potential impacts (bi-directional studies need longer investigation periods than mono-directional ones). Also, data intervals during this time span should be frequent enough to test the effect of different time periods.
- The degree of saturation of TIN-provided accessibility and LU (i.e., whether and to what extent TINs and LU have evolved during the study period) should be measured. There is a need to explore indicators which can capture the effect of change in TIN-provided accessibility over time. These indicators should take account not only of the network characteristics of transport infrastructure but also of LU constraints.
- The role of new transit in attracting or repelling employment in different sectors and the magnitude of change in land cover and type of development (residential/commercial/offices) at different proximities to the station areas require closer examination, especially in the European and Asian context. Such studies could help to increase understanding of the

feasibility of public transit investments and the possibility of success of planning concepts such as Transit-Oriented Development and Smart Growth.

- As well as improving accessibility (which directly influences LU), TINs (especially transit) can influence LU indirectly by inducing complementary policies. Under conditions of saturated accessibility and LU development, research focusing purely on the role of TIN-related accessibility on LU patterns is unlikely to find significant results. In order to identify policy effects, future research should compare TIN-LU interactions across a variety of regions and time periods. An alternative is to carry out in-depth case- study research, which can shed light on the various local and context-specific mechanisms at work. Special attention should be given to the role of transport policies which can improve the quality of transport services (e.g. increasing frequencies and travel speeds, subsidies for transit fares or restrictive parking) rather than simply the existence of infrastructure.

- Including the role of area attractiveness is necessary to explain non-significant or negative TIN results as well as their positive impact. This will involve the use of more socio-economic and context-specific data such as education, income, crime profiles of the study area, as well as physical condition of the building stock and other civil infrastructures.

- The studies reviewed in this paper have analysed the impact of new or additional TINs on LU and not the impact of removed TINs on future LU. According to Block-Schachter and Zhao (2015), the impact of TINs on LU may continue even after the transport network has been removed. However, their theory of "hysteresis" requires further empirical investigation.

- Finally, studies focusing on one side of the LU transport feedback cycle will inherently be subject to the problem of endogeneity because the feedback between the two is not considered. There is an increasing need for bidirectional studies which investigate the interaction and the leading factor between TINs and LU and how they might differ over various periods and scales. Fortunately, such investigations are increasingly possible due to the wider availability of long-term, high-resolution data and new methods for their analysis.

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# Chapter 3: Development of rail infrastructure and its impact on urbanisation in the Randstad, the Netherlands

## Abstract

Long-term, large-scale empirical studies on the simultaneous development of transport infrastructure and the built environment are scarce. This paper provides a long term study of the development of the railway network, and its impact on the built-up area, and vice versa using the case study of the Randstad in the Netherlands between 1850 and 2010. The analysis is both qualitative and quantitative. We describe the shares of the built-up area in concentric buffers of 1 km intervals from railway stations and estimate binomial logit models to predict the likelihood of new stations being built based on the amount of the preceding and subsequent built-up area and the likelihood that a new station might have encouraged further growth. Results show that during the early days stations followed existing urbanisation patterns. But as time went by, new stations were more likely to be located in undeveloped areas and less likely to be located within the established built-up areas which were already serviced by existing stations. Moreover, they prompted further growth, increasing the likelihood of more urbanisation in their vicinity.

*Keywords:* Railway network, urbanisation, long-term impacts, the Randstad.

## 3.1. Introduction

A key question in urban studies is how urban areas expand. Understanding the determinants of urban growth and the consequences of their interaction is critical information for many people, from economic geographers to spatial planners and policymakers who aim to guide and channel future urban development. Many have argued the structuring role played by transport infrastructure in shaping the cities over time (e.g. Hoyt 1939; Mumford 1961; Rodrigue, Comtois, and Slack 2009). Furthermore, it has been observed that transport infrastructure, urbanisation (more generally referred to as land use) and travel behaviour are all interrelated. Infrastructure improvements increase accessibility, making land more valuable for further development; conversely, land development creates further travel demand, and consequently induces the need for infrastructure improvements (Giuliano 2004).

The interrelationships between transport infrastructure development, land use and travel behaviour have been investigated from a variety of perspectives. Many studies focus on the impact of land use, as the spatial embodiment of human activities, on travel behaviour (see for an overview Ewing and Cervero 2010), primarily as cross-sectional studies. Another part of the literature is dedicated to the relationship between transport infrastructure and regional economic development. Here, from the viewpoint of urban economics, research focuses on investigating the impact of mainly large-scale transport infrastructure such as highways or high-speed rails on economic changes at the regional level, usually in form of before-after analyses involving aggregated data (Rietveld and Bruinsma 1998; Banister and Berechman 2001). In addition, some authors have looked at how infrastructure affects land or property values (see for an overview Huang 1994).

A limited number of studies have used long-term empirical data to analyse the relationship between the development of infrastructure network and the built environment, the latter also referred to as land use. This relationship can only be studied over a long time period because both infrastructure development and land use development are lengthy processes, and moreover, the influence of the one on the other is likely to take even more time to become evident (Wegener, Gnad, and Vannahme 1986). One significant reason for the lack of long-term studies into this interaction is the lack of consistent data over a longer period (Badoe and Miller 2000). The few studies which have managed to overcome this difficulty have measured changes in accessibility as a result of changes in the infrastructure network and its consequence for accessible population or population density, usually within different degrees of proximity to the infrastructure (Atack et al. 2010; Axhausen, Froelich, and Tschopp 2011; Koopmans, Rietveld, and Huijg 2012; Duranton and Turner 2012). Looking at the demographic details, some researchers have distinguished between working and residential populations and investigated their redistribution over time in relation to access to transport infrastructure (Giuliano et al. 2012; Herranz-Loncán 2007; Bollinger and Ihlanfeldt 1997). All these studies investigate the association between infrastructure development and population density change. While change in population density is a reasonable proxy for land use change over time, it may well overlook changes in land consumption i.e. the expansion of urban land coverage. In other words, changes to land developed for dwellings and other urban functions are not always captured by population figures. For instance, the population (density) of a municipality may remain steady while the urban land coverage may rise because of a decrease in the number of persons per household.

There are now an increasing number of studies that aim to explain the interaction between infrastructure and urban land coverage itself. These studies generally make use of digitised aerial photos. However, they usually cover a period of at most a couple of decades during the second half of the 20th century and are rarely conducted at urban scales larger than city regions. For instance,

Stanilov (2003) and Demirel et al. (2008) investigated the impact of road transport on land use distribution pattern and the growth of urban areas within the city regions of Seattle and Istanbul, respectively. To our knowledge, no studies have investigated the relationship between the railway network and urban land use during a period of over a century at a regional level.

By "urban land" we mean the physical space that is used for urban functions, including real estate for housing, services and companies, as well as infrastructure and parks. This is what we generally refer to as the built-up area (BUA). The lack of studies in this field is remarkable, because the most basic process of urbanisation is the conversion of unbuilt land into built-up areas. When we discuss the issue of suburbanisation (Dieleman, Dijst, and Spit 1999) or urban sprawl (Anas, Arnott, and Small 1998), for example, we are basically referring to a physical change in the landscape.

This paper deals with the shortcomings of the existing literature described above by providing a regional-level, long-term analysis of the impact of transport infrastructure (in this case the railway network) on urbanisation (measured as the amount of built-up area) and vice versa. The case study area is the Randstad, the economic and population core of the Netherlands, which we analyse over the period between 1850, after the introduction of the railways, and 2010.

Regarding transport infrastructure, we limit ourselves to the railway network. Railway lines have played a key role in the urbanisation processes in many parts of the world since the mid-nineteenth century. However, since the mid-twentieth century, the role of the rail network has been replaced to a large extent by the use of the car and the expanding road and motorway network. Unlike in the US, in Europe the train and other public transport modes, continued to play a significant role in everyday travel. Moreover, policymakers have always considered public transport as an important means of tackling road traffic congestion (Banister 2005). We aim to explain the influence of railway stations on the growth of BUA in the Randstad area. We describe urbanisation by using buffers with a 5-kilometre radius around the railway stations as units of analysis in our models. Our main focus is on the evolution of the railway network and the development of the BUA with regard to the buffers of railway stations and across the entire study area.

Our research questions are:

- How has the railway network evolved in the Randstad, from the time of its introduction to the present day?
- How has the process of urbanisation, measured as the amount of built-up area (BUA), taken place at varying degrees of proximity to the railway stations during this period?
- Does the opening of new railway stations encourage the development of BUA in their vicinity, and vice versa?

We answer these questions by using a hybrid method that combines qualitative descriptions with quantitative analysis. To answer our first question, we generate descriptive graphs of the evolution of the railway network, including both the number of stations and the length of lines at annual intervals from the beginning of the network to the present day, as well as maps showing the growth of the network at decennial intervals. To this quantitative picture, we add qualitative explanations from the (recent) literature. To answer our second question, we use simple quantitative measures to describe the process of urbanisation by relating the built-up area to the degree of proximity to the railway stations. And to answer our third question, we use binomial logit models which estimate the likelihood of a new station being opened as a function of the amount of BUA in its 5 km circular buffer during the periods immediately before and after.

The rest of this paper is structured as follows. In Section 2 we describe the study area and the data. To address our first question, Section 3 describes the development of the railway network using graphs and maps derived from the data and supplemented with historical literature. Section 4 focuses on the second and third research questions and encompasses the analyses of the development of built-up area in relation to the railway stations. In the final section, we discuss our conclusions.

## 3.2.    Data and method

For the empirical study of the evolution of the railway network and the built-up area (BUA), a unique database was constructed, using GIS, bringing together various sources for both for the period under study. There are different demarcations for the Randstad area and this variety is reflected in the studies (e.g. Laan 1998; Clark and Kuijpers-Linde 1994; van Eck and Snellen 2006). However, to the best of our knowledge all definitions include the four main cities of Amsterdam, Utrecht, Rotterdam and The Hague. Our chosen study area is the common denominator of all data sources available to us (Figure 3.1a). There may be minor differences with other Randstad boundaries in the north and east. This area remains the same until 1968 after which it grows by 8% due to the new Flevoland province, which is made up of land reclaimed from the IJsselmeer. Within this study area, analyses were performed on stations belonging to a smaller region, indicated in dark grey in figure 3.1b, so that changes in their surroundings would still be included in the study area.
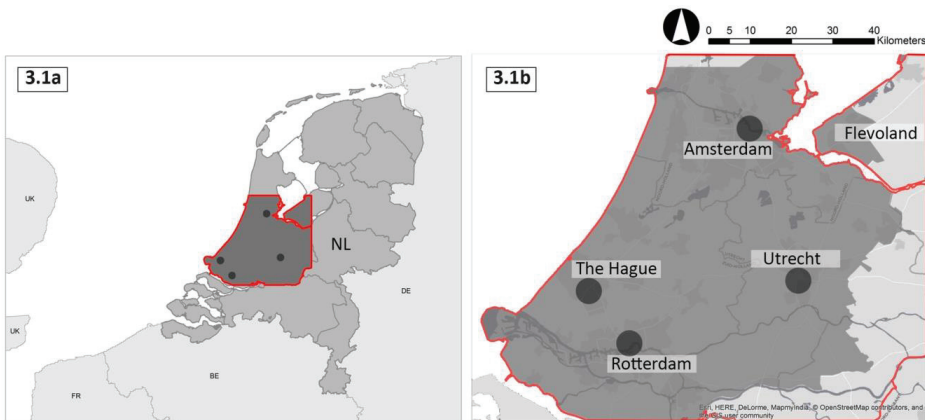


**Figure 3.1: a) Study area (the Randstad) in the Netherlands, b) train stations and their surroundings in the dark grey area were analysed.**

Gathering and building up a consistent database of the development of BUA was one of the main challenges of our research. Not only were the data sources and types different, but the measurement and categorisation of BUA were not always consistent either. We compared various data sources and their classification of BUA (i.e. buildings and paved surfaces plus transport infrastructure) and we chose the following three data sources and the most comparable categories measuring BUA between them (See Table 3.1). First, digitised vector files of the built-up area produced by the Mapping Randstad Holland group of the Delft University of Technology (Engel and Claessens 2005); second, the Historical Land Use Maps of the Netherlands, HGN, from the geo-information centre at the University of Wageningen, Alterra (Kramer and van Dorland 2009); and third the "adjusted version" of the Land Use Dataset (Mutatiereeks Bodemgebruik 1996–2010), created by Statistics Netherlands (CBS) and the

Netherlands' Cadastre, Land Registry and Mapping Agency (Kadaster) . This database was specifically created to track detailed and consistent changes in land use from 1996 to 2010. By selecting comparable data sources and similar categories to represent the BUA, we have attempted to create a consistent long-term database. However, there is one caveat concerning the comparability of the BUA before and after 1990.

Here, we see a trend break as a result of the shift from the HGN database to the CBS Mutatiereeks. The reason is that the former is based on existing land cover while the latter is defined by the land use type. This may be problematic where a designated land use has not yet developed, for instance, some undeveloped office areas may still be classified as "fields" in HGN while the CBS Mutatiereeks includes them as built-up areas based on their land use (Kramer and van Dorland 2009). This results in a higher representation of BUA for the last two time points. However we believe this will not have a substantial effect on our outcomes since it would be spread equally across the study area.

**Table 3.1. Data sources for built-up area and their formats per time point.**

| Year | Source | Type |
|------|--------|------|
| 1850 | OverHolland, Delft University of Technology | Vector |
| 1910 | OverHolland, Delft University of Technology | Vector |
| 1940 | OverHolland, Delft University of Technology | Vector |
| 1960 | HGN, Alterra, Wageningen University | Raster (cell size: 25*25m) |
| 1970 | HGN, Alterra, Wageningen University | Raster (cell size: 25*25m) |
| 1980 | HGN, Alterra, Wageningen University | Raster (cell size: 25*25m) |
| 1990 | HGN, Alterra, Wageningen University | Raster (cell size: 25*25m) |
| 2000 | Mutatiereeks Bodemgebruik 1996–2010 (year 2000), CBS | Vector |
| 2010 | Mutatiereeks Bodemgebruik 1996–2010 (year 2010), CBS | Vector |

As for the development of the railway lines and stations, we digitised the entire network with regard to passenger transport at annual intervals. This provided us with a detailed and accurate insight into the development of the railway network during our study period. We started with the state of the art National Railways dataset (Nationaal Georegister 2011). We then moved back in time towards 1839 removing (and sometimes adding) railway lines and stations on a year by year basis. The change of location of a specific station on its railway line was only mapped if it was moved more than 500 meters from its original position. Sluiter (2002) was consulted for the start and end dates of passenger services. We also used open source databases, namely the website stationsweb.nl and the Google OpenStreetMap (OSM), for the coordinates of stations that were closed down. Where no coordinates were available, these stations were located using address details or the distance to their neighbouring stations (linear referencing) and with regard to the geographical context.

We apply a hybrid method combining qualitative descriptions with quantitative analyses. The result of the detailed mapping of the development of the railway network is presented in Section 3.3.1 as descriptive graphs (Figure 3.2a–e) accompanied by historic descriptions from the literature (Section 3.3.2). In Section 3.4.1, we analyse the process of urbanisation by relating BUA to station buffers and applying some simple spatial analyses in ArcGIS 10. Here we generate a 1 km circular buffer (0–1 km) and four non-overlapping ring buffers at 1 km intervals (1–2 km, 2–3 km, 3–4 km, 4–5 km) around the stations that existed at any of the nine time points. These buffers are then intersected with the BUA

at each time point and the amount of BUA (in square kilometres) within them is compared to each other and the rest of the study area. The results are presented in Figures 3.5 and 3.6. In Section 3.4.2, we estimate seven binomial logit models. Here we use the amount of BUA in the 5 km circular buffers (obtained by merging all previous buffers) at different time points to predict the effect of BUA on the probability of new stations opening and vice versa.

## 3.3.    Development of the railway network

### 3.3.1.  Overview

The development of the rail network in the Randstad is a history of growth, decline and revival. This section provides an overview of the development of the railway network, including the total length of railway lines and station numbers. Figure 3.2a shows the number of railway stations in the study area, starting with a steep rise between 1839 and 1920, followed by a reduction by over half between the 1920s and 1950s, and a more gradual revival since then. While Figure 3.2a shows the cumulative situation, Figure 3.2b shows the numbers of stations opening and closing in each decade. Figure 3.2c depicts the changes in the total length of railway lines in the region.

During the period of growth leading up to 1920, the growth of the network length took place earlier than the growth in the number of stations, because railway lines are needed before railway stations can be developed. After a period of stabilisation, some lines were closed, however the reduction of the network length occurred later than the reduction in the number of the stations, suggesting that the reduction of stations mainly involved smaller stops on remaining lines. Figure 3.2d shows the length of lines added and closed in each decade.

Unsurprisingly, the development of railway lines and stations both follow the same broad trend: growth to a peak by 1920, decline between the 1930s and 1950s, and a period of stabilisation around the 1960s before redevelopment, although at a slower pace, from 1970s to the present day. A more detailed comparison nevertheless reveals that the number of stations has been rather volatile and experienced more variation than the total network length, probably because it is easier to establish, close down or move a station than to build a new railway line. This results in rapidly changing station densities (ratio of stations to lines) over time (see Figure 3.2e).
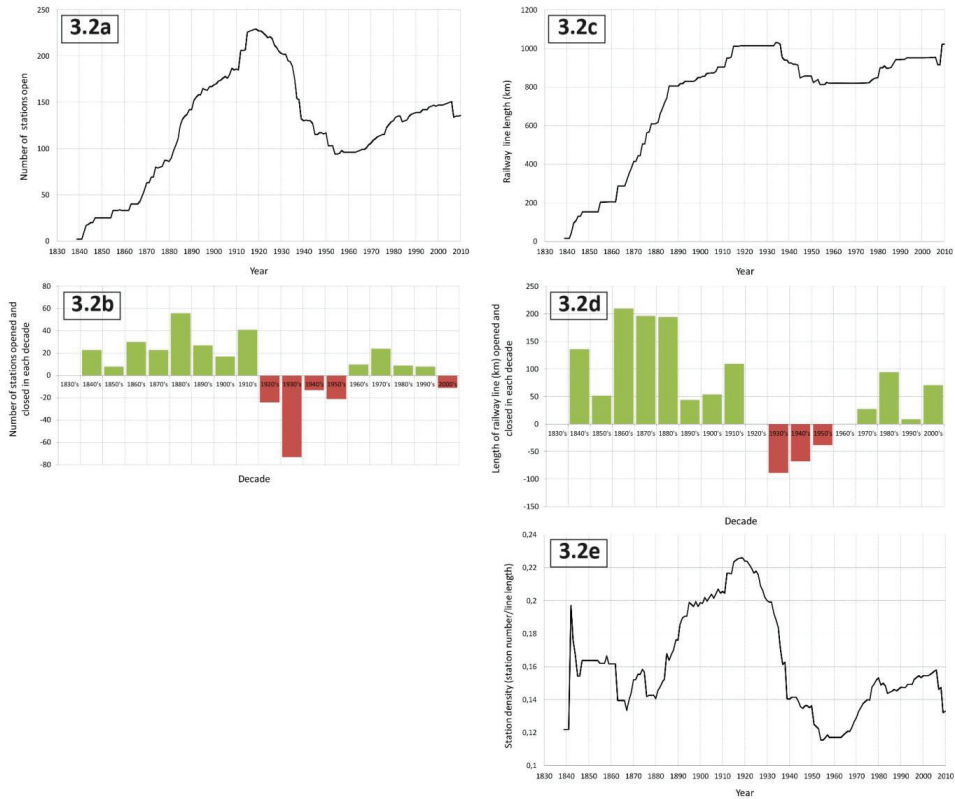
**Figure 3.2. a) Number of stations open, b) Number of stations opened and closed in each decade, c) Railway line length [km], d) Length of railway line [km] opened and closed in each decade, e) Station density (station number/line length). Source: authors.**

### 3.3.2. History of railway network development

The development of the railway infrastructure is divided into four periods corresponding with our data points and coinciding with significant phases in railway development: 1850–1910, 1910–1940, 1940–1980 and 1980–2010. We describe the development of the railway network in the context of each era and add some words concerning the development of the urban area. Figure 3.3 depicts the development of the network over 18 decades.

*Pre-1850, the advent of railways.* The Dutch forerunner of the train was the trekschuit, a barge towed by horses along the canals. In 1839, the first Dutch railway was built between Amsterdam and Haarlem. The first railway lines were built along the existing canals and the competition between the two went on till the end of 19th century when the barges finally conceded (van der Knaap 1978). From the outset, the rail network was not only market driven, but highly influenced by government policies. In the 19th century, the government was planning to use the rail network to reinforce the position of Amsterdam and Rotterdam as important ports and centres of international transit (de Jong 1992). During that time,

the urban structure consisted of many small towns, a small number of medium-sized ones and a few large ones (Deurloo and Hoekveld 1980). According to Dijksterhuis (1984) the railway network was not only designed to connect those cities, but also to connect the seaports with industrial hinterlands, and the Netherlands with its neighbouring countries. See the early backbone structure of the railway network in Figure 3.3.

*The railway boom: 1850–1910*. The industrial revolution came rather late to the Netherlands, between 1850 and 1890, resulting in demographic and economic growth in the second half of the 19th century, accompanied by large-scale migration to the cities. The relatively late and limited process of industrialisation in the Netherlands, competition from barges and unfavourable soil conditions were the main reasons behind the late development of the railway network in comparison to neighbouring countries such as Belgium (Schmal 2003; Dijksterhuis 1989).

Late growth notwithstanding, this period, especially from 1860 to 1890, is seen as the railway boom, in which the existing railway lines developed into an integrated transport network. The first Dutch railway lines did not include freight transportation but were constructed to meet the demand for passenger transport. Figure 3.3 shows the rapid development of the network in the second half of the 19th century, resulting in a railway network that does not differ so much from the current network. In the mid-1870s, the government allowed the removal of city fortifications which resulted in urban growth beyond city walls, allowing Dutch cities to expand for the first time since the 17th century in the decades that followed (1870–1920) and providing opportunities for new railways (Cavallo 2007).

To begin with, the railway lines connected the main population cores, but after 1870, there was more demand for connections to less populated regions and smaller cities and villages. Moreover, secondary stations were built on existing lines which later supported the development of suburban areas (Cavallo 2007). During this period, the length of the railway network and levels of accessibility, grew tremendously. Although the network continued to expand over the decades to come, the pace of growth slowed considerably (Koopmans, Rietveld, and Huijg 2012).

The location of railway lines for passenger transport parallel to canals and their role in connecting the existing settlements around transport connections led to a reinforcement of the existing urban structure (Dijksterhuis 1984). The network also connected and integrated large peripheral cities in the north and south of the country with the concentrated and more developed cities in what we now call the Randstad. The urban population increased along with improvements in accessibility. Suburbanisation, however, was in its infancy during this period. The gradual construction and expansion of railway routes was a major stimulus in the trend towards further suburbanisation.

*Railways and early suburbanisation: 1910–1940*. Economic growth picked up considerably at the beginning of the 20th century. The government's plan for a spatially integrated railway network continued and was accomplished by 1915. Although the total length of the network had peaked by 1940, there had been no major changes to the basic structure since 1915 (van der Knaap 1978), and mainly smaller local railways were realised during this period. In the 1910s such railways were also constructed in what we call now the Groene Hart (meaning "Green Heart" and referring to a preserved and mainly rural area at the centre of the Randstad); however, these were later closed as they did not flourish.

Following the growth of industry in and around bigger cities, many people moved to the cities. In the meantime, villages attempted to keep the factory workers in the village community, and railway companies helped in this respect by establishing stations on railway lines towards the city. So the easy travel opportunities provided by the railways contributed to early suburbanisation. The railways also

made it possible for the well-to-do to commute between their work in the city and their houses in the countryside.

During the two interwar decades, competition between the railways and road transport increased. The railways were forced to revise their services and concentrate more on longer-distance travel. Roads improved and bus services became available, sometimes as a replacement for trams, but also creating completely new links between villages and their service centres. In order to counter financial losses, the reduction in the number of regional railway lines led to the closure of around 150 stations (Cavallo 2007) and 100 kilometres of railways. Under such conditions, there were no more plans for the development and expansion of the railway network (Dijksterhuis 1989). This downturn is depicted clearly in Figures 3.2 and 3.3.

*Railways versus motorways: 1940–1980.* The era following World War II was characterised by rapid economic and demographic growth. There was a population explosion which dramatically increased the need for new housing and consequently city expansion. A shift from employment in industry to employment in business and personal services was taking place, leading to the rapid expansion of the service sector.

The road network was also improving fast. Driven by economic and population growth, a new round of industrialisation and increasing prosperity, the ownership and use of private vehicles surpassed the use of the train and other means of public transport (Dijksterhuis 1989; Annema and van Wee 2009). New roads and parking places were increasingly attracting more cars onto the roads. The growing demand for the car was further supported by the government. The railway network, meanwhile, shrank in length and the number of stations fell until 1960 (see Figure 3.3).

During this period, urbanisation continued in the form of large urban expansions in order to house population growth. From the socio-economic as well as spatial perspective, almost everything favoured and promoted car ownership and use: rapid economic growth, increased distances between home and work locations and sprawling suburbanisation.

Unlike the railway, the car caused a much more diffused pattern of commuting, which led to massive suburbanisation. This new type of commuting differed from previous patterns in the sense that it was no longer confined to public transport nodes (Dijksterhuis 1989). Moving away from its passive role in the 1940s and 1950s, the Dutch Railways finally became actively involved in planning during the 1960s. It shifted its policy from prioritising connections between larger cities to linking suburbs and growth centres to the existing railway network wherever possible (Dijksterhuis 1989). Apart from the development of heavy rail, by the end of the 1960s larger cities were investing in reinforcing and developing their internal urban rail transit networks. The Rotterdam metro began operating at the end of 1960s. Amsterdam's metro and later on Utrecht's fast tram followed in the 1970s and 1980s.

**Figure 3.3. The development of railway lines and stations during 18 decades from 1850 to 2010. Each map shows all the railway lines and stations that existed during each decade. Source: authors.**
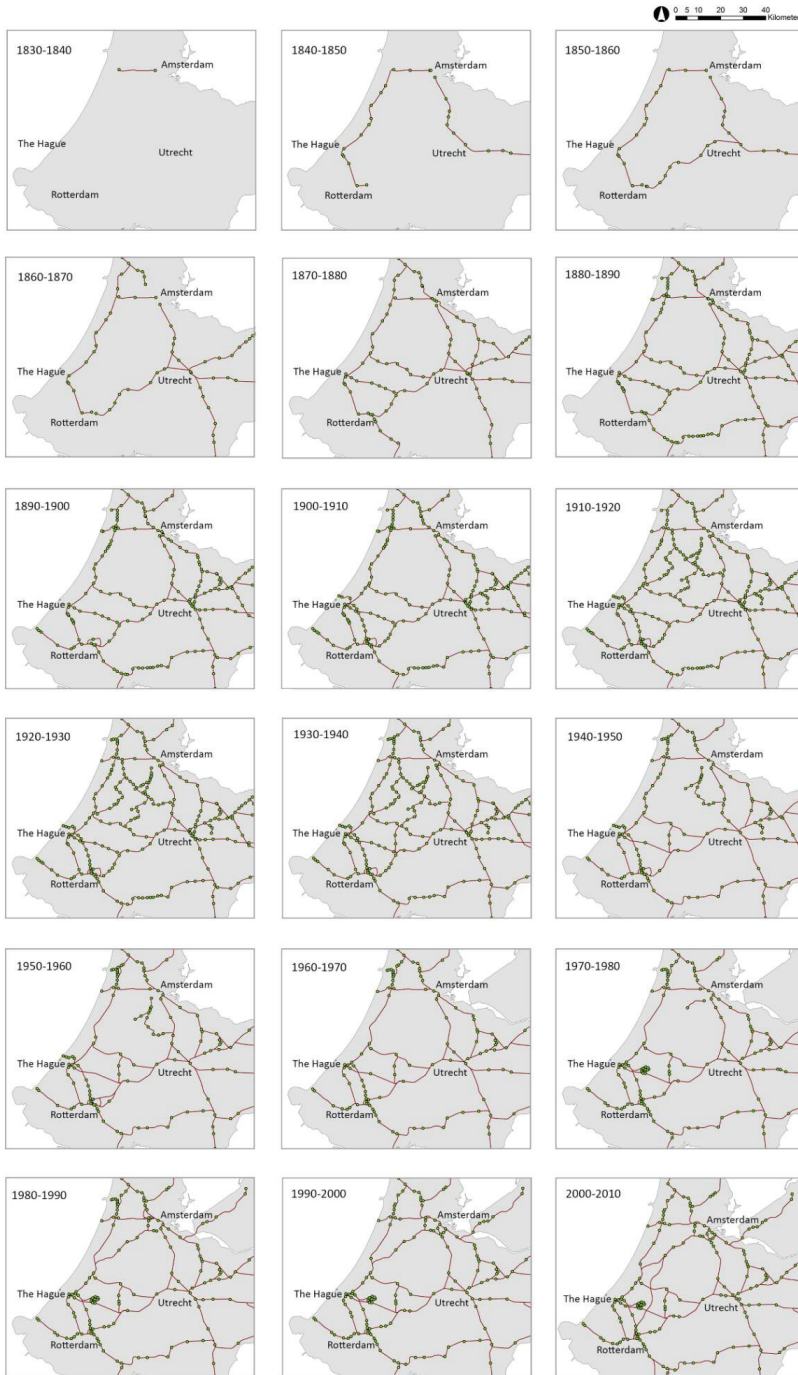
*An era of planned development: 1980–2010*. The railway network continued its relatively slow growth into the 1980s. The major additions were connections with newly developed settlements and services, such as lines to connect the new town of Zoetermeer, Schiphol International Airport and the newly reclaimed province of Flevoland. Another important addition was the decision to build a high speed line in 1997, which was implemented in the 2000s. This was intended to improve the Netherland's international accessibility and provide a more environmentally friendly alternative to the rise in air travel (Annema and van Wee 2009).

As for BUA development, this continued with the increasing exodus to suburbs (Musterd, Jobse, and Kruythoff 1991). The population decline in central cities led to the emergence of the "Compact City" policy at the end of the 1980s and during the 1990s. Previously, various planning efforts were made to curb suburbanisation such as the "Concentrated Deconcentration" and "Growth Centres" policies in the 1960s and 1970s. These policies are generally assessed as having been successful in directing the growing population into certain growth centres and curbing urban sprawl (Dieleman and Wegener 2004). The Fourth Report on Physical Planning Extra (Ministry of Housing, Physical Planning and the Environment 1991), focused on channelling new urban (re)development to locations within the existing urban areas ("brownfield" locations) and new "greenfield" locations on the edges of existing cities (the so-called VINEX locations). At the same time, the Second Transport Structure Plan (Ministry of Transport, Public Works and Water Management 1990) promoted "sustainable" transport by encouraging car-pooling and public transport use. It suggested the use of spatial planning and transport policy measures such as concentrating housing and employment around public transport nodes. Due to these policies, growth returned to the larger cities after a decade of severe stagnation (Geurs and van Wee 2006). In 2004, the National Spatial Strategy emphasised the concept of "Network Cities" which encouraged decentralisation and eventually urban growth along major transport corridors. Perhaps the best example of the implementation of this concept is the Stedenbaan(Plus), an ambitious regional-transit-oriented development programme which combines high frequency rail and public transport services with high-density urban developments around stations.

## 3.4.    Analysis

In this section, we describe urbanisation within different degrees of proximity to the railway stations using built-up area as an indicator. Furthermore, we test the effect of the opening of railway stations and the development of BUA in their vicinity and vice versa. Built-up area is measured at nine time points: 1850, 1910, 1940, and for each decade between 1960 and 2010, as depicted in Figure 3.4. Although the choice of these nine time points was primarily driven by the availability of data, the periods also coincide with some significant moments: we begin at 1850, after the opening of the first railway lines which developed into a large railway network by the end of 1910. Observing periods of further growth and decline after 1910, we continue with 1940, which coincides approximately with the beginning of World War II. Since the 1960s, the railway network was subject to heavy competition from the motorway network, with the latter encouraging further urban sprawl. We follow the changes in the railway network and urbanisation into the 21st century when the railway network continued its post-war growth and the urbanisation was channelled with the help of specific policies (1980–2010).
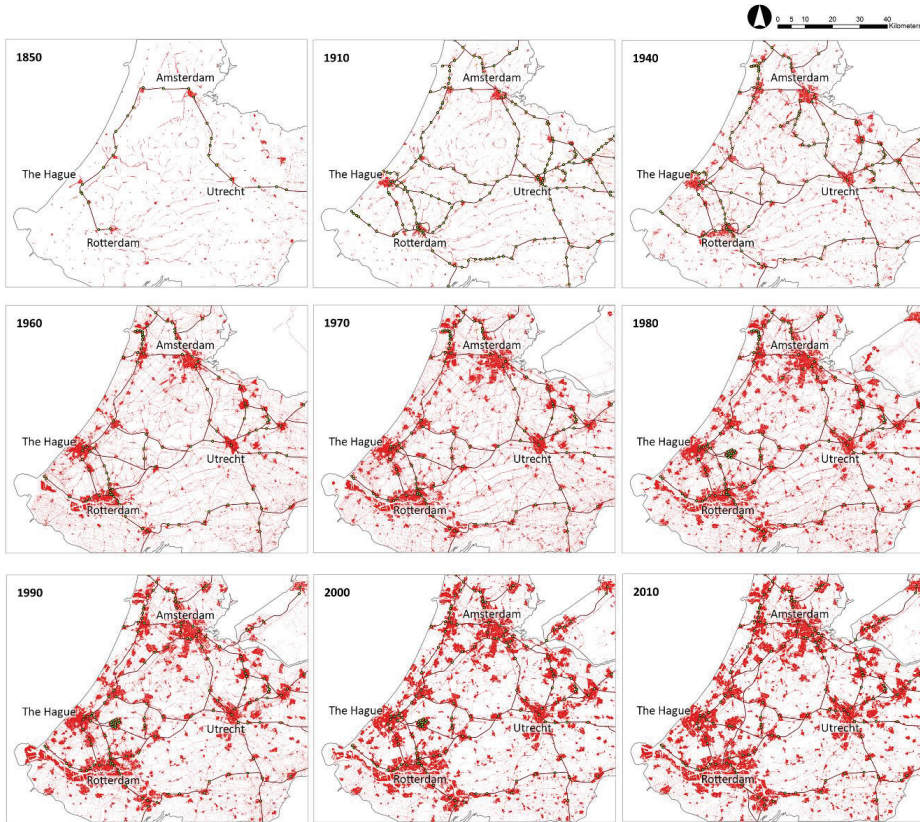
**Figure 3.4. The development of the railway network and the built-up area between 1850 and 2010.**

### 3.4.1.  Effects of the railway network on the development of built-up area

In order to compare the amount of built-up area (BUA) with respect to the distance to railway stations, 5 non-overlapping ring-buffers with intervals of 1 km were generated for existing stations at the nine points in time. Thus for years 1850, 1910, 1940, 1960, 1970, 1980, 1990, 2000 and 2010 the share of BUA within certain buffers of existing stations and for the study area as a whole were calculated. The result of these calculations is presented in Figure 3.5.

As mentioned in Section 2, the borders of the Randstad study area changed during our study period. The study area has the same borders from 1850 until 1968, but it then grows by 8% due to the addition of the newly reclaimed Flevoland province from the IJsselmeer. We disregard relatively smaller changes such as the reclamation of the Haarlemmermeer polder at the very beginning of our study period or the gradual development of the Rotterdam harbour over the course of the 20th century. The expansion of the study area to include Flevoland also magnified the growth of BUA. To control the growth of the study area, we also produced the same calculations without the Flevoland province. In Figure 3.5, we distinguish between (a) the Randstad area including Flevoland, and simply by way of comparison, (b) the area excluding Flevoland. However, general growth trends are very much the

same. Since this difference is minor and we consider the addition of Flevoland as an important event in the growth of the Randstad, we include it in all our calculations in this paper.

Figure 3.5a shows that there is an increase in the total amount of BUA within each time period, as expected. BUA grew faster in each decade than in the previous one, until 1970 when the urbanisation slowed, followed by the lowest growth rate in the 1980s. Among other factors, this may be attributed to the effectiveness of policies to curb suburbanisation before the 1970s and the economic recession during the 1980s. In the last two decades, we are again observing higher increases in the amount of BUA, with smaller increases in the 2000s in comparison to the 1990s.

Until 1910, the growth of BUA within 5 kilometres of railway stations (represented as the dotted line) was slightly higher than the overall growth of BUA. This difference is possibly due to the rapid growth in the number of stations and the fact that the suburbanisation was still railway-oriented at the time. After 1910 however, the growth within that zone slows compared to the overall growth in BUA. This is because of increasing development further away from the railway stations (> 5 km) caused by growth first in tram networks and later in car-oriented suburbanisation. In the 1980s we once again observe an increase in BUA growth within 5 km of stations that is higher than overall BUA growth. Unsurprisingly, urban growth in the > 5 km area experienced a fall during this period. In the 1990s, the growth of BUA continues more or less steadily overall and in the vicinity of stations (< 5 km), while in the 2000s we witness a slight decrease in the BUA< 5 km and therefore a slight increase in the BUA> 5 km.

Comparing growth in BUA in the 5 concentric rings, it is clear that development generally started close to the railway stations and moved outwards, as development occurred less at longer distances from the stations (Figure 3.6). In other words, when we control for the buffer area, the first ring was always more built-up than the second and so on. This distance decay trend is accentuated by the fact that the difference between the amount of BUA in the first ring compared to the second is much larger than the second compared to the third and so forth.

Figure 3.7 presents the ratio of BUA within station buffers to the total BUA of the entire study area in each year. In other words, it shows what share of the total (100%) urbanisation taking place in the whole study area is located within and outside the station buffers at each point in time. We can use this to compare growth in the different station buffers to overall growth in the Randstad.

Comparing the growth of BUA in the different buffers to the overall BUA of the study area, we can see that in 1850 the share of the total BUA that falls within station buffers is rather low for all rings. This is because the rail network had only just been established and the number of stations was still very limited. Later on, with the development of the rail network and the increase in number of stations, the share of BUA within station buffers increases.

Rings 3, 4 and 5 have been fairly stable since 1910. The BUA outside the 5 km buffer had a high share of the total BUA in 1850. This is because many cities did not have a railway station at this stage. In the next two periods however, only one fourth of the urbanised area was outside the 5 km buffer. Later, by contrast, the share of BUA increases outside 5 kilometres from the railway station (34%, 32% and 31% in 1960, 1970 and 1980) at the expense of the BUA within the 5 kilometre range. Here we witness the rise of suburban development. After 1980, the "old" situation was restored and the growth of BUA > 5 km remained broadly stable.
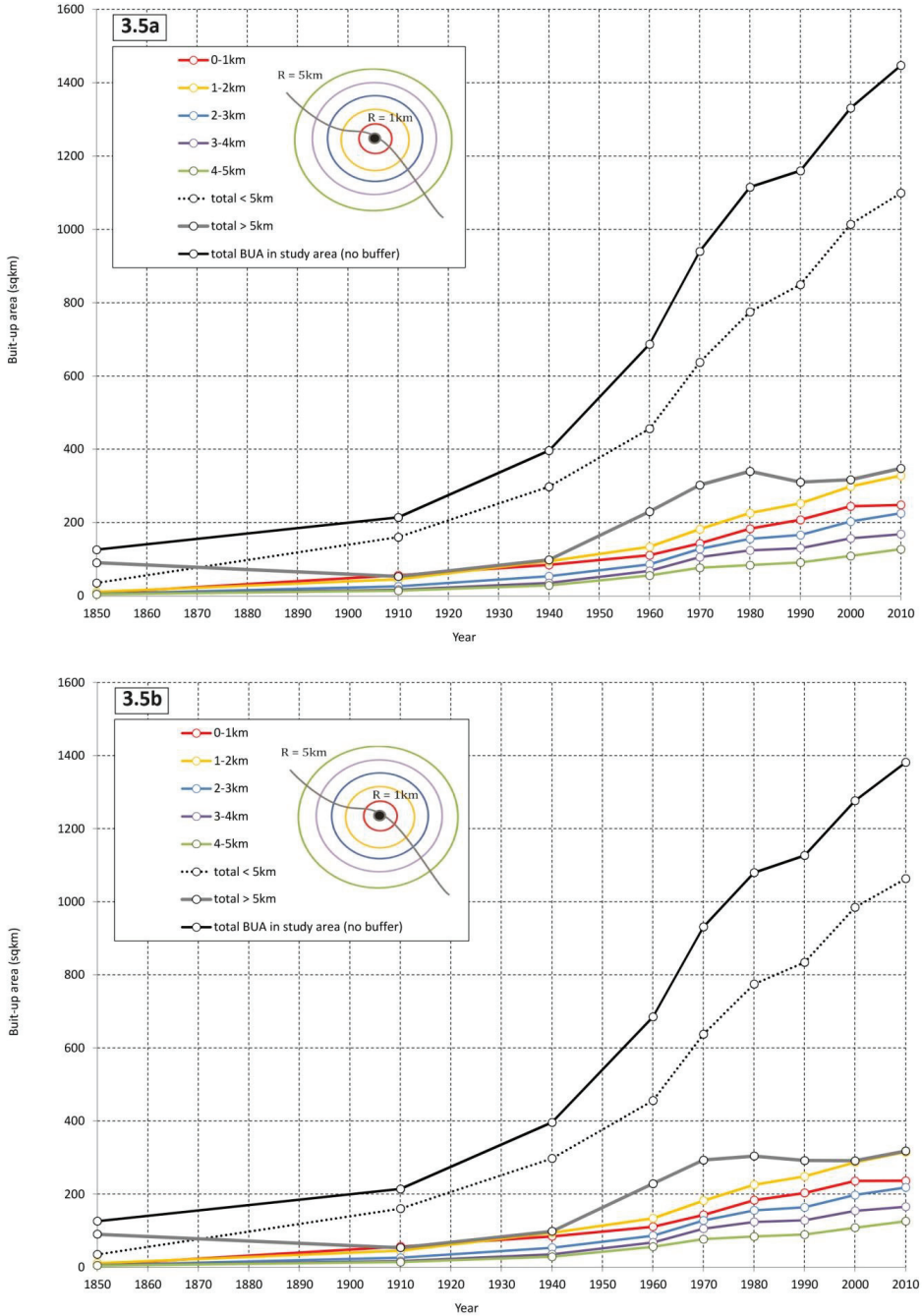
**Figure 3.5. Development of the built-up area as a whole and within the different station buffers a) including Flevoland and b) excluding Flevoland.**
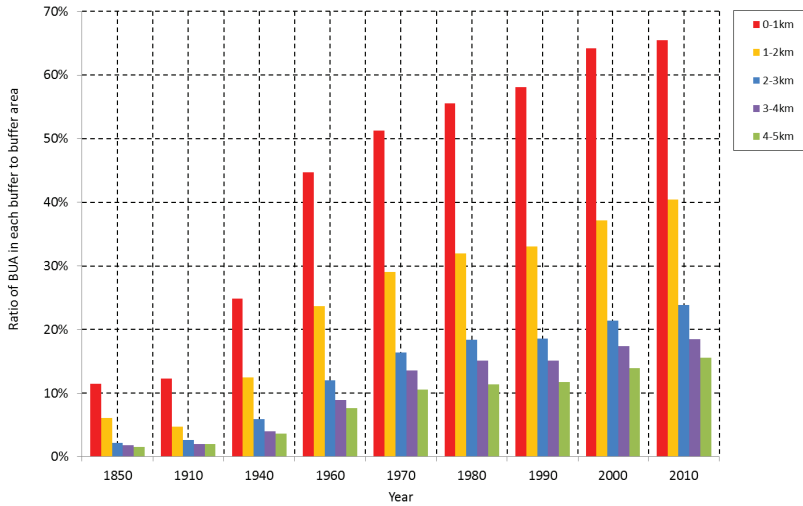
**Figure 3.6. Ratio of BUA in each buffer to buffer area.**



**Figure 3.7. Ratio of BUA in each buffer to total BUA of the study area.**

### 3.4.2. Effects of the built-up area and the opening of railway stations on each other

In this section, we test whether the opening of railway stations encourages the development of BUA and vice versa. To do this, for each study year (the nine points in time) we measure the effect of the amount of BUA in the preceding and subsequent periods within a 5 kilometre buffer around each station, on the probability of a new station being added.

Using the qualitative and quantitative insights of the previous sections, we hypothesise that in the beginning, from 1850 until the turn of the 20th century, stations followed the existing BUA, and so new stations were added in already urbanised areas. By contrast, during the second half of the 20th century, new stations were not located according to existing BUA since those areas were already served by older stations; rather, the new stations were often used as a planning tool for channelling new urbanisation. The existing BUA data for nine points in time results in 8 periods between every two successive time points: 1850–1910, 1910–40, 1940–60, 1960–70, 1970–80, 1980–90, 1990–2000, 2000–2010. We estimate seven binomial logit models, for each changeover between periods. We model the probability that a station was built in that period (1) or that it already existed (0). The independent variables are the amount of BUA in the buffer of that station in the preceding ($\text{BUA}_{t-1}$) and subsequent periods ($\text{BUA}_{t+1}$). For example, the cases for the 1970 model are the 5 km buffers of the stations existing in 1970. The dependent variable is whether or not the station was opened in the period 1960–1970 and the predictors are the amount of BUA within its buffer in 1960 and 1980. We report in terms of odds ratios, which are the changes in the BUA for a one-period change. The goodness-of-fit is indicated by McFadden's pseudo $R^2$. Note that since the full "population" (the entire study area) is modelled, the notion of significance is not meaningful. In this case, the BUA of the preceding and subsequent periods are predictors of the probability of a station being opened in the first half of each period.

As demonstrated in Table 3.2, for the 5 km buffers of stations existing in 1910, the odds ratio for BUA in the preceding period is 1.09. An odds ratio greater than one indicates that every extra square kilometre of BUA in the preceding period (1850), increased the likelihood of a station being built between 1850 and 1910. This implies that the more urbanised an area was, the more likely it was to receive a new station, or in other words that the new stations followed the existing pattern of urbanisation. Contrary to the preceding period, the odds ratio for the BUA in the subsequent period (1910–1940) is less than one (0.91). This suggests that the BUA that existed in 1940 was less likely to be in the buffer of stations opened during 1850–1910. So the BUA developed between 1910–1940 does not follow the railway stations developed earlier. We think that this result is plausible since many (almost half) of the stations existing in 1910 were closed in 1910–1940. Additionally, more stations (one-fifth of the stations existing in 1940) developed in the 1910–1940 period, which may have encouraged the development of BUA but this is invisible to us because we do not have matching BUA data for them during that period to include them in the model.

The model for stations existing in 1940 shows no impact for BUA in the preceding or the subsequent periods. In other words, new stations which opened during 1910 and 1940 were not influenced by the amount of BUA in their vicinity and seem not to have affected further BUA changes in their 5 km buffer. This again is probably due to the fact that many stations were closed prior to 1940 and are not taken into account. We suspect that the longer interval between the earlier measuring points, which is often several decades, combined with a rapidly changing railway network (Figure 3.2a–e), makes it hard to predict the interaction of stations and BUA in their buffers with the current method.

The trend changes from 1960 onwards. For new stations opening in the periods 1960–70, 1970–80, 1980–90 and 1990–2000, the odds ratios for BUA in the preceding periods are less than one. This means that every extra square kilometre of BUA in the preceding period reduced the likelihood of a new station being opened in each time frame. This finding would appear logical since the more a buffer was covered by BUA, i.e. more urbanised the area, the less space there would be for further development, so the less likely it was that a new station would be added. Hence, stations in more urbanised areas were likely to be existing stations rather than new ones. Consequently, newly added stations did not correspond to existing urbanisation. In contrast to the $\text{BUA}_{t-1}$, the odds ratio for BUA

in the following period ($BUA_{t+1}$) is greater than one. This implies that increase in the amount of BUA is more likely to be found around new stations. So new urban areas are likely to have developed around new stations. In short, the results show that after 1940, the new stations were more likely to open in undeveloped areas (i.e. in areas with less BUA), and they then encouraged further growth in the BUA.

We can clearly see a change in the trends of odds ratios, with pseudo $R^2$ suggesting that preceding and future BUAs explain most of the likelihood of stations opened during the 1970s (27%), followed by those opened in the 1980s (10%) and between 1940 and 1960 (9%).

**Table 3.2. Results of seven binomial logit models for predicting the opening of new stations regarding preceding and subsequent BUA in their 5 km buffer.**

| Dependent variable: station in 5 km buffer (0 = existing, 1 = opened in the preceding period) | | | | |
|---|---|---|---|---|
| Existing Stations at | $BUA_{t-1}$ | $BUA_{t+1}$ | Pseudo $R^2$ | No. of observations |
| **1910** | 1.09 | 0.91 | 0.03 | 166 |
| **1940** | 1.00 | 1.00 | 0.00 | 120 |
| **1960** | 0.96 | 1.10 | 0.09 | 88 |
| **1970** | 0.87 | 1.14 | 0.03 | 98 |
| **1980** | 0.59 | 1.67 | 0.27 | 124 |
| **1990** | 0.75 | 1.38 | 0.10 | 131 |
| **2000** | 0.92 | 1.09 | 0.01 | 139 |

## 3.5.    Conclusions

This paper has aimed to first provide a long-term study of the development of the railway network, over the past 160 years in the Randstad, and to investigate its impact on urbanisation, measured as the growth of built-up area, and vice versa.

We have found that the total length of railway and the total number of stations followed broadly the same trend: growing and climaxing by 1920, deteriorating between the 1930s and 1950s, stabilising in the 1960s and resuming expansion, although at a slower pace, from the 1970s to the present day. Nevertheless, station numbers underwent more variation than total railway length. The growth of the railway network was highly associated with the growth of the built-up area. As might be expected, the railways followed the existing pattern of urbanisation in the very beginning, and later urbanisation developed and intensified very close to the stations. With the introduction of the car and other modes of transport, urban development further away from stations increased, before it returned, partially, to the vicinity of stations at the turn of the 21st century. Analyses show a distance trend whereby the rings closer to the stations (especially the 0–1 km buffer) are always covered by more built-up area than further rings.

We also obtained results showing a trend change in relation to the built-up area in the vicinity (5 km circular buffer) of stations and in the likelihood of new stations being opened. Earlier stations, built between 1850 and 1910, followed the existing pattern of urbanisation, and were located in areas which were more built-up. As time went by, and in particular after World War II, new stations were less likely to be located within established urban areas because these were already serviced by existing stations.

New stations were more likely to be located in as yet undeveloped areas. Furthermore, new stations prompted urban growth, so urbanisation was more likely to happen in the vicinity of the newly opened stations.

Future research will focus on modelling urbanisation effects of railway stations not only in their direct vicinity but also at longer distances. This would allow us to include continuous measures of accessibility to railway stations. Adding the dynamics of the motorway network enables us to test the interaction between the rail network and the road network. Finally, in this paper we have observed the outcome of the development of railway network and the built-up area regardless of external factors such as planning policies. The role of transport and planning policies from the 1960s onwards should be taken into account in order to gain a more accurate insight into the development of both the railway network and urbanisation.

## Acknowledgements

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# Chapter 4: The impact of urban proximity, transport accessibility and policy on urban growth: a longitudinal analysis over five decades

*This chapter is currently under review.*

## Abstract

Transport accessibility is assumed to be a main driver of urbanisation. Like many other metropolitan regions, the Randstad, the population and economic core of the Netherlands has experienced significant urbanisation, transport network expansion and spatial policies aimed to channel urban growth. This paper investigates the long-term relationships between the development of railway and motorway networks, urbanisation, and spatial policies, by using a panel dataset consisting of grid cells measured at six time points from 1960 to 2010. Generalised Estimating Equations (GEE) analysis was applied to model the built-up area. Predictors include proximity to and accessibility by transport infrastructure, vicinity of urban areas, and spatial policies. Results indicate that road and rail accessibility alike, stably influenced urbanisation, but less than proximity to urban areas. Spatial policies played a significant role in channelling new urbanisation, while preserving the centrally located green and mainly rural area. Remarkably, the legacy of earlier policies is still significant despite shifts in predominant Dutch spatial policies. The findings are expected to be relevant for comparable poly-nuclear areas.

*Keywords*: Urbanisation, transport accessibility, spatial policies, Randstad, longitudinal analysis, Generalised Estimating Equations.

## 4.1.    Introduction

The magnitude, determinants, rate and the spatial distribution of urban growth or urbanisation are major concerns for policy makers. Accessibility, neighbourhood interactions and spatial policies are argued to be the most influential factors on contemporary land use change (Verburg et al., 2004). Transport infrastructure is believed to stimulate and guide urban growth via the improvement of accessibility (Anas et al., 1998). This assumption is demonstrated in a long tradition of policies aiming at channelling urban growth by investing in transport infrastructure. It is also known that urbanisation is more likely to happen near existing urban areas, examples being the concentric development of cities or the appearance of suburbs nearby major cities. Furthermore, where urbanisation occurs or not, is related to spatial planning and policies which designate areas for, or preserve locations from development. Examples are the planning of clustered urbanisation and restricting development in certain greenfield areas to reduce urban sprawl as implemented in Dutch spatial policies during the 1970s and early 1980s (Dieleman and Wegener, 2004).

Change in land use patterns such as urbanisation is a slow process with a low reversibility (Wegener and Fürst, 1999). Thus, it can only be studied over the long term. However, only few empirical studies investigate this process over multiple decades. Most studies investigating the long-term impact of transport infrastructures model population change as a proxy for growth and urbanisation (e.g. Baum-Snow, 2007; Duranton and Turner, 2012; Koopmans et al., 2012; Levinson, 2008). Rail networks have influenced the distribution of population and encouraged a rise in urban population especially after their emergence, although with variations across regions and time periods (Mojica and Marti-Henneberg, 2011; Da Silveira et al., 2011; Atack et al., 2010). They have also facilitated suburban population growth (Levinson, 2008; Garcia-Lopez, 2012). Similarly, road networks, specifically motorways, have attracted population to their vicinity (Garcia-Lopez, 2012; Baum-Snow, 2007; Duranton and Turner, 2012).

Fewer long-term studies directly model the share of accessibility to rail and road networks in land-cover change. They generally conclude that access to road networks increases the likelihood of conversion to urban land (Iacono and Levinson, 2009; Hu and Lo, 2007; Muller et al., 2010). The role of railways in the conversion to urban land is less evident as both positive, negative and neutral impacts are reported (see for an overview Kasraian et al., 2016).

Land use changes does not occur in isolation, and is more likely to happen close to already urban areas. Thus, neighbouring land uses play a significant role (Iacono and Levinson, 2009; Geurs and van Wee, 2006; Cervero and Landis, 1997). The influence of existing urban areas is shown to be a significant driver of conversion to urban land (Luo and Wei, 2009; Arai and Akiyama, 2004; Cheng and Masser, 2003).

From the few studies which have investigated specific policies (Verburg et al., 2004), the majority has reported their role as significant. Examples are the effect of the introduction of land markets on determining the type and location of land development (Wu and Yeh, 1997), the attraction of employment by designated New Towns (Padeiro, 2013) and the positive relation between the amount of land in the urban fringe not subject to municipal planning regulations and urban sprawl (Burchfield et al., 2006).

Based on existing literature, the following gaps are addressed. First, most long-term studies on the role of transport infrastructures, model urban change through population densities. From a spatial perspective, it is useful to measure the amount of urbanisation as the area converted from undeveloped to urban land, and the dynamics of its spatial distribution in the long run. Second, several

studies directly model land-cover change, but suffer from one or a combination of the following limitations: their time spans rarely exceed two decades; only the final decades of the 20th century are investigated; the focus is on the road network only; the study area is limited to a single city-region. Third, empirical studies quantifying the long-term impact of spatial policies on urban growth are scarce.

This study builds on previous research by examining the spatial distribution of urban areas over a longer time period, a larger urban region including a conurbation of several cities and investigating the impact of both road and rail networks, urban proximity as well as spatial policies. We assume that urbanisation is a process partly driven by transport accessibility, partly by the attraction of existing urban areas, and partly by policies aimed at influencing autonomous processes. Thus, this study investigates three assumptions. First, the proximity to rail and road infrastructure and their provided access to centres of activity encourage urbanisation. The influence of the road network however is expected to be stronger than the rail network, as the road network is larger, more fine-grained and has a higher share in the number of travelled trips. Second, existing urban area encourages further urbanisation, and large conurbations exert a stronger attraction than smaller ones. Third, urbanisation is not only an autonomous process driven by transport accessibility and attraction of existing urban area but also a process which is simultaneously influenced by spatial policies. To test these assumptions, the main research question this paper addresses is: to what extent have transport accessibility, proximity to existing urban areas and spatial policies affected the spatial dynamics of urbanisation in the Randstad? As we study this over 50 years, we examine to what extent the effects of these determinants vary over time.

This study models urbanisation in the Greater Randstad Area from 1960 to 2010. It is, however, not only interesting for Dutch planners, as urban containment and densification strategies have been applied in many regions of the world over the past decades.

## 4.2.    Research design

### 4.2.1.  Study area

The Randstad is the population and economic core of the Netherlands situated in its west and including the four major cities of Amsterdam, The Hague, Rotterdam and Utrecht (Figure 1). It is a useful case study, first because it is a polycentric urban region with a variety of development types including metropolitan areas, medium-sized and small cities and rural areas. Second, it has experienced a dynamic period of changes in land use and transport infrastructure networks. Since the 1960s, after decades of decline, the railway network's development stabilised. It has extended since the 1970s with new stations and new types of light rails. Motorways were introduced in the 1960s and significantly expanded to cover the country in the following decades. Third, the Randstad has witnessed the application of various national transport and spatial policies to curb urban sprawl during this period (1960–2010). The Concentrated Deconcentration of urban development and the designation of Growth Centres were implemented during the 1970s and early 1980s. These policies aimed to channel the suburbanisation which started in the 1950s and increased drastically between mid-1960s and the end of 1970s. Furthermore, they aimed to  preserve the Green Heart, a mainly rural area at the centre of the Randstad (Dieleman and Wegener, 2004). During the 1980s, the revival of inner cities was encouraged under the Compact City agenda (Maat et al., 2005). In the 1990s and within the Compact City agenda, the Fourth Report on Physical Planning Extra (VINEX) focused on channelling new urban (re)development to brownfield locations within the existing urban areas, and new greenfield locations

on the edges of existing cities–the so-called VINEX locations (Ministry of Housing, 1991). During the same time–and contrary to the car dominated transport policies of the 1960s and the 1970s–sustainable transport and public transport were promoted (Annema and van Wee, 2009; Ministry of Transport, 1990). In the 2000s, the concept of Network Cities was introduced, focusing on the definition of a network of cities connected by transport network corridors (Alpkokin, 2012). While these events are partly specific to the Netherlands, the general trends–such as the massive post WWII suburbanisation, the initial focus on the development of the road network which was later changed to the public transport or both, and an array of spatial policies to curb urban sprawl–could be witnessed in many (at least western) countries.

### 4.2.2. Data

Urbanisation is defined in this paper as the conversion of non-urban to urban land. Urban land is the physical space used for urban functions (including real estate for housing, services, companies, infrastructure and parks) which we generally refer to as the built-up area. Urbanisation is measured as changes in the proportion of built-up area in 500 m by 500 m grid cells. Transport accessibility and urban proximity are chosen as determinants of urbanisation based on the existing literature and because they are related to both the autonomous process of urbanisation as well as the Dutch spatial policies applied in the past decades. Transport accessibility is addressed from a location- and infrastructure-based viewpoint, measured by distance to transport nodes and travel times on the transport networks. Urban proximity is measured as the amount of urban land and the size of the largest urban agglomeration in a cell's vicinity. The investigated policies are the Dutch physical planning concepts and their spatial representations since 1960.

The study period is 1960–2010 and includes six time points: 1960, 1970, 1980, 1990, 2000, and 2010. Note that we refer to time points as "decades" for simplicity. Data for the built-up area for 1960 to 1990 is derived from the Historical Land Use Maps of the Netherlands (HGN), developed by the University of Wageningen Environmental Research Institute, Alterra, originally with a raster resolution of 25 m by 25 m. The source for the built-up area of 2000 and 2010 is the "adjusted version" of the Land Use Dataset (Mutatiereeks Bodemgebruik 1996–2010), created by Statistics Netherlands (CBS) and the Netherlands' Cadastre, Land Registry and Mapping Agency (Kadaster). This vector-based dataset enables the tracing of changes in land use patterns consistently from 1996 to 2010, and is achieved by the retroactive adjustment of earlier published land use maps compared to the final stage in 2010. The measurements of the built-up area from HGN and Mutatiereeks datasets are not fully comparable, as the first shows the existing land cover, while the latter demonstrates the land use type. However, after inspection, we believe this difference will not substantially affect the outcomes since it is equally spread across the study area.

Units of analysis are 37,891 cells of 500 m by 500 m. Measured at six time points, they construct a balanced panel (i.e., including the same number of observations for each subject) with 227,346 observations. The original 25 m by 25 m HGN cells were aggregated to reduce spurious accuracy and processing time. The investigated transport networks are rail (light/heavy railway lines and stations), and road (motorways, their exits and regional roads). To mitigate edge effects (Turner, 2007), transport networks exceeding the study area with 10 km were used to calculate transport accessibility indicators. The rail network was derived from the National Railways dataset (Nationaal Georegister, 2011). Railway networks at earlier time points were achieved by eliminating the as-yet-undeveloped railway lines and stations. The historical road network since 1960, the boundaries of VINEX developments, the Green Heart and Growth Centre municipalities were provided by the Environmental Assessment

Agency (PBL). The classification of roads and motorways were adjusted and simplified to produce a consistent and connected road network over the study period.
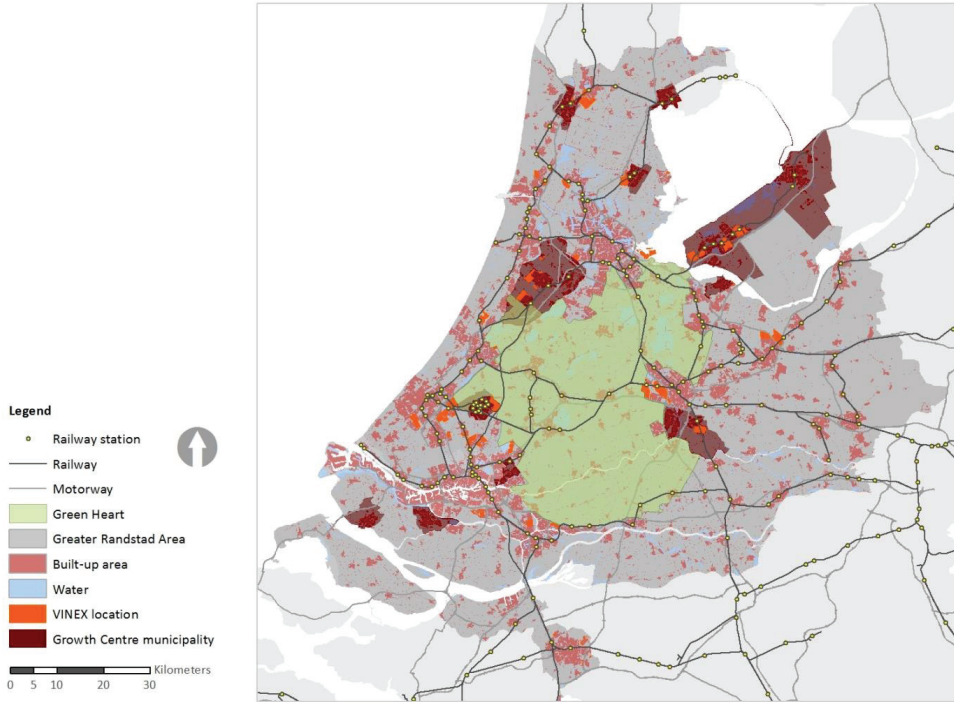


**Figure 4.1. The Greater Randstad Area in 2010.**

### 4.2.3. Variable specification

The urbanised proportion of cell $i$ at decade $t$ ($U_i^t$) ranges between zero and one. The assumptions that transport accessibility, urban proximity and spatial policies influence urbanisation are translated into six hypotheses and operationalised as eleven indicators (Table 4.1). According to these hypotheses, a cell's likelihood to become urbanised increases if one or more of the following conditions are met.

1. It is located in the vicinity of access points to transport infrastructure. This is measured by the Euclidian distance to the nearest railway station or motorway exit.

$$RD_i^t \stackrel{\text{def}}{=} d_{i,st}^t \qquad (4.1)$$

Where $RD_i^t$ is railway distance of cell $i$ at time $t$, measured as Euclidean distance $d$ between cell $i$ and the nearest railway station $st$.

$$MD_i^t \stackrel{\text{def}}{=} d_{i,ex}^t \qquad (4.2)$$

where $MD_i^t$ is motorway proximity of cell $i$ at time $t$, measured as Euclidean distance $d$ between cell $i$ and the nearest motorway exit $ex$.

2. It is close or adjacent to existing urban areas. The urban proximity is measured by the amount of urban land in a cell's vicinity.

$$UA_i^t = \sum_j a_j^t \ , j \in [1,n]| \ d_{i,j}^t \leq r \tag{4.3}$$

Where $UA_i^t$ is the urban area existing in the neighbourhood of cell $i$ at time $t$, $a_j^t$ is the urban area of the neighbour cell $j$ (from 1 to $n$) at time $t$ and $d_{i,j}^t$ is the distance between cell $i$ and its neighbour cell $j$ at time $t$ which is smaller or equal to an $r$ radius of 1.5 km.

3. It is close or adjacent to large existing urban areas (urban agglomerations), and the larger the size of the urban agglomeration in a cell's vicinity, the larger its urbanisation likelihood. For instance, of two cells with the same amount of urban land in their neighbourhood, the one near a big city is more likely to urbanise than the one near a village. This is measured as the size of the largest urban agglomeration within a 1.5 km radius of a cell.

$$LUA_i^t = \max_k(ua_k^t)| \ ua_k^t \cap C_{i,r} \neq \emptyset \tag{4.4}$$

$LUA_i^t$ is the large urban area existing in the proximity of cell $i$ at time $t$, $\max_k(ua_k^t)$ is the area of the largest urban area (from 1 to $k$) within a $C$ circle neighourhoud of cell $i$ with an $r$ radius of 1.5 km.

4. It is located close to a centre of activity, where there is a concentration of jobs and amenities. The most prominent of such concentrations in the Randstad are the so-called "Big Four" which include the cities of Amsterdam, The Hague, Rotterdam and Utrecht.

$$MRWT_i^t = \min_{act}(rwtt_{i,act}^t) \tag{4.5}$$

$$rwtt_{i,act}^t = torwtt_{i,st}^t + onrwtt_{st,act}^t \tag{4.6}$$

Where $MRWT_i^t$ is minimum railway travel time of cell $i$ at time $t$ to an activity centre by the railway network, $\min_{act}(rwtt_{i,act}^t)$ is the travel time between cell $i$ and the nearest activity centre $act$ by the railway network at time $t$. $rwtt_{i,act}^t$ is the travel time between cel $i$ and an activity centre $act$ by the railway network at time $t$. $torwtt_{i,st}^t$ is *to-rail* travel time, which is the time needed to cover the shortest Euclidian distance between cell $i$ and its nearest railway station $st$, assuming a speed of 15 km/hr. $onrwtt_{st,act}^t$ , is *on-rail* travel time, which is the time needed to cover the distance between the station $st$ that is nearest to cell $i$ and the activity centre $act$ (proxied by the central stations of Amsterdam, Utrecht, Rotterdam and The Hague Hollands Spoor station), with an assumed speed of 70 km/hr.

$$MRT_i^t = \min_{act}(rtt_{i,act}^t) \tag{4.7}$$

$$rtt_{i,act}^t = tortt_{i,ra}^t + onrtt_{ra,act}^t \tag{4.8}$$

Where $MRT_i^t$ is minimum road travel time of cell $i$ at time $t$ to an activity centre by the road network, $\min_{act}(rtt_{i,act}^t)$ is the travel time between cell $i$ and the nearest activity centre $act$ by the road network at time $t$. $rtt_{i,act}^t$ is the travel time between cell $i$ and an activity centre $act$ by the road network at time $t$. $tortt_{i,ra}^t$ is *to-road* travel time, which is the time needed to

cover the shortest Euclidian distance between cell $i$ and the road access point $ra$ (i.e., regional road or motorway exit), assuming a speed of 15 km/hr. $onrtt_{ra,act}^t$, is *on-road* travel time, which is the time needed to cover the distance between the road access point $ra$ and the activity centre $act$ (proxied by the road access point that is nearest to central stations of Amsterdam, Utrecht, Rotterdam and The Hague Hollands Spoor station), with assumed speeds of 50 km/hr and 100 km/hr for regional roads and motorways respectively.

5. It is at a location where multiple activity centres could easily be accessed using the transport networks. In other words, areas which can reach various activity centres in a shorter time are more likely to become urbanised. Examples are a city like Delft (close to both Rotterdam and The Hague) or cities in the central Green Heart like Gouda which have relatively fast access to all of the Big Four cities, represented by $act$, with $p = 4$. This is measured by the *sum* of travel times (as explained above) to the Big Four by the road and rail network calculated as:

$$SRWT_i^t = \sum_{act} rwtt_{i,act}^t , act \in [1,p] \tag{4.9}$$

Where $SRWT_i^t$ is the sum of travel times for cell $i$ at time $t$ by the railway network, and $rwtt_{i,act}^t$ is the travel time between cell $i$ and activity centre $act$ (from 1 to $p$) by the railway network at time $t$.

$$SRT_i^t = \sum_{act} rtt_{i,act}^t , act \in [1,p] \tag{4.10}$$

Where $SRT_i^t$ is the sum of travel times for cell $i$ at time $t$ by the road network, and $rtt_{i,act}^t$ is the travel time between cell $i$ and activity centre $act$ (from 1 to $p$) by the road network at time $t$.

6. It is planned for development and is not preserved by policy. This is measured by dummy variables indicating whether a cell belongs to designated Growth Centres, VINEX locations or the Green Heart.

**Table 4.1. Investigated variables.**

| Investigated variables | Description |
|---|---|
| **Dependent** | fraction of the cell which is built-up, from zero to one |
| **Independent** | |
| Transport accessibility | |
| Rail | (a) distance to nearest train station [km] |
| | (b) sum of travel times to the Big Four by the rail network [hour] |
| | (c) travel time to the nearest of the Big Four by the rail network [hour] |
| Road | (d) distance to nearest motorway exit [km] |
| | (e) sum of travel times to the Big Four by the road network [hour] |
| | (f) travel time to the nearest of the Big Four by the road network [hour] |
| Urban proximity | (g) urban land in a cell's 1.5 km circle neighbourhood [sq. km] |
| | (h) largest urban agglomeration in a cell's 1.5 km circle neighbourhood [sq. km] |
| Policy | dummy for (i) Growth Centres, (j) VINEX locations and (k) the Green Heart |

## 4.3.    Model specification

The dependent variable $U_i^t$ is the urbanised proportion of cell $i$ at time $t$, where $t$ refers to each of the six decades. The model takes into account the longitudinal nature of the data: the observations are related over time, so they are not independent. Furthermore, it accommodates the bounded nature of the response variable, namely the *share* of the built-up area in a cell, which ranges from zero to one.

Generalised estimating equations (GEE) analysis was chosen, an alternative being the random effects (RE) method. The choice of GEE-analysis was based on the relevance of its findings for policy makers as the drawn inferences are population-averaged (Allison, 2009; Gardiner et al., 2009). GEE-analysis can also estimate fractional response variables for balanced panels (Papke and Wooldrige, 2008). It imposes a "working" correlation structure between dependent observations and uses quasi-likelihood estimation. The simplest dependence between observations is *exchangeable* which assumes equal-correlation for within-subject observations, regardless of the time interval (Twisk, 2012). Matrix 4.11 shows the exchangeable correlation structure for the observations of a subject at three time points, where the correlations between time points are the same and equal to $\rho$:

$$
\begin{array}{c}
\phantom{t_1} \\
t_1 \\
t_2 \\
t_3
\end{array}
\begin{array}{ccc}
t_1 & t_2 & t_3 \\
\left[\begin{array}{ccc}
- & \rho & \rho \\
\rho & - & \rho \\
\rho & \rho & -
\end{array}\right]
\end{array}
\tag{4.11}
$$

Various correlation structures can be assumed between a subject's observations, however, imposing more complicated correlation structures increases the number of degrees of freedom due to the estimation of more correlation coefficients. The goal is to find the simplest correlation structure with the fewest degrees of freedom and the best fit for the data (Twisk, 2012).

Twisk (2004) provides equation (4.12) for GEE-analysis of a longitudinal dataset with a dichotomous outcome. This model could be applied to a proportional variable (which is the case here), as it is possible to easily transform logit with a fractional outcome to a weighted logistic regression with dichotomous outcomes with the same parameter estimates and statistical inferences (Liu and Xin, 2014). The model was estimated using the *xtgee* command (Stata 14). The distribution of the dependent variable belongs to the logit family, the link function is binomial and the assigned correlation structure is exchangeable.

$$
\text{logit}\left(U_i^t\right) = \beta_0 + \beta_1^t + \beta_{2l} \sum_{l=1}^{L} X_{il}^t + \beta_{3m} \sum_{m=1}^{M} X_{im} + corr_i^t + \epsilon_i^t
\tag{4.12}
$$

Where:

$U_i^t$ = urbanised proportion of cell $i$ at time $t$,

$\beta_0$ = intercept,

$\beta_1^t$ = coefficient for time,

$\beta_{2l}$ = coefficient for time-dependent predictor variable $l$,

$X_{il}^t$ = time-dependent predictor variable $l$ for cell $i$ at time $t$,

$L$ = number of time-dependent predictor variables,

$\beta_{3m}$ = coefficient for time-independent predictor variable $m$,

$X_{im}$ = time-independent predictor variable $m$ for cell $i$,

$M$ = number of time-independent predictor variables,

$corr_t^i$ = working correlation structure, and

$\in_i^t$ = error for cell $i$ at time $t$.

In this case, the time-dependent predictors are transport accessibility and urban proximity. Though policies did change over time, they are considered time-independent. For instance, a cell in a VINEX development is dummy-coded as VINEX for all time points while this policy was only introduced in the mid-1990s. This allows us to trace the influence of VINEX policy on a cell's proportion of urban land before and after this policy was introduced.

## 4.4.  Results

### 4.4.1.  Descriptive statistics

Table 4.2 describes the time-dependent variables for each decade. The statistics show that urbanisation, as (1) the amount of built-up area, and consequently (2) the fraction of built-up area, grows over time in a cell. The averages for the distance of grid cells to railway stations (a) and motorway exits (d), the travel time to the nearest of the Big Four (b, e) and the sum of travel times to the Big Four (c, f) by both road and rail decrease over time. However changes in road accessibility values are more drastic than the rail accessibility values. The reason is that the railway network was rather stable while the motorway network underwent major developments over the study period. Trends of urban proximity indicators (f, g) show that as time goes by and urbanisation continues, the amount of urban land and the size of the largest urban agglomeration within 1.5 km of a cell rise progressively.

**Table 4.2. Descriptive statistics of variables over the study period.**

|  | 1960 | 1970 | 1980 | 1990 | 2000 | 2010 |
|---|---|---|---|---|---|---|
| (1) Built-up area in a 500 m by 500 m cell [sq. km] | | | | | | |
| Mean | 0.02 | 0.03 | 0.04 | 0.04 | 0.04 | 0.05 |
| Std. Deviation | 0.04 | 0.05 | 0.06 | 0.06 | 0.07 | 0.07 |
| (2) Fraction of built-up area in a cell | | | | | | |
| Mean | 0.09 | 0.12 | 0.14 | 0.15 | 0.18 | 0.19 |
| Std. Deviation | 0.17 | 0.21 | 0.23 | 0.25 | 0.28 | 0.29 |
| **Independent variables** | | | | | | |
| (a) Distance to nearest railway station [km] | | | | | | |
| Mean | 6.53 | 6.43 | 6.18 | 5.53 | 5.43 | 5.37 |
| Std. Deviation | 4.91 | 4.94 | 4.92 | 4.22 | 4.22 | 4.23 |
| (b) Travel time to the nearest of the Big Four by the rail network [hour] | | | | | | |
| Mean | 0.81 | 0.80 | 0.79 | 0.74 | 0.73 | 0.73 |
| Std. Deviation | 0.41 | 0.42 | 0.42 | 0.37 | 0.38 | 0.38 |
| (c) Sum of travel times to the Big Four by the rail network [hour] | | | | | | |
| Mean | 5.00 | 4.95 | 4.91 | 4.71 | 4.68 | 4.66 |
| Std. Deviation | 1.71 | 1.73 | 1.75 | 1.57 | 1.59 | 1.59 |

| (d) Distance to nearest motorway exit [km] | | | | | | |
|---|---|---|---|---|---|---|
| Mean | 13.92 | 6.40 | 4.98 | 3.88 | 3.79 | 3.78 |
| Std. Deviation | 11.15 | 5.37 | 3.95 | 2.47 | 2.45 | 2.45 |
| (e) Travel time to the nearest of the Big Four by the road network [hour] | | | | | | |
| Mean | 0.88 | 0.66 | 0.56 | 0.50 | 0.49 | 0.48 |
| Std. Deviation | 0.56 | 0.33 | 0.32 | 0.21 | 0.21 | 0.21 |
| (f) Sum of travel times to the Big Four by the road network [hour] | | | | | | |
| Mean | 5.76 | 4.30 | 3.79 | 3.56 | 3.50 | 3.47 |
| Std. Deviation | 2.32 | 1.48 | 1.34 | 0.97 | 0.99 | 0.96 |
| (g) Urban land in a cell's 1.5 km circle neighbourhood [sq. km] | | | | | | |
| Mean | 0.61 | 0.84 | 0.99 | 1.02 | 1.22 | 1.28 |
| Std. Deviation | 0.83 | 1.00 | 1.12 | 1.19 | 1.34 | 1.41 |
| (h) Largest urban agglomeration in a cell's 1.5 km circle neighbourhood [sq. km] | | | | | | |
| Mean | 4.02 | 8.32 | 14.24 | 16.75 | 27.33 | 31.92 |
| Std. Deviation | 16.12 | 25.67 | 39.14 | 43.24 | 59.26 | 64.77 |

## 4.4.2. Models

The GEE model explains the proportion of urbanised area in a cell, based on proximity, accessibility and policy indicators. To avoid multicollinearity, we tested which proximity and which accessibility indicator best explained the outcome (Table 4.3). Policy predictors were all included as they represent different concepts, which is proved by the low correlations between them. Wald statistics of twelve different models were used to select the final model. Each model includes one transport accessibility predictor, one urban proximity predictor, three policy predictors and five dummies for the six investigated time points.

**Table 4.3. Selecting the best subset of independent variables based on WaldChi$^2$ test.**

| | Independent variables | WaldChi$^2$(10) |
|---|---|---|
| Model [1] | a, g, i, j, k | 26,940.84 |
| Model [2] | b, g, i, j, k | 27,497.32 |
| Model [3] | c, g, i, j, k | 27,538.55 |
| Model [4] | d, g, i, j, k | 26,454.35 |
| Model [5] | e, g, i, j, k | 26,901.43 |
| **Model [6]** | **f, g, i, j, k** | **27,615.78** |
| Model [7] | a, h, i, j, k | 10,878.14 |
| Model [8] | b, h, i, j, k | 12,242.26 |
| Model [9] | c, h, i, j, k | 12,715.29 |
| Model [10] | d, h, i, j, k | 9,101.24 |
| Model [11] | e, h, i, j, k | 10,438.93 |
| Model [12] | f, h, i, j, k | 10,639.42 |

Note: The names and descriptions of independent variables are presented in Table 4.1.

Table 4.3 is revealing in several ways. First, it shows that the difference between Models 1–3 (with rail accessibility indicators) and Models 4–6 (with road accessibility indicators) are marginal. This result is

contrary to previous studies which for the most part have reported significantly higher impact on land use change for road compared to rail (Kasraian et al., 2016). Second, models with travel time variables (2, 3, 5 and 6) have a better fit than those using Euclidian distances to transport nodes (1 and 4). This shows the better performance of network-based accessibility indicators over simple distance-based ones. Third, models with the amount of *urban land within 1.5 km* (1–6) have a much higher goodness of fit than those including the size of the *largest urban agglomeration within 1.5 km* (7–12). Model 6 was selected for final analysis regarding its highest Wald statistic.

Table 4.4 reports the main coefficient of each determinant, that is, its effect at base year 1960. Interactions for each determinant with each time point are basically the effects of that variable at that time point *compared to* the base year (1960), or more precisely, the difference of the coefficient at that time point with the base year. They show whether and to what extent each determinant's impact varies over time.

For interpretation, the "decade-specific" coefficient was calculated, which is the sum of coefficients for the main and interaction effects for each time point. Time is treated as a categorical variable indicated by decades. Since 6 decades are involved, 5 time interactions with each predictor are modelled for decades 1970, 1980, 1990, 2000 and 2010. Standard errors and p-values are not reported since the dataset includes the full population. The sequence of observations is expected to have no effects on the outcome, as the working correlation structure is exchangeable, assuming similar correlations between observations.

The exponentiation of coefficients yields odds ratios, indicating changes in the odds of urbanisation in a cell. For instance, the 0.955 odds ratio of *sum of travel times to Big Four by rail* implies that with every hour increase in the total travel time to the Big Four, the ratio of urbanised proportion of a cell over its non-urbanised proportion will be reduced by 0.955. This equals a 4.5% reduction in the odds of urbanisation.  Note that this effect is for the base year 1960. In order to see the variation in the effect of *sum of travel times to Big Four* on urbanisation per time point, we calculate the decade-specific coefficient by adding the coefficient of interaction effect to the main one (Allison, 2009). For instance, the decade-specific coefficient for 1970 is –0.046 + 0.011 = –0.035. Exponentiating yields an odds ratio of 0.965 which is slightly higher than that of 1960. Thus, a one hour increase in the total travel time to the Big Four reduces the odds of urbanisation by 0.965 in 1970 (or about a 3.5% reduction). The amount of urban land in a cell's neighbourhood is shown to have a very high impact on its odds of urbanisation. Every extra square kilometre built-up area in a cell's circle neighbourhood with a radius of 1.5 km almost triples its odds of urbanisation. According to the time interactions this impact witnesses a slight reduction, however it could be considered relatively stable over time.

Elasticities facilitate comparisons of the impact of unstandardised variables, but cannot be calculated for models including dummy variables. Elasticities based on a model which only includes the chosen transport accessibility and urban proximity indicators confirm that the impact of urban proximity is much larger. The results indicate that a 1% increase of total travel times to Big Four decreases urbanisation by 0.006, while a 1% increase of urbanised area in the 1.5 km circle neighbourhood of a cell increases urbanisation by 0.144.

Odds ratios for Growth Centres and VINEX in 1960 are 1.054 and 1.026. Thus, being located in a Growth Centre or a VINEX location in 1960, increases the odds of urbanisation by rather small amounts. However, it is the trend in the impacts of these policies on urbanisation which is more informative. A cell being located in a Growth Centre in 1970, 1980, 1990, 2000 and 2010 increases the odds of urbanisation by 1.106, 1.192, 1.197, 1.187 and 1.179 respectively. In other words, the odds of urbanisation for a cell in a growth centre witness an increase of 10.6% (1970), 19.2% (1980), 19.7%

(1990), 18.7% (2000) and 17.9% (2010). The rise in the odds of urbanisation from 10.6% in 1970 to 19.2% in 1980 is remarkable. This difference indicates that the amount with which the fraction of urbanisation in a cell grew specifically increased during the 1970s, which is a decade after the introduction of the Growth Centres policy.

**Table 4.4. GEE model of the proportion of urban land in a cell.**

| | Coefficient | Odds ratio | Decade-specific coefficient | Decade-specific odds ratio |
|---|---|---|---|---|
| **Main coefficients** | | | | |
| Sum of travel times to Big Four by road | −0.046 | 0.955 | | |
| Urban land in a cell's neighbourhood | 1.079 | 2.943 | | |
| Growth Centre | 0.053 | 1.054 | | |
| VINEX | 0.025 | 1.026 | | |
| Green Heart | −0.288 | 0.750 | | |
| **Interactions with time** | | | | |
| Sum of travel times to Big Four by road*decade | | | | |
| 1970 | 0.011 | 1.011 | −0.035 | 0.965 |
| 1980 | 0.015 | 1.015 | −0.031 | 0.970 |
| 1990 | 0.002 | 1.002 | −0.044 | 0.957 |
| 2000 | 0.010 | 1.011 | −0.035 | 0.965 |
| 2010 | 0.011 | 1.011 | −0.035 | 0.965 |
| Urban land in a cell's neighbourhood*decade | | | | |
| 1970 | −0.060 | 0.942 | 1.020 | 2.772 |
| 1980 | −0.085 | 0.919 | 0.995 | 2.704 |
| 1990 | −0.075 | 0.928 | 1.004 | 2.730 |
| 2000 | −0.117 | 0.889 | 0.962 | 2.617 |
| 2010 | −0.124 | 0.883 | 0.955 | 2.598 |
| Growth Centre*decade | | | | |
| 1970 | 0.048 | 1.049 | 0.101 | 1.106 |
| 1980 | 0.123 | 1.130 | 0.175 | 1.192 |
| 1990 | 0.127 | 1.135 | 0.180 | 1.197 |
| 2000 | 0.118 | 1.126 | 0.171 | 1.187 |
| 2010 | 0.112 | 1.118 | 0.165 | 1.179 |
| VINEX*decade | | | | |
| 1970 | −0.183 | 0.832 | −0.158 | 0.854 |
| 1980 | −0.296 | 0.744 | −0.270 | 0.763 |
| 1990 | −0.435 | 0.647 | −0.410 | 0.664 |
| 2000 | −0.074 | 0.929 | −0.048 | 0.953 |
| 2010 | 0.471 | 1.602 | 0.497 | 1.643 |
| Green Heart*decade | | | | |
| 1970 | 0.090 | 1.094 | −0.198 | 0.820 |
| 1980 | 0.133 | 1.142 | −0.156 | 0.856 |
| 1990 | 0.077 | 1.080 | −0.211 | 0.810 |
| 2000 | 0.077 | 1.080 | −0.211 | 0.810 |
| 2010 | 0.100 | 1.105 | −0.189 | 0.828 |

| Decade | | |
|---|---|---|
| 1970 | −0.002 | 0.998 |
| 1980 | −0.024 | 0.976 |
| 1990 | −0.041 | 0.960 |
| 2000 | −0.026 | 0.974 |
| 2010 | −0.058 | 0.944 |
| Constant | −2.900 | 0.055 |
| Wald chi$^2$(35) | 31,196.10 | |

Number of observations: 227,346; Number of groups: 37,891.

The trend of odds ratios for VINEX locations are also enlightening. Before the designation of these areas, being in a VINEX location actually reduced the chance of a cell's urbanisation by 0.854 (1970), 0.763 (1980), 0.664 (1990) and 0.953 (2000). However, the odds ratio in 2010 is 1.643. Thus the odds of urbanisation in a VINEX location rise substantially to 64.3% at this time point. The significant difference between the decade-specific odds ratios in 2000 and 2010 demonstrates the drastic role of the VINEX policy introduced in the 1990s on the spatial distribution of urbanisation in the 2000s.

The trend in the interaction of Growth Centres policy with time reveals an important issue: the effect of policies are likely to be durable and the legacy of a former policy could be long at work even when it is replaced by new policies over time. Thus, the Growth Centres policy of the 1960s has not only had an observable impact in the growth patterns of that decade, but has attracted new urbanisation ever since, regardless of the shifts in predominant spatial policies in the Randstad. Looking at the Green Heart policy, its effect in 1960 is captured by an odds ratio of 0.750. Overall, the decade-specific odds ratios for the Green Heart policy do not vary much over time. In other words, the effect of Green Heart policy on urbanisation has been stable and always strongly restrictive.

Note that the coefficients for the main effects of the decades at the bottom of Table 4.4 show the effect of that decade on the urbanisation of a cell which does not belong to a Growth Centre, VINEX location or the Green Heart, has zero travel time to the activity centres and zero urban land in its neighbourhood, in comparison to the base year 1960.

## 4.5.    Conclusion and discussion

This paper aimed to find the extent to which transport accessibility, proximity to existing urban areas and spatial policies affect the dynamics of urbanisation, based on three assumptions which were tested by applying Generalised Estimating Equations to a panel of cells in the Randstad area (1960–2010).

The first assumption–that the process of urbanisation is driven by transport accessibility, with road accessibility being more influential than rail accessibility–is partially confirmed. Transport accessibility has had a stable but marginal influence on the spatial distribution of urbanisation. The impact of rail and road accessibility on urbanisation dynamics is almost equal. Travel time accessibility indicators based on the network provide a better explanation for the likelihood of urbanisation than Euclidian proximity distances.

It is surprising that the influence of the rather stable railway network is comparable to the influence of the road network which has witnessed drastic developments over the same period. This finding contradicts previous studies which for the most part have reported significantly higher impact for road compared to rail on land use change (Kasraian et al., 2016). This could be due to the dense Randstad railway network existing as of 1960 and the fact that the motorway network is constructed relatively

parallel to the existing railways to bundle infrastructures. Moreover, Dutch anti-sprawl policies have recurrently encouraged developments at areas with high rail accessibility. This could also be due to the disutility of living in car-dependent areas in a dense metropolitan region like the Randstad with its congestions and parking limitations. Finally, the comparable impact of the rail and road networks on urbanisation patterns is derived from indicators of network accessibility to the main activity centres. While large cities are highly accessible by both road and rail, accessibility to and odds of urbanisation in smaller urban areas could be more dependent on road than rail.

Another important finding is that while the effect of transport accessibility is positive, it is rather marginal. This could be related to a number of issues. First, the effect of transport accessibility could have also been captured by urban proximity as these two are correlated to a certain extent: areas with high network accessibility are usually highly urbanised areas where people live. Second, changes in transport accessibility were not substantial during the study period. While this period witnessed the introduction and the development of the motorway network, this network still developed more or less parallel to the Randstad's already existing dense railway network. Thus, the longitudinal effect of developments in transport networks on urbanisation patterns within the Randstad has not been as drastic as for instance when the first railways were introduced into pedestrian cities. Third, the focus is on the distribution of urban growth within the Randstad. Compared to its peripheral regions, the Randstad experienced a much more rapid urbanisation, very likely at least partly due to its dense transport network and high transport accessibility. Fourth, the poly-nuclear structure of the Randstad area consisting of many medium sized and larger cities and towns could have played a role. Here, unlike monocentric metropolitan regions such as London and Paris, sharp differences between urban and rural areas and high variations in the distribution of transport infrastructure and urban land do not exist. Overall, these arguments show that stimulating and guiding urbanisation only by investing in transport infrastructures is ineffective in areas with saturated networks and accessibility. In other words, in an era and location where transport networks and their provided accessibility are saturated, significant change in land use can only be triggered by custom (integrated) transport and land use policies (see also Kasraian et al., 2016).

The second assumption was that existing urban areas drive urbanisation, with larger urban areas encouraging more urbanisation compared to smaller ones. This assumption is corroborated by the finding that the impact of existing urbanised areas in a cell's vicinity has a major influence on attracting urbanisation. Between urban proximity indicators, the amount of urban land within a cell's 1.5 km has a much higher explanatory power than the size of the largest urban agglomeration in the same neighbourhood. Importantly, the impact of urban proximity is shown to be a more powerful driver of urbanisation patterns than transport accessibility and spatial policies.

The third assumption was that spatial policies guide urbanisation. It is confirmed as spatial policies are shown to have played a significant role in channelling the new urbanisation and preserving green areas, contrary to many countries where autonomous market forces are dominant. Among all policies, the Green Heart policy has continuously exerted a restrictive effect on urbanisation in this preserved area. The Growth Centres have had a significant impact, especially in the 1970s, by attracting urbanisation and diverting it from more rural locations. Remarkably, the Growth Centres remained effective as they continued to attract urbanisation, although it is not per se desired anymore. The VINEX policy is shown to have drastically influenced the growth patterns of the 2000s. The effects of both Growth Centres and VINEX policies become observable in the urbanisation patterns of the first decade after their introduction.

Our findings on the significant role of spatial policies are in line with previous works which have claimed the success of the Concentrated Deconcentration and Growth Centres policies in the 1960s and the

1970s, and the Compact City and VINEX policies of 1980s and 1990s in redirecting urban sprawl (Faludi and van der Valk, 1994; Dieleman and Wegener, 2004; Geurs and van Wee, 2006; Dieleman et al., 1999). The added value of this work is that it empirically shows the success of these policies in redirecting urbanisation and demonstrates the time period during which the policies have become effective. At this point it is too early to judge the effect of the decentralisation promoted by the Network Cities policy.

A remarkable conclusion is the durability of previous policies. A policy's legacy can affect development patterns decades later when newer concepts are introduced. Implementation of the Concentrated Deconcentration policy through Growth Centres in the 60s not only had an observable impact in the growth patterns of the 1970s, but has attracted new urbanisation since. Thus the Growth Centres policy has remained influential regardless of the shifts in predominant Dutch spatial policies to the Compact City and VINEX in the following decades. Due to the durability of policies, a former policy could affect developments for decades and even its discontinuation will not guarantee the restoration of the situation to the pre-policy era.

Finally it is useful to reflect on how policies are applied and the complementary role of autonomous or market forces. In the Netherlands planners and policy makers provide guidelines for development usually at the national level, which are then translated into designated locations at the local scale. For instance, in the case of VINEX locations, guidelines included building in the vicinity of existing cities and connected to public transport. These guidelines were then translated to earmarked locations for VINEX development by the municipalities. In our model, guidelines' impacts are captured by variables showing a cell's distance to transport infrastructure and the amount of urban land in its vicinity. Furthermore, the effect of the guidelines' direct interpretation are included as a dummy variable for the defined VINEX/ Growth Centre/Green Heart boundaries. However, it is difficult to disentangle the effect of policy from market forces, as the latter can reinforce or nullify the first. Variables measuring transport accessibility and urban proximity also capture the impact of market forces. From a market perspective it is also favourable to build close to transport infrastructure nodes and urban agglomerations, which entails easier access to labour, resources and the advantage of the economies of scale. In the case of the Growth Centres policy it can be argued that autonomous processes followed and reinforced the trend initiated by policy. The Growth Centres policy encouraged urbanisation in specific areas which later became existing urban areas and attracted further urbanisation. Overall, the final situation is indeed the resultant of both the efforts of policy and market forces.

The paper is a step towards the accurate analysis of urbanisation which is urgently needed to formulate efficient territorial policies, especially in the European context (Salvati and Carlucci, 2015). Moreover, the findings could be relevant for other comparable poly-nuclear areas in developed countries with saturated development and transport accessibility, such as the Ruhr region in Germany, the urbanised part of Flanders in Belgium and the San Francisco Bay Area in the US. What this paper highlights, and what could possibly be applied in other regions, is that spatial policies help to curb urban sprawl. This is relevant, as the Belgian Flanders experiments with the compact city, some German cities with densification, and North American cities with the congeneric Smart Growth policies. However, future research is needed to bring to light whether those regions follow the same patterns concerning urban proximity versus accessibility, road versus rail, and the role of spatial policies.

Future research could investigate the effect of urbanisation on transport infrastructure, thus the reverse causality over the long term to correct for the inherent problem of endogeneity in uni-directional studies including this paper and contribute further to unravelling the long-term interactions between land use and transport.

**Acknowledgements**

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# Chapter 5: A pseudo panel analysis of daily distance travelled and its determinants in the Netherlands over three decades

## Abstract

As travel behaviour requires time to adjust to changes in residential location and transport infrastructure, there is a need for long-term studies quantifying the relationships between locations, individuals and travel behaviour. Such empirical evidence is critical for assessing the previous and adjusting the succeeding land use-transport policies. Existing research however, has mostly investigated travel behaviour during relatively short time periods and for a single transport mode. This paper examines the development of travel behaviour and its socio-demographic and location determinants, using Dutch National Travel Survey data from 1980 to 2010 among other sources, in the Randstad, the Netherlands. A pseudo panel analysis is conducted to investigate the effect of various indicators on average daily distance travelled by train, car and bicycle over three decades. Econometric models including pooled ordinary least squares, fixed and random effects and a hybrid model were tested to identify the best fit. The results indicate that average daily distance travelled rose until the mid-1990s before witnessing a decrease till 2010. Interestingly, half of the Randstad inhabitants have been travelling no more than 30 kilometres per day over the past thirty years. Furthermore, as people grow older, they increasingly travel more by train and bicycle. Finally, a rise in suburban inhabitants decreases the average distance travelled by train and increases that of bicycle, while a rise in rural inhabitants encourages higher distances travelled by car.

*Keywords:* Long-term, average daily distance travelled, train, car, bicycle, pseudo panel analysis, hybrid method, the Randstad.

## 5.1.    Introduction

Studies quantifying the relationships between locations, individuals, and travel behaviour development over time are very scarce (Ellder, 2014). Travel behaviour requires time to adjust to changes in travellers' residential location and new transport infrastructure, consequently its change is only observable over long time periods. Measuring the development of travel behaviour and its determinants over time is necessary for identifying the long-term effect of land-use and/or transport policies such as transit-oriented development and increase in transport infrastructure supply/service. A long-term evaluation could determine the factors who have always influenced travel behaviour, and the factors whose change has affected the change in travel behaviour over time. Finally, long-term analysis brings us closer to inferring causal relationships which are not possible with cross-sectional analysis.

Nevertheless, long-term empirical studies of land use and travel behaviour are scarce, mainly due to the unavailability of consistent datasets which include measures of travel behaviour and its determinants over a long time period. The existing long-term studies of land use and travel behaviour can be classified in three groups. The first investigates changes in travel patterns and its determinants at an aggregated level such as municipalities or tracts. Examples are induced travel studies which apply panel regression models such as fixed effects with or without instrumental variables (Noland & Lem, 2002), studies which test the before-after effect of the opening of a new transit line on the amount of transit ridership with difference-in-difference or first differences models (Baum-Snow & Kahn, 2000), or a few studies which have applied multivariate regressions for several survey waves to measure the change in factors influencing travel behaviour over time (Susilo & Maat, 2007). The second group investigates changes in individuals' behaviour over time, for instance, studies which examine the concept of self-selection with genuine panel data and longitudinal designs (van de Coevering, Maat, Kroesen, & van Wee, 2016).

Finally, a third strand of research has emerged which applies a panel approach to repeated cross-sectional travel behaviour data of individuals. This so-called pseudo panel analysis aggregates individual data into homogenous groups of observations over time, which under certain conditions can be treated as genuine panel units. Thus relations can be estimated, among other methods, with panel estimations such as fixed or random effects models. In the transport field, this method has been mainly applied to model car ownership (Dargay, 2002) and public transport demand (Tsai, Mulley, & Clifton, 2014).

The goal of this paper is to investigate the development of travel behaviour, namely average daily distance travelled and its determinants using the third method, the pseudo panel analysis. The study area is the Randstad, the population and economic core situated in the west of the Netherlands. As previous work, irrespective of applied method, has mostly investigated relatively short time periods, this study models three decades, between 1980 and 2010. In addition to previous studies, the focus is not only on a single mode, but on train, car and bicycle travel. The central research questions are:

- How has travel behaviour developed over the long term in the Randstad? What is the role of access to transport infrastructure and land use characteristics in its development while controlling for socio-demographic factors?

These questions are answered by descriptive and pseudo panel analysis applied to a dataset including socio-demographic, residential location and travel behaviour indicators over the course of three decades. As there is still no consensus about the best model type for pseudo panel analysis, this study evaluates three frequently used estimation techniques, i.e. the pooled ordinary least squares, fixed

effects and random effects estimations. Furthermore, a hybrid estimation is applied and its performance as the best-fit model is discussed.

The following section provides a brief overview of the investigated data and its preparation. Section 3 summarises and compares the estimation techniques applied to pseudo panels and elaborates on the new hybrid method. Section 4 compares the results of various estimation techniques and the difference between the three modes. The paper ends with reflections on the findings and recommendations for future policy and research.

## 5.2.  Data

A long-term geo-referenced database was constructed by bringing together various sources. Spatial, socio-demographic and travel behaviour data with varying measurements were recoded and converted to same spatial units (the municipal borders of year 2004) to make a consistent dataset for seven time points: 1980, 1985, 1990, 1995, 2000, 2005 and 2010.

Travel behaviour variables were extracted from the Dutch National Travel Survey (NTS) which provides reliable travel diary data since 1979 on an annual basis. The sample was limited to the Randstad. In some cases previous and proceeding respondents were added to the respondents of a given year (e.g. 1984 and 1986 were added to 1985) in order to increase the sample size at that time point and make it comparable with the sample size at other time points. The respondents were further filtered by their age (those younger than 20 years of age were excluded regarding their constrained mobility), whether they had reported at least one trip during the survey day using train or car or bicycle, and whether their living municipality was derivable from their trip data. The final eligible number of respondents was: 11,066 for 1980, 13,348 for 1985, 15,107 for 1990, 32,596 for 1995, 29,007 for 2000, 32,858 for 2005 and 12,690 for the year 2010.

Table 5.1 provides an overview of variables used in the analysis, their definitions and sources. The investigated travel behaviour indicators were average daily distance in kilometres travelled by (1) train, (2) car (as passenger or driver), and (3) bicycle. For multi-modal trips, the transport mode used for the longest leg of the trip was determined as the main mode. Trips and distances travelled by other modes (e.g. motorcycles, tram, bus, metro or walking) are excluded from this analysis. This was due to concerns for measurement errors (especially for walking trips) and the result of preliminary analyses showing that their final share in total distance travelled is marginal.

The chosen socio-demographic variables were the respondents' age, gender, level of education, income and household car ownership. The living municipality of respondents was categorised according to the Randstad's "daily urban systems", a concept first introduced by van der Laan (1998) and used in several studies afterwards (Schwanen, Dieleman, & Dijst, 2001; van Eck & Snellen, 2006). Though the Randstad and its borders have evolved, its daily urban systems have been relatively stable over time. The three categories of daily urban systems are "urban centres" (Amsterdam, Haarlem, The Hague, Rotterdam, Dordrecht, Utrecht, Amersfoort and Hilversum), "suburbs" (medium sized cities in the vicinity of the urban centres) and "other", including the Green Heart, which is a preserved and mainly rural area at the centre of the Randstad, plus municipalities situated in the outer Randstad ring. This category is referred to as "rural" throughout the study. Furthermore, accessibility to railway and motorway was measured as Euclidian distance from the municipality's mean centre, i.e., its centroid based on the dispersion of built-up area across the municipality, to the closest railway station and motorway exit at each time point.

**Table 5.1. Overview of variables used in the analysis, their definition and sources.**

| Variable | Definition | Source |
|---|---|---|
| **Dependent** | | |
| Travel behaviour | | |
| | Average daily distance travelled by train [km] | NTS (National Travel Survey): OVG for |
| | Average daily distance travelled by car [km] | 1980–2000, MON for 2005, OViN for |
| | Average daily distance travelled by bicycle [km] | 2010 |
| **Independent** | | |
| **Socio-demographic** | | |
| Gender | | For all socio-demographic variables, |
| Age | | NTS (National Travel Survey): OVG for |
| Household size | Number of household members | 1980–2000, MON for 2005, OViN for |
| Income | Lower, around or higher than modal income | 2010 |
| Education | | |
| Car availability | The individual has a driving licence and there is at least one car in the household | |
| Employment | | |
| **Land use** | | |
| Population density of the built-up area | Number of inhabitants in the individual's home municipality per square kilometre built-up area. Built-up area is defined as the physical space used for urban functions, including real estate for housing, services, and companies, infrastructure and parks. | Historical land use in the Netherlands (Historisch Grondgebruik Nederland, HGN) for 1980–1990 from Alterra, Wageningen University; Adjusted Land use (BBG Mutatiereeks) for 2000–2010 from Statistics Netherlands (CBS); Population at each time point from CBS |
| Location within the Randstad | Belonging to "urban centres", "suburbs" or "rural" | Based on van der Laan (1998) |
| **Accessibility** | | |
| Distance from rail | Distance from the municipality's mean centre to the closest rail station [km] | Own calculation using ArcGIS |
| Distance from motorway | Distance from the municipality's mean centre to the closest motorway exit [km] | Own calculation using ArcGIS |

## 5.3. Methodology

### 5.3.1. Pseudo panel analysis

In order to measure long-term change in travel behaviour and draw causal inferences about its determinants, the longitudinal behaviour of individuals should be investigated. However, genuine panel data, where the *same* individuals are traced over time, is often costly, small-scale and suffers from sample attrition problems. In the absence of genuine panels, the most long-term and accessible travel behaviour data is the repeated cross-sectional data. Such data is mostly collected by national agencies at the regional or country level, through travel diary surveys, over several survey waves. Repeated cross-sectional data is not a genuine panel data as *different* samples are drawn for each wave, thus it is mostly investigated in aggregated forms (e.g. at the municipality level). Pseudo panel analysis makes use of the individual-level attributes, plus econometric methods for genuine panels, while overcoming the problem that such data is in fact not a real panel. This method relies on the construction of homogenous groups of respondents based on shared characteristics which do not change over time *and* are associated with the dependent variable. Examples of time-invariant grouping variables in existing pseudo panel literature are birth year, gender, geographical region or the level of education (the last two being assumed constant over the investigation period). Each group has a number of cohorts, which equals the number of survey waves for that group. Defined groups are treated as panel units and cohort means are treated as observations in a panel. Cohort means are then traced over time just like individuals in a genuine panel data.

Pseudo panel analysis was initially introduced for analysing repeated cross-sectional data in consumer economics (Deaton, 1985). Its few applications in travel behaviour studies have been to model car ownership, public transport and induced travel demand. Dargay and Vythoulkas (1999) used it to investigate the determinants of car ownership using the British Family Expenditure Surveys from 1970 to 1994. Tsai and Mulley (2014) modelled the short-run and long-run public transport demand in Sydney, Australia over 1982–1995. Weis and Axhausen (2009) investigated the induced travel demand during 1974–2005, using Swiss National Travel Surveys.

The point of departure of pseudo panel analysis is a simple genuine panel data equation:

$$y_{it} = \beta_0 + \beta_1 x_{it} + u_i + \varepsilon_{it} \tag{5.1}$$

Where $i$ denotes the panel units (e.g. individuals, companies or countries), $t$ denotes the time period, $u_i$ is the individual-specific error term (also known as unobserved heterogeneity) and $\varepsilon_{it}$ is the independent error term. The dependent variable $y$ here is the average daily kilometres travelled by train, car and bicycle and the predictors include a number of socio-demographic and location variables (Table 5.1). When this model is applied to a pseudo panel, the equation transforms into:

$$\bar{y}_{gt} = \beta_0 + \beta_1 \bar{x}_{gt} + \bar{u}_{gt} + \bar{\varepsilon}_{gt} \tag{5.2}$$

Here the units of analysis are no longer individuals, but homogenous groups of individuals, denoted by subscript $g$ instead of $i$. Respectively, dependent and independent variables are transformed into the mean value within each group $g$ at time $t$, denoted by $\bar{y}_{gt}$ and $\bar{x}_{gt}$. The term $\bar{u}_{gt}$ specifies the group-specific error which unlike the individual-specific error $u_i$ varies over time. The reason is that the cohorts of a certain group include different members at various time points. However, it is shown that the group-specific error could be considered time-invariant (assumed not to change over time) and groups can be treated as panel units in case (1) cohorts are large enough (including at least 100

members as a rule of thumb), and (2) there is sufficient between-group variation and within-group homogeneity (Deaton, 1985; Verbeek & Nijman, 1992).

In this study, the chosen grouping criteria were (i) birth year and (ii) the level of education. Thresholds for subcategories within each criterion and respectively the number of groups were chosen regarding consistency over time (the common denominators of varying measures at different survey waves) and in an effort to maximise the number of members per all cohorts. Table 5.2 shows the constructed groups, their average cohort size and the number of cohorts.

**Table 5.2. Overview of the constructed groups based on birth year and education, their average cohort size and number of cohorts.**

| Group | Grouping Criteria | | Average cohort | Number of cohorts |
|-------|-------------------|-----------|----------------|-------------------|
|       | **Birth year**    | **Education** |            |                   |
| 1     | <= 1925           | Low       | 585            | 7                 |
| 2     | 1926–1940         | Low       | 633            | 7                 |
| 3     | 1941–1950         | Low       | 352            | 7                 |
| 4     | 1951–1960         | Low       | 221            | 7                 |
| 5     | 1961–1970         | Low       | 125            | 5                 |
| 6     | 1971–1980         | Low       | 78             | 3                 |
| 7     | 1981–1990         | Low       | 13             | 1                 |
| 8     | <= 1925           | Medium    | 1059           | 7                 |
| 9     | 1926–1940         | Medium    | 2308           | 7                 |
| 10    | 1941–1950         | Medium    | 2846           | 7                 |
| 11    | 1951–1960         | Medium    | 3227           | 7                 |
| 12    | 1961–1970         | Medium    | 3592           | 5                 |
| 13    | 1971–1980         | Medium    | 2396           | 3                 |
| 14    | 1981–1990         | Medium    | 519            | 1                 |
| 15    | <= 1925           | High      | 273            | 7                 |
| 16    | 1926–1940         | High      | 646            | 7                 |
| 17    | 1941–1950         | High      | 1108           | 7                 |
| 18    | 1951–1960         | High      | 1482           | 7                 |
| 19    | 1961–1970         | High      | 1829           | 5                 |
| 20    | 1971–1980         | High      | 1788           | 3                 |
| 21    | 1981–1990         | High      | 345            | 1                 |
|       |                   |           | Total          | 111               |
|       |                   |           | Cohorts with less than 100 members | 8 |
|       |                   |           | Final no. of cohorts | 103         |

Birth year was not registered as a continuous variable for several time points (i.e., 1990, 1995 and 2000), but classified within age bands (e.g. 0–5 year, 5–10 year). Furthermore, these classifications were not consistent over time (e.g. 0–5 year at year 1990 versus 0–6 year at year 2000). Because of

different age classifications, respondents above 20 had to be chosen in order to achieve consistent groups over time. The fact that education level might change over time will pose a marginal problem as (1) respondents older than 20 years are chosen (due to the abovementioned limitation caused by varying reported age bands for different waves), and (2) education categories (low/medium and high) are chosen broad enough, so respondents are unlikely to change their education level after they have reached the age of 20.

The final pseudo panel dataset consists of twenty-one groups, constructed based on a 7 by 3 classification of birth year and education. The number of cohorts for every group equals the number of survey waves where that group is present. Eleven of the twenty-one groups have observations for the whole study period. Thus, each of these groups has seven cohorts corresponding to 1980, 1985, 1990, 1995, 2000, 2005 and 2010 survey waves. However, groups based on the more recent birth years have increasingly less number of observations (cohorts), as their members were not yet born or were too young to qualify for the threshold age of 20 years at earlier survey waves. Eight Cohorts containing less than 100 members were excluded from the panel dataset to minimise the measurement error, leaving a total of 103 cohorts, which equals the total number of observations in the pseudo panel dataset.

## 5.3.2. Estimation techniques

The pseudo panel method is applicable with a variety of models, including dynamic models, which include a lagged dependent variable as a regressor (Dargay, 2002), random utility models and SEMs (Weis & Axhausen, 2009). The methodology's complication is due to the relationship between the chosen model and the characteristics of the constructed pseudo panel. Attention should be paid, among other issues, to the ratio of within- to between-group variation and the trade-off between cohort size and the number of groups (Tsai, Waiyan, Mulley, & Clifton, 2013). Furthermore, it is important to consider the hierarchical structure of the pseudo panel data constructed from repeated cross-sectional observations. The inherent temporal hierarchy is due to every group having several observations over the study period. In other words, observations are nested within groups. When temporal hierarchies exist, observations within the same group are very likely related to each other over time (Bell & Jones, 2015).

Table 5.3 provides a comparison of the econometric models applied to pseudo panel datasets regarding certain issues relevant to pseudo panel analysis. For the reason of simplicity, the notations correspond to genuine panel data. Each model can be transformed to be applied to a pseudo panel dataset according to equation 5.2.

*Pooled ordinary least squares*

Pooled ordinary least squares technique (POLS) has been recommended for pseudo panel datasets with larger between-group than within-group variation (Tsai et al., 2013). This technique *pools* data from all survey waves and uses all the available variation in the data, including variation between waves and groups. In the presence of unobserved group heterogeneity, this estimator will be biased and inconsistent (Tsai et al., 2013). As all observations are treated the same, the geographic and/or temporal hierarchy between the higher levels (e.g. countries, groups) and lower levels (e.g. states, observations) are overlooked. In order to control for the unobserved heterogeneity at the group level, fixed effects and random effects estimators are used. In order to deal with hierarchies, random effects (also known as mixed or multi-level) estimators are used.

*Fixed effects*

Fixed effects (FE) models have been generally used for estimating static pseudo panels (Tsai et al., 2014). This specification involves demeaning equation 2, i.e., subtracting the time-mean of each unit from each observation of that unit, which results in the omission of unobserved unit-specific effects. FE is a *within* estimator as it measures the deviation from mean *within* each unit over time. There are two caveats regarding its usage in pseudo panel analysis. First, the unobserved group heterogeneity varies over time–as opposed to individual unobserved heterogeneity which is fixed. So the rational of FE which controls for unobserved heterogeneity by "cancelling it out" would be problematic in pseudo panel analysis (Tsai et al., 2014). That is why this model is used with large cohort sizes with at least 100 members in order to ignore the measurement error. The second problem is that even if the measurement error is minimised by using large cohort sizes, FE focuses on the relation between outcome and predictors within an entity (group in this case) and disregards the differences between entities. Thus FE will be inefficient for panel data with much larger between-entity variation than within-entity variation (Allison, 2009). This condition applies to pseudo panel groups which are constructed with the aim to maximise between-group variance as opposed to within-group variance.

*Random effects*

Random effects models (RE) have also been applied to pseudo panel analysis (Dargay & Vythoulkas, 1999). This model assumes exogeneity between the regressors and the unobserved group heterogeneity. It is estimated by generalised least squares (GLS) and takes into account both between-group and within-group variations. RE takes account of the data's hierarchical structure with its multi-level structure, as it partitions the unexplained residual variance into higher and lower levels. In this case, the lower level consists of observations which are nested in the higher level of pseudo panel groups. However, if the exogeneity assumption fails to hold, RE estimates will be biased. A conventional criteria for deciding between RE and FE is the result of the Hausman test. It examines the orthogonality of unobserved group heterogeneity from other regressors and compares the efficiency of FE and RE.

*Hybrid method*

Another method–which to the best of our knowledge has not yet been applied to pseudo panel analysis in travel studies–is a hybrid estimation based on a reformulation of Mundlak (1978). This specification is specially of importance for repeated cross-sectional data with temporal hierarchies (Bell & Jones, 2015). It includes, like FE, the independent variables with a time-demeaned transformation, i.e., in the form of deviations from the group's time-mean. Thus it measures the within-group, or *time-series* variation. Furthermore, the means of higher entities over time are also included as explanatory variables. In this case, these are group-specific means, which are time invariant components of the independent variables as they are averages over time. The coefficients of these time-mean variables will show the between-group, or *cross-section* variation. Finally, the model with independent variables transformed as above is estimated with an RE model which takes the hierarchical structure into account.

The hybrid technique specifically models the unobserved heterogeneity at the group level, making Hausman test obsolete (Bell & Jones, 2015). Furthermore, the within and between effects are both measured and clearly separated, making interpretations easy. Finally the temporal hierarchy of the data is taken into account as it is a multi-level model. This specification has been suggested by others as a "hybrid" method, i.e., a compromise between FE and RE (Allison, 2009; Schmidt, 2012). Bell and Jones (2015) correctly contend that this model is in fact an RE model. However, in order to distinguish

between this method and the standard RE and to use the terminology of pervious works, this paper also adopts the term "hybrid".

**Table 5.3. Main econometric models applied to pseudo panel datasets, their Specification and characteristics.**

| Model name and specification | Controls for unobserved heterogeneity | Multi-level structure | Characteristics | Estimation technique |
|---|---|---|---|---|
| **Pooled ordinary least squares (POLS)** $$y_i = \beta_0 + \beta_1 x_i + \varepsilon_i$$ | No | No | Pools all observations; is biased in the presence of unobserved heterogeneity | OLS |
| **Fixed effects (FE)** $$(y_{it} - \bar{y}_i) = \beta_1(x_{it} - \bar{x}_i) + (\varepsilon_{it} - \bar{\varepsilon}_i)$$ | By cancelling it out | No | Unable to model time-invariant variables or between-unit effects | OLS |
| **Standard random effects (RE)** i. random intercept: $$y_{it} = \beta_0 + \beta_1 x_{it} + u_i + \varepsilon_{it}$$ ii. random intercept and slope: $$y_{it} = \beta_0 + \beta_{1j} x_{it} + u_i + \varepsilon_{it}$$ | By including it in the model and assuming its exogeneity | Yes | Can model time invariant variables and between-unit effects; biased if assumption of exogeneity is not met; assumes a random intercept which can be estimated with a fixed or random slope | GLS; ML |
| **Hybrid** $$y_{it} = \beta_0 + \beta_1(x_{it} - \bar{x}_i) + \beta_2 \bar{x}_i + u_i + \varepsilon_{it}$$ | By including it in the model, treating it as a latent variable and estimating its proportion of total variance | Yes | As above, except that it controls for exogeneity; β1 and β2 explicitly show within and between group variation, thus they are easy to interpret | GLS; ML |

Note: For the reason of simplicity, notations correspond to genuine panel data; Estimation techniques are for continuous response variables; OLS: Ordinary least squares; ML: Maximum likelihood; GLS: Generalised least squares.

## 5.4.  Results

### 5.4.1.  Descriptive analysis at the traveller level

Figure 5.1 summarises long-term trends in daily distance *per traveller* (i.e., a respondent who has reported at least one trip by either train, car or bicycle), by all and separate transport modes, from 1980 to 2010. As expected, the majority of daily distance travelled is by car, which is significantly higher than train and bicycle. The *average* daily distance travelled (the purple line) has increased since 1980, reaching a peak at 1995, and has been more or less decreasing ever since. However, there are two caveats: first, the average can be greatly influenced by outliers (e.g. a limited number of respondents who travel very long distances) and second, car trips are very dominant in the sample. The *median* daily kilometres travelled (the dashed purple line) is much lower than average, revealing that half of the travellers living in the Randstad have been travelling below 30 km per day over three decades. As many respondents did not report a bicycle or a train trip on the survey day, their medians are zero. The following section will summarise the above trends at the group level and identify the significant determinants with econometric models.

**Average and median daily distance travelled for the Randstad inhabitants**
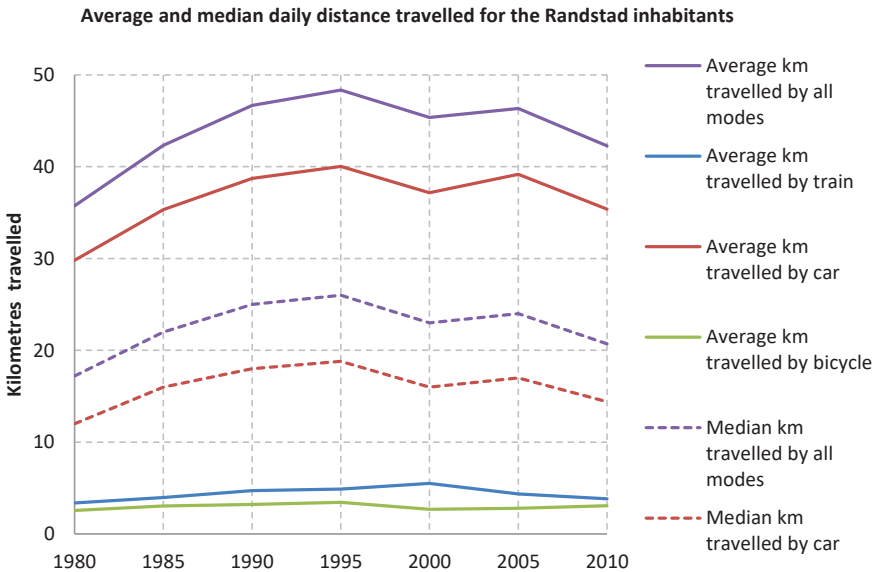


**Figure 5.1. Daily distance travelled by all and separate modes for travellers living in the Randstad from 1980 to 2010.**

### 5.4.2.  Comparison of estimation techniques

This section summarises the results of different estimations for the dependent variable average daily train kilometres travelled. It compares the standardised coefficient estimates achieved by pooled ordinary least squares (POLS), fixed and random effects (FE & RE) and hybrid techniques (Table 5.4). The dependent variable is logarithm transformed to minimise the effect of its positive skewness and

heteroscedasticity. Controlling for multicollinearity determined the final choice of independent variables. These variables include the groups' share of (1) different age bands, (2) females, (3) medium and high-income earners, and (4) people living in the suburbs and rural areas, as well as the groups' average of (5) members' household size, and (6) living municipalities distance to the closest motorway exit. Time-demeaned variables are indicated with ($d$). For instance, *% Female* ($d$),  is the deviation of the proportion of females in the group from the group-specific mean for the share of females in the group over time, the latter measured with the same variable name marked with ($m$). The results of various tests such as Breusch and Pagan Lagrangian multiplier test for random effects, Ramsey's RESET test for omitted variables and Hausman test were compared to identify model misspecification.

The first column shows the result of POLS. The signs and significance of the variables are as expected, however a significant result of Breusch and Pagan Lagrangian multiplier test indicates the presence of random effects, which means that POLS estimates are biased. The FE model in the second column includes group fixed effects, i.e., dummies for all groups (minus one) are included to absorb unobserved heterogeneity at the group level. The model fit in terms of R-squared is the highest, however it is not possible to make inferences about time-invariant variables such as averages over time, as the model cannot include them.

The last column shows the result of the hybrid specification. The *within* estimator part of this model $\beta_1(x_{it} - \bar{x}_i)$ explains the variance between waves, i.e. the development of average daily train kilometres travelled over time. In other words, it measures the effect of change in explanatory variables (marked with $d$), on change in average daily train kilometres travelled, within each group over the study period. A rise in the share of people above 40 is shown to cause a rise in the amount of average daily train kilometres travelled over time. Another significant but negative variable is the increase in percent members living in the suburbs within a group. This means that the increase in the share of suburban inhabitants over time will result in lower train kilometres travelled.

In theory, the coefficients achieved with the within estimator of the hybrid model and those of FE model should be identical. However this is not the case as the time-mean of every variable is *not* included in the model (e.g. year) (Schmidt, 2012). Furthermore, the fact that the analysed pseudo panel dataset is highly *unbalanced* (i.e., there is a high variation regarding the number of cohorts for every group), plays a role (Allison, 2009).

The *between* estimator part of the model, $\beta_2\bar{x}_i$ , explains the variance at the group level. In other words, it measures differences between groups at the cross section. The coefficients measure the explanatory power of time-invariant variables (marked with an $m$), in this case the time-means of higher-entities  which are the groups. Here, two variables are significant and negative: the groups' share of people in their fifties and average distance to the motorway exit. This means that, considering the whole study period as a cross section, groups with higher share of people in their fifties or less average distance to motorway exits are associated with lower daily train kilometres travelled.

The different signs for the share of people in their 50s, measured by the within and between estimators of the hybrid model might seem contradictory. However, it should be kept in mind that the within estimator measures the variables' deviation from average while the between estimator measures their average over time. So, while an increase in the share of people in their 50s over time will result in higher train kilometres, in general higher shares of 50s is associated with lower train kilometres travelled. Regarding the effect of time points, the average daily train kilometres has been increasingly decreasing with more recent survey waves.

**Table 5.4. Model estimates based on POLS, FE, RE and hybrid techniques for the natural logarithm of average daily distance travelled by train [km].**

| Independent variables | Pooled ordinary least squares | Fixed effects | Random effects | Hybrid |
|---|---|---|---|---|
| Age | | | | |
| % 30–39 | −0.293* | | −0.286** | |
| % 40–49 | −0.193 | | −0.176 | |
| % 50–64 | −0.277** | | −0.213** | |
| % 65 or older | −0.175 | | −0.157 | |
| % Female | 0.238* | | 0.149 | |
| Household size | −0.175 | | −0.105 | |
| % Medium income | 0.191 | | 0.120 | |
| % High income | 0.756*** | | 0.631*** | |
| % Living in suburb | −0.221** | | −0.282*** | |
| % Living in rural area | 0.057 | | 0.050 | |
| Dist. to motorway exit | −0.320** | | −0.261 | |
| Age (d) | | | | |
| % 30–39 | | −0.071 | | 0.069 |
| % 40–49 | | 0.150 | | 0.338* |
| % 50–64 | | 0.396 | | 0.566* |
| % 65 or older | | 0.548 | | 0.574* |
| % Female (d) | | −0.005 | | 0.004 |
| Household size (d) | | 0.133 | | −0.009 |
| % Medium income (d) | | −0.198 | | −0.193 |
| % High income (d) | | −0.166 | | −0.086 |
| % Living in suburb (d) | | −0.329** | | −0.165** |
| % Living in rural area (d) | | 0.141 | | 0.080 |
| Dist. to motorway exit | | −0.263 | | −0.338 |
| Age (m) | | | | |
| % 30–39 | | | | −0.112 |
| % 40–49 | | | | −0.049 |
| % 50–64 | | | | −0.436** |
| % 65 or older | | | | −0.802 |
| % Female (m) | | | | 0.051 |
| Household size (m) | | | | −0.794 |
| % Medium income  (m) | | | | −0.105 |
| % High income  (m) | | | | 0.236 |
| % Living in suburb  (m) | | | | 0.116 |
| % Living in rural area | | | | 0.217 |
| Dist. to motorway exit | | | | −0.460** |

| Year | | | | |
|---|---|---|---|---|
| 1985 | −0.645 | −0.313 | −0.548 | −0.471 |
| 1990 | −0.832** | −0.623 | −0.660 | −1.231* |
| 1995 | −0.853** | −0.654 | −0.661 | −1.326* |
| 2000 | −0.957* | −1.141 | −0.811 | −2.027** |
| 2005 | −1.264** | −1.399 | −1.069 | −2.420** |
| 2010 | −1.815*** | −1.602* | −1.454** | −2.797** |
| Constant | 2.132*** | 1.015 | 1.971*** | 2.757*** |
| Group fixed effects | no | yes | no | no |
| R-squared | | | | |
| within | | 0.466 | 0.373 | 0.453 |
| Between | | 0.113 | 0.722 | 0.891 |
| Overall | 0.602 | 0.808 | 0.590 | 0.739 |

N=103; Standardised coefficients (robust standard errors in parentheses); * $p<0.10$, ** $p<0.05$, *** $p<0.001$; All independent variables except for year dummies are standardised.

### 5.4.3. Comparison of average distances travelled by train, car and bicycle and their determinants over time

Table 5.5 shows the results of the hybrid method for the natural logarithm of average daily distances travelled by train, as well as car and bicycle. Train results in the first column are explained in the previous sub-section.

Results in the second column indicate that an increase in age until 65, as well as people living in rural areas are associated with higher car kilometres travelled over the study period. While in general, groups with higher share of people above 50 (especially above 65), and higher average household size, travel lower distances by car per day. As expected, groups with a higher share of high-income people and suburban inhabitants also have higher car kilometres travelled. Results in the third column show that an increase in age within the group results in progressively higher average daily bicycle kilometres travelled over the study period. This implies that people are increasingly biking more as they become older (especially above 50). On the other hand, groups with higher share of people in their 30s, medium-income earners and with lower average distance to motorway exits, have lower bicycle kilometres.

**Table 5.5. Comparison of the result of the hybrid model for the natural logarithm of average daily distance travelled by train, car and bicycle [km].**

| Independent variables | Average daily distance travelled by train | | Average daily distance travelled by car | | Average daily distance travelled by bicycle | |
|---|---|---|---|---|---|---|
| Age (d) | | | | | | |
| % 30–39 | 0.069 | (0.118) | 0.104** | (0.038) | 0.095** | (0.042) |
| % 40–49 | 0.338* | (0.184) | 0.163** | (0.067) | 0.197** | (0.074) |
| % 50–64 | 0.566* | (0.298) | 0.244** | (0.111) | 0.280** | (0.105) |
| % 65 or older | 0.574* | (0.329) | 0.149 | (0.121) | 0.298** | (0.112) |
| % Female (d) | 0.004 | (0.047) | 0.002 | (0.013) | −0.021 | (0.016) |
| Household size (d) | −0.009 | (0.163) | 0.010 | (0.062) | −0.067 | (0.051) |
| % Medium income (d) | −0.193 | (0.177) | 0.040 | (0.034) | −0.035 | (0.024) |
| % High income (d) | −0.086 | (0.123) | −0.012 | (0.030) | −0.031 | (0.037) |
| % Living in suburb (d) | −0.165** | (0.054) | −0.003 | (0.018) | 0.038* | (0.020) |
| % Living in rural area (d) | 0.080 | (0.136) | 0.037** | (0.017) | −0.011 | (0.018) |
| Dist. to motorway exit (d) | −0.338 | (0.235) | −0,011 | (0.036) | −0.037 | (0.037) |
| Age (m) | | | | | | |
| % 30–39 | −0.112 | (0.140) | −0.021 | (0.024) | −0.060* | (0.033) |
| % 40–49 | −0.049 | (0.126) | 0.010 | (0.025) | 0.024 | (0.046) |
| % 50–64 | −0.436** | (0.148) | −0.042** | (0.018) | 0.008 | (0.029) |
| % 65 or older | −0.802 | (0.714) | −0.303*** | (0.084) | −0.267 | (0.174) |
| % Female (m) | 0.051 | (0.146) | 0.017 | (0.020) | 0.021 | (0.053) |
| Household size (m) | −0.794 | (0.589) | −0.203** | (0.069) | −0.170 | (0.193) |
| % Medium income  (m) | −0.105 | (0.123) | 0.020 | (0.016) | −0.063** | (0.029) |
| % High income  (m) | 0.236 | (0.276) | 0.192*** | (0.041) | −0.097 | (0.084) |
| % Living in suburb  (m) | 0.116 | (0.197) | 0.046** | (0.020) | −0.051 | (0.058) |
| % Living in rural area  (m) | 0.217 | (0.230) | 0.046 | (0.037) | 0.062 | (0.059) |
| Dist. to motorway exit  (m) | −0.460** | (0.203) | −0.021 | (0.033) | −0.152** | (0.055) |
| Year | | | | | | |
| 1985 | −0.471 | (0.462) | 0.130** | (0.062) | 0.145** | (0.073) |
| 1990 | −1.231* | (0.693) | 0.117 | (0.123) | −0.184 | (0.148) |
| 1995 | −1.326* | (0.771) | 0.124 | (0.133) | −0.108 | (0.175) |
| 2000 | −2.027** | (0.918) | −0.081 | (0.184) | −0.675*** | (0.199) |
| 2005 | −2.420** | (1.046) | −0.080 | (0.237) | −0.786** | (0.271) |
| 2010 | −2.797** | (1.155) | −0.398 | (0.278) | −0.791** | (0.318) |
| Constant | 2.757*** | (0.722) | 3.547*** | (0.145) | 1.459*** | (0.184) |
| R-squared | | 0.453 | | 0.765 | | 0.648 |
| Between | | 0.891 | | 0.987 | | 0.826 |
| Overall | | 0.739 | | 0.908 | | 0.714 |

N=103; Standardised coefficients (robust standard errors in parentheses); * p<0.10, ** p<0.05, *** p<0.001; All independent variables except for year dummies are standardised.

## 5.5.    Conclusions and discussion

This paper investigated the trends in average daily distance travelled and its determinants, for the three modes of train, car and bicycle, from 1980 to 2010 in the Dutch metropolitan region of the Randstad, using descriptive and pseudo panel analysis with various econometric models. Its aim was to find out how travel behaviour has developed over the long term in the Randstad and to pinpoint the impact of access to transport infrastructure and land use characteristics on the development of travel behaviour. Its specific contribution to the field is threefold. First, it investigated the development of travel behaviour over a very long time period. Second it compared average daily distance travelled between three transport modes (train, car and bicycle) and their determinants over time. Finally it applied a new hybrid method to the pseudo panel analysis in travel studies.

Analysis at the traveller level revealed that median daily distance travelled in the Randstad has remained under 30 kilometres, even at its highest point in 1995. In other words, half of the Randstad inhabitants have been travelling no more than 30 kilometres a day over the past thirty years (and this is excluding those who reported no trip during the survey day). This makes alternative transport modes with relatively limited range such as electric cars and bicycles suitable for the Dutch context and especially the Randstad.

Regarding the effect of *change* (of determinants) *on change* (of travel behaviour) at the group level, a rise in age is increasingly related to higher train and bicycle kilometres travelled. In other words, as people grow older, they increasingly travel more by train and bicycle. This is true also for car up to 65 years (unsurprisingly, as it is easier for the Dutch elderly to travel by train and bicycle while being fit for driving a car is more demanding). This calls for an increase in train and bicycle facilities for the elderly, e.g. cheaper train travel and safer bicycle infrastructure.

Moreover, an increase in a group's suburban inhabitants (which in panel terms equals a respondent's move to the suburbs) results in lower train kilometres, though higher bicycle kilometres travelled. The first is probably due to a lower supply and service quality of suburban rail infrastructure in comparison with the big cities. The latter could be for the reason that it is easier to bike in a suburban environment than congested big cities. A rise in the rural inhabitants is associated with higher car kilometres. This is expected as the "rural" category includes municipalities in the Green Heart and the Randstad's outer ring which mostly lack an efficient and well-connected rail infrastructure, have less disincentives for car use and more space for parking. A more integrated connection of these areas with the existing railway infrastructure, providing higher service frequencies as well as disincentives for car travel could help mitigate the use of car in these locations.

Pseudo panel analysis provides the opportunity to analyse travel behaviour over long time spans at a relatively disaggregated (group) level while using available travel survey datasets. There are, however, a number of caveats to be considered. First, it is not possible to control for the issue of residential self-selection with this method. Furthermore, the extent to which the grouping criteria for the construction of pseudo panel groups and the characteristics of the constructed groups bias the results, is not clear and calls for further investigations, such as the work of Tsai et al. (2013). Despite these caveats, pseudo panel analysis contributes to investigating changes in travel behaviour and its determinants over time spans and at a level of aggregation which has not been possible before. Moreover, the hybrid specification applied in this paper is suitable for  analysing pseudo panel datasets, as it was shown to outperform conventional models overall, since it (1) explicitly models unobserved group heterogeneity, (2) can include time-invariant variables, (3) takes account of the temporal hierarchy of repeated cross-sectional data, and (4) measures both within- and between-group variation in a manner which is easy to interpret.

This study used a static specification, future research could identify short- and long-term rate of change in travel behaviour in response to land use and transport infrastructure, e.g. by incorporating dynamic partially adjusted models (Tsai et al., 2014) and compare the findings achieved by static and dynamic specifications. Furthermore, the model fit in terms of R-squared was shown to be highest for car, compared to train and bicycle. This suggests that the chosen variables can explain the variation in distance travelled by car more than train and bicycle. It is important to identify and estimate the role of other train and bicycle related factors such as train fare prices, quality and supply of  bicycle and train infrastructure or attitudes towards their use, which could provide more insight into how their travel behaviour varies from car. Finally, this analysis measured the impact of land use on travel behaviour. Nevertheless, it is very likely that a reverse relation exists where travel behaviour affects land use over the long time span of the study. Further research should include the possibility of reverse causality and measure its impact as well.

## Acknowledgments

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# Chapter 6:    Conclusions

This thesis sets out to unravel the relations between transport infrastructure networks (TINs), land use (LU) and travel behaviour (TB) (1) in the long term. It investigates these relationships (2) empirically, (3) at a regional level, (4) with a spatial focus on the role of and the effect on land use, while (5) comparing the role of both road and rail networks whenever possible. The overarching question of the thesis is:

*What are the long-term relations between transport infrastructure networks, land use and travel behaviour at the regional level?*

The main research question of this thesis was broken down to four sub-questions which were addressed in Chapters 2 to 5. This chapter summarises and discusses the findings on the investigated sub-questions and elaborates on recommendations for policy and future research.

## 6.1.    Summary of findings

Chapter 2, "Long-term impacts of transport infrastructure networks on land-use change: an international review of empirical studies", involves a literature review which addresses the following sub-question:

a) *To what extent does the existing empirical literature provide evidence on the long term relationship between transport infrastructure networks and land use?*

This chapter reviews previous studies on the long-term influence of transport infrastructure networks (TINs), namely the road and the rail networks on land use (LU), the latter indicated by employment and population density, land cover and development type (residential, office, commercial, industrial). The reviewed studies are empirical and cover various stages in history, time spans and regions of the world. The results show that proximity to rail is generally considered to have influenced population distribution and is correlated with population growth, especially after the emergence of the railway

network. However, there are also exceptional cases where the presence of railways has no, or a negative relation with population density. These cases were reported for lagging regions, trunk lines which were not beneficial to the local study area, or areas which already had a dense rail service for a while. Proximity to rail is shown to have promoted conversion to residential LU and development of higher residential densities by a number of studies. However, findings on its role in increasing employment density are inconclusive, indicating that its success is more dependent on exogenous factors such as complementary policies and area attractiveness, which are mostly favourable in downtown areas.

For the road network, studies generally suggest that the presence of or the proximity to major highways is associated with the conversion to urban land, increases in employment densities and commercial and industrial development. However, this is not always the case for residential uses, suggesting that living in the direct vicinity of motorways can be unattractive. Almost all of the studies which had examined the impact of access to both road and rail on LU found lower coefficients or no significance for access to rail compared to the road network, regardless of the study period. However, it should be noted that these studies mostly focused on changes during the second half of the 20th century and onwards, when the rail network was assumed to have lost its initial impact.

This chapter also discusses the exogenous factors which can influence the supply of TINs and LU and determine their relation. The supply of TINs can be drastically influenced by technological innovations, infrastructure investments and mobility policies. As for LU, regional demand, land availability, area attractiveness and spatial policy play important roles. The conclusion is, while these factors have been mentioned, they have not always been explicitly addressed in the empirical literature. This is especially true in the case of area attractiveness and spatial/transport policies.

This chapter concludes with the observation (depicted in a scheme) that on the whole, the magnitude of TINs' impact on LU depends on the stage of TIN development coinciding with the stage of LU development. Regarding the leading factor between TINs and LU, the number of bi-directional studies are too small to draw definitive conclusions. However the findings suggest that the more developed of the two is likely to have the upper hand in leading the other's development, unless a significant advance in transport technology or an effective policy intervention occurs which succeeds in setting a new trend. In other words, whether it is TINs or LU which leads seems to be closely related to the concurrence of TINs and LU saturation stages as well.

While Chapter 2 investigates the long-term relationship between land use and transport infrastructure by means of literature review, Chapter 3 analyses this relationship empirically. This chapter focuses on the relation between the railway network and urbanisation in the Dutch Randstad, from 1850 to 2010, a time span which has hardly been investigated. Here, the following questions are taken up:

b) *In what way have land use and transport infrastructure developed over the long term in the Randstad in general and in relation to each other? At what time has new transport infrastructure led to new urbanisation or vice versa?*

The analysis of the development of the railway network shows that the total length of railway and the total number of stations follow broadly the same trend: growing and climaxing by 1920, deteriorating between the 1930s and 1950s, stabilising in the 1960s, and resuming expansion, although at a slower pace, from the 1970s to the present day. Nevertheless, station numbers witness more variation than total railway length. The growth of the railway network is highly associated with the growth of the built-up area. As might be expected, the railways follow the existing pattern of urbanisation in the very beginning, and later urbanisation develops and intensifies very close to the stations. With the

introduction of the car and other modes of transport, urban development further away from stations increases, before it returns, partially, to the vicinity of stations at the turn of the 21st century. Analyses show a distance trend whereby the rings closer to the stations (especially the 0–1 km buffer) are always covered by more built-up area than further rings.

The findings of this chapter confirm the suggested scheme at the end of Chapter 2 which predicts the impact of transport infrastructure network on land use. Initially, i.e., from 1850 to 1910, there is a high impact of TINs on LU. This impact is manifested as the urbanisation in the vicinity of train stations, measured within a 5km radius, which is more than the general urbanisation trend in the Randstad at the time. However, as time goes by, and while urbanisation in the vicinity of stations continues, the impact of rail loses momentum. This is shown by a generally lower slope of urbanisation in the vicinity of stations in comparison to the general urbanisation in the Randstad after 1910. This decrease in the railway impact among others was due to a gradual decrease in both the additional accessibility provided by railways and the available land for development in its vicinity (with the exception of new stations planned in as-of-yet-undeveloped areas). In other words, developments in both land and TIN-related accessibility became saturated.

Regarding the question whether it were the railways or urbanisation which appeared first, early railway stations (again, from 1850 to 1910) were shown to have followed the existing urbanisation pattern at the time, which was more developed and prevailed between the two. However, especially after WWII, stations were located, or rather planned, in undeveloped areas which have the capacity for further development. Dominating in these areas, they promoted further growth in their vicinity.

Finally, one should not overlook the influence of policies, economic recession and other exogenous factors pinpointed in Chapter 2 on the ultimate impact of railways on urbanisation over time. The emergence of motorways and the pervasive use of private automobiles–due to advances in transport technology coupled with political decisions to invest in more roads–are assumed to have played a significant role in reducing the impact of railways and promoting suburbanisation after WWII. Chapter 4 investigates the role of the motorway network in addition to the railway network, as well as the role of spatial policies and urban proximity on the spatial distribution of urban areas. This chapter addresses the question below:

c) *To what extent have transport accessibility, proximity to existing urban areas and spatial policies affected the spatial dynamics of urbanisation in the Randstad?*

Chapter 4 investigates the dynamics of the spatial distribution of urbanisation in the Greater Randstad Area over a period of drastic change from 1960 to 2010 and examines to what extent the effects of these determinants vary over time. Its underlying assumption is that urbanisation is a process partly driven by transport accessibility, partly by the attraction of existing urban areas, and partly by policies aimed at influencing autonomous processes. Transport accessibility and urban proximity are chosen as determinants of urbanisation because they are related to both the autonomous process of urbanisation as well as the Dutch spatial policies applied in the past decades. Generalised Estimating Equations (GEE) analysis with a logit function is applied to a longitudinal dataset of approximately 40,000 cells of 500 m by 500 m, observed at six time points. GEE-analysis is chosen because of its capability to control for the dependence between observations and to model a fractional response variable, which is in this case the proportion of urban land in a cell. Furthermore, interactions with time are included to investigate the temporal variations in the effects of urbanisation determinants.

The results of this chapter indicate that transport accessibility has influenced the spatial distribution of urbanisation at a stable rate over the study period. A striking finding is that the influence of the

railway network–a network which has been more or less stable over the study period–is comparable to the influence of the road network which has witnessed drastic developments over the same period. This result is in contrast to previous studies which for the most part have reported significantly higher impact for road compared to rail on land use change (see Kasraian et al., 2016 for an overview of these studies). This finding is possibly due to the Randstad's already existing dense railway network, the parallel construction of the motorway network to the railway network, Dutch spatial policies encouraging developments at locations with high rail access and the disutility of living in car-dependent areas in a congested Randstad with its parking limitations. Finally, the comparable impact of the rail and road networks on urbanisation patterns is derived from indicators of network accessibility to the main activity centres. While large cities are highly accessible by both road and rail, accessibility to smaller urban areas could be better by road than by rail.

This chapter demonstrates that network-based transport accessibility indicators, especially *total travel time to the centres of activity* provide a better explanation for the increase in the likelihood of urbanisation compared to the Euclidian distances to access points of transport infrastructure such as rail stations and motorway exits. However, the impact of existing urbanised areas in a cell's vicinity is shown to be by far a more powerful driver of urbanisation patterns than transport accessibility. This chapter concludes that overall, the proximity of existing urban areas has constantly been the most influential attractor of further urbanisation.

Another important finding of this chapter is that while the effect of transport accessibility is positive, it is rather marginal. This could be related to the correlation of transport accessibility and urban proximity (thus the effect of the first could also be captured by variables measuring the latter) and/or the unsubstantial change of the transport infrastructure network during the study period (although motorways emerged during this period, they were built more or less parallel to the then existing railway lines). Furthermore, the fact that the focus is placed on the distribution of urban growth *within the Randstad* rather than comparing it with less developed peripheral regions and finally the poly-nuclear structure of this region are probably linked to the limited role of transport accessibility.

Importantly, chapter 4 investigates spatial planning and policies, which are shown to have played a significant role in channelling the new urbanisation and preserving green areas, contrary to some other countries such as the US. This chapter shows that, the Green Heart policy has continuously had the most restrictive effect on the development of urban land in this preserved area. On the other hand, the Growth Centres policy has had a significant impact in the 1970s and is still effective. As for the impact of the VINEX policy, it is shown to have drastically influenced the growth patterns of the 2000s.

A critical conclusion of this chapter is that policies are durable, or in other words, the legacy of a policy can affect development patterns decades later when newer concepts are introduced. This is demonstrated by the finding that the Concentrated Deconcentration by designation of Growth Centres in the 1960s not only had a significant impact on the growth patterns of the 1970s, but has attracted new urbanisation ever since. Thus the Growth Centres policy has remained influential regardless of the shifts in predominant Dutch spatial policies to the Compact City and VINEX in the following decades. This chapter closes with an elaboration on the complementary role of market forces on the dynamics of urbanisation and how it could be captured by the investigated determinants. It concludes that all in all, it is more accurate to conclude that the final urbanisation pattern in the Randstad is the resultant of both the efforts of policy and market forces.

While Chapters 2–4 examine the relation between transport infrastructure networks and land use, Chapter 5 investigates the consequence of this relationship for travel behaviour. This chapter takes up on the following questions:

> d) How has travel behaviour developed over the long term in the Randstad? What is the role of access to transport infrastructure and land use characteristics in its development while controlling for socio-demographic factors?

Chapter 5 examines the development of travel behaviour and the role of transport infrastructure and land use as its determinants, while controlling for socio-demographic characteristics during the period between 1980 and 2010. It uses travel behaviour data from the Dutch National Travel Surveys provided by Statistics Netherlands (CBS) and Socialdata, and processed by van Goeverden from the Faculty of Civil Engineering, Delft University of Technology. Since genuine panel data is not available for such a long period, a pseudo panel analysis is conducted to model the effect of various indicators on average daily distance travelled by train, car and bicycle over three decades. With the help of the pseudo panel method, repeated cross-sectional data can be treated as a genuine panel on which longitudinal analysis can be performed. This method relies on the construction of homogenous groups of respondents based on shared characteristics which do not change over time (e.g. birth year, gender, region or education level) and are associated with the dependent variable.

Descriptive analysis at the traveller level reveals that median daily distance travelled in the Randstad has remained under 30 kilometres, even at its highest point in 1995. In other words, half of the Randstad inhabitants have been travelling no more than 30 kilometres a day over the past thirty years (and this is excluding those who reported no trip during the survey day).

The results of the hybrid model (a combination of Random and Fixed effects) show that the significant socio-demographic variable whose change over the study period results in the change of travel behaviour is age: a rise in age is increasingly related to higher train and bicycle kilometres travelled. In other words, as people grow older, they increasingly travel more by train and bicycle. This is true also for car up to 65 years, which is not surprising, as it is easier for the Dutch elderly to travel by train and bicycle while being fit for driving a car is more demanding.

In this chapter, the role of land use on travel behaviour is proxied by the impact of residential location–being urban, suburban or rural. The findings show that an increase in the inhabitants of suburban areas–at the cost of leaving the urban cores–is associated with significantly lower distances travelled by train, but higher distances travelled by bicycle. The first is probably due to a lower supply and service quality of suburban rail infrastructure in comparison with the big cities. The latter could be for the reason that various land uses are further apart in the less dense suburban environment compared to urban cores, which necessitates travelling longer distances to perform activities. A rise in the *rural* inhabitants is linked to higher car kilometres. This is expected as the "rural" category includes municipalities in the Green Heart and the Randstad's outer ring which mostly lack an efficient and well-connected rail infrastructure, have less disincentives for car use and offer more space for parking. A rather surprising finding is that a higher average distance to a motorway exit is associated with lower daily train and bicycle kilometres travelled. This can be for the reason that the network of motorways and railways follow more or less the same pattern across the Randstad. Many motorways are constructed parallel to railways in an attempt to bundle transport infrastructures. Areas with high distance from motorway exits are most likely in the Green Heart and the outer rings, which also lack proper train connections. Similarly, in such "in-the-middle-of-nowhere" areas, biking would not be a feasible option either.

## 6.2.    Conclusions

This thesis analyses relationships between transport infrastructure networks, land use and travel behaviour in the long term, with various transport modes and over various stages in history. Its point of departure is the transport land use feedback cycle (Figure 6.1) which theorises the complex relationships between transport infrastructure networks, land use and travel behaviour and the exogenous factors which influence them (Wegener & Fürst, 1999; Bertolini, 2012). Based on this framework, improvements in the transport infrastructure network increase accessibility, making land more valuable for further development. At the same time, land development generates travel demand and consequently induces the need for infrastructure improvements (Giuliano, 2004).
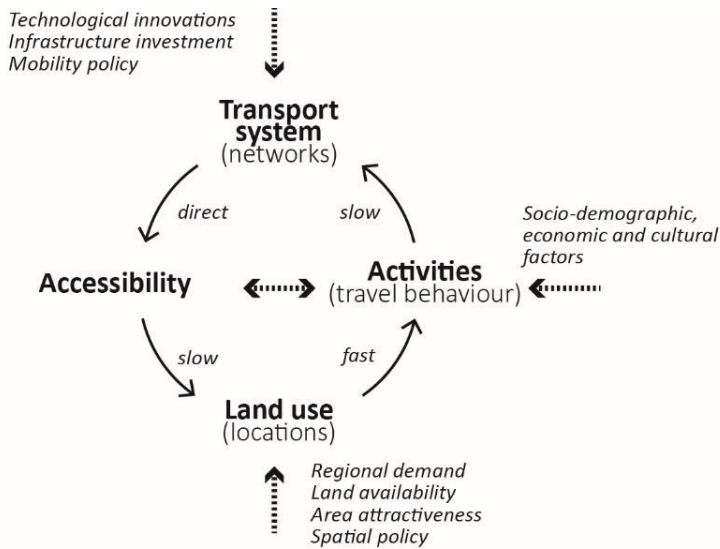


**Figure 6.1. Transport land-use feedback cycle (Wegener & Fürst, 1999; adapted by Bertolini, 2012).**

Throughout, this thesis confirms empirically the relations suggested in this frame work. When investigating the reverse impact of land use on transport infrastructure, the intermediary step of travel behaviour change  was excluded and the change in transport infrastructure network was modelled directly in response to land use change (dashed vertical line in Figure 6.2a). This choice was due to the lack of comprehensive and consistent historical data on travel behaviour, a limitation which other studies have faced.

All things considered, it can be concluded that transport infrastructure networks determine land use in general, urbanisation (i.e., the conversion of undeveloped to built-up land) in specific, and travel behaviour as a consequence. Long-term relations between transport infrastructure networks, land use and travel behaviour exist. The transport land use feedback cycle predicts these relations correctly–at least for the majority of the cycle which is tested in this thesis. The following paragraphs break down the cycle into relationships between its components and explain the findings of this thesis based on these relationships. The timeline of the key findings of thesis, as well as their context are presented in Figure 6.3.
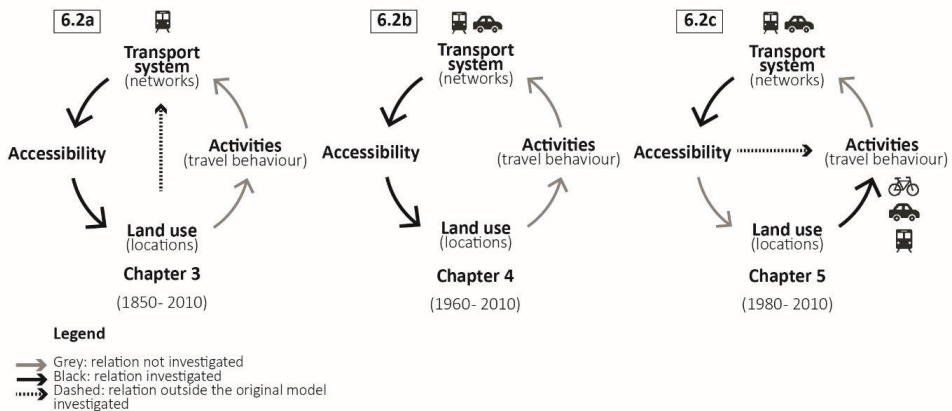
**Figure 6.2a–c. The land use transport feedback cycle relations empirically investigated in each chapter: investigated links as they were suggested by the model, and those outside the original model.**

Transport infrastructure networks have changed land use and continue to do so. The railway network played an important role in the redistribution of  population, particularly soon after its initial development in the second half of the 19th century (Figure 6.2a). Conversely, the results show that land use does influence transport infrastructure (the reverse link). This is specifically seen in the case of initial railway stations following the existing urbanisation patterns. This trend however changes in the second half of the 20th century where new stations are more likely to be located in undeveloped areas and encourage further urbanisation in their vicinity.

Overall, the contemporary impact of railways and motorways on guiding the spatial distribution of land use (measured here as urbanisation patterns) is limited, especially at times and within locations of transport infrastructure saturation (Figure 6.2b). Network based accessibility indicators capture the influence of transport infrastructure networks better than simple Euclidian distances to transport nodes. Interestingly, the road and railway networks have had more or less the same influence on the spatial distribution of urbanisation in the Randstad. However, the greatest driver of urbanisation is the proximity to urban land. Exogenous factors such as spatial planning and policies are shown to have played a significant role in the distribution of urbanisation. In the Randstad, the Green Heart policy has continuously had the most restrictive effect on the development of urban land in this  preserved area. On the other hand, the Growth Centres policy has had a significant impact in the 1970s and is still effective. As for the impact of the VINEX policy, it is shown to have drastically influenced the growth patterns of the 2000s.

The link between transport infrastructure networks and land use with travel behaviour, becomes manifest in this thesis as the role of access to railways and motorways in combination with land use characteristics such as residential location in determining travel behaviour (Figure 6.2c). Residential location plays an important role in determining individuals' travel behaviour, however its influence varies for different transport modes. Those who live in the suburbs travel longer distances by car. An increase in the inhabitants of suburban areas–at the cost of leaving the urban cores–is linked to lower distances travelled by train and higher distances travelled by bicycle. An increase in the inhabitants of rural areas is associated with higher distances travelled by car. Access to transport infrastructure influences travel behaviour, however this influence also varies per transport mode.
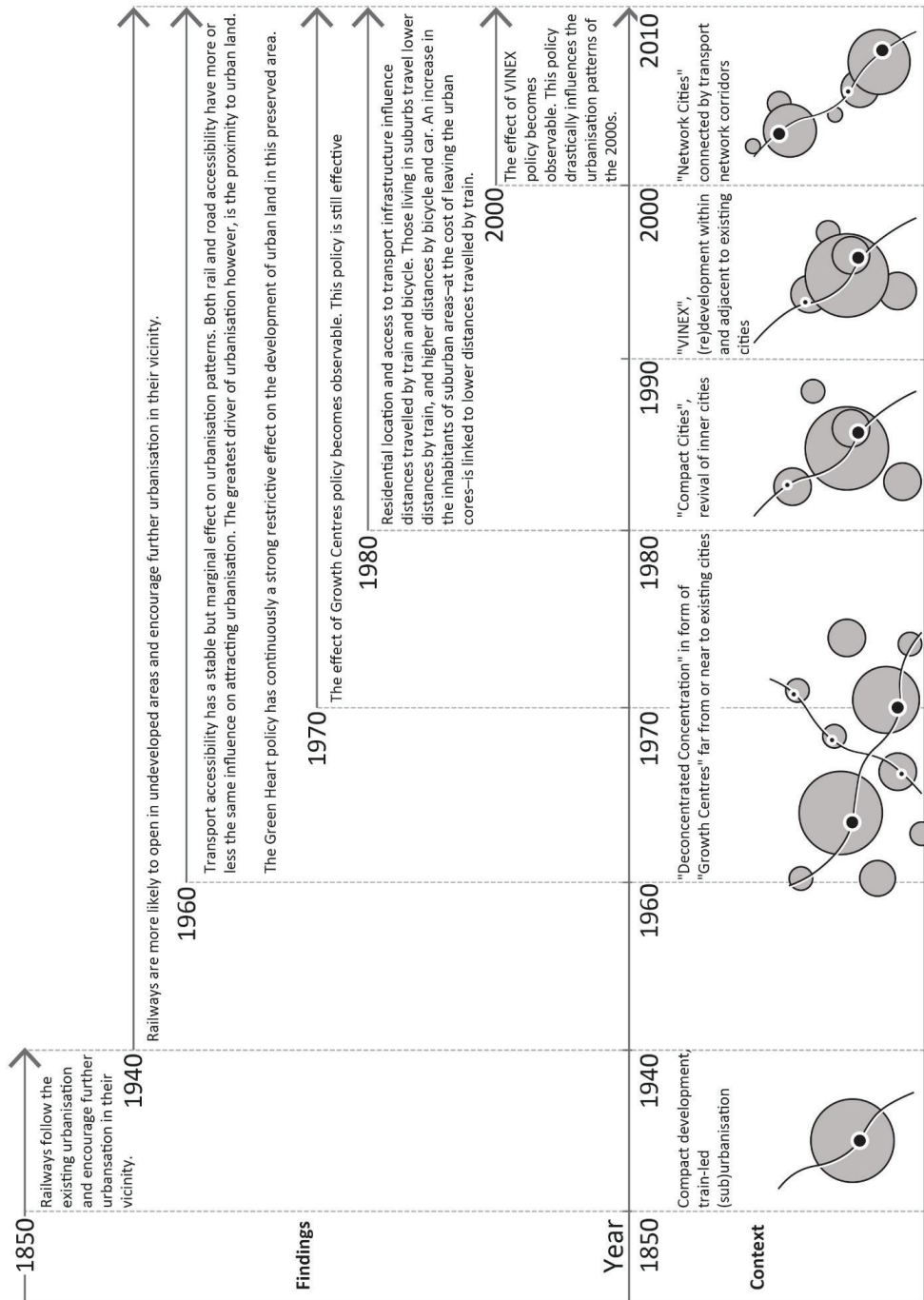
**Figure 6.3. Timeline of the key findings of the thesis and their context.**

Train and bicycle travel behaviour are more influenced by access to transport infrastructure than car. This is demonstrated by the finding that residents of areas further away from transport infrastructure networks, travel lower distances by rail and bicycle. While residential location and access to transport infrastructure influence travel behaviour, the degree of their influence has varied over time and they have a lower explanatory share than some socio-demographic characteristics such as age and income (the latter is especially influential on car travel behaviour).

## 6.3. Discussion

The outcomes of this thesis add to the ongoing worldwide debates on several topics and have various policy implications.

First, this thesis provides evidence on the structuring role of transport infrastructure on land use. Interestingly, it concludes that the extent of the impact of road and rail since 1960 on urbanisation patterns is more or less the same, which is contrary to previous literature which have for the most part consistently found a higher land use impact for road than rail (see Kasraian et al., 2016 for an overview of these studies). This result is very likely influenced by the context of the study (i.e., the Greater Randstad Area, elaborated further below). Based on this finding it seems that the recurrent concept of encouraging development at locations with good access to public transport has been successful in limiting car-led urban sprawl.

Second, this thesis shows that the impact of transport infrastructure networks on land use (measured as urbanisation) is weakening over time as transport networks, their provided accessibility and urbanised areas become saturated. This finding contributes to the discussion on the "transport land use connection" (Giuliano, 1995; Cervero and Landis, 1995; Handy, 2005) by concluding that the contemporary role of transport on urbanisation is rather marginal. The policy implication of this finding is that stimulating and guiding urban growth only by investing in transport infrastructures is unlikely to yield results in the face of network and accessibility saturation and/or in areas which lack space for growth.

Third, this thesis furthers the understanding and assessing of urban containment and densification strategies which aim to curb urban sprawl and guide urban growth by a host of measures encouraging compact, mixed-use development and the use of transit and active transport modes. Examples are the "Concentrated Deconcentration", "Growth Centres" and "Compact City" policies in the Netherlands or the "Smart Growth" approach in North America. The findings of this thesis show that policies of compact development in and adjacent to built-up areas and in combination with transport infrastructure can curb urban sprawl by redirecting growth to designated locations. As demonstrated, urban growth is attracted to areas with lower total travel times to the main centres of activity. Therefore measures to reduce the overall network travel times, and develop locations close to main activity centres are likely to have been effective in containing the urban sprawl. The findings also conclude that built-up areas attract further urbanisation. Consequently the Dutch Compact City approach which focused on the intensification *within* the existing urban areas rather than allocating new areas for development has been successful in curbing urban sprawl. Furthermore, the findings indicate that locations adjacent to the existing agglomerations with high transport access are more likely to grow. Thus, the reasoning behind the Dutch VINEX policy within the Compact City agenda as a measure to contain suburbanisation was actually valid. However, problems arose when locations without connections to the public transport were designated as VINEX and furthermore, most of these locations were urbanised as low rather than high density developments. Importantly, this thesis concludes that policies are durable, i.e., the legacy of a policy can affect development patterns decades

later regardless of the shifts in predominant spatial policies. Thus, a former policy could affect developments for decades and even its discontinuation will not guarantee the restoration of the situation to the pre-policy era.

Fourth, this thesis contributes to the long-standing debate on the influence of the so-called "built-environment" or "urban form" on travel behaviour (Ewing & Cervero, 2010; Transportation Research Board, 2009). Its findings indicate that the built environment–manifested in the residential location and access to transport infrastructure–does influence travel behaviour, especially that of train and bicycle. However, this impact is rather limited. This thesis shows that half of the Randstad inhabitants have been travelling no more than 30 kilometres a day over the past thirty years. The implication of this finding is that alternative transport modes with relatively limited range such as electric cars and bicycles are suitable for the Dutch context and especially the Randstad. Furthermore, baby boomers are shown to be travelling more, especially by train and bicycle. This necessitates an increase in train and bicycle facilities for the elderly such as cheaper train travel and safer bicycle infrastructure. Importantly, the impact of transport accessibility on travel behaviour varies per transport mode. Distances travelled by train and bicycle are more influenced by access to transport infrastructure than car. Failing to upgrade the existing rail infrastructure, especially in terms of its level of service, and improving bicycle infrastructure could entail the loss of train and bicycle users. Finally, the impact of land use, or more specifically residential location also differs per various transport modes. In short, as others have shown, residential location matters. If train travel is to increase in the suburbs and rural areas, a more integrated connection with the existing railway infrastructure, higher level of service as well as stronger disincentives for car travel are needed to help mitigate the use of car and promote train travel in these locations.

It is important to take into account the possible influence of the context of the study, i.e., the Greater Randstad Area, on the outcomes and to assess the generalisability of the findings of this thesis. The finding that the road and rail networks have had more or less the same impact on the distribution of urbanisation since 1960 could be due to several reasons:

- First, there is a dense and relatively integrated railway network in the Randstad which has existed since 1960.
- Second, the motorway network is constructed more or less parallel to the existing railway network in an effort to bundle the transport infrastructure.
- Third, the Dutch anti-sprawl policies have recurrently encouraged developments at areas with high rail accessibility.
- Fourth, this could be due to the disutility of living in car-dependent areas in a dense metropolitan region like the Randstad with its congestions and parking limitations.
- Finally, the comparable impact of the rail and road networks on urbanisation patterns is derived from the network accessibility indicator to the Big Four. While the large cities are highly accessible by both road and rail, accessibility to smaller urban areas is likely to be better by road than by rail.

Similarly, the finding on the generally limited role of transport accessibility on urbanisation patterns in the Randstad since 1960 could be due to the contextual reasons below:

- The effect of transport accessibility could have also been captured by urban proximity indicator as these two are correlated to a certain extent: areas with high network accessibility are usually highly urbanised areas where people live.

- Changes in transport accessibility were not substantial during the study period. While this period witnessed the introduction and the development of the motorway network, this network still developed more or less parallel to the Randstad's already existing dense railway network. Thus, the longitudinal effect of developments in transport networks on urbanisation patterns within the Randstad has not been as drastic as for instance when the first railways were introduced into cities where walking was the dominant mode of transport.
- This thesis focuses on the distribution of urban growth *within the Randstad*. In comparison to its peripheral regions, the Randstad experienced a much more rapid urbanisation, which could very likely be due to its dense transport network and high transport accessibility.
- The limited role of transport accessibility could be also partly related to the poly-nuclear structure of the Randstad area which consists of many medium sized and larger cities and towns. In the Randstad, unlike monocentric metropolitan regions such as London and Paris, sharp differences between urban and rural areas and high variations in the distribution of transport infrastructure and urban land do not exist.

While context is decisive, the outcomes of this thesis are relevant for and can be generalised to other regions worldwide. The general trends in the development of transport networks and urbanisation in the Randstad–such as the introduction of the railway network in the second half of the 19th century followed by train-led urbanisation, massive post WWII suburbanisation accompanied by the drastic growth of the road network, the initial focus on the development of the road network which was later changed to the public transport or both, and an array of spatial policies to curb urban sprawl–could be witnessed in many (at least western) countries. The findings of this thesis are specifically of interest to other comparable poly-nuclear areas in western countries with saturated development and transport accessibility. Examples are the Ruhr region in Germany, the urbanised part of the Flanders in northern Belgium and San Francisco Bay Area in the US. However, further work is needed to bring to light whether those regions follow the same patterns concerning urban proximity versus accessibility, road versus rail, and the role of spatial policies.

Future research could examine the impact of travel behaviour on transport infrastructure networks, (i.e., the arrow in the top right-hand side of the transport land use feedback cycle in Figure 6.1), to answer the following questions: "At what point, or passed which threshold, will the change in travel behaviour entail changes in the supply of transport infrastructure? And how fast is this process of "induced supply"?". Moreover, there is an increasing need for bidirectional studies which investigate the interaction and the leading factor between TINs and LU and how they might differ over various periods and spatial scales. Such studies will be able to address the problem of endogeneity which arises from the feedback system between TINs and LU and identify the directions of causality (the chicken or egg problem) between the two.

A fundamental question raised by this thesis which is in need of further investigation is: "Is it possible to investigate all the relationships in the transport land use feedback cycle in a single integral model?". Such a model will not only have to take into account the endogeneity between the components of the cycle, but more importantly has to be able to measure these feedback mechanisms with various response times in the long term.

This thesis examined the determinants of travel behaviour over decades. The investigation of travel behaviour determinants at a much finer scale, using GPS and/or smart card data if possible in combination with individual sociodemographic data, while going back as long as data availability allows for, will provide insight about these determinants at a more disaggregate scale. Finally, this thesis was concerned with the long-term relationships between land use, transport and travel

behaviour up to present. It is becoming increasingly critical to investigate the role of emerging technologies on these relationships. "How could the requirements for electrical mobility change land use patterns? Would the pervasive use of e-shopping and 3d printing decrease the average distances travelled and change the distribution and form of retail land uses? Could autonomous driving free up space in congested cities?". These questions could be points of departure for investigations into the future relationships between transport infrastructures, land use and travel behaviour.

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# Summary

## Introduction

The magnitude, determinants, rate and the spatial distribution of urban growth are main concerns for policy makers. Understanding the determinants of urban growth, or urbanisation, and the consequences of their impact on one another is critical information for many people, from economic geographers to spatial planners and policymakers who aim to guide and channel future urban developments. Many have argued the structuring role played by transport infrastructure, such as the railway and road networks, in shaping the cities over time. Examples are developments oriented around the railway and tramway lines after their emergence at the turn of the 20th century. Furthermore, it has been observed that transport infrastructure, land use (the location of activities) and travel behaviour (how people travel) are all interrelated. These relations are theorised among others by the so-called transport land use feedback cycle: infrastructure improvements increase accessibility, which is the ease of reaching land use over a network. A location with improved accessibility becomes more valuable for further development; conversely, land development creates further travel demand, and consequently induces the need for infrastructure improvements.

It is important to investigate the relationships between transport infrastructure networks, land use and travel behaviour because they are irreversible processes which will affect development patterns for decades to come. These interrelationships have critical consequences for the functioning and growth of cities. Comprehending and planning the development of cities is becoming increasingly important as they are expected to grow progressively and house more than half of the world's population. A population which is expected to rise more and more. More importantly, the forthcoming developments in cities will occur under conditions where the planet cannot afford to face, and will increasingly have to pay higher costs for negative economic, social and especially environmental consequences such as the rising issues with fossil fuels, greenhouse gas emissions and global warming.

The interrelationships between transport infrastructure development, land use and travel behaviour have been investigated from a variety of perspectives. Some studies have focused on the impact of transport infrastructure on land use, others the reverse, and very few on both. There is also a rich body of literature which examines the role of land use and transport infrastructure networks in determining travel behaviour. A number of these investigations are long term, but for the most part they have been carried out at a single time point or over short timespans. Developments in transport infrastructures and land use are long-term processes which demand long time periods to take place and become observable. Thus, longitudinal approaches are needed in order to truly understand how these components are related, and how the change in one is linked to the change in another. In this thesis long term is defined as at least a decade, while going back as far as data availability allows for. Long-term investigations enable the identification of effective land use and transport policies which can improve the functioning of cities, reduce unwanted environmental, economic and social impacts, and achieve sustainable urban development.

However, such long-term empirical analysis is largely missing from the existing literature. In specific, empirical investigations into the land use impact of both road and rail networks at the regional scale, and the subsequent outcome of these impacts for travel behaviour are scarce. The primary focus of this thesis is to unravel the relationships between transport infrastructure networks, land use and travel behaviour in the long term. Furthermore, it investigates these relationships empirically, at a regional level, with a spatial focus on the role of and the effect on land use, while comparing the role of both road and rail networks whenever possible.

## Research questions and study area

The central research question of this thesis is:

*What are the long-term relations between transport infrastructure networks, land use and travel behaviour at the regional level?*

This question is broken down into four sub-questions, each addressed in a separate chapter. Each chapter focuses on a specific relationship between transport infrastructure networks, land use and travel behaviour, while using the transport land use feedback cycle as the point of departure. Chapter 2 uses literature review and Chapters 3–5 apply quantitative empirical analyses as their method of investigation. The empirical analyses are performed on the study area of the Greater Randstad Area.

The Greater Randstad Area is the population and economic core of the Netherlands situated in its west and includes the four major cities of Amsterdam, The Hague, Rotterdam and Utrecht. The Randstad is a useful case study for a number of reasons. First, it is a polycentric urban region with a variety of development types. Second, the investigated study periods within the time span of 1850 to 2010 display various trends of development in transport infrastructure networks and land use which are typical for many countries worldwide. These trends include the introduction of railway networks in the second half of the 19th century and train-led urbanisation which continued into the first decades of the 20th century, the introduction of the motorway network after WWII accompanied by massive suburbanisation and finally a revival of the railway network since the 1970s which included the introduction of new types of light rail and eventually the high speed rail. Fourth, the Randstad has witnessed the application of various national transport and spatial policies to curb urban sprawl. These policies range from the Concentrated Deconcentration of urban developments and the designation of Growth Centres (implemented during the 1970s and early 1980s), the Compact City agenda (the 1980s) which was materialised as the VINEX policy (the 1990s), and finally the concept of "Network Cities"

(the 2000s). The Randstad has also witnessed a shift from car dominated transport policies of the 1960s and the 1970s to promoting "sustainable" transport and public transport in the 1990s.

The investigated sub-questions are:

a) *To what extent does the existing empirical literature provide evidence on the long-term relationship between transport infrastructure networks and land use?*

b) *In what way have land use and transport infrastructure developed over the long term in general and in relation to each other? At what time has new transport infrastructure led to new urbanisation or vice versa?*

c) *To what extent have transport accessibility, proximity to existing urban areas and spatial policies affected the spatial dynamics of urbanisation in the Randstad?*

d) *How has travel behaviour developed over the long term in the Randstad? What is the role of access to transport infrastructure and land use characteristics in its development while controlling for socio-demographic factors?*

Investigated transport modes and land use characteristics differ per chapter based on the research questions and data availability. An overview of each chapter, its scope, method and gained results are presented below.

## Chapter 2

Chapter 2 addresses the first sub-question based on the paper "Long-term impacts of transport infrastructure networks on land-use change: an international review of empirical studies", published in the journal *Transport Reviews*. This chapter provides a systematic review of empirical long-term literature from around the world, with time spans ranging from approximately a decade to a century within the period of 1831–2010. It adds to previous literature reviews on the impact of transport infrastructure networks on land use by including (i) recent empirical evidence from studies published since 1995, (ii) on both road and rail, (iii) from different parts of the world including Europe, USA and East-Asia, (iv) while focusing on long-term impacts as opposed to short-term impacts.

It concludes that proximity to the rail network is generally associated with population growth (particularly soon after the development of railway infrastructure), conversion to residential uses and the development of higher residential densities. Meanwhile, proximity to the road network is frequently associated with increases in employment densities as well as the conversion of land to a variety of urban uses including commercial and industrial development. Compared with road infrastructure, the impact of rail infrastructure is often less significant for land cover or population and employment density change. In the end, this chapter presents a scheme which can predict the likely extent of transport infrastructure networks' impact on land use, and the likely leader between the two, based on the saturation in transport networks and their provided accessibility, and land-use development.

## Chapter 3

The second group of sub-questions are addressed in Chapter 3, "Development of rail infrastructure and its impact on urbanisation in the Randstad, the Netherlands", published in the *Journal of Transport and Land Use*. This chapter provides a long-term study of the development of the railway network, its impact on urbanisation and vice versa, using the case study of the Randstad in the Netherlands, from

1850 to 2010. Its added value is quantifying these relationships at a spatial scale (a conurbation of several cities) and time period (over one and a half century) which have hardly been investigated before. Furthermore, this chapter contributes to the methodology for investigating the chicken and egg problem between transport infrastructure networks and land use with its bi-directional approach which measures the impact of railways on urbanisation *and vice versa*.

Developments in both urbanisation and the railway network are followed since the emergence of railways in the Randstad till 2010 and are explained using historical literature accompanied by descriptive graphs and maps. The total length of railway and the total number of stations are shown to have followed broadly the same trend: growing and climaxing by 1920, deteriorating between the 1930s and 1950s, stabilising in the 1960s and resuming expansion, although at a slower pace, from the 1970s to the present day. Nevertheless, station numbers experience more variation than total railway length. The growth of the railway network is demonstrated to be highly associated with urbanisation, measured by the shares of the built-up area in concentric buffers of 1 km intervals from railway stations.

To identify the direction of impact between the railway network and urbanisation, this chapter tests whether and when the opening of new railway stations has encouraged the development of urbanisation in their vicinity, or vice versa, by means of binomial logit models. Results show that during the early days stations followed existing urbanisation patterns. As time goes by however, new stations are more likely to be located in undeveloped areas rather than the established built-up areas which are already serviced by existing stations. Moreover, the more recent stations prompt further growth, increasing the likelihood of more urbanisation in their vicinity.

## Chapter 4

Chapter 4, "The impact of urban proximity, transport accessibility and policy on urban growth: a longitudinal analysis over five decades", investigates the third sub-question. This chapter examines the spatial distribution of urbanisation in the Greater Randstad Area over a period of drastic change from 1960 to 2010. The aim is to identify the magnitude of the impact of transport accessibility, urban proximity and spatial policies on the spatial distribution of urban growth, and to investigate whether and to what extent their impacts have changed over time. It applies Generalised Estimating Equations (GEE) analysis with a logit function to a longitudinal dataset of 500 m by 500 m grid cells, observed at six time points. GEE-analysis is chosen because of its capability to control for the dependence between observations and to model fractional response variables, which in this case is the proportion of urban land in a cell. Furthermore, interactions with time are included to investigate the temporal variations in the effects of urbanisation determinants.

The results indicate that transport accessibility has influenced the spatial distribution of urbanisation at a stable rate over the study period. Interestingly, the effect of rail and road accessibility on the spatial distribution of urban growth has been more or less the same. It is observed that network-based transport accessibility indicators, especially total travel time to the centres of activity provide a better explanation for the increase in the likelihood of urbanisation compared to the Euclidian distances to access points of transport infrastructure such as rail stations and motorway exits. However, the impact of existing urbanised areas in a cell's vicinity is shown to be by far a more powerful driver of urbanisation patterns than transport accessibility. This chapter concludes that overall, the proximity of existing urban areas has constantly been the most influential attractor of further urbanisation. Spatial planning and policies are shown to have played a significant role in channelling the new urbanisation and preserving green areas, contrary to many other countries such as the US. Among all

policies, the Green Heart policy has continuously had the most restrictive effect on the development of urban land in this  preserved area. On the other hand, the Growth Centres policy has had a significant impact in the 1970s and is still effective. As for the impact of the VINEX policy, it is shown to have drastically influenced the growth patterns of the 2000s.

## Chapter 5

This chapter titled "A pseudo panel analysis of daily distance travelled and its determinants in the Netherlands over three decades" addresses the final group of sub-questions. This is achieved by investigating the change in travel behaviour and its socio-demographic and location determinants, using Dutch National Travel Survey data from 1980 to 2010 among other sources, in the Randstad. The study period which covers three decades is exceptionally long for travel behaviour studies. This chapter includes bicycle travel behaviour in addition to that of train and car, regarding its important share in the Dutch travel behaviour. The measured travel behaviour characteristic is average daily distances travelled by the train, car and bicycle. Similar to the previous chapter, investigated transport infrastructure networks are the rail and road networks. The residential location of respondents is chosen as a proxy for land use characteristics.

A pseudo panel analysis is conducted to investigate the effect of various indicators on average daily distance travelled by train, car and bicycle over three decades. With the help of pseudo panel analysis, repeated cross-sectional data can be treated as a genuine panel on which longitudinal analysis can be performed. Various econometric models including pooled ordinary least squares, fixed and random effects and a hybrid model are tested to identify the best fit. The descriptive analysis indicates that average daily distance travelled rose until the mid-1990s before witnessing a decrease till 2010. Interestingly, half of the Randstad inhabitants have been travelling no more than 30 kilometres per day over the past thirty years. The results of the econometric model indicate that the main socio-demographic variable whose change over the study period results in the change of travel behaviour is age: a rise in age is increasingly related to higher train and bicycle kilometres travelled. In other words, as people grow older, they increasingly travel more by train and bicycle. This is true also for car up to 65 years. Furthermore, it is shown that an increase in the inhabitants of suburban areas–at the cost of leaving the urban cores–is associated with significantly lower distances travelled by train, but higher distances travelled by bicycle. Moreover, a rise in the *rural* inhabitants is linked to higher car kilometres.

## Conclusions

This thesis concludes that transport infrastructure networks determine land use in general, urbanisation (i.e., the conversion of undeveloped to built-up land) in specific, and travel behaviour as a consequence. Long-term relations between transport infrastructure networks, land use and travel behaviour exist. Transport infrastructure networks have changed land use and continue to do so. The railway networks played an important role in the redistribution of  population, particularly soon after their initial development in the second half of the 19th century. Conversely, the results show that land use does influence transport infrastructure. This is specifically seen in the case of initial railway stations following the existing urbanisation patterns. This trend however changes in the second half of the 20th century where new stations are more likely to be located in undeveloped areas and encourage further urbanisation in their vicinity.

Overall, the contemporary impact of railways and motorways on guiding the spatial distribution of land use (measured as urbanisation patterns) is limited, especially at times and within locations of transport

infrastructure saturation. Interestingly, the road and railway networks have had more or less the same influence on the spatial distribution of urbanisation in the Randstad. However, the greatest driver of urbanisation is the proximity to urban land. Exogenous factors such as spatial planning and policies are shown to have played a significant role in the distribution of urbanisation. in the Randstad. Here the Green Heart policy has continuously had the most negative effect on the development of urban land in this  preserved area. On the other hand, the Growth Centres policy has had a significant impact in the 1970s and is still effective. As for the impact of the VINEX policy, it is shown to have drastically influenced the growth patterns of the 2000s.

The link between transport infrastructure networks and land use with travel behaviour, becomes manifest in this thesis as the role of access to railways and motorways in combination with land use characteristics such as residential location in determining travel behaviour. Residential location plays an important role in determining individuals' travel behaviour, however its influence varies for different transport modes. Those who live in the suburbs travel longer distances by car. An increase in the inhabitants of suburban areas–at the cost of leaving the urban cores–is linked to lower distances travelled by train and higher distances travelled by bicycle. An increase in the inhabitants of rural areas is associated with higher distances travelled by car. Access to transport infrastructure influences travel behaviour, however this influence also varies per transport mode. Train and bicycle travel behaviour are more influenced by access to transport infrastructure than car, demonstrated by the finding that residents of areas further away from transport infrastructure networks, travel lower distances by rail and bicycle. While residential location and access to transport infrastructure influence travel behaviour, the degree of their influence has varied over time and they have a lower explanatory share than some socio-demographic characteristics such as age and income (the latter is especially influential on car travel behaviour).

## Discussion

The outcomes of this thesis add to the ongoing worldwide debates on several topics and have various policy implications. First, this thesis provides evidence on the structuring role of transport infrastructure on land use. Interestingly, it concludes that the extent of the impact of road and rail since 1960 on urbanisation patterns is more or less the same, which is contrary to previous literature which have for the most part consistently found a higher land use impact for road than rail. This result is very likely influenced by the context of the study (the Greater Randstad Area). Based on this finding it seems that the recurrent concept of encouraging development at locations with good access to public transport has been successful in limiting car-led urban sprawl.

Second, this thesis shows that the impact of transport infrastructure networks on land use is weakening over time as transport networks, their provided accessibility and urbanised areas become saturated. This finding contributes to the discussion on the "transport land use connection" by concluding that the contemporary role of transport on urbanisation is rather marginal. The policy implication of this finding is that stimulating and guiding urban growth only by investing in transport infrastructures is unlikely to yield results in the face of network and accessibility saturation and/or in areas which lack space for growth.

Third, this thesis furthers the understanding and assessing of urban containment and densification strategies which aim to curb urban sprawl and guide urban growth by a host of measures encouraging compact, mixed-use development and the use of transit and active transport modes. Examples are the "Concentrated Deconcentration", "Growth Centres" and "Compact City" policies in the Netherlands or the "Smart Growth" approach in North America. The findings of this thesis show that policies of

compact development in and adjacent to built-up areas and in combination with transport infrastructure can curb urban sprawl by redirecting growth to designated locations. Importantly, this thesis concludes that policies are durable, i.e., the legacy of a policy can affect development patterns decades later regardless of the shifts in predominant spatial policies. Thus, a former policy could affect developments for decades and even its discontinuation will not guarantee the restoration of the situation to the pre-policy era.

Fourth, this thesis contributes to the long-standing debate on the influence of the so-called "built-environment" or "urban form" on travel behaviour. Its findings indicate that the built environment–manifested in the residential location and access to transport infrastructure–does influence travel behaviour, especially that of train and bicycle. However, this impact is rather limited. The results show that half of the Randstad inhabitants have been travelling no more than 30 kilometres a day over the past thirty years. The implication of this finding is that alternative transport modes with relatively limited range such as electric cars and bicycles are suitable for the Dutch context and especially the Randstad. Furthermore, baby boomers are shown to be travelling more, especially by train and bicycle. This necessitates an increase in train and bicycle facilities for the elderly such as cheaper train travel and safer bicycle infrastructure. The impact of transport accessibility on travel behaviour varies per transport mode. Train and bicycle travel behaviour are more influenced by access to transport infrastructure than car. Failing to upgrade the existing rail infrastructure, especially in terms of its level of service, and improving bicycle paths could entail the loss of train and bicycle users. Finally, the impact of land use, or more specifically residential location also differs per various transport modes. In short, as others have shown, residential location matters. If train travel is to increase in the suburbs and rural areas, a more integrated connection with the existing railway infrastructure, higher level of service as well as stronger disincentives for car travel are needed to help mitigate the use of car and promote train travel in these locations.

The thesis' discussion section also elaborates on the possible influence of the context of the study (i.e., the Greater Randstad Area) on the outcomes to assess the generalisability of its findings. It concludes that while context is decisive, the outcomes of this thesis are relevant for and can be generalised to other regions worldwide. The general trends in the development of transport networks and urbanisation in the Randstad–such as the massive post WWII suburbanisation, the initial focus on the development of the road network which was later changed to the public transport or both, and an array of spatial policies to curb urban sprawl–could be witnessed in many (at least western) countries. The findings of this thesis are specifically of interest to other comparable poly-nuclear areas in western countries with saturated development and transport accessibility. Examples are the Ruhr region in Germany and the urbanised part of the Flanders in northern Belgium and San Francisco Bay Area in the US.

# Samenvatting

## Inleiding

De omvang, determinanten, snelheid en de ruimtelijke spreiding van stedelijke groei zijn van groot belang voor beleidsmakers. Het begrijpen van de determinanten van verstedelijking en de gevolgen van hun invloed op elkaar, zijn van cruciaal belang voor beleidsmakers, van economische geografen tot ruimtelijke planners, die de toekomstige stedelijke ontwikkelingen trachten te sturen. Doorgaans wordt betoogd dat de vervoersinfrastructuur, zoals de spoorweg- en wegennetwerken, een structurerende rol heeft in de vorming van steden. Voorbeelden zijn de stedelijke ontwikkelingen rondom de spoor- en tramlijnen tijdens de overgang naar de 20e eeuw. Verder is waargenomen dat transportinfrastructuur, ruimtegebruik (locatie van activiteiten) en verplaatsingsgedrag (hoe mensen reizen) met elkaar verbonden zijn. De "transport land use feedback cycle" vormt hiervoor het theoretische kader: infrastructuurinvesteringen verbeteren bereikbaarheid, locaties worden daardoor waardevoller, de behoefte aan mobiliteit neemt toe, waardoor vervolgens weer de behoefte aan infrastructuurverbeteringen toeneemt.

Onderzoek naar de relaties tussen transportnetwerken, ruimtegebruik en verplaatsingsgedrag is van belang, aangezien het onomkeerbare processen betreft die decennia lang invloed hebben op stedelijke ontwikkelingspatronen. Het belang van begrip en planning van het stedelijk gebied neemt toe omdat steden steeds sneller groeien, inmiddels meer dan de helft van de wereldbevolking huisvesten en nog verder zullen groeien. Nog belangrijker is dat deze ontwikkelingen een steeds grotere impact hebben op de aarde.

De onderlinge relaties tussen transportinfrastuctuur, ruimtegebruik en verplaatsingsgedrag zijn vanuit verschillende perspectieven onderzocht. Sommige studies hebben zich toegespitst op de impact van transportinfrastuctuur op ruimtegebruik, sommige op de omgekeerde relatie en enkele op beiden. Veel literatuur beschrijft de rol van ruimtegebruik en transportinfrastructuurnetwerken ten opzichte van verplaatsingsgedrag . Een aantal van deze onderzoeken richt zich op de lange termijn, maar de meeste bestaande onderzoeken omvatten een korte periode of één bepaald moment. De ontwikkeling

van transportnetwerken betreft langetermijnprocessen, dus moet het onderzoek ook over de lange termijn gedaan worden. Dit vraagt om een longitudinale aanpak. In de literatuur review van dit proefschrift is lange termijn gedefinieerd als tenminste één decennium, in het empirisch gedeelte zijn veel langere perioden geanalyseerd. Lange termijn-onderzoek maakt het mogelijk om effectief ruimtegebruik en transportbeleid te formuleren, teneinde het functioneren van steden te verbeteren, ongewenste effecten op milieu, economie en sociale aspecten te beperken en duurzame stedelijke ontwikkeling te bewerkstelligen.

In de bestaande literatuur ontbreken dergelijke empirische lange-termijnanalyses echter grotendeels. Empirische onderzoeken naar de specifieke invloed van ruimtegebruik van weg- en spoornetwerken op de regionale schaal en de effecten op verplaatsingsgedrag, zijn schaars. Het doel van dit proefschrift is om de relaties tussen transportinfrastructuurnetwerken, ruimtegebruik en verplaatsingsgedrag op lange termijn te ontrafelen. Daarnaast worden deze relaties empirisch onderzocht, op regionaal niveau, met een ruimtelijke focus op de rol van en het effect op het ruimtegebruik, waarbij de rol van zowel weg- als spoornetwerken waar mogelijk wordt vergeleken.

## Onderzoeksvragen en studiegebied

De centrale onderzoeksvraag van dit proefschrift is:

*Wat zijn de langetermijnrelaties tussen netwerken van transportinfrastructuur, ruimtegebruik en* verplaatsings*gedrag, op regionaal schaalniveau?*

Deze vraag is opgesplitst in vier deelvragen, die elk in een apart hoofdstuk worden behandeld. Elk hoofdstuk richt zich op een specifieke relatie tussen transportnetwerken, ruimtegebruik en verplaatsingsgedrag en gebruikt de "transport land use feedback cycle" als uitgangspunt. Hoofdstuk 2 omvat een literatuurreview en de hoofdstukken 3-5 empirische analyses over het studiegebied: de Randstad.

De Randstad is een polycentrische stedelijke zone, gelegen in het westen van Nederland en omvat de vier grote steden Amsterdam, Den Haag, Rotterdam en Utrecht. De Randstad is om een aantal redenen een nuttige casestudy. Ten eerste is het een polycentrische stedelijke regio met een verscheidenheid aan stedelijke ontwikkelingssoorten. Ten tweede, de onderzochte studieperiodes tussen 1850 en 2010 tonen verschillende ontwikkelingstrends in transportinfrastructuurnetwerken en ruimtegebruik die typerend zijn voor veel andere landen. Voorbeelden zijn de introductie van de spoorwegen in de tweede helft van de 19e eeuw, de daardoor veroorzaakte verstedelijking die in de eerste decennia van de 20ste eeuw voortgezet werd, de introductie van het snelwegennetwerk en de daaruit voortvloeiende massale verstedelijking en de uiteindelijke heropleving van het spoorwegennet sinds de jaren zeventig, waaronder de introductie van diverse light-railnetwerken en de hogesnelheidslijn. In de loop van de decennia zijn er diverse nationale transport- en ruimtelijke beleidsconcepten bedacht, ingevoerd en weer verlaten om stedelijke spreiding te beperken. Deze variëren van Gebundelde Deconcentratie van stedelijke ontwikkelingen en de aanwijzing van Groeikernen (geïmplementeerd in de jaren zeventig en begin jaren tachtig), de Compact City-agenda (jaren tachtig) die in het VINEX-beleid (jaren negentig) werd gerealiseerd en tenslotte het concept van de Netwerk Verstedelijking (jaren 2000). De Randstad is ook getuige van een verschuiving van het door de auto gedomineerde transportbeleid van de jaren 60 en 70, naar het bevorderen van duurzaam vervoer en openbaar vervoer in de jaren negentig.

De onderzochte deelvragen zijn:

a) *In hoeverre levert de bestaande empirische literatuur bewijs voor de langetermijnrelatie tussen netwerken van transportinfrastructuur en ruimtegebruik?*

b) *Op welke manier hebben ruimtegebruik en transportinfrastructuur zich op de lange termijn afzonderlijk en in relatie tot elkaar ontwikkeld? Wanneer heeft nieuwe transportinfrastructuur geleid tot nieuwe verstedelijking of omgekeerd?*

c) *In hoeverre hebben bereikbaarheid, nabijheid van bestaande stedelijke gebieden en ruimtelijk beleid de ruimtelijke dynamiek van de verstedelijking in de Randstad beïnvloed?*

d) *Hoe heeft verplaatsingsgedrag zich op lange termijn in de Randstad ontwikkeld? Wat is de rol van bereikbaarheid van transportinfrastructuur en kenmerken van ruimtegebruik bij de ontwikkeling ervan, gecontroleerd voor sociaal-demografische factoren?*

Onderzochte vervoerswijzen en kenmerken van de gebouwde omgeving verschillen per hoofdstuk op basis van de onderzoeksvragen en databeschikbaarheid. In het navolgende zijn de analyses beschreven per hoofdstuk, inclusief de reikwijdte, de methode en de verkregen resultaten.

## Hoofdstuk 2

Hoofdstuk 2 behandelt de eerste deelvraag op basis van het artikel "Long-term impacts of transport infrastructure networks on land-use change: an international review of empirical studies", gepubliceerd in Transport Reviews. Het geeft een systematische evaluatie van de wereldwijde empirische literatuur, met perioden die variëren van ongeveer een decennium tot een eeuw in de periode 1831-2010. Het draagt bij aan de eerdere literatuurstudies over de impact van transportinfrastructuurnetwerken op landgebruik door (i) recente empirische gegevens te bevatten van studies gepubliceerd sinds 1995, (ii) op zowel weg als spoor, (iii) uit verschillende delen van de wereld, waaronder Europa , De VS en Oost-Azië, (iv) terwijl zij zich richten op de effecten op de lange termijn in tegenstelling tot de effecten op korte termijn.

Het concludeert dat de nabijheid van het spoorwegnet in het algemeen verband houdt met de bevolkingsgroei (met name kort na de ontwikkeling van de spoorweginfrastructuur), de omzetting naar woningbouw en de ontwikkeling van hogere woondichtheid. Verder wordt de nabijheid van het wegennet vaak geassocieerd met toename van de werkgelegenheidsdichtheid, evenals de conversie van bestaand ruimtegebruik naar commerciële en industriële bestemmingen. Vergeleken met de weginfrastructuur is de invloed van de spoorweginfrastructuur vaak minder belangrijk voor het ruimtegebruik of de verandering van de bevolking en de werkgelegenheidsdichtheid. Uiteindelijk presenteert dit hoofdstuk een schema dat de invloed van het transportinfrastructuur netwerk op ruimtegebruik en de waarschijnlijke initiator van de twee kan voorspellen, gebaseerd op de verzadiging van de transportinfrastructuur gerelateerde bereikbaarheid en ontwikkeling van het ruimtegebruik.

## Hoofdstuk 3

De tweede groep van deelvragen wordt behandeld in hoofdstuk 3, "Development of rail infrastructure and its impact on urbanisation in the Randstad, the Netherlands", gepubliceerd in het *Journal of Transport and Land Use*. Dit hoofdstuk geeft een langetermijnstudie van de ontwikkeling van het spoorwegnet, de invloed ervan op de verstedelijking en vice versa, waarbij de Randstad tussen 1850 en 2010 als casus fungeert. De toegevoegde waarde is de kwantificatie van deze relaties op een

regionale schaal (een agglomeratie van meerdere steden). Bovendien is het onderzoek gedaan over lange termijn (meer dan anderhalve eeuw), een dermate lange periode die nauwelijks eerder is onderzocht. Ook draagt dit hoofdstuk bij aan de methodologie voor het onderzoeken van het "kip en ei" probleem tussen netwerken van transportinfrastructuur en ruimtegebruik, door middel van een tweerichtingsbenadering die zowel de impact van spoorwegen op verstedelijking meet als omgekeerd.

Ontwikkelingen in zowel de verstedelijking als het spoorwegnet worden gevolgd sinds de opkomst van spoorwegen in de Randstad tot 2010 en worden uitgelegd met behulp van historische literatuur vergezeld van beschrijvende grafieken en kaarten. De totale lengte van de spoorwegen en het totaal aantal stations blijken in grote mate dezelfde trend te hebben gevolgd: groei met een climax in 1920, afname tussen de jaren 1930 en 1950, stabilisatie in de jaren 1960 en verdere uitbreiding, alhoewel in een langere tempo, van 1970 tot hedendag. Niettemin ervaren stations meer veranderingen dan de spoorwegen zelf. De groei van het spoorwegnet blijkt sterk geassocieerd te zijn met de verstedelijking, die gemeten is door de proporties van het bebouwde gebied binnen stralen van één tot vijf kilometers rondom de stations te beschouwen.

Om de richting van de impact tussen het spoorwegnet en de verstedelijking te identificeren, toetst dit hoofdstuk waar en wanneer de opening van nieuwe treinstations de ontwikkeling van de verstedelijking in hun omgeving heeft aangemoedigd, of omgekeerd, met behulp van binomiale logitmodellen. Resultaten tonen aan dat de eerste stations de bestaande verstedelijkingspatronen volgden. Naarmate de tijd verstrijkt, zullen de nieuwe stations eerder in onontwikkelde gebieden liggen dan de gevestigde bebouwde gebieden die al door de bestaande stations worden bediend. Bovendien vergroten de nieuwe stations de kans op meer verstedelijking rondom.

## Hoofdstuk 4

Hoofdstuk 4, "The impact of urban proximity, transport accessibility and policy on urban growth: a longitudinal analysis over five decades", onderzoekt de derde deelvraag. In dit hoofdstuk wordt de verstedelijking in de Randstad onderzocht in een periode van drastische verandering van 1960 tot 2010. Het doel is om de impact van de bereikbaarheid, stedelijke nabijheid en ruimtelijk beleid op stedelijke spreiding te identificeren en om te onderzoeken in hoeverre hun impact in de loop van de tijd is veranderd. Hiertoe zijn Generalised Estimating Equations (GEE) met een logitfunctie geschat, met gebruikmaking van een longitudinale dataset met rastercellen van 500 meter bij 500 meter, gemeten voor zes decennia. GEE is gekozen vanwege de mogelijkheid om te controleren op de afhankelijkheid tussen waarnemingen en modellen van fractionele responsvariabelen, waarvan de afhankelijke variabele hier het verstedelijkte aandeel in een cel is. Bovendien worden interacties met de tijd opgenomen om de temporale variaties in de effecten van verstedelijking determinanten te onderzoeken.

Uit de resultaten blijkt dat de bereikbaarheid van het vervoer, de stedelijke spreiding in een stabiele mate heeft beïnvloed tijdens de studieperiode. Interessant genoeg is het effect van bereikbaarheid van spoor- en wegennet op de ruimtelijke spreiding van stedelijke groei ongeveer hetzelfde. Er wordt opgemerkt dat op het transportnetwerk gebaseerde bereikbaarheidsindicatoren, vooral de totale reistijd naar de activiteitencentra, een betere indicator  is voor de toename van de kans op verstedelijking in vergelijking tot de euclidische afstanden tot toegangspunten van de transportinfrastructuur, zoals treinstations en snelwegafritten. De impact van bestaande verstedelijkte gebieden in de nabijheid van een cel blijkt echter verreweg een sterkere beïnvloeder van verstedelijkingspatronen dan transportbereikbaarheid. In dit hoofdstuk wordt geconcludeerd dat in het algemeen de nabijheid van bestaande stedelijke gebieden voortdurend de meest invloedrijke

aanjager van verdere verstedelijking is geweest. Ruimtelijke ordening en beleid blijkt een belangrijke rol te spelen bij het sturen van de nieuwe verstedelijking en het behoud van groene gebieden. Het Groene hart-beleid heeft continue het meest beperkende effect gehad op de verstedelijking binnen het beschermde Groene hart gebied. Aan de andere kant heeft het beleid van de groeikernen in de jaren zeventig een significante impact gehad op de verstedelijking en is nog steeds effectief. Ook het VINEX-beleid heeft de stedelijke groeipatronen van de jaren 2000 drastisch beïnvloed.

## Hoofdstuk 5

In dit hoofdstuk, getiteld "A pseudo panel analysis of daily distance travelled and its determinants in the Netherlands over three decades", wordt de laatste groep deelvragen geanalyseerd. Dit is bereikt door de veranderingen in het verplaatsingsgedrag en zijn sociodemografische en locatie-determinanten te onderzoeken, met behulp van het Onderzoek Verplaatsingsgedrag (OVG) en de opvolgers daarvan, te weten MON en OViN, van 1980 tot 2010 in de Randstad. De studieperiode van drie decennia is uitzonderlijk lang voor studies over verplaatsingsgedrag. In dit hoofdstuk worden ook verplaatsingsgedrag per fiets naast die van trein en auto gelegd. Het gemeten verplaatsingsgedrag kenmerk is de gemiddelde dagelijkse afstand die per trein, auto en/of fiets wordt afgelegd door een reiziger. Net als bij het vorige hoofdstuk zijn onderzochte transportinfrastructuurnetwerken de spoor- en wegennetwerken. De woonplaats van de respondenten wordt gekozen als indicator voor ruimtegebruikskarakteristieken.

Er wordt een pseudo panelanalyse uitgevoerd om het effect van verschillende indicatoren op de gemiddelde dagelijkse afstand die per trein, auto en fiets over drie decennia is afgelegd te onderzoeken. Met behulp van pseudo panelanalyse kunnen meerdere doorsnedegegevens worden behandeld als een echt paneel waarop longitudinale analyse kan worden uitgevoerd. Verschillende econometrische modellen inclusief *pooled ordinary least squares*, *fixed effects*, *random effects* en *hybrid* modellen worden getest om de beste fit te vinden. De beschrijvende analyse toont aan dat de gemiddelde dagelijkse afstand is toegenomen tot het midden van de jaren negentig daarna is er een daling waarneembaar tot 2010. Interessant is dat de helft van de inwoners van Randstad de afgelopen dertig jaar niet meer dan 30 kilometer per dag heeft gereisd. De resultaten van het econometrische model geven aan dat de belangrijkste sociodemografische variabele voor verandering van het reisgedrag leeftijd is: een stijging van de leeftijd is steeds meer gerelateerd aan hogere trein- en fietskilometers. Met andere woorden, als mensen ouder worden, reizen ze steeds meer met de trein en de fiets. Deze trend zien we ook terug bij autogebruikers tot een leeftijd van 65 jaar. Verder blijkt dat een toename van de inwoners van de voorstedelijke gebieden een verband toont met aanzienlijk lagere afstanden die per trein en grotere afstanden die per fiets worden afgelegd. Bovendien is een toename van het aandeel plattelandsbewoners gekoppeld aan een hoger aandeel autokilometers.

## Conclusies

Dit proefschrift concludeert dat netwerken van transportinfrastructuur de gebouwde omgeving, en daardoor ook het verplaatsingsgedrag beïnvloeden. Langetermijnrelaties tussen transportnetwerken, ruimtegebruik en verplaatsingsgedrag blijken inderdaad te bestaan. Transportnetwerken hebben ruimtegebruik veranderd en blijven dit doen. De spoorwegen hebben een belangrijke rol gespeeld in de herverdeling van de bevolking, met name kort na hun opkomst in de tweede helft van de 19e eeuw. Omgekeerd blijkt uit de resultaten dat het ruimtegebruik de transportinfrastructuur beïnvloedt. Dit is duidelijk zichtbaar bij de eerste spoorwegstations die de bestaande verstedelijkingspatronen volgen.

Deze trend verandert echter in de tweede helft van de 20ste eeuw, waar nieuwe stations zich in relatief onontwikkelde gebieden bevinden en daar verdere verstedelijking in hun omgeving stimuleren.

In het algemeen is de huidige impact van spoorwegen en snelwegen op de spreiding van het ruimtegebruik (gemeten als verstedelijkingspatronen) beperkt, vooral binnen locaties met verzadigde transportinfrastructuur en bebouwd gebied. Interessant genoeg hebben de wegen- en spoornetwerken ongeveer dezelfde invloed gehad op de spreiding van verstedelijking in de Randstad. De grootste stimulator van verstedelijking is echter de nabijheid van stedelijk gebied. Exogene factoren zoals ruimtelijke ordening en beleid blijken een belangrijke rol te spelen in de spreiding van de verstedelijking in de Randstad. Het Groene hart-beleid heeft continue het meest beperkende effect gehad op de verstedelijking binnen het beschermde Groene hart gebied. Aan de andere kant heeft het beleid van de groeikernen in de jaren zeventig een significante impact gehad op de verstedelijking en is nog steeds effectief. Ook het VINEX-beleid heeft de stedelijke groeipatronen van de jaren 2000 drastisch beïnvloed.

Woonplaats speelt een belangrijke rol bij het bepalen van het reisgedrag van individuen, maar de invloed daarvan varieert per vervoerswijze. Degenen die in de buitenwijken wonen, reizen langere afstanden per auto. Verder blijkt dat een toename van de inwoners van de voorstedelijke gebieden een verband toont met aanzienlijk lagere afstanden die per trein en grotere afstanden die per fiets worden afgelegd. Een toename van de inwoners van plattelandsgebieden wordt geassocieerd met grotere afstanden die per auto worden afgelegd. Bereikbaarheid van transportinfrastructuur beïnvloedt verplaatsingsgedrag, maar deze invloed varieert ook weer per transportmodus. Het trein- en fietsreisgedrag wordt meer beïnvloed door de bereikbaarheid van transportinfrastructuur dan de auto, dit wordt aangetoond door de bevinding dat bewoners van gebieden verder weg van transportinfrastructuurnetwerken lagere afstanden per trein en per fiets afleggen. Terwijl de woonplaats en de bereikbaarheid van transportinfrastructuur invloed hebben op het gedrag van de reiziger, is de mate van invloed ervan door de tijd heen verschillend en hebben zij een lager verklarend aandeel dan sommige sociodemografische kenmerken zoals leeftijd en inkomen (de laatste is vooral invloedrijk op het verplaatsingsgedrag per auto).

## Discussie

De uitkomsten van dit proefschrift voegen iets toe aan meerdere wereldwijde debatten en hebben verschillende beleidsimplicaties. Ten eerste levert dit proefschrift bewijs voor de structurele rol van de transportinfrastructuur met betrekking tot ruimtegebruik. Een opvallende conclusie is dat de mate van impact van wegen en spoor sinds 1960 op verstedelijkingspatronen ongeveer gelijk is, wat in strijd is met eerdere literatuur die voornamelijk een hogere invloed op het ruimtegebruik voor de weg dan het spoor hebben gevonden. Dit resultaat is zeer waarschijnlijk beïnvloed door de studiecontext, dat wil zeggen, het is waarschijnlijk specifiek voor de Randstad. Op basis van deze bevinding lijkt het concept om ontwikkeling te stimuleren op locaties met goede bereikbaarheid van het openbaar vervoer succesvol in het beperken van de door de auto geleide verstedelijking.

Ten tweede blijkt dat de impact van de transportinfrastructuurnetwerken op het ruimtegebruik in de loop van de tijd verminderd als vervoersnetwerken, hun bereikbaarheid en verstedelijkte gebieden verzadigd raken. Deze bevinding draagt bij aan de discussie over de "transport land use connection" door te concluderen dat de hedendaagse rol van transport op verstedelijking nogal marginaal is. Beleid dat het sturen van stedelijke groei slechts door middel van investeringen in vervoersinfrastructuur probeert te bewerkstelligen zal niet het gewenste effect hebben in gebieden die geen ruimte hebben voor groei of kampen met verzadigde transportnetwerken.

Ten derde richt dit proefschrift zich op het begrijpen en beoordelen van stedelijke bundelings- en verdichtingsstrategieën, bedoeld om stedelijke spreiding te verminderen en stedelijke groei te stimuleren. Deze strategieën gebruiken verschillende maatregelen die de ontwikkeling van gemengd gebruik, het gebruik van openbaar vervoer en actieve vervoerswijzen bevorderen. Voorbeelden zijn Gebundelde Deconcentratie (Concentrated Deconcentration), Groeikernen (Growth Centers) en Compacte Stadsbeleid (Compact City) in Nederland en de "Smart Growth" benadering in Noord-Amerika. De bevindingen van dit proefschrift laten zien dat beleidsmaatregelen van compacte ontwikkeling in en naast bebouwde gebieden en in combinatie met transportinfrastructuur, stedelijke spreiding kunnen verminderen door de groei op aangewezen locaties te concentreren. Belangrijk is dat dit proefschrift concludeert dat beleidsmaatregelen duurzaam zijn, dat wil zeggen dat de nalatenschap van een beleid, ontwikkelingspatronen decennia later nog kunnen beïnvloeden, ongeacht de verschuivingen in overheersend ruimtelijk beleid.

Ten vierde draagt dit proefschrift bij aan het langdurige debat over de invloed van de gebouwde omgeving op verplaatsingsgedrag. Uit de bevindingen blijkt dat de gebouwde omgeving invloed heeft op het verplaatsingsgedrag, met name dat van treinreizigers en fietsers. Deze impact is echter vrij beperkt. Uit de resultaten blijkt dat de helft van de inwoners van de Randstad de afgelopen dertig jaar niet meer dan dertig kilometer per dag reist. De implicatie van deze bevinding is dat alternatieve vervoerswijzen met relatief beperkt bereik, zoals elektrische auto's en fietsen, geschikt zijn voor de Nederlandse context en met name de Randstad. Bovendien blijkt dat babyboomers meer reizen, vooral met de trein en de fiets. Dit vraagt om verbeteringen van de trein- en fietsfaciliteiten voor ouderen. De invloed van de bereikbaarheid van het vervoer op verplaatsingsgedrag varieert per transportmodus. Trein- en fiets- verplaatsingsgedrag is meer beïnvloed door de bereikbaarheid van transportinfrastructuur dan autoverplaatsingsgedrag. Om de toenemende gebruikersaantallen van trein en fiets te bedienen, is het van belang dat de huidige spoor- en fietsnetwerken worden opgewaardeerd. Tenslotte verschilt de impact van het ruimtegebruik per woonplaats en per vervoerswijze. Kortom, zoals anderen al hebben aangetoond, is de woonplaats van belang. Als de treinreizen in de buitenwijken en de plattelandsgebieden moeten toenemen, is er een geïntegreerde verbinding met de bestaande spoorweginfrastructuur nodig. Bovendien helpen het ophogen van treinfrequenties en het ontmoedigen van autogebruik, het treinreizen te stimuleren.

In de discussie is verder uitgeweid over de mogelijke invloed van de studiecontext–de Randstad–op de onderzoeksresultaten en de generaliseerbaarheid van de bevindingen. Het concludeert dat, hoewel de context van cruciaal belang is, de uitkomsten van dit proefschrift relevant zijn voor andere regio's wereldwijd. De algemene trends in de ontwikkeling van vervoersnetwerken en verstedelijking in de Randstad, zoals de massale post-WWII suburbanisatie, waar eerst de focus op de ontwikkeling van het wegennet lag en later deels verschoof naar het promoten van het openbaar vervoer, kunnen we in veel (tenminste westerse) landen terug zien, dit ging vaak gepaard met ruimtelijk beleid dat de verstedelijking trachtte te beperken. De bevindingen van dit proefschrift zijn van specifiek belang voor vergelijkbare polynucleaire gebieden in westerse landen, die kampen met verzadigde transportnetwerken en beperkte ruimtelijke ontwikkelingsmogelijkheden. Voorbeelden zijn het Ruhr gebied in Duitsland en het verstedelijkte deel van Vlaanderen in Noord-België en het San Francisco Bay gebied in de VS.

# About the author

Dena Kasraian was born in Tehran, Iran, 1984. She earned her MSc in Architecture, Urbanism and Building Sciences (Cum Laude) in 2010 at Faculty of Architecture & the Built Environment, Delft University of Technology, Delft, the Netherlands. She has a BSc in Architecture (2007) from the Faculty of Architecture and Urbanism, Shahid Beheshti University (SBU), Tehran, Iran and a BSc in French Literature (2009) from the Faculty of Literature and Humanities of the same university.

During her PhD study she participated in two major research projects. First, the *Interreg IVB North Sea Region Programme, E-mobility* project, where she was in charge of *Work package 3.8: Analysis of consumers' potential for electric vehicles*. Second, the *CASUAL* (Co-creating Attractive and Sustainable Urban Areas and Lifestyles – Exploring new forms of inclusive urban governance) project, funded by the Netherlands Organisation for Scientific Research (NWO) under the Urban Europe Joint Programming Initiative, which resulted in her PhD thesis. Furthermore, she was teacher assistant for BSc course *Research methods and data analysis; building and spatial development domain*, Faculty of Technology, Policy and Management, TU Delft from 2013 to 2016.

Before her PhD candidacy, she worked as a researcher at TU Delft's Department of Urbanism under the Chair of Metropolitan and Regional Design and *U-lab, Laboratory for cities and landscapes,* as well as *Rudy Uytenhaak Architectenbureau*. Her earlier professional work as an architect took place from 2005 to 2008 at *Lotus Architecture* and *Jodat & Associates Consulting Engineers*.

*Awards*

- Grant for Doctoral School Program Urban Systems and Sustainability 2014, *IDEA League* (an alliance among four leading European universities of technology including TU Delft, ETH Zürich, RWTH Aachen and Chalmers)

- UFD-Strukton Master awards 2010 – A joint award by Universiteitsfonds Delft and Strukton Co. for master theses with innovative sustainable solutions
- Best Graduation Projects 2010, *Blauwe kamer, Magazine for Landscape and Urbanism 4*, p. 60.
- HSP Huygens scholarship 2009 – Scholarship for excellent students by Dutch Ministry of Education, Culture and Science/Nuffic
- First prize for the architectural competition *Sazegan Co. head office,* 2005 (Pardis, Tehran, Iran), construction completed

*Publications*

- Kasraian, D., Maat, K., & van Wee, B. (2017). A Pseudo-panel Analysis of Daily Distance Travelled and its Determinants in the Netherlands Over Three Decades. Transportation Research Board 96th Annual Meeting, Washington DC, United States.
- Kasraian, D., Maat, K., & van Wee, B. (2016). Development of rail infrastructure and its impact on urbanisation in the Randstad, the Netherlands. *Journal of Transport and Land Use, 9*(1), 151–170, doi: 10.5198/jtlu.2015.665
- Kasraian, D., Maat, K., Stead, D., & van Wee, B. (2016). Long-term Impacts of Transport Infrastructure Networks on Land-use Change: an International Review of Empirical Studies. *Transport Reviews, 36*(1), 772–792, doi: 10.1080/01441647.2016.1168887
- Hubers, C., Maat, K., & Kasraian, D. (2015). Existing and Potential Train Users: What Difference Does the Built Environment Make? Transportation Research Board 94th Annual Meeting, Washington DC, United States.
- Maat, K., & Kasraian, D. (2014): Analysis of consumers' EV potential. Report written within the framework of Activity 3.8 of the Interreg IVB project E-Mobility NSR, Delft University of Technology.

*Languages*

- Farsi (native)
- English (fluent)
- Dutch (proficient user)
- French (proficient user)
- Arabic (basic user)

*Skills*

- Multidisciplinary research combining urban and travel-related issues
- Analysis of long-term data (longitudinal and repeated cross-sectional)
- Spatial quantitative analysis using ArcGIS and statistical packages
- Urban and architectural design and visualisation

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Sparing, D., *Reliable Timetable Design for Railways and Connecting Public Transport Services,* T2016/5, May 2016, TRAIL Thesis Series, the Netherlands

Rasouli, S, *Uncertainty in Modeling Activity-Travel Demand in Complex Urban Systems,* T2016/4, March 2016, TRAIL Thesis Series, the Netherlands

## Summary

This thesis unravels the long-term relationships between transport networks, land use and travel behaviour at a regional scale. It investigates these relationships by applying various methods to an extensive long-term geo-referenced database, in the case of the Greater Randstad Area in the Netherlands. Its findings shed light on the roles of rail and road networks, land use and spatial policies on the development of cities and the travel behaviour of their inhabitants over time.

## About the Author

Dena Kasraian has studied and worked in the fields of architecture, urbanism and urban mobility. She is interested in conducting multidisciplinary research among these fields and specifically investigating transport-land use interactions, using geographic information systems and quantitative spatial analysis.