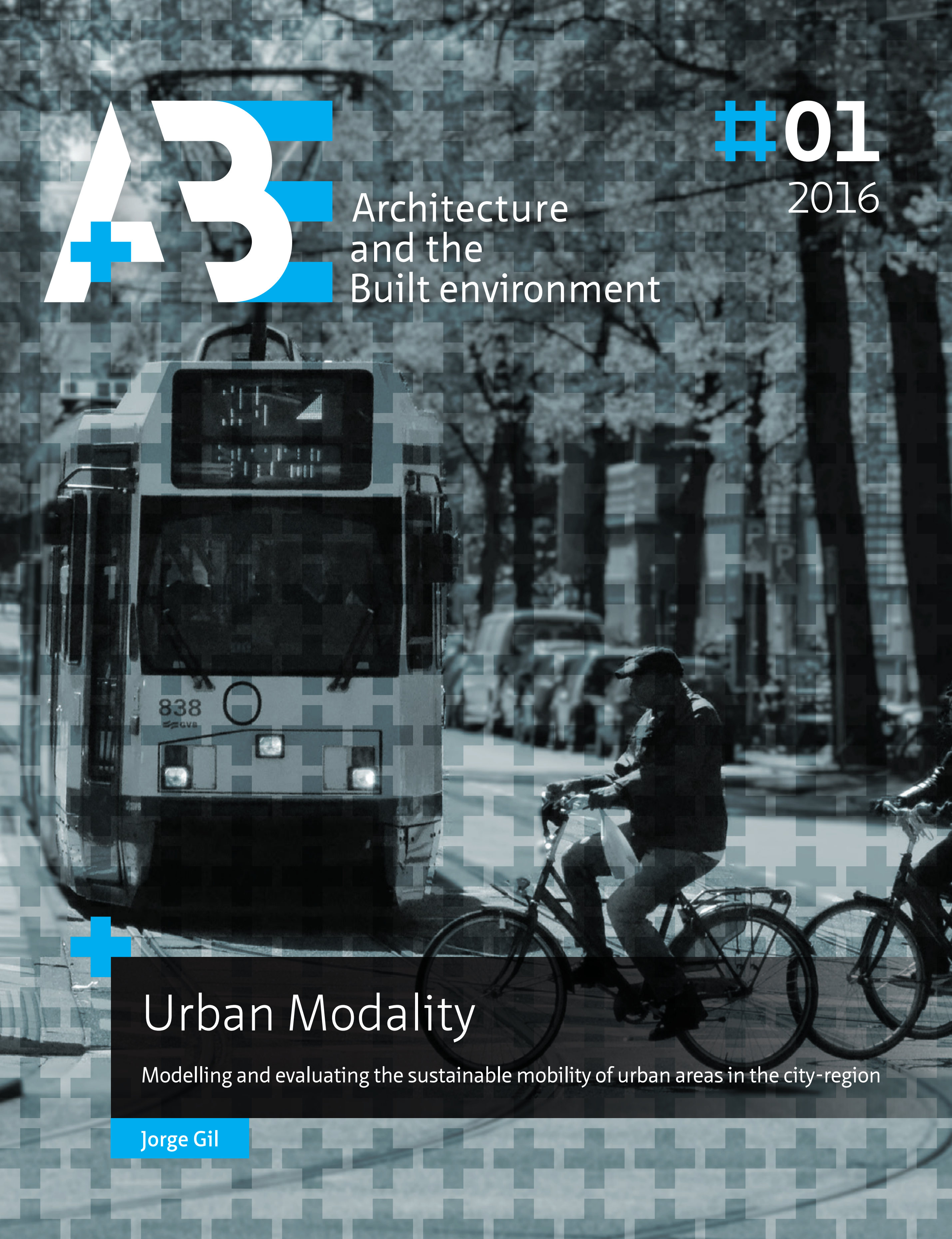


#01
2016

Architecture
and the
Built environment

Urban Modality

Modelling and evaluating the sustainable mobility of urban areas in the city-region

Jorge Gil

Urban Modality

Modelling and evaluating the sustainable mobility of urban areas in the city-region

Jorge Gil
Delft University of Technology, Faculty of Architecture and the Built Environment, Department of Urbanism

Architecture and the Built environment

abe.tudelft.nl

Design: Sirene Ontwerpers, Rotterdam

Cover: "Crossing", Floris Oosterveld (modified levels, contrast and focus)

ISBN 978-94-6186-608-0
ISSN 2212-3202

Urban Modality

Modelling and evaluating the sustainable mobility of urban areas in the city-region

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 23 februari 2016 om 15:00 uur
door Jorge Albeerto LOPES GIL
Architect, Faculdade de Arquitectura, Universidade Técnica de Lisboa, Portugal
MSc Built Environment: Virtual Environments, The Bartlett, University College London
geboren te Lisbon (Portugal)

Dit proefschrift is goedgekeurd door de

promotor: Prof. V. Nadin
copromotor: Dr. ir. S.A. Read

Samenstelling promotiecommissie bestaat uit

Prof. dr. B. Van Wee,	voorzitter
Prof. V. Nadin,	promotor
Dr. ir. S.A. Read,	copromotor

Onafhankelijke leden

Prof. dr. W.A.M. Zonneveld,	BK, TU Delft
Prof. M. Batty,	University College London
Prof. Lars Marcus,	Chalmers University of Technology
Dr. D. Stead,	OTB, TU Delft
Dr. E.J. Meijers,	OTB, TU Delft

This research was funded by the Portuguese Science and Technology Foundation (Fundação para a Ciência e Tecnologia) under the POPH/FSE and QREN programmes, with an individual research grant from 2009 to 2013 (SFRH/BD/46709/2008), and with the 'City Induction' project grant from 2007 to 2011 (PTDC/AUR/64384/2006), which is thankfully acknowledged.

Preface

When living in different cities, or different neighbourhoods within a metropolitan region, we experience locally dominant travel patterns: some places seem to be made for walking, other places can only be lived by driving or cycling, and others are dominated by public transport. London is a city of public transport, Amsterdam is a city of bicycles, and Lisbon is a city of cars for anyone living outside its centre, which is largely walkable. We might struggle to import into different neighbourhoods a preferred way of travelling in our daily routines, and it is often required that we learn and adapt to what each place has to offer. And at different stages of our lives we might choose to move to a different neighbourhood, in order to accommodate the travel needs of our changing lifestyle. Each urban environment seems to have natural modes of travel supported by its infrastructure and urban morphology, a 'modality'.

The car has been dominant in metropolitan areas for the previous decades, and urban development both at the regional and local scales has privileged its use. In many urban areas, public transport is a marginal alternative, pedestrians are at best an afterthought, and the bike is not even considered as a real (utilitarian) mode of transport. And the car infrastructure, once in place, actually hinders the use of those alternative modes of transport. Presently, personal mobility is being discussed and implemented by the built environment and transport professions in a context of sustainable development. It is accepted that it must be predominantly multimodal: combining different modes of transport for different purposes and travel distances, making greater use of soft modes and public transport, and ultimately replacing the use of the car. However, one is faced with cities and neighbourhoods shaped by a legacy of car infrastructure that organises the metropolitan regions and guides people's daily routines. And one is relying on models of sustainable neighbourhood development focused on the local walking environment, but giving limited consideration to multimodal travel in the wider context of the city-region. While public transport might be introduced locally, it is often insufficient to offer a real alternative for longer distance travel that can be successfully embraced by the general population.

The motivation behind this research has been to understand how a region is structured by its mobility infrastructures, supporting the different modes of travel, and to explore how the local neighbourhoods relate to this multimodal structure. And in doing so, to start to understand how this structure contributes to the neighbourhoods' natural modality, and promotes or constrains the success of new sustainable urban developments. Having previously worked with urban models that focus on individual transport modes (pedestrians and cars), the main aim was to develop an integrated urban model of multimodal infrastructure networks, and analyse the configuration of each mode and their integrated effect in the region. Combining such an instrument with the present spatial models of sustainable urban development, I hope to obtain a more comprehensive description and understanding of urban areas that supports interventions in existing areas, and the planning of new ones, towards viable solutions for sustainable travel patterns.

Acknowledgements

A research of this nature would have never been possible without the direct or indirect support of many people:

- My supervisors at the TU Delft Department of Urbanism, Vincent Nadin and Stephen Read, for their academic experience, sound advice, inspiration, and persistence.
- The external members of the defense committee, Bert van Wee, Mike Batty, Lars Marcus, Will Zonneveld, Dominic Stead and Evert Meijers for their availability to review and discuss this work.
- The journal editors and conference organisers, who enabled the publication and wider dissemination of this work, and all the reviewers involved, who provided important comments to improve the quality of the research.
- The 'City Induction' project team at the TU Lisbon, José Pinto Duarte, José Nuno Beirão, Nuno Montenegro and Júlio Almeida, for pushing me into this adventure, and for many stimulating discussions and work collaborations.
- My colleagues at the TU Delft, Verena Balz, Bardia Mashoodi, Dena Kasraian, Pirouz Nourian, Alex Wandl, Birgit Hausleitner, Egbert Stolk, for their companionship in sharing the struggles of PhD life, but also the enthusiasm of sharing new ideas, methods, articles and data sources. And for their hospitality on many occasions.
- My friends and fellow PhD researchers Miguel Serra (my PhD buddy), Alain Chiaradia, Stephen Law and Pete Ferguson, for sharing, reviewing and discussing our related research and ideas.
- Many other researchers whom I met personally or had contact with remotely, who gave useful feedback, asked relevant questions, made suggestions, or gave encouragement to carry on.
- The administrative staff of the TU Delft Department of Urbanism, Amber, Karin, Linda and Danielle, for ensuring the best possible hospitality over the years.
- The developers and contributors of open source software, volunteered geographic information and open data platforms. In particular, the staff at the DANS data archive (Netherlands).
- All my friends and familly, for sharing laughs, food and drink, and reminding me that there's much more to life than (PhD) work.
- My parents, Nuno and Maria Cândida, for their unconditional support and love, at every stage of my life and academic career.
- And my partner Raquel, and my daughters, Clara and Alice, for their patience, and making the desire to enjoy their company the main motivation to finish this work.

Contents

1 Based on the manuscript of: Gil, J. and Duarte, J.P. (2013). 'Tools for the evaluation of sustainable urban design: a review '. Proceedings of the ICE - Urban Design and Planning 166 (6), pp. 311–325. (Main author, 95% contribution)

2 Based on the manuscript of: Gil, J., Beirão, J.N., Montenegro, N., Duarte, J.P. (2012). 'On the discovery of urban typologies: data mining the many dimensions of urban form'. Urban Morphology 16 (1), pp.27–40. (Main author, 85% contribution)

3 Based on the manuscript of: Gil, J. (2015),'Building a multimodal urban network model using OpenStreetMap data for the analysis of sustainable accessibility'. In: Jokar Arsanjani, J., Zipf, A., Mooney, P., Helbich, M. (Eds.), OpenStreetMap in GIScience: Experiences, Research, Applications, Lecture Notes in Geoinformation and Cartography. Springer, Berlin, Heidelberg, pp. 229-251.

4 Based on the manuscript of: Gil, J. (2014). 'Analysing the configuration of multimodal urban networks '. Geographical Analysis 46, pp. 368–391

5 Based on the manuscript of: Gil, J. and Read, S. (2014).' Patterns of sustainable mobility and the structure of modality in the Randstad city-region'. A|Z ITU Journal of the Faculty of Architecture 11 (2), pp. 231-254. (Main author, 85% contribution)

Summary

This thesis proposes a framework for evaluating the mobility potential and performance of urban areas in the city region, as an instrument to support urban development that contributes positively to regional sustainable mobility objectives. The research takes a quantitative approach, modelling and measuring the characteristics of a city-region and of its individual urban areas, in terms of travel patterns and socio-economic characteristics of the resident population, and in terms of built environment characteristics. It then explores how the built environment defines the affordances of urban areas for travelling by particular modes of transport, i.e. its walk-ability, cycle-ability, drive-ability and transit-ability, by developing a typology of what I call their 'urban modality'. And finally the work combines this typology with the socio-economic characteristics of urban areas to determine their sustainable mobility potential and performance. It focuses on the case of the Randstad region of the Netherlands and its VINEX neighbourhoods, which are an emblematic example of new urban areas created under a policy programme with sustainable mobility objectives.

A key stance in this work is the understanding that the location of an urban area in the region can be indicative of its population's travel patterns, because the built environment (infrastructural) and socio-economic characteristics are interrelated and present strong regional spatial patterns. What types of urban areas support sustainable travel patterns, and what are their spatial characteristics? How do new neighbourhoods compare to the best performing urban areas, and to other areas of the same 'modality' type? These are some of the questions addressed in this study. There are two main contributions of this research: the methods for building and analysing integrated multimodal network models, and the framework for contextual performance evaluation using urban area typologies.

The integrated multimodal network model combines the various mobility infrastructure networks and the buildings' land use to create a detailed description of the region, using open spatial data and open source Geographic Information Systems (GIS) technologies. The network model's spatial analysis covers local urban form indicators, such as street layout, network density and land use mix, as well as regional indicators of multimodal accessibility and network configuration (its structure), to give a holistic profile of urban areas across modes and scales of travel.

The analysis results go through exploratory data mining and classification procedures to identify urban form typologies of urban areas. It is shown that there is a relation between this 'urban modality' of urban areas and the travel patterns of their residents, measured as a set of sustainable mobility indicators related to mode share and distance travelled. For this reason, 'urban modality' offers the possibility for ex-ante

evaluation of sustainable mobility potential of planned urban areas. Furthermore, when combined with the socio-economic profile of the resident population, 'urban modality' defines a context for the ex-post evaluation of sustainable mobility performance of existing urban areas.

The evaluation of suburban areas together with the more central historical urban areas gives invariably a high score in sustainable travel to the central areas, and rates the suburban areas negatively. On the other hand, the evaluation of sustainable mobility performance in the context of suburban areas of the same type allows the finer distinction of underperformers that have scope for improvement, and overachievers that provide examples of (relative) success. This contextual evaluation can become a decision support instrument for "hard" and "soft" planning measures involving sustainable mobility targets.

Applying this method to the set of VINEX neighbourhoods of the Randstad leads to the conclusion that despite being planned following the same policy objectives, the neighbourhoods have different types of 'urban modality', thus present different levels of sustainable mobility potential. Neighbourhoods identified as underperformers within their context can be targeted for soft measures related to transport services, technology and individual attitudes to travel, to fulfil the potential of their 'urban modality' type. However, if this potential is not deemed satisfactory or if they already overachieve, only by retrofitting a set of infrastructure and land use characteristics will lead to a different 'urban modality' type, and a change in potential. Such a change can be lengthy, costly and sometimes impossible to implement ex-post.

The thesis is based on a collection of published articles in peer-reviewed academic publications, with the first and last chapters providing an overview of the research and of its findings, and defining the main narrative thread.

Samenvatting

In dit proefschrift wordt een kader voorgesteld voor de evaluatie van het potentieel en de prestaties op het gebied van mobiliteit van stedelijke gebieden in de stadsregio. De evaluatie is bedoeld als instrument ter ondersteuning van stadsontwikkeling dat positief kan bijdragen aan regionale doelstellingen met betrekking tot duurzame mobiliteit. In het onderzoek wordt een kwantitatieve benadering gehanteerd: de kenmerken van een stadsregio en de verschillende stedelijke gebieden hierbinnen worden gemodelleerd en gemeten op basis van reispatronen en sociaaleconomische kenmerken van de bewoners, en van de kenmerken van de gebouwde omgeving. Vervolgens wordt onderzocht hoe in de gebouwde omgeving de affordantie van stedelijke gebieden voor het reizen wordt gedefinieerd door middel van specifieke vormen van transport: loopbaarheid, fietsbaarheid, rijdbaarheid en ov-baarheid. Hiervoor is een typologie ontwikkeld van wat ik de 'stedelijke modaliteit' van stedelijke gebieden noem. Ten slotte wordt deze typologie gecombineerd met de sociaaleconomische kenmerken van stedelijke gebieden om het potentieel en de prestaties van duurzame mobiliteit van de stedelijke gebieden te bepalen. Het werk richt zich in het bijzonder op de Randstad-regio en zijn Vinex-wijken: een kenmerkend voorbeeld van nieuwe stedelijke gebieden die zijn ontstaan in het kader van een beleidsprogramma met doelstellingen voor duurzame mobiliteit.

Een belangrijk uitgangspunt voor dit werk is het inzicht dat de locatie van een stedelijk gebied in de regio een indicatie kan vormen voor de reispatronen van de bevolking van het gebied, omdat de infrastructurele en sociaaleconomische kenmerken van de gebouwde omgeving met elkaar samenhangen en sterke regionale ruimtelijke patronen laten zien. Welke typen stedelijke gebieden ondersteunen duurzame reispatronen en wat zijn de ruimtelijke kenmerken van deze gebieden? Hoe presteren nieuwe wijken in vergelijking met de beste stedelijke gebieden en met andere gebieden van hetzelfde type 'modaliteit'? Dit zijn voorbeelden van vragen die in dit onderzoek worden behandeld. Het onderzoek steunt op twee belangrijke pijlers: de methoden voor het bouwen en analyseren van geïntegreerde multimodale netwerkmodellen en het kader voor contextuele prestatie-evaluatie door middel van typologieën van stedelijke gebieden.

In het geïntegreerde multimodale netwerkmodel worden de diverse infrastructurele mobiliteitsnetwerken gecombineerd met het landgebruik voor gebouwen, met als resultaat een gedetailleerde beschrijving van de regio. Hiervoor is gebruikgemaakt van vrij beschikbare ruimtelijke gegevens en open-source GIS-technologie (Geografische Informatie Systemen). In de ruimtelijke analyse van het netwerkmodel worden plaatselijke indicatoren voor stedelijke vormen behandeld, zoals stratenplan, netwerkdichtheid en gemengd landgebruik, alsmede regionale indicatoren van multimodale toegankelijkheid en netwerkconfiguratie (-structuur). Hieruit ontstaat

een holistisch profiel van stedelijke gebieden met aandacht voor de verschillende vormen en schalen van vervoer.

De analyseresultaten worden onderworpen aan verkennende datamining- en classificatieprocedures om typologieën voor stedelijke vormen van stedelijke gebieden te kunnen identificeren. Aangetoond wordt dat er een relatie bestaat tussen deze 'stedelijke modaliteit' van stedelijke gebieden en de reispatronen van de bewoners, gemeten als set indicatoren voor duurzame mobiliteit in relatie tot het aandeel van de vervoersvorm en de afgelegde afstand. Hierdoor biedt het begrip 'stedelijke modaliteit' de mogelijkheid tot een ex-ante evaluatie van het potentieel van duurzame mobiliteit van geplande stedelijke gebieden. In combinatie met het sociaaleconomische profiel van de bewonerspopulatie definieert 'stedelijke modaliteit' bovendien een context voor de ex-post evaluatie van de prestaties van duurzame mobiliteit van bestaande stedelijke gebieden.

Bij de evaluatie van voorstedelijke gebieden vergeleken met de meer historische stadskernen krijgt duurzaam reizen naar centraal gelegen stadsdelen steevast een hogere score, en worden gebieden in de voorsteden negatief beoordeeld. Anderzijds kan, door de evaluatie van de prestaties van duurzame mobiliteit in de context van stedelijke gebieden van hetzelfde type, een verfijnder onderscheid worden gemaakt als het gaat om onderpresteerders met ruimte voor verbetering en overpresteerders met voorbeelden van (relatief) succes. Deze contextuele evaluatie kan uitgroeien tot een ondersteuningsinstrument voor besluitvorming over 'harde' en 'zachte' planningsmaatregelen met doelen voor duurzame mobiliteit.

Toepassing van deze methode op de Vinex-wijken in de Randstad leidt tot de conclusie dat de wijken, hoewel ze volgens dezelfde beleidsdoelstellingen zijn gepland, verschillende typen 'stedelijke modaliteit' hebben en dus verschillende niveaus van potentieel voor duurzame mobiliteit te zien geven. Wijken die binnen hun context als onderpresteerder worden aangemerkt, kunnen in aanmerking komen voor zachte maatregelen met betrekking tot vervoersdiensten, technologie en persoonlijke attitudes ten opzichte van reizen, zodat ze het potentieel van hun type 'stedelijke modaliteit' kunnen waarmaken. Als dit potentieel echter niet bevredigend wordt geacht of als ze reeds overpresteren, kan alleen het achteraf wijzigen van een aantal kenmerken voor infrastructuur en landgebruik leiden tot een ander type 'stedelijke modaliteit' en dus ook tot een ander potentieel. Daarmee kunnen veel tijd en geld gemoeid zijn, en soms blijkt het zelfs onmogelijk om een dergelijke verandering ex post te implementeren.

Dit proefschrift is gebaseerd op een verzameling artikelen die in peer-reviewed wetenschappelijke publicaties zijn verschenen. In het eerste en het laatste hoofdstuk wordt een overzicht van het onderzoek en van de bevindingen gegeven, en wordt de belangrijkste narratieve lijn van het werk gedefinieerd.

1 Introduction

The first chapter of this thesis provides an overview of the research project, and lays out its theoretical and methodological foundations. Given that this thesis is based on a collection of articles, this is a critical chapter in establishing the thread between the subsequent chapters. The introduction starts by setting the background theme of sustainable mobility, explaining its various objectives and the role attributed to urban form in resolving some of the problems brought by the current travel patterns of persons in metropolitan areas. It follows with an overview of existing models of sustainable urban and regional development that focus on addressing the challenges of sustainable mobility. From this we reach the problem statement, which highlights the need to create models to describe and understand the multi-scale and multi-modal complexity of a city-region's infrastructure and urban form, how this relates to its population travel patterns, in order to plan better functioning city-regions. This leads to the research aims and questions, which are to create an integrated multimodal urban network model to measure the characteristics of urban areas and to evaluate how these compare and perform in light of sustainable urban mobility objectives, followed by statements on the thesis' audience, societal and scientific relevance. The next section draws together key concepts and approaches that are recurrent in the following chapters, namely contextual urban evaluation, sustainable mobility indicators, urban form and accessibility indicators and spatial network analysis, and it introduces the concept of urban modality. The section on research design and methods moves us to more concrete matters, introducing the specific case study of the present work, namely the urban areas of the Randstad city region of the Netherlands, and providing an overview of the research design and workflow, the data sources and the quantitative methods used. The present chapter concludes with an outline of the individual chapters of the thesis.

§ 1.1 Background

Urban areas and city-regions face serious sustainability problems linked to the current car based personal travel patterns, affecting the environment and the socio-economic fabric of society (Table 1). Since the 1970s, planning policy and guidance has been concerned with these problems triggered initially by the oil, energy and economic crises, and accompanied by an increasing environmental awareness (Meadows et al., 1972; ICT, 1974). This was followed by the consolidation of the triple bottom line concept of sustainability in the Brundtland report (1987) with the inclusion of social concerns. Since then, this integrated perspective is at the basis of contemporary conceptions of and proposals for sustainable development.

To address the problems of transport within a sustainable development framework, we see local, national and supra-national institutions worldwide present their visions on urban mobility in policy and guidance documents setting challenging targets (CLG, 2001; European Commission, 2007, 2011; DfT, 2009; European Council, 2010; Parliament of the State of Victoria, 2010). As an example, the European Commission's White Paper – Roadmap to a Single European Transport Area (2011) has a set of 10 goals, which includes several specifically related to the movement of persons within city-regions:

"1) Halve the use of 'conventionally fuelled' cars in urban transport by 2030; phase them out in cities by 2050;[...]
4) By 2050, complete a European high-speed rail network. [...] By 2050 the majority of medium-distance passenger transport should go by rail.[...]
8) By 2020, establish the framework for a European multimodal transport information, management and payment system."

To achieve such goals we need integrated solutions combining a series of instruments (Table 2), including changes to the mobility infrastructure and, as a consequence, to the spatial structure and form of urban environments. Academic research has in the past couple of decades focused on obtaining evidence on the influence (and its strength) of urban form on travel patterns, and despite identifying the significant importance of socio-economic dimensions and personal attitudes on the individual travel choices, it is accepted that the urban environment provides the conditions for different modes of travel. From this stream of research, 'Transit-oriented development' (TOD) has established itself as the standard normative model for sustainable mobility at the neighbourhood scale, while the concept of 'Multimodal urban regional development' offers a theoretical model to address sustainable accessibility, a key objective of sustainable transportation and mobility. The link between sustainable mobility goals and these urban models is explored in the remainder of this section.

§ 1.1.1 The goals of sustainable transportation and mobility

The current mobility trend within metropolitan regions has been for increasing number and longer trips mostly by private car with a wide range of negative impacts. Some impacts are a direct consequence of this trend, namely high levels of energy consumption, CO_2 emissions, noise, air pollution, congestion, traffic accidents, and degradation of the urban landscape with transportation specific infrastructure and the use of open space for car parking (Banister, 2005; Black, 2010; Bruun et al., 2012). Other impacts are an indirect consequence of increased car mobility, namely sprawl and the decentralisation of land use, development pressures in rural areas, disinvestment in the public transport sector and increased accessibility inequalities (Banister, 2005; Bruun et al., 2012). These indirect negative consequences have locked us in a 'vicious circle' of 'car dependency' that further contributes to all other negative impacts, as demonstrated in various studies relating sprawl and low density urban areas to high levels of car use and CO_2 emissions (Newman and Kenworthy 1999; Kenworthy and Laube, 1996, 1999; Ewing et al., 2002; Kenworthy 2008).

Sustainable transport and mobility (i.e. transport activity) has been concisely defined by the OECD (2002):

"A sustainable transportation is a transport system that provides "access to people, places, goods, and services in an environmentally responsible, socially acceptable, and economically viable manner."

And more recently, the European Council (2010) has adapted an expanded definition by the Centre for Sustainable Transportation of Canada (2002):

"A sustainable transport system [is] defined as one that:

• allows the basic access and development needs of individuals, companies and societies to be met safely and in a manner consistent with human and ecosystem health, and promotes equity within and between successive generations;
• is affordable, operates fairly and efficiently, offers choice of transport mode, and supports a competitive economy, as well as balanced regional development;
• limits emissions and waste within the planet's ability to absorb them, uses renewable resources at or below their rates of generation, and, uses non-renewable resources at or below the rates of development of renewable substitutes while minimising the impact on the use of land and the generation of noise."

The objectives of sustainable transport and mobility, as discussed by numerous authors are summarised in Table 1.1 (CST, 2002; WBCSD, 2004; Banister, 2005; European Commission et al., 2007; Black, 2010; Bruun et al., 2012), including specific objectives of each general objective.

GENERAL OBJECTIVE	SPECIFIC OBJECTIVES
Hazards reduction	Reduce CO_2 emissions Reduce air pollution Reduce land consumption Reduce urban landscape degradation Reduce noise Reduce accidents
Travel reduction	Reduce energy consumption Reduce congestion Reduce distance travelled Reduce need to travel
Modal shift	Reduce car use in urban areas Increase walking and cycling Increase share of public transport Replace medium and long distance car travel by rail
Accessibility	Maintain or increase accessibility (while reducing mobility) Narrow the accessibility divides

TABLE 1.1 Summary of the objectives of sustainable transport and mobility

The general objectives of sustainable transport and mobility are: hazards reduction, which includes environmental and personal hazards; travel reduction, which includes travel distance and frequency, but also costs of travel in energy and congestion; modal shift, which involves replacing the transport modes used for travel by others with lower impact in terms of hazards, energy and congestion; and improving accessibility. This last objective is the most complex and integrative because it includes aspects of land use and transport infrastructure (Halden, 2002; Bertolini et al., 2005, Curtis, 2011), and can directly or indirectly impact on the other objectives. Therefore, accessibility is considered to be one of the key objectives of sustainable transportation and mobility and an important indicator to consider when evaluating sustainable development.
To tackle this set of objectives we require new policies, planning and design practices for our cities (Wegener, 2007; Banister and Marshall, 2000), based on integrated solutions and policy packages that combine technological improvements at the level of infrastructure and vehicles, regulation and pricing mechanisms, information and education initiatives, and land use and infrastructure development (Priemus, 1995; Newman and Kenworthy, 1999; Banister and Marshall, 2000; Banister, 2005, 2008; Black, 2010; EEA, 2010). Examples of these measures or mechanisms are listed in Table 1.2.

GENERAL SOLUTION	SPECIFIC MEASURES
Technology	Efficient vehicles Alternative fuels Road capacity reduction Create cycling facilities Crossings with priority for pedestrians and bicycles Public transport priority lanes Increase public transport capacity and speed Park and Ride Traffic calming Telecommuting
Regulation and pricing	Road, vehicle and fuel taxes Reduce speed limits Parking charges Car pooling Area access control Increase public transport frequency Reduce public transport cost
Information and education	Provide real-time information on public transport services Travel information centres Education in schools New guidelines in driver training Employee travel schemes
Land use	Location of development Increase accessibility to jobs and services Design of the local urban environment Use of Decision Support Systems in planning

TABLE 1.2 List of possible solutions and measures to achieve sustainable transport and mobility

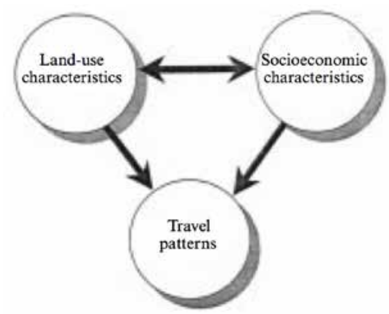
§ 1.1.2 The role of urban form

Urban planning and design provides an integrated platform to pursue important goals of sustainable mobility because changes to infrastructure and urban form are seen as effective measures to achieve goals related travel substitution, travel reduction, modal shift and accessibility. These changes might be slow to implement and to produce results when compared with fiscal, regulatory or technological measures, but they are profound and effective in the long run (Dijst 1997; Boarnet and Crane 1999; Stead, Williams, and Titheridge 2000; Banister and Marshall 2000). Furthermore, the outcomes of these infrastructure and urban form measures are long lasting and difficult or impossible to revert, due to time, cost, resources, or legal constraints (van Wee and Handy, 2014). For these reasons, these spatial factors cannot be ignored or underestimated.

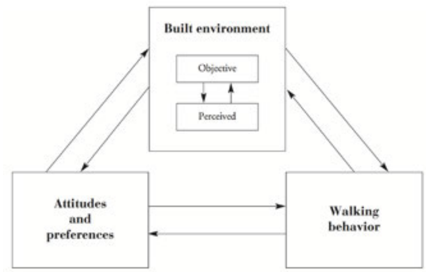
Given the perceived role of urban form in influencing sustainable mobility outcomes (i.e. travel behaviour and/or travel patterns), numerous studies have been carried out over the past two decades to explore this relation and ultimately measure the influence of urban form on travel (for example, Handy, 1992; Ewing, 1995; Cervero 1996; Cervero and Kockelman 1997; Banister et al., 1997; Moudon et al., 1997; Bagley and Mokhtarian, 1999, 2002; Stead, 2001; Bagley et al., 2002; Snellen et al., 2002; Cervero and Duncan, 2003; Boarnet and Crane, 1999; Camagni et al., 2002; Schwanen et al., 2004; Næss, 2005; van de Coevering and Schwanen, 2006; Lee and Moudon, 2006; Chen and McKnight, 2007; Kenworthy, 2008; Marshall and Garrick, 2010, 2012; Silva et al., 2014). There is equally a number of literature reviews providing essential insight into the current knowledge on the relation between urban form and travel, how the problem has been tackled thus far and the conclusions one can draw from that body of work (Cervero and Seskin, 1995; Crane, 2000; Ewing and Cervero, 2001, 2010; Stead and Marshall, 2001; van Wee 2002; van Wee and Maat, 2003; Geurs and van Wee, 2003; Handy, 2005; Cao et al., 2009; van Wee and Handy, 2014).

The main conclusion that emerges from these studies and literature reviews is that the relation between urban form or neighbourhood type and travel is present but the degree of direct influence on travel outcomes is not clear or as strong as expected (for example, Ewing, 1995). In fact, it is acknowledged by the authors that numerous other factors, in particular socio-economic, lifestyle and attitudinal factors, play a fundamental role in influencing residential location choice and in directly determining individual travel behaviour (Bagley and Moktharian, 1999, 2002; van Wee et al., 2002; Bagley et al. 2002; Schwanen and Mokhtarian, 2005; Handy, 2005, 2006; Cao et al., 2006; de Vos et al., 2014). These other factors explain in part the observed relation of travel patterns with urban form and neighbourhood type.

However, from these studies it also becomes clear that it is extremely difficult to establish simple causality between all these factors and travel outcomes (Handy, 2005), even when carrying out longitudinal studies, which are very rare in the field. This is due to the number of factors involved, the complexity of interrelations between those factors (Figure 1.1) and the dynamics of the system as a whole (Bagley et al. 2002). Indeed, urban form, socio-economic and attitudinal characteristics interact and influence each other in bi-directional relationships (Stead et al., 2000; Bagley et al., 2002; Handy et al. 2006).



1



2

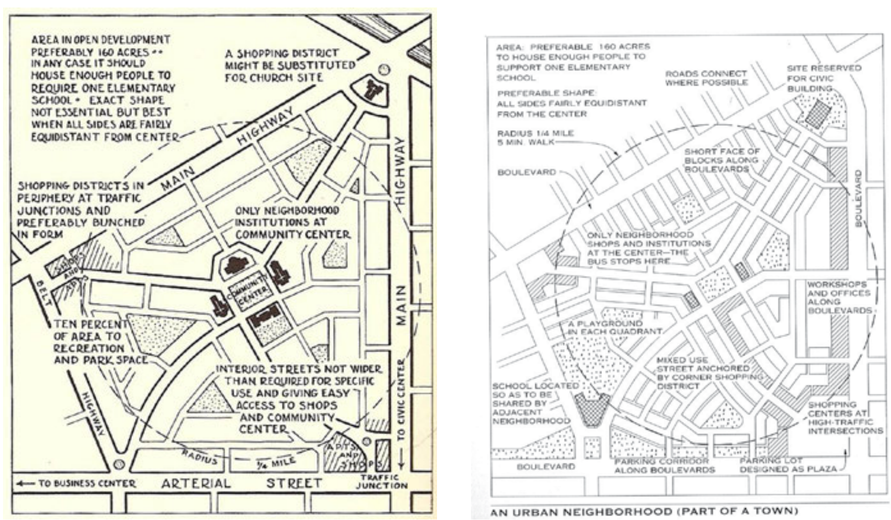
FIGURE 1.1 Conceptual models of the relationship between urban form, socio-economic characteristics and travel patterns, 1) Stead et al., 2000 and 2) Handy et al., 2006.

Despite these conclusions, there is widespread agreement that urban form (i.e. land use and the mobility infrastructure), to some degree, has an impact on travel outcomes and at least provides the infrastructural and spatial conditions to make specific travel choices (Handy, 1996) and enact a preferred (more sustainable) lifestyle (Williams et al., 2008). If we observe the spatial distribution of travel in a region (see for example Chapter 7 and the maps in Appendix E), there are clear travel patterns that correspond to specific types of urban area, however one chooses to define these. The fact that, in these studies, land use characteristics show a small effect on travel should also lead to conclusions regarding the selected urban form indicators, such as population density or distance to city centre. One should not draw the general conclusion that there is no influence of the built environment on travel, but instead seek to gain a better understanding and better description of the form and structure of urban areas and neighbourhoods.

In this respect, the provision of accessibility is seen as an important contribution of land use planning and policy to sustainable mobility, in making a range of activities accessible by more sustainable modes of transport (van Wee and Handy, 2004), even if in the short term and for certain individuals this possibility does not determine their travel choices. In this sense, one can say that the urban environment has characteristics that support or hinder the adoption of a sustainable mobility lifestyle and results in specific travel patterns. One should consider the space-time context and population characteristics of the different urban areas rather than simpler aggregate urban form characteristics (van de Coevering and Schwanen, 2006).

§ 1.1.3 From transit-oriented development to multimodal urban-regional development

Since the 1980's several urban design models have been proposed for the development of sustainable neighbourhoods and cities, such as eco-city, urban village, traditional neighbourhood development, or compact city. These are inspired by the traditional cities and 19th and early 20th century suburban development in Europe. They share some common principles related to land use, urban form and infrastructure, namely concentrated development, medium to high population density, decreasing from the centre to the periphery, mixed-use, connected pedestrian streets, and availability of public transport (Urban Task Force, 1999, 2007; Dieleman et al., 1999; Kenworthy, 2006). Their focus is primarily on walkable neighbourhood and community development, reviving and adapting the concept and principles of 'Neighbourhood Unit' by Clarence Perry (1929) (Figure 1.2.1) (Colison, 1954), translated to today's neo-traditional neighbourhood development principles, materialised in the 'New Urbanism' movement in the United States (Figure 1.2.2).



1 *2*

FIGURE 1.2 Neighbourhood unit model, 1) original, by Clarence Perry (source: New York Regional Survey, Vol 7. 1929), 2) adapted, by Duany and Plater-Zyberk

One urban neighbourhood development model originating in the US based on this strand of theory and practice is the 'Transit-oriented development' (TOD) model proposed by Peter Calthorpe (1989). This model addresses explicitly the issues of sustainable mobility through urban form by prioritising quality public transport as a means to reduce the use of the car when travelling between neighbourhoods. The public transport node takes centre stage in the TOD model, locating high density

TOC

development around it with a concentration of commercial and office space. As for the rest of the neighbourhood, one follows similar principles to those of walkable neighbourhoods, offering connected street networks with quality public spaces, and regulating car use and parking. However, TOD specifies a larger neighbourhood radius (half a mile or 800 m) in comparison with that of the 'Neighbourhood Unit' model (quarter mile or 400m), in order to accommodate the population requirements of the public transport service (Figure 1.3).

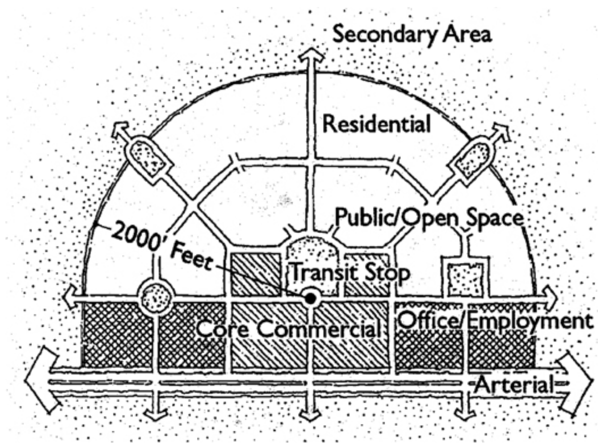


FIGURE 1.3 TOD model diagram, Calthorpe, 1989

Notably, the TOD model is not restricted to defining local neighbourhood urban design characteristics. Calthorpe (1993) developed the TOD model further to encompass the regional scale (Figure 1.4), where several neighbourhood units are distributed in the landscape and interconnected by transportation infrastructure. In this regional model there is a hierarchy of TOD's (urban TOD and neighbourhood TOD) based on the type of transportation infrastructure available to each one, and they are surrounded by a secondary urban area and nature further afield. Calthorpe consolidates the mobility infrastructure model in the concept of 'Urban Network' (2002), where a hierarchy is developed for the infrastructure networks of the car and transit modes, further differentiating the regional field that serves as context for the planning of TOD neighbourhoods, and also differentiating the types of urban development in the region (Figure 1.5).

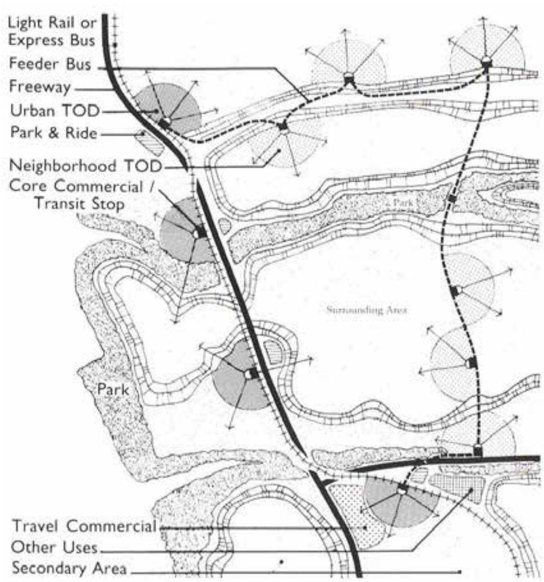


FIGURE 1.4 TOD model for the region, Calthorpe, 1993

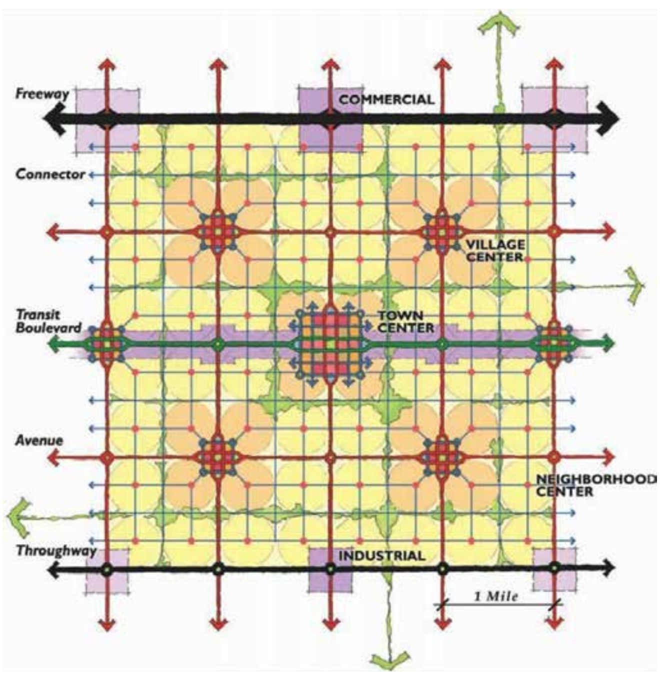
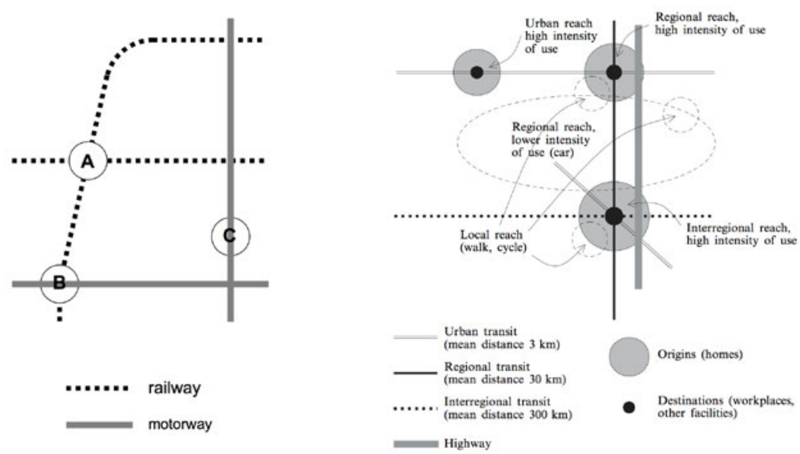


FIGURE 1.5 Urban Network model, Calthorpe, 2002

In Calthorpe and Fulton's *'The Regional City'* (2001) the focus is on the regional model for TOD, where the authors stress the importance of an integrated regional planning approach between land use and transport. Access to services and jobs is put forward as one of the key descriptors of the region that can be used to differentiate its urban environments and to plan the location and distribution of TOD neighbourhoods of various types. Furthermore, it is stressed that if this relation between land use and transport at the regional level breaks, a carefully designed walkable neighbourhood is most likely to fail to achieve its goal (Calthorpe and Fulton, 2001, p.70). The success of TOD implementations is very much dependent on the integration of the neighbourhoods in a much larger network within a city or city-region (Reconnecting America, 2011). Calthorpe's TOD model has thus progressed from a simple and well-defined normative (prescriptive) model for the neighbourhood, to a far more complex model for the region. Although the theoretical description of this model in Calthorpe and Fulton (2001) is comprehensive and structured, it is not prescribed to the same level of detail as the neighbourhood model. The regional model offers many nuances, relations and dependencies between its components that are only illustrated by examples and case studies. These complex relational dimensions seem difficult to grasp using the design guide tools and rules on offer in the prescriptive neighbourhood model.

TOD has been used by local governments, urban designers and developers as a prescriptive model for new development and urban regeneration, with many examples documented in numerous publications on sustainable urban form and reviews on TOD (Newmand and Kenworthy, 1999; Dittmar and Ohland, 2003; Cervero et al., 2004; Reconnecting America, 2007; Jacobson and Forsyth, 2008; Curtis et al. 2009; Knowles, 2012), and has been adopted in planning policy and guidance across the globe (Institute for Transportation and Development Policy, 2014). However, this is known to require the adaptation of the TOD model to accommodate differences in planning systems, geographic and cultural differences and local preferences of the population. This transfer of the TOD model to other locations has mixed success, as reported in the case of the Netherlands, with its European and national specificities (Pojani and Stead, 2014). The guidelines from the prescriptive TOD model serve mostly as inspiration and seem to be cherry-picked by different actors, not necessarily producing a coherent and consistent version for local implementation. For planning and design, one needs to move from imported prescriptive models to descriptive models that are inherently context-sensitive (Pojani and Stead, 2015).

These two limitations of the prescriptive TOD model, i.e. the dificulty in specifying the complexity of the region and the context-sensitive requirement for urban design practice, calls for the introduction of different types of operational and conceptual models for regional urban design. Other authors contribute new concepts to the design of the city-region to achieve successful and sustainable urban development (Dijst, 1997; Cervero, 1998; Frey, 1999). According to these authors, the metropolitan region should be understood as a network structure, a complex relation of multiple centres. Furthermore, these centres are part of and organised through a hierarchy of multiple infrastructure networks, supporting the activities of the local centres and neighbourhoods (Bertolini and Dijst, 2003; Hall and Pain, 2006; Read and Bruyns, 2007; Read, 2009; Read and Sulis, 2010). These conceptual models have similarities to Calthorpe's regional urban model and can be seen as an evolution of the ABC location policy in the Netherlands from the 1980's and early 90's (Dijst, 1997; Schwanen et al., 2004) to the morphological scheme by Bertolini and le Clercq (2003) (Figure 1.6).



1 2

FIGURE 1.6 Diagrams of the 1) ABC development policy of the Netherlands and 2) Multimodal urban-regional development morphological scheme (source: Bertolini and le Clercq, 2003)

However, in these more recent models, accessibility is proposed as an important tool to study the integration of land use and transport at the local as well as regional scales (Handy, 1993; Geurs and Van Wee, 2004; Bertolini et al., 2005; Silva and Pinho, 2010), that eventually can facilitate the description and evaluation of these integrated plans offering a way towards analytic and descriptive urban models. Luca Bertolini and colleagues have proposed several conceptual frameworks to describe and measure the sustainable accessibility of the urban region, as the main goal of planning for sustainable travel patterns (le Clercq and Bertolini, 2003; Bertolini et al., 2005; Cheng et al., 2007).

The 'Node place model' (Bertolini, 1999) can be used to classify urban areas in terms of their sustainable mobility potential, based on the balance between the qualities of the local environment (place) value in terms of density and diversity of activities, and the mobility (node) value in terms of quality of public transport service provision. The place and node values are calculated using custom sets of indicators, defined and selected for each specific study. Therefore, it does not prescribe what a solution should look like, but provides a framework for comparing, evaluating and planning urban areas with an awareness of the regional context.

The ‘Multimodal urban-regional development’ concept (Bertolini and le Clercq, 2003; Figure 1.7) offers a framework to classify urban areas in terms of mobility infrastructure and land use characteristics. Such a classification defines the differentiated character of the region based on the different transport modes of its environments: car, transit, walking and cycling, and different combinations of these. The term ‘mobility environments’, more commonly used for local environments of public transport interchange (Bertolini and Dijst, 2003), has also been used to refer to urban areas in the city-region, characterised by their different integration with the mobility infrastructure (Bertolini, 2006). Because the different environments have specific transport mode characteristics beyond a more general mobility potential, I will refer to this as the ‘**modality**’ of an environment (see section 1.5.5).

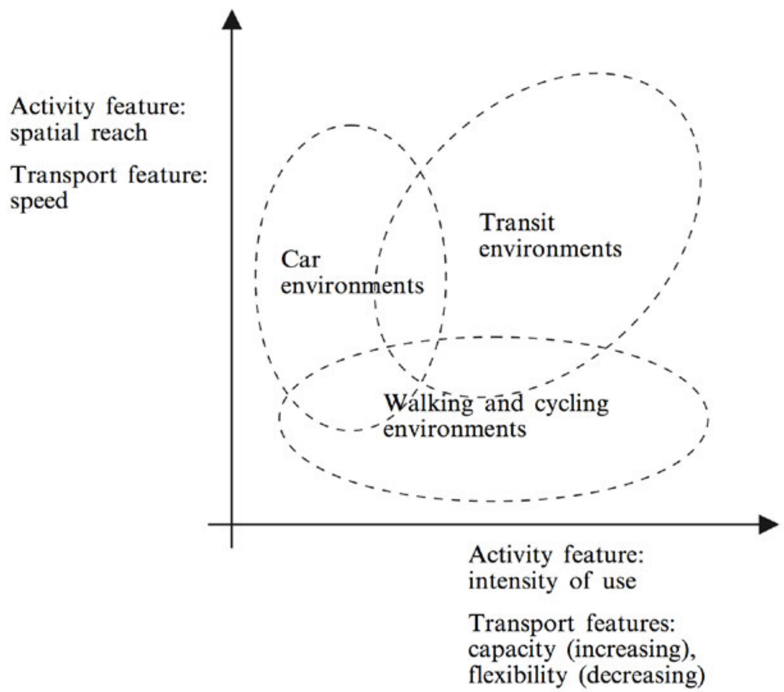


FIGURE 1.7 Diagram of the multimodal urban-regional development conceptual scheme, (source: Bertolini and le Clercq, 2003)

From the different local and regional models for sustainable mobility presented, we can extract a general understanding of the city-region that is instrumental for the remainder of this research: a city-region made up of different types of urban areas, organised and defined by the different mobility infrastructures and by their accessibility to people, activities and jobs. Furthermore the regional models highlight the importance of developing planning support tools to make the integrated and relational nature of land use and transport more tangible, with operational models that are adaptable to real cases, beyond the theoretical description and prescription of normative models.

§ 1.2 Problem Statement

To achieve the goals of sustainable mobility of people we need city-regions with an integrated and 'seamless' multimodal transport system that articulates neighbourhoods and vibrant city centres, matching the needs of the population, businesses and institutions, while reducing the distance and frequency of trips completed by private car, by shifting mobility to public transport and soft transportation modes such as walking and cycling (Banister, 2008; European Commission, 2007b). However, to create these conditions, we must operate in a framework of complexity:

- a networked, multi-scale and multi-modal environment;
- with urban form and several other factors interacting;
- establishing non-linear relations with the mobility outcomes.

To operate more effectively in this framework, urban design and planning needs to engage with the dynamics of contemporary mobility (of people, information, resources), its multi-modal and multi-speed nature (Ascher, 1995), and requires improved **models, methods and tools** for research and decision support in practice that:

- facilitate an **understanding** of the relational nature and structure of the city-region;
- represent the **modality** of its urban areas (i.e. walk-ability, cycle-ability, drive-ability, transit-ability);
- are **context sensitive** and adaptable to different regions and different locations.

This is the nature of the challenge that the present work tries to address.

The city-region must be understood as a diverse and relational whole, made up of multiple places and multiple levels in a networked rather than an areal structure (Read, 2013). To address the problem of sustainable mobility one should not focus on singular normative concepts that are locked on standards imported from different contexts (Ben-Joseph, 2004); nor on models that only address the local conditions of the environment, such as urban village or traditional urban development, ignoring the position of these places in a wider region; neither on models that define land use from simple areal measurements of the region, e.g. density and distance to city centre, ignoring the structure of the mobility networks and the richness of the local characteristics (Massey, 1991; Healey, 2006). The regional travel patterns emerge from the interactions between a range of different urban areas that form the city-region, and from the activities that happen within those urban areas, supported and organised by the multimodal infrastructure networks that operate at various scales across the region (Dupuy, 2008; Read, 2009). This multimodal urban regional development approach must integrate quantitative measures, such as accessibility, that describe the spatial structure of the regional context, with measures that describe the qualities of the local environment. The city-region is composed of a diversity of urban environments that play different roles in its functioning, and make different contributions to its mobility outcomes.

But, while acknowledging the role of the environment in providing the background conditions, these mobility outcomes are also directly influenced by a range of other factors, such as socio-economic, technological, regulatory, individual attitudes and preferences. The interdependence of these factors leads to non-linear relations between individual factors and mobility outcomes, which confound causality. Empirical evidence is essential to understand the mobility performance of neighbourhoods and regions, but the results of different cases are not immediately comparable, and the studies have been inconclusive or contradictory. A better understanding of the problem requires a context sensitive perspective where multiple methods can be applied to the same case, and the methods are systematic and flexible to be applied effectively to different cases.

Research and practice must use models, methods and tools that are able to operate in this complexity and diversity of the city-region, to support better understanding and strategic decision-making (Healey, 2006; Curtis and Scheurer, 2010; Curtis et al., 2013). Models must depart from constrained normative models and acknowledge the wider regional and geographically specific context. Methods and tools must integrate a wide range of spatial measures and indicators of urban form and accessibility, addressing multiple travel modes and purposes. Methods and tools need to evaluate the empirical evidence available and act on the existing environment, or evaluate urban design and planning alternative scenarios based on principles provided by context sensitive models.

§ 1.3 Research aim and questions

The primary aim of this research is to develop an approach to evaluating the sustainable mobility potential and performance of urban areas that takes into account the spatial context of the region, in support of strategic urban design and planning with regards to sustainable mobility objectives.

Associated with this aim are a series of secondary aims (or requirements):

- To develop an analytic multimodal urban network (MMUN) model that measures and describes the spatial structure of the city-region and its individual urban areas;
- To classify the urban areas according to their multimodal spatial structure, integrating the concept of accessibility and configuration with local urban form characteristics;
- To understand how the multimodal spatial structure relates to the travel patterns of the residents of urban areas;
- To deliver these aims in a form that is accessible and reproducible, by using open data and open source software.

§ 1.3.1 Research questions

The motivating question that this research will address is the following:

What are the types of urban areas that support or constrain sustainable travel patterns?

From travel survey data it is possible to extract the travel patterns of different locations, and from a sustainable mobility perspective assess their performance. And given a detailed description of the locations in the city-region, it is possible to identify infrastructural characteristics that consistently relate to those travel patterns. Once we characterise urban areas with better sustainable mobility performance, we should address a further question to support strategic urban design and planning:

What are the urban environment characteristics necessary to (re)produce the best preforming urban areas?

Through the course of this research, additional sub-questions are addressed to operationalize the measurement of urban modality, the evaluation of urban areas, and achieve the stated research aims:

How do we integrate the mobility infrastructure of different modes in a regional network model?

Each mode caters for a specific scale of travel, and its infrastructure is set-up accordingly. It is necessary to define a level of detail to represent each mode that is appropriate for the scale of the region, that integrates consistently with other modes, and that is feasible given data and analysis constraints.

How can we analyse this model to produce meaningful descriptions of urban modality?

Multimodal transport models are commonly used in geography and transportation for calculating individual routes or service areas, using the network as a means to get from A to B. However it is less common to calculate and describe the spatial structure of the multimodal network itself.

How can we evaluate the sustainable mobility performance of urban areas to support strategic planning?

Finding that urban areas with fundamentally different spatial and socio-economic characteristics present differentiated sustainable mobility performance might not be surprising. Identifying successful urban types and extracting their spatial characteristics (normative model) can guide the planning of new urban areas towards sustainable mobility goals. While evaluating the actual performance of existing urban areas, given their current spatial constraints, can help deal with mobility problems after the fact, i.e. when existing urban areas fail to achieve those goals.

How do VINEX neighbourhoods compare to traditional inner city areas? And to other suburban neighbourhoods?

VINEX neighbourhoods have been developed as part of national spatial planning policy containing sustainable mobility objectives, and their contribution to these goals has been questioned because the travel patterns of their residents are not necessarily more sustainable than those of other suburban neighbourhoods (see section 1.6.1.1). The most sustainable travel patterns can still be found in traditional inner city areas, but these might have unique characteristics unmatched by other areas in the region. VINEX neighbourhoods should be compared to other urban areas not only in terms of absolute travel patterns, but also in terms of socio-economic and spatial characteristics.

§ 1.4 Audience and relevance

In general, this thesis is targeted at urban design and planning researchers and practitioners with an interest in integrated land use and transport models related to sustainable mobility and sustainable urban form. In particular, it is of greater interest to those applying quantitative methods to the measurement, analysis and evaluation of urban and regional environments, especially those using spatial network models. However, it is eminently multidisciplinary, and the audience can come from a variety of research backgrounds, namely urban planning and regional development, transportation and infrastructure planning, urban design, quantitative geography and geomatics, or other fields involved in urban evaluation, urban modelling, spatial network analysis, or urban data mining. This audience should extend to practitioners involved in strategic planning, master planning, and neighbourhood design and development. All readers, whatever their background, will hopefully find useful insights, guidance and tools in the outputs and conclusions of the various chapters.

§ 1.4.1 Societal relevance

As highlighted in the background section, the current travel patterns, based on the extensive use of the private car, have negative implications in various areas of the environment, society and the economy. In recent years, the concern with sustainable mobility, the desire to increase walking and cycling not only for sustainable transportation but also personal health reasons (Southworth, 2005), and increase the use of public transport, has manifested itself in policy and planning actions at all levels of government, from the supra national to the local (e.g. cycle infrastructure development, sustainable mobility plans, European mobility week), and also in initiatives from non governmental organisations and citizen movements (e.g. Cycle to work day, Critical Mass). While this signals an awareness and willingness to change the current situation, one needs to modify the urban environment and mobility infrastructure, improve the transportation technology, as well as change the attitudes and behaviour of the population. And, in a period of economic and property development crisis, strategic planning must identify priority intervention areas to focus investment. Models and tools that support strategic planning for sustainable mobility play an important role in this (Aultman-Hall et al., 1997; Handy and Clifton, 2001; Curtis and Scheurer, 2010; Curtis, 2011; Curtis et al., 2013; Papa et al., 2013).

The proposed multimodal urban network model implemented in a Geographic Information System (GIS), and integrated with an appropriate evaluation framework, is a suitable tool for planning support in the discursive, reflexive, dialectic and participative process of strategic planning (Curtis, 2011). Such a tool can be used to understand the present conditions and to test scenarios, by creating modified versions of the present land use and infrastructure, thus obtaining new descriptions and evaluations of possible, future conditions. The proposed evaluation framework is an example of such a planning support tool, providing an understanding of the characteristics of existing urban areas in their regional context, and comparing actual performance against potential outcomes determined by this context. This contextual knowledge allows focusing on urban areas with greater untapped potential for change, and identifying the specific type of intervention required. The study demonstrates this approach with an assessment of the VINEX neighbourhoods, identifying critical intervention sites (Chapter 7).

The proposed evaluation framework is based on a system of urban form indicators, which is the format most commonly used in practice for evaluating and monitoring sustainable urban development (SUD). The study reviews existing SUD evaluation tools (Chapter 2) and produces a summary of relevant assessment criteria to be included in comprehensive SUD evaluation frameworks (Appendix A), currently being used in a human services transportation plan by senior planners of the Atlanta Regional Commission, US. Furthermore, the neighbourhood classification framework explores a wider range of possible urban form indicators, integrating those found in existing tools with others used in academic research, related to multimodal accessibility and configuration. This expands the analysis and evaluation scale to incorporate the regional context of urban areas.

GIS platforms are becoming more accessible and user friendly, are being widely adopted by local governments to support planning and decision making, and their use is becoming fundamental to comply with data management and sharing standards, such as the EU INSPIRE directive. The GIS model and methods developed in this thesis use open data, volunteered geographic information and open source software that are accessible to all. This makes the work more easily reproducible but also adaptable to other geographic locations, without high financial and technical demands. It also demonstrates the application and value to planning of such data and software tools, encouraging their use and leading to their further development and growth.

§ 1.4.2 Scientific relevance

This thesis develops a multimodal urban network model that is an example of integrated urban model to support the strategic planning of urban areas and regions (Wadell, 2002). This integrated network model brings together concepts and techniques from different research communities to provide an extended and detailed description of the built environment, that reveals the spatial structure of the multimodal city-region.

On the one hand, the research expands the concept of 'sustainable accessibility' (Bertolini et al., 2005; Cheng et al., 2007) that measures accessibility to quantify the regional spatial characteristics of a location with regards to opportunities reachable by different modes. This research measures the network configuration to quantify the regional structure of the multimodal infrastructure. This is an intrinsic accessibility characteristic of the network independent of the location of activities or the individual behaviour of travellers, thus can support the planning of multimodal infrastructure and the regional strategic planning of urban areas (Scheurer and Curtis, 2008). On the other hand, the research expands previous research on the configuration of urban street networks (Hillier and Hanson, 1998; Hillier, 1996; Porta and Latora, 2007; Figueiredo, 2009; Sevtsuk, 2010; Chiaradia et al. 2012). It integrates the multimodal mobility infrastructure in the network model, differentiating various private and public transport modes, which is an important requirement for meeting the objectives of sustainable mobility. Furthermore, the model developed supports analysis using different concepts of distance in the same network, which enables the comparison of different approaches of network analysis but also the selection of the most appropriate ones for a given mode.

The present research contributes to the studies on sustainable mobility and accessibility, developing a typology of 'modality' of urban areas: the built environment characteristics that support specific modes of travel. Many studies on urban form and travel distinguish neighbourhood types, such as 'historic', 'traditional', 'neo-traditional', or 'suburban' (Handy, 1992; Frey et al., 2006), or differentiate them in terms of the prevalent transport mode, such as 'pedestrian versus automobile' or 'transit versus automobile' neighbourhoods (Cervero and Radisch 1996; Cervero and Gorham 1995; Handy et al. 2005). These types are important to synthesise the distinct character of urban neighbourhoods, but are often subjective classifications based on pre-conceived ideas from normative urban design models (see Section 1.1.2) and difficult to apply systematically by others in different studies. However, statistical classification methods can extract objective neighbourhood classifications (Bagley et al., 2002; Cutsinger and Galster, 2006; Song and Knaap, 2007; Behnisch and Ultsch, 2009; Serra et al., 2013; Kamruzzaman et al., 2014; Jaques and El-Geneidy, 2014), and the clustering approach used in this study builds on this work to define 'urban modality' types. This typology can be used to understand and evaluate the mobility performance of urban areas in a contextual and multi-level approach, aggregating local areas at the regional level using types that are meaningful, rather than using political or geographic boundaries (van den Berg et al. 1998; Snellen et al., 2002; Bulkeley and Betsill, 2005; Geurs and van Wee, 2006).

Finally, the work on the evaluation framework, review of SUD tools, and implementation of sustainable urban form indicators in GIS gave a direct contribution to the urban evaluation module of the 'City Induction' research project (Duarte et al., 2012; Gil and Duarte, 2008; Gil et al., 2010, 2011).

§ 1.5 Approach and key concepts

In order to meet the targets of the sustainable mobility of people, planning practice can benefit from the use of planning and decision support instruments. These instruments can guide the planning process and assess its outcomes, thus being useful ex-ante, in evaluating alternative scenarios and plans, and ex-post, in monitoring the performance of plans and allowing the adjustment of current policy or the implementation of new one (Alexander, 2006; Hunt et al., 2008; Oliveira and Pinho, 2010). Several instruments have been developed over the years to support the development of sustainable urban neighbourhoods, including rating systems based on systems of indicators (e.g. LEED for Neighbourhood Development, BREEAM Communities, SPeAR by Arup, DPL by IVAM), and guidance documents (e.g. Shaping Neighbourhoods by Barton et al., 2003, 2010). A review of these instruments is given in Chapter 2.

These planning and decision support instruments are, to different degrees, comprehensive in covering sustainability issues. Most have a significant focus on urban form characteristics and local accessibility, given its perceived impact on travel patterns (see Section 1.1.2) and given the travel pattern's environmental, economic and social impacts. They are, however, largely restricted to the local evaluation of the neighbourhood, isolated from its urban and regional context, except for the occasional indicator related to the site's immediate vicinity and its location in an existing urban area. In this thesis I will attempt to overcome this limitation in evaluating the sustainable mobility performance of urban areas by looking at mobility from a multimodal and multi-scale perspective and taking an approach of contextual evaluation.

§ 1.5.1 Evaluation framework

The proposed evaluation approach is to extend the geographic boundaries of the analysis of urban areas and consider their strategic position in the region, integrating the local urban form and accessibility characteristics with the regional scale structure and accessibility (see Section 1.1.3). This approach uses an comprehensive description of urban form, which includes a collection of spatial indicators of accessibility and configuration, to quantitatively and systematically describe the multimodal infrastructure and multi-scale characteristics of urban areas that cater for the different modes of travel, i.e. walking, cycling, car and public transport modes. This quantitative analysis of the region situates the urban areas in their regional context and results in a synthesis of 'urban modality' of urban areas, i.e. how urban areas support specific modes of travel. The evaluation framework then uses empirical data on the travel patterns of urban areas to assess performance outcomes (ex-post) and to define potential outcomes (ex-ante) of the different urban modality types.

The evaluation framework is context-sensitive, in that the sustainable mobility potential is defined and performance is assessed in the context of the specific socio-economic and spatial characteristics of the existing urban areas in the region, using empirical data (see Chapter 7). This presents two advantages: first, evaluation is not based on criteria and target values imported from other geographic and planning contexts; second, evaluation is not based on local/global myths of successful urban development as all urban areas are evaluated. The sustainable mobility performance of an urban area is evaluated against other areas of identical characteristics, for a robust assessment method of achievement. An urban area with good potential for walking might seem to be doing well if compared to others with low potential, but actually underperform when compared with those of a similar potential. Likewise, an urban area might seem problematic in terms of public transport usage when compared with the sustainable mobility of regional transit hubs, but come out as a success case in the context of urban areas of similar kind. With this contextual approach, the selected assessment objectives, criteria, indicators and the overall evaluation method are of general applicability to other urban regions. The key concepts of this evaluation framework related to the different indicators and the analysis model are explained next.

§ 1.5.2 Sustainable mobility indicators

Several studies have compiled lists of sustainable mobility and transport indicators (Gilbert and Tanguay, 2000; Banister and Marshall, 2000; European Commission, 2001; Gilbert et al., 2002; Schreffler, 2002; Litman, 2007; Costa, 2008; Renne, 2009; EEA 2010, 2011). Most of these sets of indicators are comprehensive, addressing all modes of transport and covering the various objectives listed in Table 1, with the exception of the European Environmental Agency (EEA) indicators that focus entirely on the 'Hazards reduction' objective. The various sets of indicators can be used to assess actual performance and applied in objectives based evaluation frameworks, i.e. measuring the progress towards or away from predefined sustainability goals.

To assess the sustainable mobility of an urban area or region one can select a relevant set of indicators from this long list of possible indicators. In this thesis, the indicators are used to assess the sustainable mobility of residents of urban areas, and not the sustainability of the transportation system as a whole. As such, the selection (Table 1.3) is focused on the travel reduction and modal shift objectives of Table 1, because these indirectly impact on the hazards reduction objective, and are to some extent directly affected by urban form and land use. Urban form and accessibility indicators are addressed separately in the next section (1.5.3).

The selected assessment criteria (Table 1.3) reflect the multimodal nature of the sustainable mobility objectives, and the multi-scale nature of the mobility of persons in the city-region. Each assessment criterion is composed of a combination of different indicators or measurements to address separately non-motorised (walking and cycling) and motorised (car and public transport) modes of travel, as well as neighbourhood, city and regional travel. The evaluation is obtained by assessing if the indicators' results move in the desired direction of sustainability, in relation to predefined objectives (a specific value or change) or to the baseline values of the regional context.

OBJECTIVES	CRITERIA	INDICATORS	SUSTAINABILITY DIRECTION
Modal shift	Non-motorised share	Neighbourhood walking share Neighbourhood cycling share City cycling share	Increase
	Car share	Neighbourhood car share City car share Regional car share	Decrease
	Public transport share	Neighbourhood transit share City transit share Regional transit share	Increase
Travel reduction	Distance travelled	Overall total distance Non-motorised distance share Car distance share Public transport distance share	Decrease Increase Decrease Increase
	Travel duration	Overall total duration Non-motorised duration share Car duration share Public transport duration share	Decrease Increase Decrease Increase
	Travel frequency	Overall number of trips per day	Decrease

TABLE 1.3 Selected sustainable mobility indicators related, to travel reduction and modal shift.

The sustainable mobility indicators are outcome indicators, and as such are more useful for ex-post evaluation of an urban area's performance. In order to measure these indicators, one requires empirical data on the travel activity of the population of the city-region (see section 1.6.2). The focus is here on studying the aggregate travel patterns of the residents of different urban areas, as opposed to the travel behaviour of individuals. The aggregate patterns are more naturally related to the urban form and accessibility of urban areas, while individual behaviour is more susceptible to reflect specific lifestyle, attitudes and preferences. For this reason, the indicators include all typical daily travel purposes, such as work, education, shopping, leisure, as the aim is to evaluate the mobility outcomes of the daily life of all individuals and not specific groups. These sustainable mobility indicators are dependent variables of the present study, used in Chapters 6 and 7.

§ 1.5.3 Urban form and accessibility indicators

Urban form and accessibility indicators are useful in the evaluation of the sustainable mobility of urban areas, since these characteristics of the built environment are perceived to directly or indirectly influence travel patterns. These are *service quality indicators* of how the built environment and the mobility infrastructure supports specific modes of travel. Hence, these indicators can be measured to determine an urban area's potential for sustainable mobility, informing the ex-ante evaluation of plans, i.e. what type of travel outcomes can be expected from alternative options, or supporting the ex-post evaluation of mobility performance (sustainable mobility indicators), i.e. to what extent the outcomes meet the potential and the targets.

Sustainable urban form should be seen from a holistic perspective encompassing multiple dimensions (Dempsey et al. 2008), namely: the urban street layout and network connectivity; the presence and quality of mobility infrastructure; the density of construction, people and activities; the spatial distribution and variety of land use; and building quality. Existing literature offers a range of urban form indicators encompassing all these dimensions.

In the land use and travel literature covered in Section 1.1.2 the built environment is often described using aggregate statistics of administrative areas, such as population density or size, number of workers or jobs, or the distance to the nearest urban centre. These give a general spatial description of land use at the metropolitan level but do not capture the characteristics of the mobility infrastructure, nor the characteristics that locally differentiate the neighbourhoods. It is in these studies that the influence of urban form on travel outcomes is weaker. Therefore one can conclude that this spatial description is not adequate and does not capture the essence of regional and local urban form and structure in a way that is relevant to travel, or at least that it must be complemented with further indicators.

Several studies describe the built environment using indicators based on the principles of sustainable neighbourhoods summarised in the 3Ds (Cervero and Kockelman, 1997), i.e. Density, Diversity, and street Design. These principles have more recently

TOC

been expanded to 5Ds (Ewing and Cervero, 2010) to include Destination accessibility and Distance to transit, and even 7Ds to include Demand management (e.g. parking restrictions) and Demographics. Such studies have had a great influence on existing instruments for SUD evaluation, which provide comprehensive lists of urban form indicators largely based on the above principles (see Appendix A for a summary of assessment criteria). From the more general assessment criteria one can develop a set of urban form indicators that is directly relevant to the assessment of sustainable mobility objectives. However, such a set of urban form indicators only covers the neighbourhood's local characteristics. Furthermore, it lacks a multi-scale and relational dimension: indicators of how the neighbourhoods relate to each other in the city-region, and how the mobility infrastructure networks differentiate the character of neighbourhoods across the region. These shortcomings need to be addressed by an expanded set of urban form indicators.

The approach in this thesis is to use GIS to describe and quantify the city-region at a disaggregate level, using significant urban elements such as streets, individual buildings and public transport infrastructure, in order to characterise its urban areas as well as the regional spatial structure. The research adopts a holistic perspective, selecting urban form indicators that cover different dimensions of sustainable urban form and sustainable neighbourhood development, and adds to those accessibility and configuration indicators, capable of describing the structure of the region.

Accessibility measures the relative importance of a location based on the distance to other locations on the network and to opportunities associated with activities in those locations (Hansen, 1959; Ingram, 1971; Dijst et al., 2002; Batty, 2009). It is an integrated urban form indicator, where the street layout, the transportation infrastructure, the population and land use location interact. It is also a multi-scale indicator, because it is measured from a location up to a desired distance, instead of measuring within a predefined spatial boundary. For these reasons it is seen as an important instrument to integrate land use and transport plans, and is used as an indicator to evaluate planning scenarios and policy measures (Handy, 1993; Kolars and Malin, 1970; Handy and Niemeier, 1997; Dijst et al., 2002; Le Clercq and Bertolini, 2003; Geurs and van Wee, 2004; Cheng et al., 2007; Anderson et al., 2011). Accessibility can be used to build a profile of an entire city-region (Silva and Pinho, 2010), or can be measured from every location or individual building, to characterise the urban areas in a region, which is the approach taken in this work.

While accessibility measures the activities or opportunities available through the infrastructure networks, it does not characterise these networks directly (Batty, 2009). The measures of configuration represent the structure and hierarchy of the multimodal networks, that differentiate urban areas and cities through classification (Crucitti et al., 2006b) or in the way the networks are organised (Read and Bruyns, 2007). This configuration can also be an indicator of attraction and flow potential of elements of the network, e.g. junctions, street segments or rail stations (Hillier et al., 1993; Penn et al. 1998; Schwander, 2007). For these reasons, configuration indicators have been used in the study of sustainable urban development and sustainable mobility (Scheurer and Porta, 2006; Porta and Latora 2007; Scheurer and Curtis, 2008; Chiaradia et al., 2012; Gil and Read 2012).

To characterise urban areas for the evaluation of their sustainable mobility potential and performance, taking into account the local built environment and also their location in the context of the city-region, the present work uses a set of urban form assessment criteria organised in four groups: proximity, density, accessibility and configuration. These assessement criteria are exemplified in Table 1.4, and the urban form indicators used to calculate them are defined in Chapter 6. All urban form indicators are calculated along the mobility networks, and are adjusted for the different mobility modes (walking, cycling, car, rail, tram and bus) because each mode uses different infrastructure elements and has different reach.

THEME	FOCUS	ASSESSMENT CRITERIA (EXAMPLES)
Proximity	Infrastructure	Distance to nearest rail station Distance to nearest cycle lane Distance to nearest motorway
Density	Infrastructure	Street network connectivity Rail station provision Pedestrian network reach
	Land Use	Shops within walking distance Jobs within walking distance
Accessibility	Land Use	Jobs accessible by public transport Jobs accessible by car
Configuration	Infrastructure	Network centrality of rail stations Network hierarchy of local cycle network

TABLE 1.4 Summary table of the urban form assessment criteria.

§ 1.5.4 Spatial network analysis

A spatial network model based on standard geographic data sets and implemented in a GIS platform has been shown to provide ways to calculate the urban form indicators necessary for the assessment criteria presented in Table 1.4. Such a model can be sufficiently high resolution in spatial terms, using small and disaggregate spatial units (i.e. street segments, transit stops, individual buildings), while at the same time covering an entire city-region (Chiaradia et al., 2008), thanks to data availability and the capabilities of today's GIS platforms. Furthermore, it can have a multi-layered structure, integrating the road network, the public transport networks, and the land use activities (van Nes, 2002; Sevtsuk, 2010). Finally, it has an inherent relational (topological) nature that integrates the local elements together forming a structural description of the wider city-region. This relational nature is what allows the measurement of connectivity between elements and distances along the network, as a basis for calculating the various urban form indicators. For a comprehensive overview of spatial networks and their analysis, the review by Barthelemy (2010) provides a good starting point. The spatial network model implemented in this study is described in detail in Chapter 4. It is a descriptive (analytic) model for quantitative measurement, instead of a predictive model for simulation of individual behaviour and dynamic phenomena. It adopts an integrative analysis approach, using a range of different algorithms to measure the required urban form indicators, and a range of different notions of distance to accommodate the different scales and transportation modes. These different approaches are described next.

In order to analyse the spatial network model, the geographic representation of the network layers is translated into a mathematical graph, on which a variety of algorithms can be used to obtain different measures. The graph representation of networks is widely used in geography and transportation to solve routing and distance related problems, namely calculate the shortest, fastest or least-costly path, the distance matrix between a set of locations, the nearest feature to a given location, the service area of a location within a given distance or time constraint, or the travelling salesman problem, defining the most efficient route to visit a set of locations. The simpler shortest route and service area algorithms are useful to calculate node, density and accessibility measures to understand urban networks (Cheng et al., 2013) and obtain urban form and accessibility indicators such as those in Table 1.4.

The graph representation can also be used to describe the structure of the network, the hierarchy of its elements, or identify communities of elements (Newman, 2010). This type of analysis is more common in fields such as the social sciences, biology, engineering and physics, but has also been used to measure the structure of transportation networks back in the 1960s (Garrison, 1960; Garrison and Marble, 1962; Kansky, 1963; Hargett and Chorley, 1969). In particular, network centrality measures (Freeman, 1978), which calculate the mean distance of shortest routes from a location (closeness) and the frequency of shortest routes through a location (betweenness), have been applied in urban studies to measure the structure and configuration of street networks (Hillier and Hanson 1984; Hillier, 1996; Jiang and Claramunt, 2004; Porta et al., 2006a, 2006b; Xie and Levinson, 2007; Wagner, 2008; Figueiredo, 2009; Sevtsuk, 2010; Chiaradia et al., 2012) and public transport networks (Scheurer et al., 2007; Schwander, 2007; Erath et al., 2009).

In all these algorithms, an important parameter is the weight, translated into the notion of distance or impedance of the network's links. The conventional impedance value corresponds to metric or time distance, and can have associated an additional cost, e.g. financial. This impedance is equally applicable to multimodal transportation networks (Friedrich, 1998; Mouncif et al., 2006). However, different topological and geometric distances are also used in urban network analysis, and shown to be particularly relevant to measure structure and configuration in relation to movement and activity of people (Hillier and Iida, 2005; Peponis, Bafna, and Zhang, 2008). There are some examples of this type of distance applied to the study of multimodal networks (Chiaradia et al., 2005; Scheurer and Curtis, 2008; Gil, 2012; Gil and Read 2012; Law et al., 2012). The present work takes, also in this respect, a comprehensive approach and builds the network model in such a way that any of the aforementioned types of distance or impedance can be used to calculate its urban form indicators. This allows exploration and comparison of the different approaches, and gives the flexibility to choose a type of impedance that is adequate to the indicator or the transport mode being considered.

The multimodal network has a hierarchical and multi-level nature (Van Nes, 2002; Marshall, 2006; Ducruet et al. 2011; Read, 2013) that can be understood as a coupling of different systems that are not on the same level or scale (Figure 1.8). The interconnection of the different mobility infrastructures forms a complex structure that requires us to move from a simple Euclidean metric space to explore topological space as well. And the construction and functioning of the different infrastructures follows diverse principles and rules, therefore it is expected that different types of distance must be used in spatial network analysis to measure the selected urban form indicators.

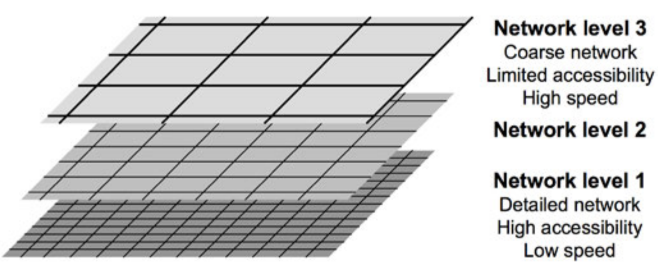
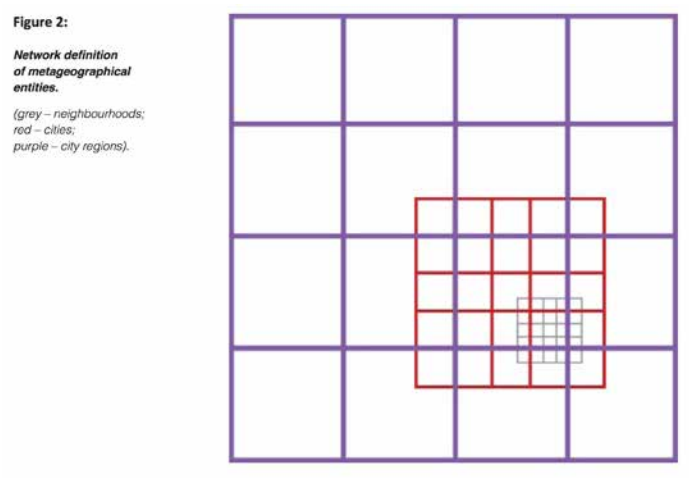


Figure 3-7: Illustration of multilevel network

1

TOC



2

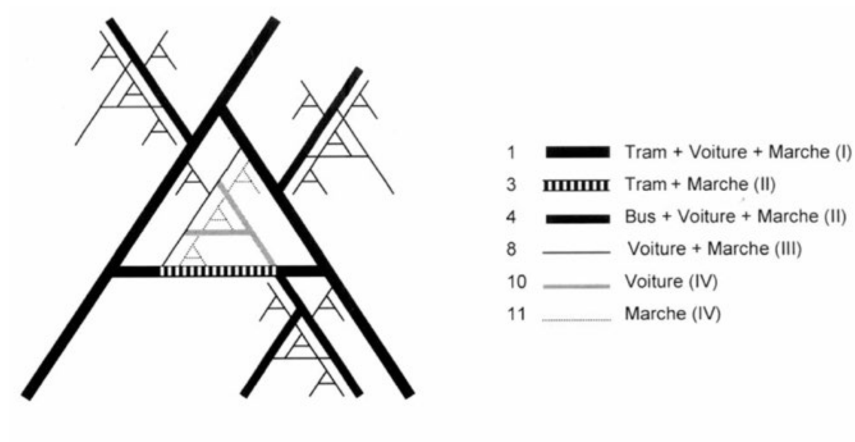


Schéma 13. Exemple d'organisation du réseau viaire suivant une hiérarchie favorable aux transports collectifs. Le système comprend deux modes de transports publics (bus et tramways) et deux modes qui ne sont pas des transports publics. Il comprend également six types de voies de communications et quatre niveaux.

3

FIGURE 1.8 Diagrams of the multi-level and hierarchical nature of metropolitan transportation infrastructure networks, sources: 1) van Nes, 2002; 2) Read, 2013; 3) Marshall, 2006.

§ 1.5.5 Urban modality: from description to synthesis

Chapters 4 and 5 of this thesis provide the specific details on the construction of an integrated multimodal urban network model in GIS, and on its analysis to measure proximity, density, accessibility and configuration of the mobility infrastructure. This spatial model is a descriptive model that is not dynamic and does not have a representation of time, which is adequate for a cross-sectional study such as this. The main aim of this model is to record, illustrate and quantify the spatial characteristics of the city-region and its urban areas, and to foster understanding (Hanson, 1986). The simplicity of the descriptive model is compensated by the multi-scale, multi-level and granular quality of the description, and current methods of data analysis, data visualisation and knowledge discovery can provide leverage to identify patterns and synthesise the results of the analysis.

A corollary of this work is the development of the concept of 'urban modality'. Urban areas have infrastructure characteristics supporting specific modes of transport. These characteristics are invariants that define an affordance of the built environment (Gibson, 1979), which we call its modality, i.e. the possibility of moving by specific modes of transport. Urban areas afford walk-ability, cycle-ability, transit-ability, and car-ability to different degrees; therefore, specific environments have specific types of modality. The study uses an unsupervised clustering method to develop a typology of 'urban modality' of the city-region (Chapter 6), classifying urban areas according to their specific invariant combinations/units of mobility infrastructure and land use, and consequently the modes of transport that they support. This classification is based on the spatial characteristics of urban areas described by the comprehensive collection of urban form and accessibility indicators discussed in Section 1.5.3.

The systematic classification of 'urban modality' provides a synthesis of the urban form and accessibility indicators of urban areas. This typology can be used to create new normative models for setting planning goals and for developing evaluation benchmarks, and to provide a context to evaluate the sustainable mobility performance of urban areas.

§ 1.6 Research design and methods

In order to address the research aims and questions, and following the approaches outlined in the previous section, this thesis conducts a cross-sectional empirical study of the Randstad city-region of the Netherlands. The study describes the spatial and socio-economic characteristics of the region and evaluates the sustainable mobility performance of its urban areas, focusing on the set of recently developed VINEX neighbourhoods. This section provides an overview of the research, a brief introduction to the case study, to the data used in the work, and to the main quantitative methods applied to analyse and explore this data. The research design is illustrated in the diagram of Figure 1.9.

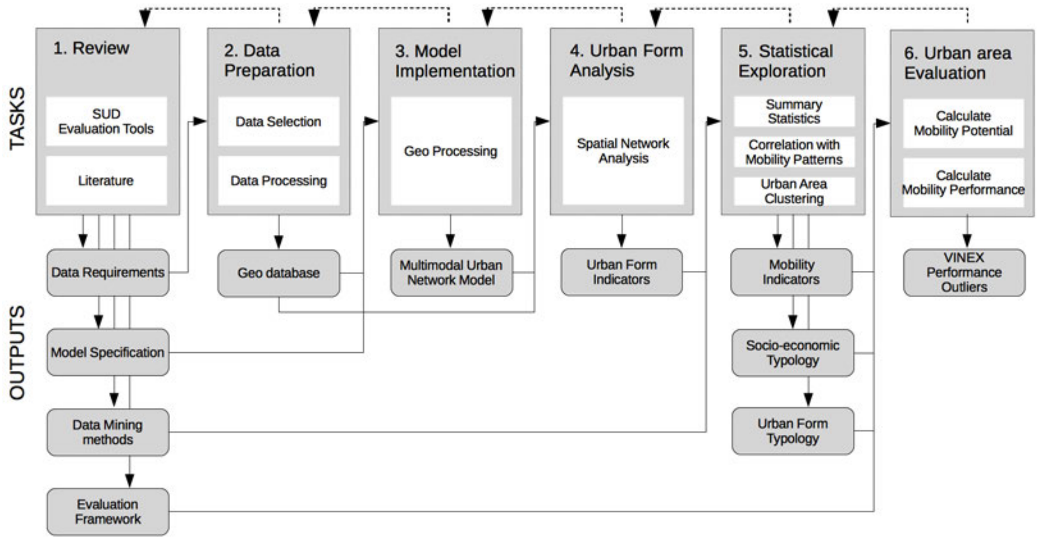


FIGURE 1.9 Schematic diagram of the research design structure, flow and outputs.

The research is organised into six main tasks, namely: Review, Data Preparation, Model Implementation, Urban Form Analysis, Statistical Exploration, and Urban Area Evaluation. The first task is where the literature review on the topics highlighted in sections 1.1 to 1.3 takes place, which informs the other stages of the study from a theoretical and methodological perspective. The review also includes a quantitative desktop study of the structure and content of sustainable urban development (SUD) evaluation tools that are used in practice, which is presented in Chapter 2. The outputs of the review task are the definition of data requirements, a draft model specification, the identification of relevant data mining methods (Chapter 3) and the definition of an evaluation framework. The subsequent tasks deal directly with the case study (section 1.6.1). The data preparation task involves the selection of datasets from diverse sources based on the data requirements, and their analysis, visualisation and storage in a spatial database using GIS tools (section 1.6.2). The model implementation task uses the data sets to build a multimodal urban network model of the city region (Chapter 4) following the initial draft specification. The urban form analysis task uses the network model to calculate a wide range of urban form and regional accessibility characteristics of urban areas (Chapters 5 and 6). These results are used in the statistical exploration task, together with the remaining empirical data, to study relations between urban form, socio-economic characteristics and travel patterns, and to define typologies of urban areas for urban form and socio-economic characteristics (Chapters 6 and 7). The urban area evaluation task concludes the quantitative work, developing a method for contextual regional evaluation of sustainable mobility potential and performance, and carrying out an assessment of VINEX neighbourhoods to identify neighbourhoods that stand out in their (positive or negative) performance (Chapter 7). The various quantitative methods and tools used in the different research tasks are introduced in section 1.6.3.

Although the research design has a linear sequence of tasks and there is a chain of dependency between tasks based on their outputs, the process is iterative and the tasks overlap in time with opportunities for revision, which might lead to reworking the previous task. For example, implementing the model tests the adequacy of the data set requirements and might require the identification and preparation of additional data sets; the first urban form analysis results allow the assessment of the network model implementation, leading to adjustments to its structure or the correction of mistakes; and statistical exploration of the analysis results can lead to adjustments of the urban form analysis parameters. Of course, not all revisions have led to updates of the work, as time to carry out the study is restricted. Some outstanding issues of the study that can be improved are revisited in the final chapter (Chapter 8).

§ 1.6.1 Case study

The case study of this work is the Randstad city-region in the Netherlands, looking at its urban areas, with a special focus on its VINEX neighbourhoods or districts. These are new urban areas developed within a common historical, cultural and socio-economic context, with explicit sustainable mobility national policy objectives.

The Randstad is one of the paradigmatic polycentric city-regions in Europe (Hall and Pain 2006). It comprises the four largest cities in the country (Amsterdam, Rotterdam, The Hague and Utrecht) and a series of middle size cities (Amersfoort, Haarlem, Leiden, Dordrecht and Hilversum), which together constitute the Randastad's Daily Urban Systems (DUS) against a background of suburban neighbourhoods and a mostly preserved rural and natural area at the centre called the "Green Heart". The Randstad does not correspond to an official administrative division with defined boundaries, but it can be defined by the boundaries of the municipalities that form the Functional Urban Region (Hall and Pain 2006). In this study we use the classification of municipalities found in Van Eck and Snellen (2006) (Figure 1.10).

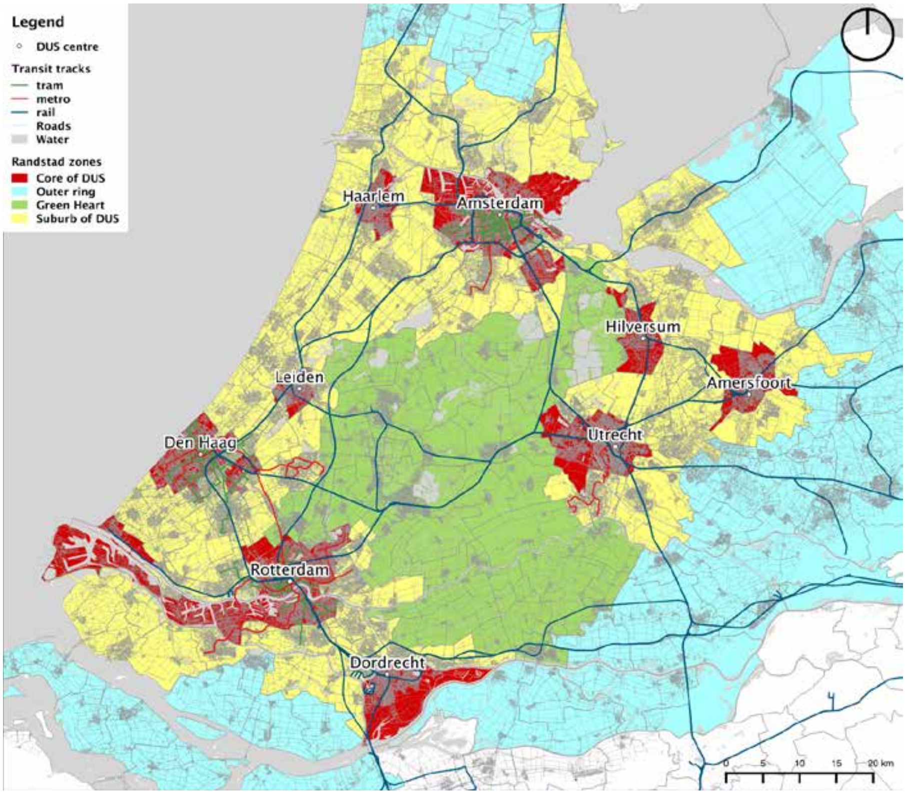


FIGURE 1.10 Map of the Randstad city-region, showing its zones, main urban centres, and main mobility network infrastructure.

The Randstad's urban centres and their suburbs are served by an established multimodal mobility network of local walking and cycling infrastructure, road and public transport networks, all connected by rail and motorway networks at the regional, national and even international scale. The Randstad's combination of mobility infrastructure networks with land use concentration and mix should offer the baseline conditions for sustainable mobility within the local neighbourhoods and across the region.

The Randstad's current configuration is the result of a long spatial planning tradition based on carefully planned neighbourhood development since World War II (Wassenberg, 2006) that over the decades has evolved from implicit to explicit sustainable urban development (Goedman et al., 2008). Urban development policy responded to the threats of sprawl with compact development and 'concentrated deconcentration' principles, which have been successful especially in terms of the land use and infrastructure configuration of the region, even if the mobility outcomes were not as successful (Dielemen et al., 1999; Geurs and Van Wee, 2006). More recent regional development is a product of policy documents published since the late 1980s (Buijs 1992, VROM 2001, VROM 2008). The Fourth Spatial Planning Framework Extra

TOC

from 1990-1993, also known as VINEX, introduced a program of urban expansion of new residential areas focusing on the core concepts of sustainable neighbourhood development and sustainable mobility in particular, where urban and transport planning went hand in hand (Galle et al., 1997; Dijst, 1997). The Fifth Spatial Planning Framework, the latest spatial strategy for the Netherlands at the time of writing, reinforces these objectives and sets as key priority the reduction of traffic congestion, the intensification of land use and the development of the network for multimodal transport provision (VROM, 2001; Snellen and Hilbers, 2007) with the aim of achieving a more sustainable mobility pattern nationwide.

1.6.1.1 VINEX neighbourhoods

The VINEX neighbourhoods, resulting from the Fourth Spatial Planning Framework, have been progressively implemented over the past 20 years in the Netherlands (Mensink and Boeijenga, 2008), and around 40 of these neighbourhoods are located in the Randstad region (Figure 1.11, Section 1.6.2.2). They represent a range of different urban areas, mostly developed in brownfield and green field sites around urban centres, originally planned to have good public transport links around a higher density core connecting them to the main urban centre. Internationally they have become emblematic examples of contemporary urban design and low carbon communities (see Houten in Foletta and Field, 2011; Amersfoort in PRP et al., 2008), and set the model for metropolitan development elsewhere (Larta, 2009). Regular study tours by students and practitioners learn from this model (Falk, 2007; TCPA, 2009), reporting back praise for their architectural and environmental qualities, but also identifying shortcomings in the lack of mixed uses, the social segregation and the sometimes poor public transport provision. While they can provide examples of best practice, studies indicate that some of the key policy objectives related to sustainable mobility have not been achieved in all cases, i.e. increase in walking and cycling in the neighbourhood (Hilbers, 2008), use of public transport for commuting or reduction of car use. In particular, the VINEX neighbourhoods in green field sites have not lead to more sustainable travel patterns when compared to other parts of the country and continue to perform worse than new and old inner city locations (Hilbers, 1999; Hilbers and Snellen, 2005). Ultimately, these neighbourhoods offer a variety of new types of contemporary urban development (Lorzing, 2006), and even if they do not solve all the problems that they were set out to address initially, they “provide a useful model for coherence in sprawl” (Betsky, 2006).

§ 1.6.2 Spatial data framework

The present work makes use of spatial data for the quantitative description, analysis and visualisation of the case study city-region and its individual urban areas, requiring a careful consideration of data sources, data management and spatial analysis units. At its core is a spatial database that combines a selection of secondary data sets that is capable of providing a description of urban areas in the region based on the components of the land use and travel conceptual model in Figure 1.1 (mobility, socio-economics and urban form) and supporting the approach for each component described in section 1.2.

Table 1.5 presents a summary of the initial data requirements (layers and attributes) for the stated research approach and design. In a time of exploding data availability, with an ever-increasing number of bigger data sets publicly accessible, it is important to define requirements beforehand to help the identification and selection of appropriate data sets.

THEME	LAYER	ATTRIBUTES
Mobility	Journeys	Origin; destination; purpose; day of the week; mode; distance; duration
Socio-economic	Boundary	Gender; age; household size; household composition; occupation; income; level of education; car ownership
Infrastructure	Roads	Mode (car, bicycle, pedestrian); length; speed restrictions
	Road intersections	Mode; typology
	Parking	Places; regulations
	Public transport stops	Mode (rail, metro, tram, bus, ferry)
	Public transport routes	Mode; distance
Land use	Buildings	Area; floors
	Activities	Area; land use category
	Land surface	Built; paved; green; bridge; tunnel
	Water	Bridge; tunnel
Administration	Boundary	Name; code; population

TABLE 1.5 Summary of the data requirements for the spatial database.

1.6.2.1 Data selection

The data sets used in the study are publicly available, stemming from official open data repositories and from projects providing crowd sourced and volunteered geographic information (VGI). The main reason behind this choice is to allow the work to be easily reproducible by others, repeatable with updated data and applicable to different geographic locations where equivalent data sources exist. To cover the data categories and attributes in Table 5, several data sets were considered and compared, as each offers different content and characteristics, e.g. file format, spatial resolution, year, attributes, coverage, and data quality. The final selection of main data sets used in the study is listed in Table 1.6. This list covers the period from 2009-2012 when most of the data selection and modelling work was carried out.

DATA SET	PROVIDER	SOURCE	THEMES
MON 2004-2009	MVWRDVS	https://easy.dans.knaw.nl/ui/home	Mobility, Socio-economic
OpenStreetMap	Contributors	http://download.geofabrik.de/europe	Infrastructure
OpenOV	Contributors	http://www.openov.nl/	Infrastructure
BAG 2012	Kadaster	http://geoplaza.vu.nl/	Land use
TOP10NL 2009	Kadaster	https://easy.dans.knaw.nl/ui/home	Land use
Wijk- en buurtkaart 2009	CBS	http://www.cbs.nl/	Administration
Geonames	Contributors	http://www.geonames.org/	Administration

TABLE 1.6 List of the main data sets used in the study.

The mobility and socio-economic data was extracted from the Mobility Survey of the Netherlands (MON) (Ministerie van Verkeer en Waterstaat, Rijkswaterstaat, and Dienst Verkeer en Scheepvaart 2011), merging the data sets from 2004 to 2009. The street network data was extracted from the OpenStreetMap (OSM) (http://openstreetmap.org/) data set of the Netherlands, downloaded as a full data dump in May 2012 from Geofabrik. The public transport data was partly extracted from the same OSM data set, and partly from the static timetable database of the OpenOV project. The buildings and land use data was extracted from the Basisregister Addressen (BAG) of 2012, but restricting if to buildings with a construction date up to 2009. Additional topographic data indicating waterways, roads and not built land surfaces was extracted from the TOP10NL 2009 vector data set by the Dutch Kadaster. For background cartography, municipal administrative boundaries were taken from the Wijk- en buurtkaart (District and Neighbourhood Map) 2009 data set by the Centraal Bureau voor de Statistiek (CBS) (national statistics office), and a comprehensive list of place names and locations from the Geonames data set. These data sets fulfil the data layer requirements to different degrees, depending on the quality of the individual data sets. The only data layer that could not be found was related to outdoor car parking spaces. Although some larger parking areas are represented in OSM data, not all spaces are indicated.

At the later stages of the study several community initiatives have emerged, such as:

- Bag42.nl (http://calendar42.com/en/bag42/);
- CitySDK (http://dev.citysdk.waag.org/)
- OpenDataNederland (http://opendatanederland.org/)
- OpenTopoNL (http://www.opentopo.nl/)
- NLExtract (http://www.nlextract.nl/).

And official data repositories have been created in line with government open data policy, such as the Publieke Dienstverlening Op de Kaart (PDOK) (https://www.pdok.nl/) or the Nationaal Georegister (http://nationaalgeoregister.nl/). These projects and initiatives consolidate the required data sets in platforms that make them more easily accessed and updated, and reinforce the viability of replicating the research.

1.6.2.2 Data Preparation

The data sets, once identified and selected, were loaded into a PostGIS spatial database for cleaning, attribute selection and reclassification, and for aggregating into the layers of the network model. One of the reasons to use this specific database platform relates to its robustness in dealing with the number and size of data sets, and its performance when running attribute and spatial queries. In addition, it is the native platform of the OpenStreetMap data, retaining the full integrity of the attributes. The resulting spatial data model is presented in Appendix B, as a series of diagrams of the individual data tables, their attributes and their relations, and illustrated in Appendix C through a series of maps. Details on the usage of the individual datasets are given in the relevant chapters of this thesis.

All data sets have been reduced to cover the case study area only. The spatial context of the data is the Randstad, as defined in Figure 1.10, with the study area including the Core and Suburbs of the DUS and the 'Green Heart', and the 'Outer Ring' defining the analysis limit. Data in the 'Outer Ring' is considered for spatial analysis but not included in the statistical analysis of the results. In the case of the infrastructure networks and buildings layers, the analysis limit is defined by a 15km buffer around the study area, which approximates the limit of the municipal boundaries.

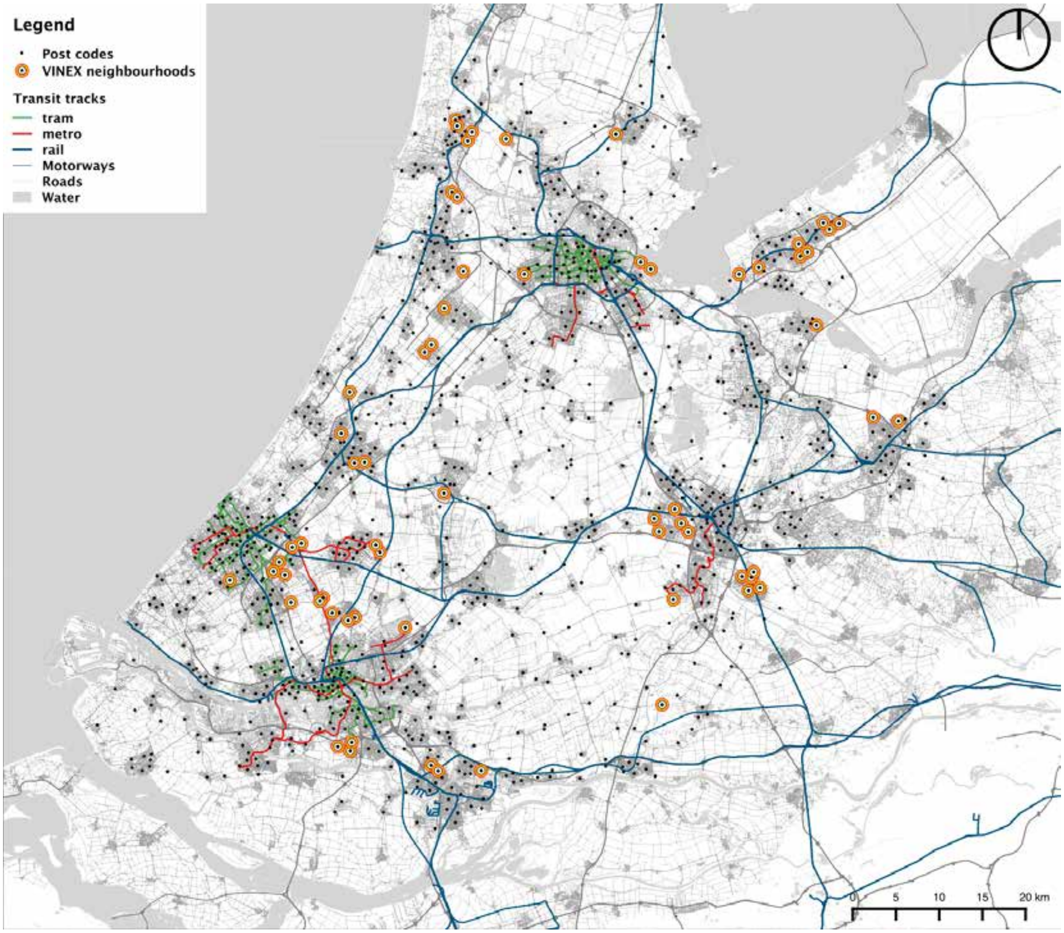


FIGURE 1.11 Map of the 4-digit postcode locations of the Randstad city-region, highlighting the location of VINEX neighbourhoods.

The spatial unit of analysis in the study area is the four-digit postcode, which corresponds to a small urban area equivalent to a neighbourhood. This is the highest resolution of the MON origin and destination data for the selected time period. In the study region there are 1063 postcodes of which 63 correspond to VINEX urban areas (Figure 1.11). From the 40 VINEX neighbourhoods existing in the Randstad some neighbourhoods are large and cover multiple postcodes. The complete set of postcodes represents the statistical sample of the characteristics of the region, i.e. land use, socio-economic and travel. The postcodes are represented by points at the coordinates of the residential unit located closest to the residential weighted centre of the postcode area. This ensures that the spatial unit of analysis corresponds to an actual location and that it is relevant to the phenomenon under study, i.e. the travel patterns of the residents of each postcode. These postcode points are source points used for the calculation of urban form indicators using spatial analysis methods (Section 1.6.3.2).

In the following Chapters and in the Appendices we get an illustrated profile of the Randstad city-region, demonstrating the use of these data sets. There are series of maps (or map books) of the travel patterns in the region (Appendix E), of the accessibility analysis results (Appendix G), of the main urban area types of the Randstad (Appendix J) and of the urban form of VINEX neighbourhoods (Appendix K). The maps highlight the strong spatial patterns that exist, indicating strong relations between the various dimensions analysed. However, spatial and statistical analyses are essential quantitative methods of this work, from the selection and familiarisation with the data sets, to the calculation of the final results.

§ 1.6.3 Quantitative methods

This work makes use of quantitative methods, i.e. statistical analysis and GIS spatial analysis, albeit focusing on a range of simple techniques that can be more easily explained and understood, and involve less subjective decisions by the operator or parameter tweaking to work with the specific case study. These simpler techniques ensure that the research is more easily repeatable by the authors, reproducible by others, and generally applicable to other cases. The quantitative methods are applied to all tasks of the research, and additional explanation of their specific application can be found in the relevant chapters of this thesis. Here, I list the most important methods used (Table 7) and provide general principles behind their selection and usage.

RESEARCH TASK	STATISTICAL ANALYSIS	CHARTS	SPATIAL ANALYSIS	MAPS
Review	Summary statistics	Bar chart		
Data preparation	Descriptive Statistics Gini coefficient Summary statistics	Histogram Line chart	Spatial query	Thematic maps Choropleth maps
Model implementation	Descriptive statistics	Histogram	Spatial query Spatial join	Thematic maps
Urban form analysis	Descriptive Statistics Gini coefficient Summary statistics Correlation	Histogram Box plot Scatter plot	Shortest distance Point density Accessibility Network centrality	Choropleth maps
Statistical exploration	Descriptive statistics Gini coefficient Correlation Hierarchical Clustering PAM	Histogram Box plot Scatter plot Mosaic plot Line chart Radar chart		Thematic maps Choropleth maps
Neighbourhood evaluation	Summary statistics QCD	Bar chart		Thematic maps

TABLE 1.7 Summary of the different quantitative methods used in the research.

1.6.3.1 Statistical analysis

In terms of statistical analysis, descriptive statistics are always calculated for the original data sets and analysis results, including mean, median, standard deviation, minimum, maximum, range, quartiles, and inter-quartile range. These simple measures are fundamental to understand the data and to support decisions regarding more advanced analytical and visualisation methods. The Gini coefficient and the Quartile Coefficient of Dispersion (QCD) were also found very useful in giving an indication of the amount of dispersion and variation in each variable. In terms of bivariate statistics, to identify relations between variables, this study used both Pearson's and Spearman's correlation coefficient, with preference for the latter because it is rank based and does not require data transformation. In order to use a consistent method for the various data sets and the various variables within each data set, the choice went in most cases for non-parametric methods (quartile and rank based measures), given that in many cases the data is not normally distributed. Finally, the data is in many cases summarised as percentage frequencies or normalised, allowing the comparison of different cases and categories. This is used in the review task, in the data preparation task to produce mobility indicators, and in the neighbourhood evaluation task.

The most advanced statistical method used in the statistical exploration and neighbourhood evaluation tasks is the automatic classification of typologies using hierarchical and k-medoids clustering (or Partition Around Medoids (PAM)). This is an elaborate procedure that requires the use of most of the other techniques mentioned so far, to understand and select the variables for classification, to identify an appropriate number of classes, and to describe those classes. Nevertheless, in data mining terms, this is still a well-known and conventional procedure. Its application is explained in Chapter 3, and it is applied in Chapters 5 and 6.

1.6.3.2 Spatial analysis

Spatial analysis methods are used in data preparation, model implementation, and urban form analysis. These methods include simple spatial queries, to select features from the data sets based on spatial relations (e.g. intersection, contained), and spatial joins, to aggregate data from one data set onto another based on spatial relations or finding the nearest features (see Chapter 4 for details). Network analysis methods, based on the distance between two locations and the service area from a location along the infrastructure network, are extensively used in the calculation of all urban form indicators listed in Table 1.4 (in Section 1.5.3), taking the individual postcode points as origins, this study's spatial unit of analysis (see Section 1.6.2.2). These methods are used in the calculation of proximity, measuring the distance from the postcode to the nearest target feature; location density, measuring the network length, number

TOC

of network features or activities within a given service area; accessibility to activities, measuring their area weighted by the distance to reach them within a time budget; and network configuration, measuring closeness and betweenness centrality (see Chapters 4 and 5). In the case of network centrality, the results are aggregated at the postcode point, by calculating the mean value within the service area from each point.

1.6.3.3 Data visualisation

Throughout this research, the quantitative methods have been supported by visual representations, be it charts or maps. This approach is important because the complementary use of various methods gives a more complete picture of the data and allows the identification of errors, patterns or trends. Table 1.7 summarises the combined use of the various methods.

Charts produced in R Studio were used to analyse individual variables (histograms, box plots), compare categories and groups on the same variable (box plots and bar charts), display the profile of a category on multiple variables (bar charts and radar charts) or show the relation between variables (scatter plots and mosaic plots). Maps were produced in QGIS, and can be simple thematic maps, presenting a selection of features and layers according to a theme (e.g. Figures 1.10 and 1.11), or choropleth maps, displaying the features coloured according the values of a variable. The choropleth scale used is in most cases based on quantiles because it is more generally applicable irrespective of the data's distribution. Equal ranges and natural breaks were also used in specific cases, when looking to give a specific visual accent of the variable. It was surprising to find that the data set reports and many studies did not contain any visual display of the data, especially when the data used is predominantly spatial or related to spatial phenomena. Some had accompanying table books with extensive summary statistics, but no charts or maps, not even to explain the location or spatial boundaries of the data provided.

§ 1.6.4 Software tools

To conclude the research design section, it is important to note that the quantitative methods mentioned so far have been carried out exclusively on an open source software stack (Table 1.8). This stack keeps the work in line with the objective of making the research accessible and reproducible by others. Open source software tools are available at no cost for research, and are cross platform, running in a variety of operating systems. In addition, this open source software stack is supported by a dedicated research and developer community, which often includes or is led by the researchers that have developed the original theory and methods. The community ensures the validation of the tools and the improvement of the methods with regular updates. Finally, the software requires or supports the use of scripting to carry out the various tasks. This can be daunting for some, but it facilitates keeping exact records of the workflows, it allows the development of custom algorithms whenever required, which in this case was necessary in the model implementation and urban form analysis tasks, and makes the sharing of the work more straightforward. The transparent and collaborative nature of the open source approach is fast turning these tools into the standard for scientific research. The source code of the methods and workflows presented in this thesis can be accessed in a Github repository (https://github.com/jorgegil/phdThesisCode), described in Appendix M.

SOFTWARE	VERSION	PURPOSE	SOURCE
osmosis	0.43	OSM data extraction	http://wiki.openstreetmap.org/wiki/Osmosis
PostgreSQL	9.1 – 9.2	Relational database, for data storage and management	http://www.postgresql.org/
PostGIS	1.5 – 2.0	GIS spatial data analysis, spatial data extension for PostgreSQL	http://postgis.net/
pgrouting	1.05	Network analysis, shortest route and service area calculations, for PostGIS	http://pgrouting.org/
QGIS	1.6 – 2.6	Desktop GIS for mapping and spatial data editing	http://www.qgis.org/en/site/
R	2.15 – 3.1	Statistical analysis platform	http://www.r-project.org/
RStudio	0.96 – 0.98	Integrated development environment for R	http://www.rstudio.com/
R igraph	0.65 – 0.66	Network analysis, including centrality measures	http://igraph.org/ (Csardi and Nepusz, 2006)

TABLE 1.8 List of the open source software stack used in the research.

Note: For the Mac OSX platform, the compiled version of most of the software listed can be obtained from William Kyngesburye's repository (http://www.kyngchaos.com/software/index)

§ 1.7 Thesis outline

To conclude the introduction, the outline of the thesis provides an overview of its structure and organisation with a summary of the individual chapters. The chapters are based on mostly published articles, with the exception of the first and last chapters, and for this reason they can be read independently without detriment to their full understanding. Nevertheless, they are stringed together in a logical sequence that builds the overall argument of the thesis. In this argument the reader can follow two main threads: a planning and urban studies oriented thread (Chapters 2, 6, 7), and a GIS modelling and analysis oriented thread (Chapters 3, 4, 5).

Chapter 1

The introduction provides the background to and design of the research. It sets the problem in the context of urban regional sustainability and mobility, and discusses existing planning theories used to develop urban areas to deliver sustainable mobility outcomes. The problem addressed by this thesis is the need to support complex planning decisions with models and tools that improve understanding and evaluate the performance of urban areas. The chapter proceeds to present the research aim, questions, and the relevance of this study. The key approaches and concepts to deal with the problem are described next, followed by the research design, case study and methods. The introduction concludes with an overview of how the thesis is organised, highlighting the relation between the various chapters.

Chapter 2

This chapter offers a review of existing tools for the evaluation Sustainable Urban Development (SUD), representing the state of the art in practice and current thinking in the fields of urban design and planning. The review focuses on several aspects of the problems raised in the introduction (Chapter 1), namely the dimensions of urban form, the relations between sustainability indicators, the definition of an evaluation boundary and the context of the evaluation. The tools reviewed are based on systems of indicators, which are summarised in a list of urban form assessment criteria in Appendix A. In addition, this review sets principles for developing SUD evaluation frameworks using systems of indicators, supporting the identification and definition of indicators related to mobility and accessibility developed in Chapters 6 and 7.

Chapter 3

A key proposition in this thesis is the application of data mining methods to the large data sets typical of urban environments for the objective classification and differentiation of urban areas. These methods facilitate the description of their complex composition, thus supporting contextual planning and decision-making. This chapter presents a classification method based on the k-medoids statistical clustering technique that is context-sensitive, multi-dimensional, systematic, exploratory, and quantitative. Although the test case addresses urban block and street typomorphologies, the method also works to classify urban areas using characteristics aggregated at the postcode level. This is demonstrated in Chapter 6 to define ‘modality environments’ and in Chapter 7 to build the socio-economic profile of the Randstad city-region.

Chapter 4

The multimodal urban network model is a fundamental component of the research design of this thesis. This chapter presents the process of building such an integrated network model, combining the selected urban data sets of the case study presented in Chapter 1. Various algorithmic procedures developed to create this model support the reproducibility of the process and address specific challenges of using OpenStreetMap (OSM) and open data. The spatial data model design adopts a level of simplification that is adequate to the OSM data availability and quality, suitable to the measurement of sustainable accessibility of urban areas, and applicable in practice. The results demonstrate the measurement of multimodal routes and catchment areas, which are the basis of the spatial analysis carried out in Chapter 5 and of the urban form indicators calculated in Chapter 6.

Chapter 5

The multimodal urban network model introduced in Chapter 4 describes the detail of a local environment in the context of a wider city-region, for disaggregate, scalable, and relational analysis of its components. In this chapter the model is used for multimodal spatial configuration analysis of the Randstad region, drawing from the graph representation and analysis features of various existing network models. A series of experiments using different network centrality metrics and conceptions of distance (i.e., physical, topological, and cognitive) test the model's performance against empirical data. The conclusions, regarding analysis parameters and relevant combinations of multimodal layers, are applied to the selection and definition of the urban form indicators used in Chapter 6.

Chapter 6

Having, to this point, developed and tested an instrument to measure sustainable accessibility, this chapter explores the relation between the multimodal network structure of urban areas and their resident's travel patterns, using the lens of 'urban modality' to profile the Randstad city-region. First, the individual urban areas of the city-region are analysed calculating network proximity, density and accessibility for different transport modes. From these results, the metrics most significantly related to multimodal travel patterns are selected to form a set of urban form indicators. These indicators are used to construct a typology of urban areas of the Randstad, which demonstrate support for specific transport modes, i.e. walking, cycling, car use, local and regional transit. This classification contributes to the evaluation of sustainable mobility potential of urban areas, carried in Chapter 7.

Chapter 7

This chapter evaluates the performance of urban areas in terms of sustainable mobility objectives, proposing an approach for strategic planning support., using the case of the VINEX neighbourhoods of the Randstad region. The travel patterns of their residents are set in the context of similar urban areas in terms of urban form and socio-economic characteristics, to carry out a context-sensitive evaluation. The aim is to create an objective definition of mobility potential and performance that allows the identification of special cases (positive and negative). These cases deserve further study to establish guidelines and benchmarks, or require planning intervention to achieve unrealised potential. In either case, the results provide strategic direction and should prioritise investment.

Chapter 8

The final chapter gathers the conclusions of the various chapters and revisits the initial problem statement and research questions. It summarises how the work carried out contributes to address the challenges of planning for sustainable mobility in urban regions, either through concrete findings or an improved understanding of the problem. In addition, the chapter takes a critical view on the multimodal urban network model developed, suggesting improvements or alterations to its structure and analysis, and concludes pointing new directions for future research.

2 Tools for the evaluation of sustainable urban design: a review[1]

Abstract

The present policy objective of sustainable urban development (SUD) has created the need for methods of ex-ante evaluation of local area development projects that assess the contribution of alternative solutions to the general sustainability goals. For this reason, we have seen the evolution of building energy assessment methods into sustainable neighbourhood assessment methods that are more integrative and contextual to accommodate the complexities of the urban scale. This article identifies and reviews a selection of SUD evaluation tools that are applicable to the early stages of urban design projects, to provide a clearer picture of the state of play to those needing to use such tools and those wanting to develop new ones. The review follows an analytical framework covering the format, structure, content and output of the tools, based on the recommendations of planning evaluation theory and the requirements of urban design practice. Since no single tool stands out from the review, the choice is not simple and there is scope to further improve existing tools and develop new ones. The paper concludes proposing a strategy for the development of robust and compatible SUD evaluation methods, based on four goals: Collaboration, Compatibility, Customisation and Combination.

1 This chapter is based on the manuscript of: Gil, J. and Duarte, J.P. (2013). 'Tools for evaluating the sustainability of urban design: a review'. Proceedings of the ICE - Urban Design and Planning 166 (6), pp. 311–325. doi:10.1680/udap.11.00048. (Main author, 95% contribution)

§ 2.1 Introduction

The European Union's report 'Sustainable Urban Development in the European Union: A Framework for Action' (European Commission, 1998) and the Leipzig Charter (European Council, 2007) have laid out the principles and strategies towards a sustainable urban development policy to be followed by national and local governments. Furthermore, several national policy and guidance documents such as the fifth National Policy document on Spatial Planning in the Netherlands (VROM, 2001), Planning Policy Statement 1 in the UK (DCLG, 2005) and the Sustainable Urban Development Act of 2010 in the US (Kerry et al., 2010), put sustainable development as the core objective of planning. However, evaluation procedures are necessary to assess if local urban development initiatives can contribute to the progress towards the national goals of sustainable urban development (SUD) (Curwell and Cooper, 1998; Hunt et al., 2008; Oliveira and Pinho, 2010). Hence, academia, industry and government have developed several evaluation methods and frameworks to support decision-making during the SUD process (Bentivegna et al., 2002; Brandon and Lombardi, 2010). Due to the complexity of planning's process and object we do not find a unique evaluation approach, and the evaluation methods and frameworks that exist are appropriate for specific stages of the urban development process, for specific spatial or temporal scales of development, and often for specific sustainability issues.

This review addresses current SUD evaluation tools that are holistic in the coverage of sustainable development issues, that can support the assessment of alternative urban design options at the neighbourhood scale, and are applicable from the early stages of the design phase of the urban design process (Llewelyn-Davies and Alan Baxter and Associates, 2007, p.110; RIBA, 2007). The aim is to assess the compliance of these SUD evaluation tools with the recommendations of planning theory but also their adequateness for use in urban design practice, in order to facilitate the choice of tool or to guide the future development of new tools. We use the term tool in a broad sense, encompassing a range of design and decision support instruments.

The next section of this paper reviews the methods of sustainability evaluation from planning theory in light of the requirements of evaluation tools for planning practice, compiling a set of key principles from both domains. This lays out the foundations for the analytical framework presented in the third section, which addresses the format, structure, content and output of SUD evaluation tools. The fourth section describes the process of identification and selection of relevant SUD evaluation tools, resulting in a summary of the tools reviewed. This is followed by the analysis of the tools based on the analytical framework presented earlier, highlighting the general trends and particular characteristics of individual tools. The paper concludes with a discussion of the development of SUD evaluation tools, and how this should be used to link planning evaluation theory and urban design practice.

§ 2.2 The evaluation of sustainable urban design

There has been a constant evolution of planning evaluation methods from Cost Benefit Analysis (CBA) to Planning Balance Sheet (PBS) and Multi-criteria Analysis (MCA), from Environmental Impact Assessment (EIA) to Strategic Environmental Assessment (SEA) and Social Impact Assessment (SIA). According to Alexander (2006), this evolution has represented a recognition of the complexities of the evaluation process in urban planning, and meant a move to scientifically and technically more sophisticated methods: from 'simple' calculation methods to complex assessment frameworks; from an environmental focus to an integrated sustainability agenda; from an aggregated or reductionist strategy to a disaggregated and multi-dimensional approach. This evolution reflects the progress of planning evaluation theory from a positivist stance of instrumental rationality to a dialectic stance of communicative rationality (Khakee, 2003).

On the other hand, planning practice has remained positivist, believing in objective quantitative measurement (Khakee, 2003). This is reflected in the adoption of indicator systems and aggregate indices for the monitoring of SUD progress, such as the European Common Indicators (ECI) (Ambiente Italia Research Institute, 2003) or the 'Sustainable Development Indicators' pocket guide in the UK (Defra, 2009). The adoption of simpler evaluation methods is linked to the requirements of planning practice and policy (Briassoulis, 2001; Rydin et al., 2003), since practice needs normative and positive theory (Alexander, 1997; 2000). Therefore, despite the mandate for EIA in the US and for SEA or EIA in the EU, these complex frameworks have limited use in practice (Jensen and Elle, 2007; Hacking and Guthrie, 2008; Steinemann, 2001). Their complexity of implementation and their information gathering demands reduce their ability to function in a quick, iterative and interactive fashion, which is a requirement of smaller projects and of the early stages of any project (Becker, 2004; Ding, 2008; Cole, 1999). Disaggregate indicator systems, combined with MCA principles, have become the preferred method of evaluation at a more local and detailed scale of planning, such as neighbourhood development and design (Carmona, 2003; Colantonio, 2008; Hacking and Guthrie, 2008).

In this field, we have also witnessed an evolution since the late 90's. The building energy measurement and rating systems used in the building design process, e.g. GBTool, LEED, BREEAM, started to embrace a more holistic perspective towards sustainability and the measurement of performance against benchmarks (Cooper, 1999). With this step it also became clear that the evaluation of SUD of an urban area could not be restricted to the measurement of the individual buildings that constitute it, due to the systemic nature of the urban environment (Curwell and Cooper, 1998). This was recently demonstrated by the post-occupancy assessment of flagship zero carbon development BedZED, in the UK, where location and accessibility were the most cited problems by its residents (BioRegional, 2009). New SUD evaluation frameworks were created that kept the simpler quantitative nature of the original indicator systems, but would address the context of urban design, the social and public dimensions of the problem, and the characteristics of the planning process (Curwell and Cooper, 1998). The SUD evaluation frameworks need to respond to several requirements in order to be effectively applied as decision and design support tools to urban design practice in the ex-ante evaluation of design proposals:

- To have an integrated conception of SUD (Gasparatos et al., 2009; Hacking and Guthrie, 2008; Munda, 2006);
- To reflect a widely accepted vision that provides guidance during the design process (Jensen and Elle, 2007; Cole, 1999; 2005; Leitmann, 1999);
- To agree objectives and targets to work towards, instead of comparing to the reference base line scenario (Cole, 1999; Pope et al., 2004);
- To allow for early stage deployment, when little data on a project is available (Cole, 1999; Hunt et al., 2008);
- To use disaggregate measures and include MCA features (Gasparatos et al., 2009; Ding, 2008; Hacking and Guthrie, 2008; Munda, 2006);
- To offer interaction with the design, being sensitive to design changes (Leitmann, 1999; Cole, 1999);
- To allow for (re)iteration, assessing alternatives and supporting the evolution of the design (Becker, 2004; Cole, 1999; 2005; Oliveira and Pinho, 2010; Leitmann, 1999);
- To offer communication methods that make the results clear and understandable to the various stakeholders (Cole, 1999; Becker, 2004; Walton et al., 2005; Oliveira and Pinho, 2010; Leitmann, 1999);
- To assess the planning process itself, in terms of dialogue and participation of the various stakeholders (Munda, 2006; Gaffron et al., 2008; Oliveira and Pinho, 2010; Khakee, 2003).

This set of requirements lays out the foundation of the analytical framework used to review selected SUD evaluation tools.

§ 2.3 An analytical framework for SUD evaluation tools

In this section we introduce the analytical framework used to assess how the selection of SUD evaluation tools responds to the needs of urban design practice and if it follows the recommendations of planning evaluation theory. This analytical framework focuses on four different aspects of the tools, namely their format, structure, content and output. The format is about their type and what they offer as product. The structure is about how the concept of SUD is implemented and organises the system of indicators. The content is about the different themes addressed by the individual indicators. Finally, the output is about the way the results are processed and presented.

§ 2.3.1 Tool format

The selected SUD evaluation tools are classified according to one of the following tool types, adapted from Jensen and Elle's typology (2007) to fit the specificities of the design phase of the urban design process.

- **Design Guides** – are descriptive collections of SUD themes that present general principles and, in some cases, a detailed structure of indicators that includes benchmark values. They often offer checklists as practical instruments to guide the design process.
- **Calculation Tools** – are software tools for the direct calculation of SUD indicators. They do not offer a fixed evaluation framework but allow the aggregation of indicators for visualisation in simple charts, and in some cases, display thematic maps of individual indicators.
- **Assessment Tools** – are advanced checklists with software implementation. Values are entered in forms for each SUD theme of a structured evaluation framework, and the results are plotted in charts to give a visual and quantitative profile of different design options.
- **Rating Tools** – are similar to assessment tools, but the output is a label with a score. They require precise calculation of indicators and include target values and weights for aggregating the results into the final score.

It is also important to note the software platform that supports the tool, and what method of data input is offered. Finally, one must understand the possibilities for customising the tool for the specific context of the project by configuring or selecting the indicators (Becker, 2004; Pope et al., 2004).

§ 2.3.2 General tool structure

An essential characteristic of a SUD evaluation tool is that it should offer a hierarchical structure supporting the selection and development of meaningful sustainability indicators (Archibugi, 2006; Becker, 2004). This structure progressively links higher-level concepts of sustainability, present in policy targets and the development vision, to specific issues that are relevant to the project and to objectives that can be measured (Mitchell, 1996; Briassoulis, 2001). This hierarchy should provide compatibility with evaluation standards and theory, provide a clearer understanding of the issues and give greater relevance to the results (Carmona and Sieh, 2008).

The proposed general structure for SUD evaluation tools consists of five hierarchical levels with increasing detail and specificity, namely:

- **Sustainability dimensions** – the core goals of sustainability, often based on the three pillars, also known as triple bottom line (TBL), of environment, society and economy;
- **Urban sustainability issues** – the themes of concern to SUD, that need to be addressed to achieve the core goals, e.g. resources, accessibility, viability;
- **Evaluation criteria** – the aspects that need to be assessed in order to verify the response of the plan to the issue, e.g. energy consumption, waste production, access to public transport or access to jobs;
- **Design indicators** – the measurements that are indicative of the performance of the design, with specific measurement units and methods, e.g. percent of residents within 400m walking distance of a public transit stop, average distance in meters to the nearest doctor;
- **Benchmark values** - the reference or target values that the indicators need to meet to achieve specific quality levels. In the case of reference values they come from baseline assessment of similar cases, while target values are objective goals from a more universal sustainability vision.

Figure 2.1 presents a diagram of the general tool structure, with the size of each level indicative of the expected number of elements. This diagram highlights the critical transitions between levels, where one has to associate general sustainability concepts with urban environment specific concepts, and translate theoretical concepts into empirical measures (Pope et al., 2004), supported by research, theories and empirical evidence. Furthermore, the arrow on the left indicates a top-down direction of definition of the system of indicators, starting from the high-level sustainability principles. Pope et al. (2004) suggest starting at the issues level because the TBL can be reductionist, however we understand this to be a problem only if indicators are directly linked to the dimensions of sustainability, without the intermediate levels. The arrow on the right indicates the bottom-up direction of measurement and aggregation for interpretation of the evaluation results, where the indicators linked to objectives influence the path of action towards sustainability (Pope et al., 2004).

TOC

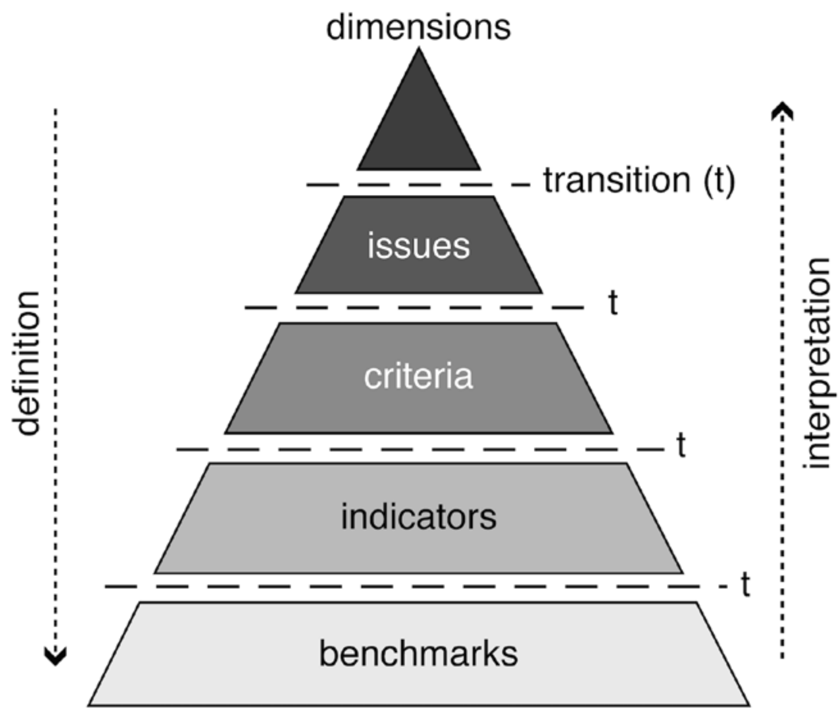


FIGURE 2.1 General structure of SUD evaluation tools with five hierarchical levels, indicating a top-down definition and a bottom-up interpretation of the system of indicators and benchmarks, with critical conceptual transitions between levels, requiring either theory or empirical evidence

§ 2.3.3 Tool content

The content of the selected SUD evaluation tools is reviewed by identifying what each individual indicator is measuring and viewing it under two different lenses, to assess the tool's applicability to the early stages of the design phase of the urban design process.

The first lens examines how far the tools have evolved from building assessment methods. We quantify the indicators that consider aspects of detailed building design, e.g. building materials, technologies or energy use levels. While these indicators can be useful at later stages of urban design, they require information that is not readily available when building massing is being developed. Providing this information is speculative and at best sets the desirable target. We also quantify how many indicators cover each pillar of the TBL to make a more integrated and holistic sustainability assessment, especially in relation to social concerns. We finally quantify how many indicators consider the urban context and location, and how many measure aspects of planning process, e.g. mechanisms of public participation. These are all important dimensions of the SUD planning process that are not usually found in building assessment methods (Curwell and Cooper, 1998; Ding, 2008).

The second lens examines to what extent the tools measure directly the design outcome. This is defined by the dimensions of urban form as proposed by Dempsey et al. (2008) in the context of SUD, i.e. land use, density, mobility infrastructure, street layout and building type, as well as accessibility, which is identified as a unifying measure. In the design process it is important that the indicators make the consequences of design actions directly observable and understood by the stakeholders to facilitate the interaction and iteration processes. In contrast, we quantify to what extent the tools include indicators that measure externalities of the urban design process. These can be market conditions such as the affordability of the housing stock, or aspects of individual lifestyle such as the levels of home working. Furthermore, we quantify the indicators that can only be measured at a different stage of the development process, with data collected prior to the design stage for baseline assessment or after the design stage for monitoring progress, e.g. crime rates, population profile, resident satisfaction.

§ 2.3.4 Tool output

The final stage of analysis looks at the tools' output and what strategies they offer to tackle the serious difficulties in assessing the results of indicators, raised by Briassoulis (2001). On the one hand, how the various targets are set in benchmark values, which according to Briassoulis is a difficult if not impossible task. Having pre-set values is satisfactory if the levels are adequate for the local geographic or policy context, or to obtain results that are comparable with reference cases. According to other authors, customisation of these values is a pre-requisite for the evaluation process (Mitchell, 1996; Pope et al., 2004; Hunt et al., 2008). On the other hand, how the various disaggregate indicators are summarised using weights, if the synergies between indicators are accounted for and how transparent this aggregation process remains (Becker, 2004; Hacking and Guthrie, 2008). While a final score might be interesting for certification of a final proposal, it is not useful during the design stage because the complexity of the urban design process does not lend itself for optimisation strategies (Munda, 2006). It is more important to assess the disaggregate impacts and identify synergies in order to propose alternatives.

Also important is the visual feedback provided by the tools because formal measurement and informal interpretation go hand in hand (Carmona, 2003). Effective graphic communication of the results allows the involvement of a wider group of stakeholders and it can provide a clearer overview of the strengths and weaknesses of a proposal, thus operationalising the evaluation process (Becker, 2004).

§ 2.4 Selecting a relevant set of SUD evaluation tools

Having established an analytical framework for the review of SUD evaluation tools, the next step is to identify and to select a group of relevant tools. We are reviewing tools that can support the assessment of alternative master plans, or detail urban design options, during the design phase of the urban area renewal and development process. The best way to produce a design outcome that moves closer to sustainability goals is if these support tools are used from the earliest stage of planning, namely from the development visioning stage (Hunt et al., 2008).

§ 2.4.1 The sources of information

The tool selection process is based on a survey of various sources, including previous SUD evaluation tool reviews, academic research projects and the Internet. Previous reviews have analysed sets of SUD tools for urban area development (Hunt et al., 2008; Karol and Brunner, 2009; Kapelan et al., 2005). Hunt et al. (2008) reviewed tools that have been applied over the years in the development of Birmingham Eastside, in the UK, concluding on their usefulness but identifying requirements for their wider dissemination. Karol and Brunner (2009) reviewed tools that are relevant to support the development of multi-housing subdivision projects in the specific context of Western Australia, focusing on their content, relating themes to more general sustainability concepts and the objective sustainability targets. The results of academic research projects are another rich source of information. Several projects have compiled the state-of-the-art in SUD evaluation tools, identifying hundreds of different tools through extensive review of literature, stakeholder workshops and consultation (Deakin et al., 2002; Cremasco, 2007; Walton et al., 2005; Jones and Patterson, 2007; Bourdeau and Nibel, 2004; Levett-Therivel, 2004). In the process, they have further developed the understanding of SUD evaluation by establishing classification parameters for different phases of the urban development process, different time and spatial scales of intervention, all sustainability dimensions and a wide range of stakeholders. Table 2.1 gives a brief overview of relevant projects.

PROJECT	ORIGIN	PERIOD	WEBSITE / DATABASE
BEQUEST	EU	1998-2001	http://vp.salford.ac.uk/bequest/bequest-Webs/bqtoolkit/index2.htm
CRISP	EU	2000-2003	http://crisp.cstb.fr/ (Last accessed 12/04/2010)
HQE2R	EU	2001-2004	http://hqe2r.cstb.fr/default.asp (Last accessed 12/04/2010)
PETUS	EU	2003-2006	http://www.petus.eu.com/
SustainabilityA-Test	EU	2004-2006	http://www.sustainabilitya-test.net/
SUE-MoT	UK	2003-2009	http://www.sue-mot.org/

TABLE 2.1 Overview of research projects reviewing SUD evaluation tools.

Of particular relevance to this review were the databases, reports and articles resulting from these projects that review integrated evaluation methods applicable at the urban scale (Jensen and Elle, 2007; Levett-Therivel, 2004; Blum and Grant, 2004; McCreadie and BRE, 2004) and those that describe SUD evaluation frameworks that incorporate those methods (Deakin et al., 2001; Bentivegna et al., 2002; Deakin et al., 2002; Jones and Patterson, 2007). A final source of information on SUD evaluation tools was the Internet and references in professional planning resources, as these cover more recent tools not necessarily from an academic origin.

§ 2.4.2 Tool identification and selection

The first task was to identify a list of candidates for review from the enormous quantity of SUD evaluation tools available. This meant selecting those tools that can be applied at the neighbourhood scale and offer integrated assessment of all sustainability dimensions, leaving out those targeted specifically at the building, building components, whole city or regional scales, or that focus on specific issues like energy or transport. Also excluded were the tools for which no other information could be found beyond the initial database entry or report reference.

Table 2.2 presents the short list of 35 tools identified, including the tool's name, country of origin and the count of different organisations involved in its development, i.e. government agencies (Gov), academic institutions (Aca), industry members (Ind) and non-governmental organisations (NGO). These tools were reviewed to select those that can be used for ex-ante evaluation of projects to compare design alternatives and have the form of a system of indicators. Particular attention was given to tools endorsed by national or local government.

NAME	COUNTRY	GOV	IND	ACA	NGO
Action Towards Local Sustainbility (ATLAS)	EU	5	1		
BRE Sustainability Checklist	UK		1		
BREEAM Communities *	UK		1		
CityCAD	**UK**		**1**		
CommunityViz	US		1		1
Dashboard of Sustainability	CAN				1
Duurzaamheids Profiel van een Locatie (DPL)	**NL**		**2**		
ECOCITY	**AT, DE, NL**	**1**		**2**	
Ecological Footprint	US			1	
Ecosistema urbano	IT			1	
Environmental Impact Assessment (EIA)	EU	1			
European Common Indicators (ECI) *	IT, EU	1	1		1
HQE2R (ISDIS systems and INDI model) *	FR, EU			10	
INDEX	**US**		**1**		
Land use Evolution and Impact Assessment Model (LEAM)	US			1	
LEED for Neighbourhood Development (LEED-ND)	**US**	**2**	**1**		
Multicriteria assessment tool (NAIADE)	ES		1		
OnePlanetLiving	UK				2
PERS	UK	1	1		
PLACE3S	US	3			
Placecheck	UK				1
PoleStar	US				1
Propolis *	EU		6	2	
Quality of Life Indicators *	UK	1			
South East of England Development Agency (SEEDA) Sustainability Checklist	**UK**	**1**	**1**		**1**
Sistema de indicadores y condicionantes para ciudades grandes y medianas (SIC)	**ES**	**1**	**1**		
Shaping Neighbourhoods (SN)	**UK**			**1**	
Social Impact Assessment (SIA)	EU			1	
SOLUTIONS	**UK**			**6**	
Spaceshaper	UK		1		
Spartacus	EU		4	1	
SPeAR®	**UK**		**1**		
Sustainable Urban Landscapes: The Site Design Manual for B.C. Communities (SUL)	**CA**			**1**	
Toolbox for Regional Policy Analysis	US	3			
Urbanizing Suburbia *	UK			1	

TABLE 2.2 List of the 35 SUD evaluation tools identified. Highlighted in grey are the 11 tools selected for detailed review.

Table 2.2 presents the short list of 35 tools identified, including the tool's name, country of origin and the count of different organisations involved in its development, i.e. government agencies (Gov), academic institutions (Aca), industry members (Ind) and non-governmental organisations (NGO). These tools were reviewed to select those that can be used for ex-ante evaluation of projects to compare design alternatives and have the form of a system of indicators. Particular attention was given to tools endorsed by national or local government.

Some candidates were excluded because they have been superseded by more recent versions, namely SPARTACUS and PROPOLIS being integrated in SOLUTIONS. Other candidates were excluded because they are evaluation frameworks that integrate several tools but lack specific methods (Cole, 2005; Brandon and Lombardi, 2010) and are more suitable for the final stage of design certification, namely EIA, SIA and BREEAM Communities. In the case of BREEAM Communities (BRE Global 2009), several of its indicators use data from the development process instead of the design output, such as the presentation of impact assessment reports and emails between the planning team, being more suited for a retrospective analysis (Brandon and Lombardi, 2010). In fact, the BREEAM Communities framework recommends the use of other practical assessment methods, some of which are covered in this article. This first review resulted in a short list of 11 tools selected for detailed review, highlighted in blue in Table 2.2

§ 2.4.3 Summary of the selected tools

In the following paragraphs we provide a short summary of each of the tools selected for detailed review.

CityCAD (http://www.holisticcity.co.uk/) is a design support software developed in the UK by Holistic City targeted at urban design professionals. It offers a parametric model for urban master plans within a CAD environment that provides real-time feedback on a variety of sustainability and quality of life indicators, while changes are made to the design.

Duurzaamheids Profiel van een Locatie (DPL) (http://www.ivam.uva.nl/index.php?id=560) is a sustainable neighbourhood assessment software from the Netherlands developed by IVAM that can be used at various stages of the development process. The software has been used by more than 35 municipalities in the Netherlands and is endorsed by the government in the sustainable procurement of urban development projects.

ECOCITY Book 2 (Gaffron et al., 2008) is a guidance document resulting from the EU research project ECOCITY 'Urban Development towards Appropriate Structures for Sustainable Transport' (2002-2005). It developed an Ecocity vision based on existing guidance and principles of SUD. This book provides guidance on the sustainable urban planning process and includes an assessment method based on sustainability indicators.

INDEX (http://www.crit.com/) is an integrated decision support tool developed by Criterion Planners in the USA based on a GIS platform. It supports all stages of the urban development process, from initial assessment to monitoring of the conditions, and has a range of different modules for this purpose including some simulation modules. Its set of indicators includes several from the LEED-ND system.

Leadership in Energy and Environmental Design Neighbourhood Development (LEED-ND) (http://www.usgbc.org/DisplayPage.aspx?CMSPageID=148) is a rating system developed by the US Green Building Council (USGBC) in collaboration with the Congress for the New Urbanism (CNU) and the Natural Resources Defence Council (NRDC) in the USA. It is the result of a consultation process concluded in 2009 that resulted in the publication of the rating system specification and a project checklist. The certification process has several stages and is carried out by the USGBC through accredited professionals.

South East of England Development Agency (SEEDA) Sustainability Checklist (http://southeast.sustainabilitychecklist.co.uk/) was an on-line decision support tool developed by SEEDA and the Building Research Establishment (BRE) in the UK. It offered guidance for the design of new urban development projects in light of current policy and best practice. The project was subsequently adapted to several other regions in the UK, but is no longer supported since the closure of all Regional Development Agencies in March 2012.

Sistema de Indicadores y Condicionantes para ciudades grandes y medianas (SIC) (MMAMRM and BCN, 2010) is a system of indicators for measuring the sustainability of cities officially approved in 2010 as the standard for Spanish cities. It was developed by a workgroup of municipalities of the Local Agenda 21 programme under technical supervision of the Agencia de Ecologia de Barcelona.

Shaping Neighbourhoods (SN) (Barton et al., 2010) is a book by academics from the University of the West of England in the UK, providing guidance in the design of sustainable, healthy neighbourhoods. It offers theoretical principles but also practical guidelines on urban form and a series of checklists for different stakeholders and different stages of the development process.

Sustainability Of Land Use and Transport In Outer Neighbourhoods (SOLUTIONS) (http://www.suburbansolutions.ac.uk/) was a UK research project (2004-2008) to develop and assess different urban design and development scenarios for the future in terms of their sustainability. Within this project, an evaluation framework was developed based on sustainability indicators for the local (Barton et al., 2009) and regional scales (Mitchell et al., 2005).

Sustainable Project Appraisal Routine (SPeAR®) (http://www.arup.com/Projects/SPeAR.aspx) is an integrated decision support software developed by Arup / Oasys in the UK in 2000. Although it has been designed to use in all types and scales of projects it has been used in master planning at Arup (McGregor and Roberts, 2003). It is known for the circular diagram that summarises the results.

Sustainable Urban Landscapes (SUL): The Site Design Manual for B.C. Communities (http://www.jtc.sala.ubc.ca/projects/DesignManual.html) is a design guidance tool produced at the University of British Columbia in Canada with support of regional and national government agencies. It offers an introduction to the assessment method using several case studies, as well as design codes and a sustainability checklist.

§ 2.5 Review of the selected tools

In this section we review the selected SUD evaluation tools based on the analytical framework defined in section 2.3. For each aspect of the framework we highlight the main findings or trend if it exists, with the details for each individual tool summarised in tables and charts.

One initial consideration is about the extent to which the selected SUD evaluation tools are explicit about background references. These references can originate in theoretical research, empirical research, policy and guidance documents or industry best practice and standards, and they should inform all aspects of tool development. However, some tools do not have a references section nor footnotes making those links (CityCAD, INDEX, LEED-ND), in contrast with DPL or SEEDA that have comprehensive references to local policy documents, or the tools that involved academic institutions. This omission leads to a lack of transparency on the reasons behind certain features, settings or selections of indicators.

§ 2.5.1 Format of the tools

The format characteristics of the selected SUD evaluation tools are summarised in Table 2.3, including tool type, product type, software platform (with any auxiliary tools in brackets), input data used for measurement and customisation options.

TOOL	TYPE	PRODUCT	PLATFORM	INPUT DATA	CUSTOMISA-TION
CityCAD	Calculation	Commercial software	CAD	Design	Configuration of settings
DPL	Assessment	Commercial software	Spreadsheet	Design data	Alternative calculation
ECOCITY	Guide	Free report	Checklist	Result	-
INDEX	Calculation	Commercial software	GIS	Design	Selection of indicators
LEED-ND	Rating	Commercial service, Free guide	Spreadsheet, (GIS)	Result	Reserved credits
SEEDA	Assessment	Free software	Web-site	Result	-
SIC	Assessment	Free report	(GIS, other)	(Design)	-
SN	Guide	Book	Checklist	Result	-
SOLUTIONS	Assessment	Free report	(Other)	-	-
SPeAR®	Assessment	Commercial software	Spreadsheet	Result	Selection and custom indi-cators
SUL	Guide	Free report	Checklist	Result	-

TABLE 2.3 Summary of the format of the selected SUD evaluation tools.

The first characteristic that we highlight is the type of tool. The selected tools cover the four types defined earlier – design guides, calculation tools, assessment tools and rating systems. However, only one tool is a rating system, which seems to confirm that the aggregation of the measurements into a single score is not an essential feature for design support. The differences between calculation and assessment tools become clearer in the other stages of the review, in particular the reason why INDEX is considered a calculation tool.

The type has implications on the other characteristics of the tool. Design guides are available in the form of book or report without a supporting software platform and offer paper checklists to facilitate assessment. Some assessment tools are only available to the general public in the form of a report, although they mention auxiliary software that is used in the assessment process. The software platforms are mostly commercial, with the exception of the SEEDA web site and the LEED-ND checklist. They come in two types: spreadsheets or design platforms such as CAD and GIS.

The type of input data required for measurement depends on the software platform, with consequences on the ease of data entry and maintenance. Design platforms store the design directly, facilitating the measurement, calculation and update of alternative design options, rendering the evaluation process more interactive and iterative. Spreadsheets are normally used as digital checklists that store the result of each indicator, previously calculated by other means. The only exception is DPL that takes as input design measurements and data and calculates the indicators automatically.

Finally, the customisation possibilities are very much dependent on all the previous characteristics. Most paper or digital checklists offer limited possibilities for customising the system of indicators. The software tools are eventually more flexible: LEED-ND has four reserved credits that can be defined to accommodate regional characteristics, SPeAR accepts the replacement of up to 10% of its indicators, DPL offers alternative calculations for some indicators based on different input data and INDEX offers the possibility of freely combining the indicators into a custom system of indicators specific to the project.

§ 2.5.2 Configuration of the tools

The selected tools are all based on collections of SUD indicators grouped under hierarchical levels. However, the terms used to describe each level vary between tools, and even the term ‘indicator’ is not used consistently being only explicitly defined in ECOCITY. To review the selected tools they were conformed to the general structure of Figure 2.1 by matching the tools’ levels to the proposed levels based on their characteristics and role in the evaluation process. Figure 2.2 presents the configuration of each of the selected SUD evaluation tools based on the number of elements in each level. A look at the group of charts reveals that most tools do not present a complete SUD evaluation hierarchy: they do not cover the full range of levels, they have gaps or the levels are not clearly separated.

At the top level, only one tool is explicitly based on the TBL (DPL), while other tools adapt the TBL by separating the environmental dimension into ‘environment’ and ‘resources’ (SOLUTIONS, SPeAR) or by adding a ‘transport’ dimension (SUL). Several tools start from a set of dimensions that is specific to the urban development context (ECOCITY, SEEDA, SIC, SN), more akin to the ‘issues’ level, making them less compatible with general definitions and policy on sustainable development. However, three tools do not address any high level concepts of sustainability (CityCAD, INDEX, LEED-ND).

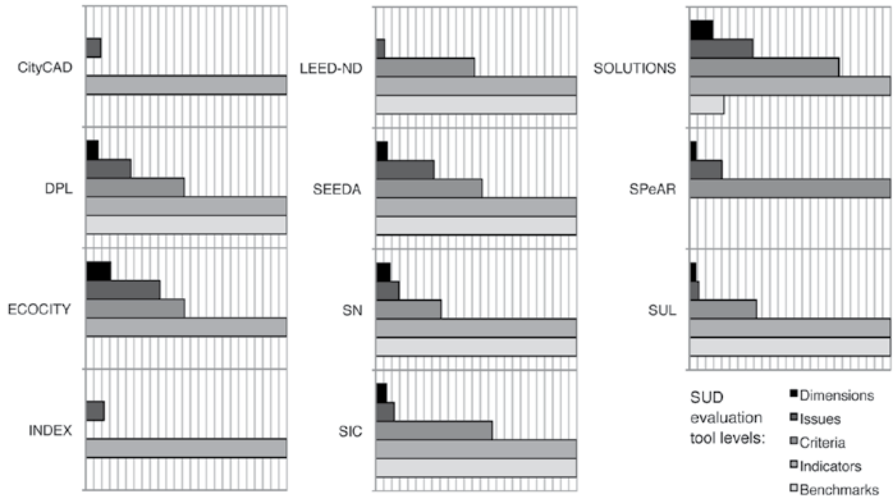


FIGURE 2.2 Configuration of the selected SUD evaluation tools, based on the general structure defined in the analytical framework.

Most tools include all the other levels down to the definition of targets in the form of benchmark values or design patterns (SUL). SPeAR does not specify design indicators or benchmark values and only defines what should be evaluated and why, leaving the system open for application in many different contexts. CityCAD and INDEX consist of collections of design indicators associated to urban issues without a complete hierarchical organisation. These gaps in the SUD evaluation structure force conceptual jumps in the construction and interpretation of a system of indicators, making it difficult to link the specific measurements of urban form to a general understanding of progress towards sustainability.

§ 2.5.3 What are the tools measuring?

We now look at the content of the tool's indicators to understand what they are measuring, and to what extent it is relevant to the early design stages of urban area development. We do so using two 'lenses': one, to view to what extent the tools measure the sustainability of an urban area; the other, to view to what extent they measure the design outcome. The first 'lens' is illustrated in Figures 2.3 and 2.4.

Figure 2.3 shows the representativeness of each pillar of the TBL amongst the indicators of a tool. Since few tools start from the TBL this measure was inferred from the content and phrasing of each indicator. All the tools cover the three pillars of sustainability, except for LEED-ND that lacks any indicator explicitly addressing the economic dimension. On the other hand, the social dimension is well represented in every tool, demonstrating the importance that social aspects have to urban area development.

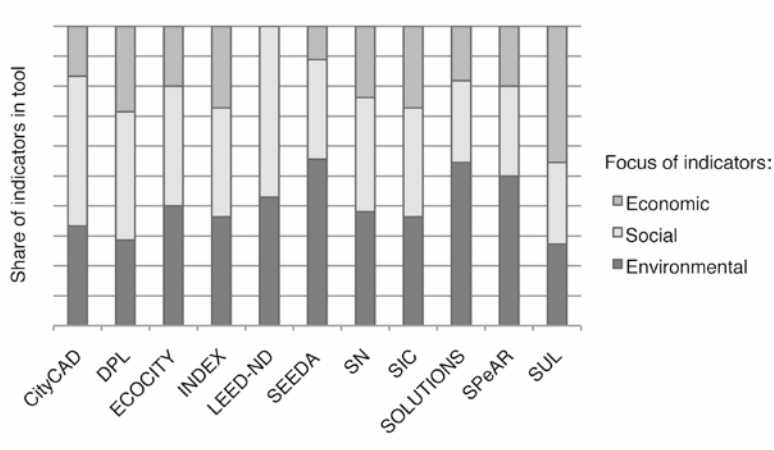


FIGURE 2.3 Representativeness of the three pillars of sustainability in the selected SUD evaluation tools. The bars indicate how many times each pillar is addressed by an indicator.

Figure 2.4 shows the share of indicators that address building design details, the urban context and the planning process. Most tools include 25% or more indicators addressing building design issues, showing that they have directly evolved from or incorporate building evaluation frameworks (LEED-ND, SEEDA, SIC, SPeAR). Only the SOLUTIONS tool has no indicator of building design, demonstrating its focus on the planning scale. When it comes to urban context, such as the immediate surroundings of an urban area or its location within the city, CityCAD and ECOCITY fail to address it. CityCAD takes as input the design of the master plan and no other contextual information. It also lacks any indicator specifically about the planning process, alongside DPL, INDEX and SOLUTIONS, in contrast with the tools that have involved government institutions or are strongly based on local policy (ECOCITY, LEED-ND, SEEDA, SN). However, one can argue that all the SUD evaluation tools reviewed support an interactive and communicative planning process and their use should provide implicit demonstration of that concern by the urban development team. INDEX, in particular, provides an extensive description of how the tool integrates into the various stages of the planning process.

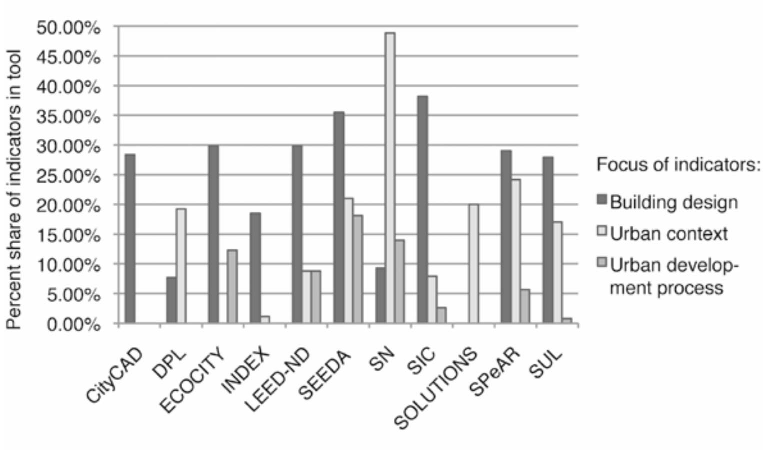


FIGURE 2.4 Percent share of indicators that demonstrate how far the tools have evolved from building energy assessment tools to urban design assessment tools. Less building design related indicators, and more urban context and development process indicators, demonstrates a tool oriented towards urban design evaluation.

The second 'lens' is illustrated in Figure 2.5. It shows the extent to which the indicators are measuring the urban design outcome, supporting an iterative design process where stakeholders are capable of assessing different design alternatives and designers more readily understand the implications of their actions. In general, the tools considered for review have more than 40% of indicators measuring urban form, especially CityCAD, INDEX, SOLUTIONS and SUL, with the exception of SEEDA. And if we combine these urban form indicators with those assessing aspects of the sustainable planning process, all tools display more than 50% of relevant indicators. This was one of the last selection criteria applied to the list of tools in Table 2.2, where those with an asterisk have shown less than 33% of relevant indicators.

In contrast, Figure 2.5 also shows indicators that measure externalities of the urban design process, and ones that would only be applicable for assessing the existing conditions or ex-post for monitoring the development progress. Only SUL has no indicator addressing design externalities because its focus is on design principles and design codes, while SN has the most, such as 'sense of community' and 'healthy life styles' that cannot be measured from the urban design output alone. When it comes to addressing different stages of the planning process, DPL has 30% of its indicators requiring survey data of existing population, employment, crime and pollution, or questionnaires of residents that would only be obtained in the monitoring stage of urban development.

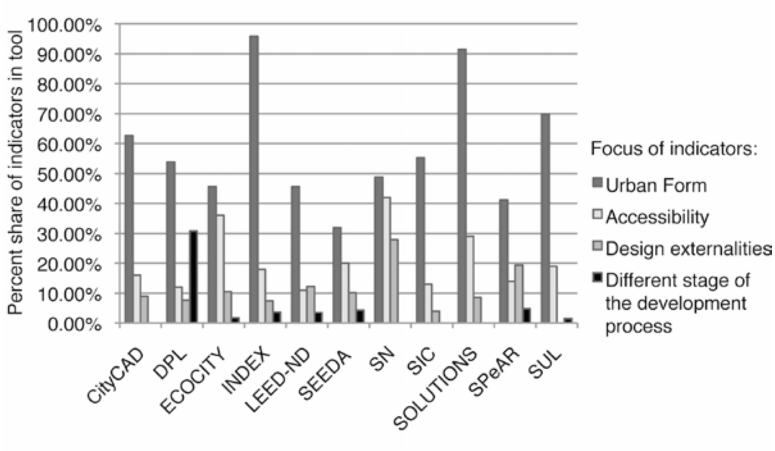


FIGURE 2.5 Percent share of indicators that demonstrate to what extent the tools measure directly aspects of urban form. More urban form and accessibility indicators, and less indicators measuring design externalities or different stages of the development process, demonstrates a tool with high potential of interaction with the design team.

§ 2.5.4 Output of the evaluation results

The final stage of this analysis is to consider the output of the SUD evaluation, looking at the multi-criteria features and at the graphical output, summarised in Table 2.4. All the evaluation tools reviewed are based on disaggregate systems of indicators and one should expect them to provide multi-criteria features for dealing with weighting, aggregation, synergies and benchmarks of the indicators.

Regarding weights and aggregation, an essential aspect of MCA, five tools feature them explicitly, either hardcoded in the model (LEED-ND, SEEDA, SOLUTIONS) or customisable for each project (DPL, INDEX). The custom option is preferable because determining the weights is a task of the evaluation process eventually more important than the results, in promoting the discussion between stakeholders and in keeping the aggregation transparent (Hacking and Guthrie, 2008). Where the tools lack such features, one should use an external MCA method.

Another important feature that should be addressed in systems of indicators are the synergies or interrelations between indicators. One approach is to build these relations into the evaluation models, making certain indicators depend on the results of others, or duplicating indicators under different issues to propagate their impact (DPL, LEED-ND, SPeAR). Another approach is to explain the issue without attempting to resolve it. Design guides make the relations explicit in tables and diagrams mapping the overlaps between different levels of the system's hierarchy (ECOCITY, SN, SOLUTIONS), or cross-referencing related assessment criteria, indicating their link to different issues and other criteria (LEED-ND, SN, SUL).

Another approach is to use indicators that involve multiple aspects of urban form, e.g. non-residential density combines land use and density. Accessibility indicators are particularly integrative in relating urban layout, mobility infrastructure, density and land use (Dempsey et al., 2008). This means that a change to any of the urban form dimensions involved will have an impact on the measurement results. Accessibility indicators are present in every tool (see Figure 2.5) and in the case of ECOCITY and SN represent almost all urban form indicators.

TOOL	WEIGHTS	AGGREGATION	SYNERGIES	BENCHMARKS	STANDARD OUTPUT
CityCAD	-	-	-	-	Map, Table, Chart, Report
DPL	Custom	Issue	Buil-in	Fixed	Chart
ECOCITY	-	-	Diagrams	Fixed	Chart
INDEX	Custom	Full	-	Custom	Map, Table, Chart
LEED-ND	Fixed	Full	Buil-in	Fixed	Label
SEEDA	Fixed	Issue	-	Fixed	Chart, Table
SIC	-	-	-	Fixed	-
SN	-	-	Diagrams	Fixed	-
SOLUTIONS	Fixed	Criteria	Diagrams	Fixed	Chart, Table
SPeAR	-	Issue	Buil-in	-	Chart
SUL	-	-	References	Fixed	-

TABLE 2.4 Summary of the output characteristics of the selected SUD evaluation tools.

Regarding benchmark values, most tools offer fixed sets of levels to test the indicators against. INDEX is the only tool that offers an open platform where these benchmarks are defined early on, as part of the planning evaluation process.

Finally, we make a brief reference to the graphical output offered by the selected tools. Most tools feature a standard chart to summarise the result, acknowledging the importance of communicating the results clearly, succinctly and to a wide audience. Because of the complexity of the subject matter, and in an attempt to avoid masking the multi-criteria nature of the evaluation process, the preferred chart is the multi-level pie chart for which SPeAR became known (Carmona and Sieh, 2008), with small variations between the different tools. The tools based on graphical software platforms, CityCAD and INDEX, feature the possibility of mapping the results in a 2D or 3D representation of the urban area, offering spatial disaggregation of several indicators. We perceive this as essential information for urban design teams, because it reports directly on the design outcome and increases the level of interaction of the tools.

§ 2.6 Discussion

In this final section of the article, we make a series of general recommendations regarding the development of SUD evaluation tools for urban design practice, based on the findings of the analysis of tools and the recommendations of planning evaluation theory.

Starting from the proposition that there is a gap between theory and practice (Alexander, 1997; Khakee, 2003), this review seems to confirm it to some extent. If we look back at Table 10 and focus on the institutions involved in the development of the different tools, we find that only in two (closely related) cases was there direct collaboration between industry and academia, and in another case between government and academia. Academic initiatives are independent and government, industry and NGOs form partnerships. Of course, there are references to policy and to academic research in some of the tools reviewed, and some of the research projects listed in Table 9 have included consultation of different stakeholder groups. But this influence should be reinforced in future generations of SUD evaluation tools to achieve greater conceptual robustness. We propose a four-goal strategy: **Collaboration, Compatibility, Customisation and Combination.**

To start, there should be **Collaboration** between different types of institutions, because the theory/practice gap also seems to be one of direct involvement in each other's activities. The aim of collaboration is not necessarily to remove this theory/practice gap by aligning individual practices, but to create bridges for knowledge transfer and to offer opportunities for cross validation of knowledge and practices in real contexts (Alexander, 2006). We have seen such initiatives in the past, such as the UrbanBuzz programme in the UK (http://www.urbanbuzz.org/).

The aim of **Compatibility** is to develop accepted SUD definitions into a standard theoretical framework of SUD principles and issues, which would offer clarity and legitimisation to the evaluation tools that adopt them (Carmona and Sieh, 2008; Walton et al., 2005; George, 2001; Oliveira and Pinho, 2010). These high-level standards would be used for top down structuring of the systems of indicators, as shown in Figure 2.1, linking the sustainability dimensions to the design indicators and benchmark values. The results from these systems would be more compatible and comparable (Archibugi, 2006). With such a starting point, one might avoid the pitfalls of calculation tools that offer a long list of indicators driven by the available data and what can be calculated with given the software platform, resulting in data rich and information poor evaluations (Carmona and Sieh, 2008).

Obviously, complete standardisation is not possible, nor desirable (Carmona, 2003), and should be complemented with **Customisation** at the detail level of indicators and benchmark values to address the complexities and specificities of urban design projects and of the local context (Mitchell, 1996). Otherwise SUD evaluation tools can include design principles that are not universally accepted, require data that is not available locally, or include indicators and benchmark values that are not relevant to the specific geographic, policy or project context.

It is unlikely that Compatibility and Customisation lead to convergence into a single tool. Therefore, the **Combination** of tools and methods is advisable. One should consider the use of different tools by different stakeholders, or at different phases of the development process (Levett-Therivel, 2004), as long as they are compatible. If the tools start from a common standard theoretical framework it becomes easier to choose complementary methods, such as indicator systems, MCA, EIA or SEA, as recommended in integrated evaluation frameworks (Archibugi, 2006). At another level, combination should enable the pairing of different tool formats, namely the design guide and the calculation software (see Table 2.3). The former offers sound theory and a universally accessible format, the latter offers operational and interactive qualities for design support with effective output for communication. As Alexander (2006) concludes, the solution is to blend both extremes in a process that integrates sound knowledge and effective communication.

§ 2.7 Conclusions

The present article has reviewed the state-of-the-art in SUD evaluation tools that are suitable for application at the early stages of urban area design and development. It identifies a set of eleven tools based on systems of indicators, confirming the preference for this evaluation method for application in practice at the scale of the urban area. The review then applies an analytical framework to the selected tools, following recommendations of planning evaluation theory and requirements of practice. This covers aspects of their format, structure, content and output, and reveals a very diverse picture with some general trends but no single tool standing out as the 'right one' to use, especially in terms of sustainability framework structure. Each tool shows strengths and weaknesses, leaving urban design teams interested in using an evaluation tool in their project with the option to adopt the tool with the content most compatible with the local geographic or policy context, or a tool that better supports the design process with the most convenient input, platform and output options.

To conclude, the review explores the gap revealed between theory and practice in the development of SUD evaluation tools, where collaboration between academic and other institutions is most rare. It proposes a strategy for the development of future tools around four goals: Collaboration, Compatibility, Customisation and Combination. This strategy should facilitate the development of tools that are more robust and compatible in terms of sustainability principles, but also flexible in adapting to the local context. These could form a collection of different but compatible tools and methods that can be more readily combined to offer comprehensive planning evaluation frameworks, catering for the different expertise of the various stakeholders and the various stages of the SUD process.

3 On the discovery of urban typologies: data mining the many dimensions of urban form[2]

Abstract.

The use of typomorphology as a means of understanding urban areas has a long tradition amongst academics but the reach of these methods into urban design practice has been limited. In this paper we present a method to support the description and prescription of urban form that is context-sensitive, multi-dimensional, systematic, exploratory, and quantitative, thus facilitating the application of urban typomorphology to planning practice. At the core of the proposed method is the k-means statistical clustering technique to produce objective classifications from the large complex data sets typical of urban environments. Block and street types were studied as a test case and a context-sensitive sample of types that correspond to two different neighbourhoods were identified. This method is suitable to support the identification, understanding and description of emerging urban forms that do not fall into standard classifications. The method can support larger urban form studies through consistent application of the procedures to different sites. The quantitative nature of its output lends itself to integration with other systematic procedures related to the research, analysis, planning and design of urban areas.

2 This chapter is based on the manuscript of: Gil, J., Beirão, J.N., Montenegro, N., Duarte, J.P. (2012). 'On the discovery of urban typologies: data mining the many dimensions of urban form'. Urban Morphology 16 (1), pp.27–40. (Main author, 85% contribution)

§ 3.1 Introduction

The use of typomorphology as a means of understanding urban areas has a long research tradition (Moudon, 1994, 1997). However, the reach of these methods into urban design practice has been limited (Hall, 2008), encountering resistance in the established urban development processes and within the architecture and planning communities (Samuels and Pattacini, 1997; Trache, 2001). This is despite recognition of the importance of typology-driven approaches in achieving responsive and responsible urban environments (Habraken 1988; Kelbaugh 1996; Rapoport, 1990; Samuels 1999) and increased interest in their application in urban design and education (Beirão and Duarte, 2009; Lee and Jacoby, 2011; Parish and Müller, 2001).

Several possible causes are advanced by the various authors: first, the analytical process is laborious and not entirely objective; secondly, the classic urban typomorphology studies are based on very specific geographical regions and focus on restricted urban form traditions; thirdly, more work is required on recent city forms (Maller, 1998); and fourthly, there is a need to integrate different morphological approaches to obtain a more complete and complex set of urban environmental attributes (Conzen, 2010; Osmond, 2010; Wineman et al., 2009). When type is applied to practice other problems are identified. These include a lack of conceptual rigour and incomplete understanding of the typological approach; a difficulty in going beyond a type's superficial traits; and an ignorance of the deeper significance and history of specific types (Grant, 2001). In particular, Shane (2011) identifies the current challenge to the typological urban design approach posed by very rapid large-scale urbanization in non-Western countries and the increasing number of informal settlements. He doubts the existence of typologies suitable for those specific contexts and the adequacy of the methods in research and practice to cope with the dynamic nature of the problem.

The use of computer technology to support urban morphological studies and to build bridges to contemporary urban design processes is essential and its effectiveness has been shown in data analysis and the visualization of urban form at all scales (Lee et al., 2006; Lo, 2007; Moudon, 1997; Osmond, 2010).

In this paper a method is presented that supports the description and prescription of urban form in typomorphological studies and typological urban design processes. The goal is to facilitate the application of urban typomorphology in planning practice by developing a method that is context-sensitive, multi-dimensional, systematic, exploratory, and quantitative. The proposed method takes a large number of attributes of the characteristics of a given urban area, uses data mining techniques to reveal the block and street types present in that area and presents the results in a detailed quantitative format amenable to application in parametric modelling of urban design. At the core of the proposed method is the k-means statistical clustering technique that deals with large complex data sets typical of urban environments and produces objective classifications that are site and project specific and not derived from previously defined types. The proposed method thereby helps to reveal the intrinsic nature of local types and identify previously unknown morphological types.

The paper is structured as follows. Firstly, the application of quantitative methods to urban form classification is reviewed, introducing the concept of data mining as a technique for multivariate classification that can be applied to architecture and planning. The stages in the proposed typological exploration method are then described, explaining the various operations and the outcomes of each stage. In the following section, the results are presented of a test case that demonstrates the capability of the method to identify different types that are consistent with two distinct urban fabrics. The discussion focuses on the possibilities and benefits of applying the proposed method to typomorphological research and typological urban design practice. In conclusion the method is assessed, highlighting strengths and shortcomings and considering possible future work.

§ 3.2 Quantitative classification of urban typologies

Several urban form studies provide detailed analysis, description and quantification of urban environments, offering different methods to classify urban entities in order to obtain urban typologies in search of a better understanding of city form and its qualities. Some focus on the typologies of neighbourhoods (Peponis et al., 2007; Wineman et al., 2009) or identification of 'urban structural units' (Haggag and Ayad, 2002; Osmond, 2010). Others focus on the overall form of settlements (Marshall and Gong, 2009). Here we shall concentrate on studies that address the components of these larger scale entities, namely the urban block and the street.

Urhahn and Bobic (1994) identify principles of good city life and catalogue urban neighbourhoods through a quantitative and qualitative description. The study covers several scales, from city to district, block and building, and includes different classification bases, namely form, density, land use, and mobility infrastructure. The final presentation of the typology is textual for more complex dimensions, such as urban context and accessibility, but it is quantitative for the built form dimensions. Overall it is highly visual, displaying the various attributes of each area in a disaggregate format. Interestingly, they formally ignore the street as a classification entity, although it receives a brief mention in some descriptions.

Streets receive full attention from Stephen Marshall (2005), underlining the importance of urban layout and configuration for urban quality. He exposes the limitations of certain classifications and catalogues of types as they offer a univariate interpretation on a theme, resulting in a fragmented view. Marshall uses quantitative attributes relating to configuration, composition, complexity, and constitution of streets, combined in triangular multivariate charts, to define street typologies.

Berghauser-Pont and Haupt (2004, 2010) take a similar multivariate approach in relation to urban blocks around the theme of development density, using a set of four indices. A novel aspect is that they create an interactive on-line tool so that users can systematically measure neighbourhoods and compare them with the ones in the main catalogue, thus classifying new designs or identifying new typologies (http://www.permeta.nl/spacemate/index2.html). They restrict their themes to three or four variables in order to achieve a way of defining and visualising the typology. However, other methods allow a higher dimensional classification of types.

§ 3.2.1 Systematic classification using data mining techniques

The data mining process is characterized by a recursive withdrawal procedure supported by a statistical platform leading to information discovery, and is commonly used to perform three different tasks (Fayyad, 1996): first, classification – arranging the data into predefined groups; secondly, clustering – where the groups are not predefined and the algorithm creates natural groups of similar items; and thirdly, regression – to find a function that models the data with the least error.

Technically data mining is the process of finding data correlations or data patterns amongst dozens of fields in large relational databases. Data mining seems to facilitate the discovery of data patterns that would be very difficult, if not impossible, to reveal by manual means and to quantify. The relevance of these techniques to urban morphological research and design is that they allow the users to analyse the complex urban environment from different angles simultaneously, categorize it, and summarize the relationships identified.

Recent studies use clustering as a classification technique in the comparative study of buildings: for example, in defining archetypal office building layouts (Hannah, 2007), and Arabic house types (Reffat, 2008) and in identifying residential building types according to energy use, correlated with building age (Alexander et al., 2009). At the urban scale there have been studies on urban block shape and density (Laskari, 2008), of neighbourhoods (Thomas et al., 2010) and of whole cities (Crucitti et al., 2006; Figueiredo and Amorim, 2007). These examples demonstrate that the use of techniques of semi-automatic classification of data patterns according to multiple variables reveals building and urban form types in a systematic way. The method we propose focuses on the identification of individual block and street types using a k-means clustering technique, which is described next.

§ 3.3 A method for the discovery of urban form types

The method for identifying urban form types based on data mining techniques uses the recommendations in Witten and Frank (2005). It has three main phases: representation, analysis and description. These are broken down into the following tasks:

1. Representation
   a. Preparation of the plan
   b. Selection of classification attributes
2. Analysis
   a. Spatial analysis of the plan
   b. Statistical clustering of attributes
3. Description
   a. Statistical profiling of types
   b. Semantic description of types

§ 3.3.1 Representation

The representation phase involves the preparation of the geometric data of the plan and the selection of classification attributes. The information can be gathered in a geographical information system (GIS) to facilitate management, analysis and visualization of the large amounts of data, although it could conceivably be done in other platforms.

The selection of classification attributes is an important step in the process and it is essential to reach agreement on which attributes to use to describe the urban form, how they relate to performance, and how to calculate them. Because different attributes give different meanings, one needs a meaningful set tailored to address the specific problem in order to obtain useful typologies. 'The best way to select relevant attributes is manually, based on a deep understanding of the learning problem and what the attributes actually mean' (Witten and Frank, 2005, p. 289).

There is not a right or wrong set of attributes. But there are different perspectives (Habraken, 1988; Marshall and Gong, 2009); focusing on structural, geometric, relational, physical, stylistic, historical or socio-economic characteristics. One of the benefits of this method is the ability to combine a large and varied set of attributes originating from different aspects of urban morphology, thus facilitating an integrated approach (Conzen, 2010).

§ 3.3.2 Analysis

In the analysis phase the attributes of the site plan are measured the importance and relation between these are evaluated statistically. After completing spatial analysis it is important to visualize the individual urban form attributes through maps, as it helps the verification of representation or calculation mistakes. This is also a first step in becoming familiar with the individual morphological characteristics. At this stage, traditional urban morphological studies resort to town-plan analysis to understand and describe the urban environment (Maller, 1998; Osmond, 2010), but this is when clustering becomes a useful support method by analysing all the attributes simultaneously.

Before proceeding it is still necessary to transform the attributes to obtain a normal distribution of values required by most statistical operations and perform pair-wise correlations to identify and exclude dependent attributes, which would bias the study towards their specific theme.

A classic k-means clustering technique (Witten and Frank, 2005, p.137) is then applied to identify urban form types within the given area. Clustering allows the classification of instances in multi-dimensional space where there are no classes defined beforehand. The k-means algorithm, as found in most standard statistical analysis packages, is a partitioning process that subdivides a large data set into a k number of clusters seeking to minimize the mean distance between all members of each cluster. To determine the best number of clusters (k) one can use a scree plot. This chart plots the sum of squared distances of every instance to its cluster centroid, for all clusters and for an increasing number of clusters. As the number of clusters increases, this distance will naturally decrease. As a result of the k-means clustering analysis, for every element in our plan, the cluster number it belongs to and its distance to the cluster's centroid are obtained. This allows the most central element of the cluster to be selected as an archetype.

§ 3.3.3 Description

The description phase translates the results of the clustering process into urban form types using a quantitative profile and a semantic definition; two formats that are useful for urban analysis and design. To facilitate the description process we translate the attributes, which in most cases are continuous numerical values (for example, area or length) into classes of values. This is called data discretization (Witten and Frank, 2005, p.296) and can be achieved with quantiles, equal intervals, natural breaks or domain knowledge classes. Ideally there are domain knowledge classes that are meaningful to the community of experts or practitioners.

The quantitative profile of each urban form type indicates the range of values of the various attributes and their composition in terms of classes of values. For the semantic description of the types we only focus on those characteristics that are dominant or unique in order to highlight the specificities of each type.

§ 3.4 Demonstrating and testing the method

The method presented in the previous section is now applied to an urban data set for demonstration purposes and to test whether it offers the desired characteristics: context-sensitive, multi-dimensional, systematic, exploratory and quantitative.

The test case consists of two neighbourhoods in Lisbon, Portugal, that are adjacent but different in character. he first is the Expo 98 PP4 site, the northern part of the 1998 world exhibition site, which is a contemporary neighbourhood, planned from scratch on a brownfield site and developed over the first decade of the twenty-first century. The adjacent Moscavide is a neighbourhood founded in 1928 and developed more slowly over the following decades: it has suffered from densification, in particular inside the urban blocks, owing to a strongly bounded location without room for expansion. Can this method identify different urban form types between these two sites?

§ 3.4.1 Representation

We first prepare the features describing the two neighbourhoods, both in terms of geometry and plan information (Figure 3.1), and load these data layers in a GIS:

- **Building**: any built-up object, both public and private.
- **Open space**: empty space within blocks, both public and private.
- **Plot**: the legal boundary of a property, containing buildings and open space
- **Block**: group of plots and private or public open space, forming an island surrounded by the transport network.
- **Pavement**: the public space between the blocks and the roads.
- **Road centre line**: linear representation of the street network.

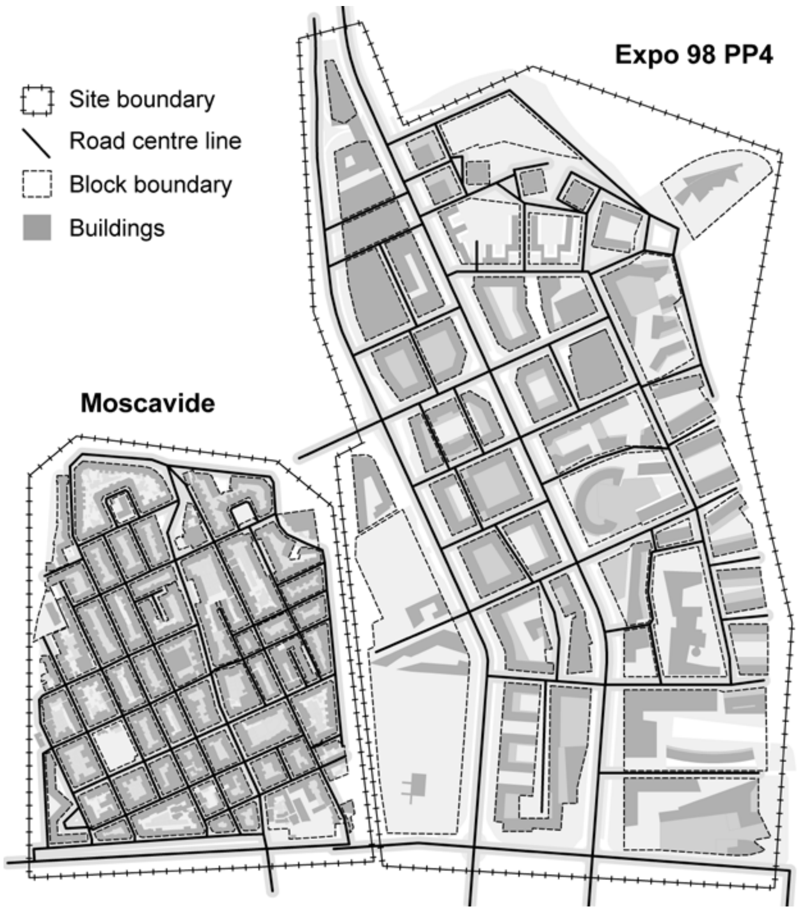


FIGURE 3.1 Plan of the two test areas (Moscavide and Expo98 PP4)

We then select a combination of different types of characteristics to demonstrate the potential for multi-dimensional and interdisciplinary urban morphological studies (Table 3.1). This includes built form and open space dimensions for blocks and streets, density metrics for blocks, and network configuration metrics for streets (Berghauser-Pont and Haupt, 2009; Figueiredo and Amorim, 2005; Hillier, 2007; Marshall, 2005).

ENTITY	ATTRIBUTE	THEME	CODE	CALCULATION
Block, street	Length	Dimension	LEN	m
	Width	Dimension	W	m
	Orientation	Dimension	DIR	degrees
	Solar orientation	Dimension	SOLO	N,S,E,W
	Number of buildings	Density	BLDN	integer
Block	Area	Dimension	TA	m2
	Built-up area (footprint)	Dimension	BA	m2
	Gross floor area	Dimension	GFA	m2
	Perimeter	Dimension	PER	m
	Proportion	Shape	PROP	LEN / W
	Area perimeter ratio	Shape	APR	TA / PER
	Floor area ratio	Density	FAR	GFA / TA
	Ground space index	Density	GSI	BA / TA
	Layers (number of floors)	Density	L	GFA / BA
	Open space ratio	Density	OSR	(TA-BA)/GFA
	Private space area	Land use	PRVA	m2
	Public space area	Land use	PUBA	m2
Street	Pavement width	Land use	PAVW	m
	Pedestrian area	Land use	PEDA	m2
	Connectivity	Network	CON	Degree
	Continuity (angular)	Network	CNT	Degree
	Global accessibility	Network	ACCG	Closeness
	Local accessibility	Network	ACCL	Closeness
	Global movement flow	Network	MOVG	Betweenness
	Local movement flow	Network	MOVL	Betweenness

TABLE 3.1 The block and street characteristics selected for analysis and for typological classification.

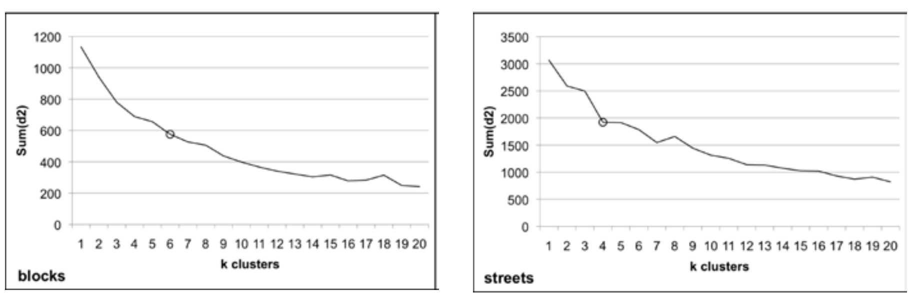
§ 3.4.2 Analysis

Using GIS, we perform spatial analysis operations to obtain all the required attribute values listed in Table 3.1 and produce maps of the individual attributes of blocks and streets (Figure 3.2). This information is used in the classification of urban form types, but after inspection of the maps it becomes clear that individual characteristics are unable to capture the different character of the two neighbourhoods. One would normally resort to a subjective and laborious process of cross-referencing the various maps to piece together a collection of possible urban form types or to match the instances in the plan to the types of a pre-defined typology.

1 2

FIGURE 3.2 Blocks distinguished according to 1) area (TA) and 2) floor area ratio (FAR). From individual morphological characteristics it is not possible to distinguish the different neighbourhoods or identify prevalent types.

Using the proposed method, we run the clustering analysis on all attributes simultaneously and obtain sets of block and street clusters with different numbers of classes (k) each. To select the most suitable number of classes we produce a scree plot (Figure 3.3) and choose the smallest k where the plot shows a kink after which the curve becomes flatter.



1 2

FIGURE 3.3 Scree plot of 1) blocks and 2) streets clusters. The circle indicates the selected k number of clusters.

As a result we obtain six clusters of blocks and four clusters of streets, where each cluster represents an urban form type. To verify whether the distinction between types is clear we create a map of the blocks and one of the streets distinguishing the cluster identification number of each instance (Figure 3.3). Visual inspection of the cluster instances on the plan of the urban area demonstrates the extent of typological overlap between neighbourhoods. Some blocks in Moscavide are more recent and correspond to the types found in the Expo 98 site, and some street types, such as the cul-de-sac, are universal and can be found in both areas.

1 *2*

FIGURE 3.4 The six block clusters (1) and the four street clusters (2). The different types belong to the different neighbourhoods and only a few types occur on both sites – these are more recent blocks in the Moscavide neighbourhood that do not follow its traditional urban form, and street types that are more universal such as the cul-de-sac.

§ 3.4.3 Description

The resulting clusters can be described quantitatively and semantically to convert them into meaningful and useful urban form types. The quantitative descriptions of the types include a series of reference values - maximum, minimum and mean - of each attribute in a given type, and the representation of the type in a profile chart (Figure 3.5). To achieve this the range of values of each attribute is separated into quartiles. In the profile chart each attribute is represented by a bar displaying the share that it has of each class of values (high, medium-high, medium-low and low) in a particular type.

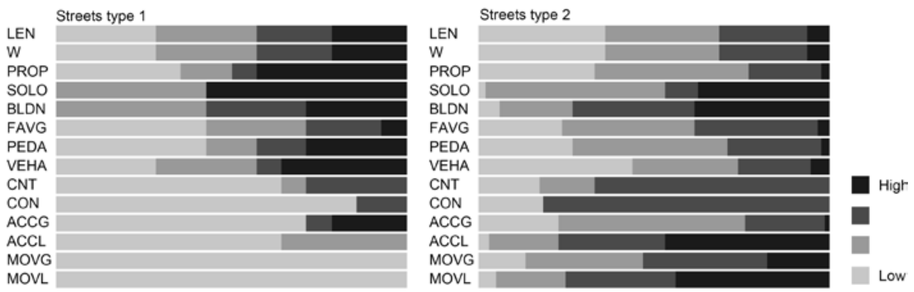


FIGURE 3.5 Sample profile charts for streets of types 1 and 2. These charts show the characteristics make that differentiate between types (box A). The traits of a type that is dominant (box B) or unique (box C) are also identified.

A quantitative analysis of the profile chart provides the dominant and unique characteristics of a type. Dominant characteristics are considered to be those that have a 70 per cent or higher share of a single class value – for example, 94 per cent of type 3 blocks have an area of public space classified as very low. Unique characteristics are regarded as being those that have a class share that is 50 per cent above or below the average of that class among all types: for example, only 6 per cent of type 2 blocks have very low open space ratio as compared with the average of 48 per cent. The various dominant and unique characteristics are translated into a succinct description of the six block types and four street types (Table 3.2) and are presented together with a sample of the 'archetype' blocks and streets (Figure 3.6), where we define 'archetype' as the instance in each type that is closest to the centre of its cluster.

FEATURES	TYPE	DESCRIPTION
Blocks	1	Closed block, medium density with private courtyard only
	2	High density, compactness and pressure on open space
	3	Low density with private open space
	4	Open block of medium density with privileged public space
	5	Open public space with no built-up area
	6	Large, low density block with equipment and associated public space
Streets	1	Very low or no continuity and movement flow
	2	High connectivity and continuity streets
	3	Low continuity streets
	4	Long streets with wide pavements and high average of tall buildings

TABLE 3.2 Description of block and street types based on their dominant and unique characteristics.

TOC

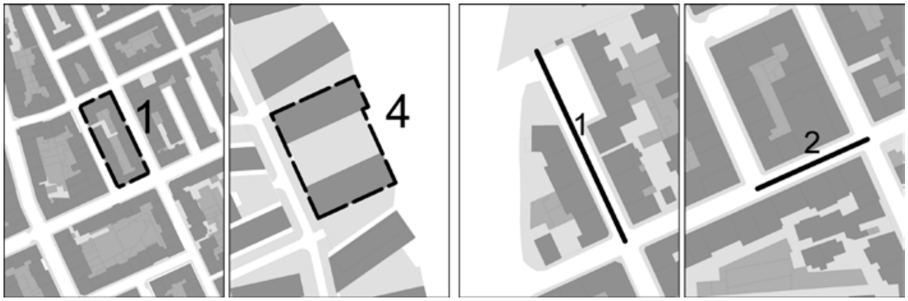


FIGURE 3.6 Plan of the archetypes of block types 1 and 4 and street types 1 and 2, as described in Table 3.2

§ 3.4.4 Results

The results of applying the proposed method to the test case are encouraging because it has been possible to classify the blocks and streets in a meaningful way that identifies the two neighbourhoods. By statistically correlating the instances of the types to their neighbourhood, Expo 98 or Moscavide, the degree to which the types are characteristic of a neighbourhood can be observed. We find that some types clearly correspond to one of the areas, while a few types have an even share of instances in both areas; for example, 'Block type 3' and 'Street type 3' (Table 3.3). The overall coefficient of determination (R^2) between clusters and neighbourhoods is 0.67 for the block clusters and 0.58 for the street clusters, where a value of 1 would correspond to complete identity between the two variables.

FEATURES	TYPE	TOTAL INSTANCES	EXPO 98 (%)	MOSCAVIDE (%)
Blocks	1	45	0.00	100.00
	2	16	93.75	6.25
	3	17	52.94	47.06
	4	22	90.91	9.09
	5	2	50.00	50.00
	6	2	100.00	0.00
Streets	1	14	28.57	71.43
	2	96	3.13	96.88
	3	44	63.64	36.36
	4	66	95.45	4.55

TABLE 3.3 Percentage of block and street instances from the two neighbourhoods present in each type.

§ 3.5 Discussion

Using the method described in this paper it has been possible to identify a series of different block and street types that correspond to two different neighbourhoods, creating a context sensitive sample of types. This method is thus suitable to support the identification, understanding and description of emerging urban form types that do not fall into standard classifications either because they are in new urban areas, or in informal settlements, or in cultures and geographical locations that have not been studied before. The method is systematic and can support larger studies through consistent application of the procedures to wider areas or different sites. It facilitates the process of grasping the complex relations of attributes. However, it is important to recognize that skill is required in the selection of attributes and in the interpretation of the results.

The method can support site-specific and project-specific sets of urban form attributes. The set of attributes used in the test case is by no means optimal or finite and can be customized according to the requirements of the specific research or urban development project. For example, the temporal dimension, frequently used in the form of building age or historic period, was explicitly excluded from the test set so that it could be used for validation of the results, but in other cases it can be included as a classification attribute. However, it is necessary to consider the possibility of defining a basic set of attributes that can be consistently applied by different people across various projects and locations irrespective of their local significance. This is a requirement for larger comparative morphological studies and for the identification of more universal types (Marshall and Gong, 2009). Since the proposed method can operate with a very large set of attributes, it would support an integrated approach using attributes from different pieces of urban morphological research. One of the outputs of quantitative typological profiling is the degree of significance of each attribute within the local sample. This contributes to the contextual nature of the method despite having started with a more general set of attributes.

Finally, the quantitative nature of the output lends itself to further integration with other systematic procedures related to research and analysis or to planning and design of urban areas. An example of the first case is the definition of 'urban structural units' (Haggag and Ayad, 2001; Osmond, 2010) or other types of neighbourhoods that should be characterized by typological homogeneity. Once a local set of types has been identified using the proposed method, the boundaries of those analytical areas can be more easily defined, either visually or using computational methods such as spatial clustering. With regard to the second case, integration with planning and design practice, this method can be applied when the objective is to use a context-sensitive typological approach based on precedents: on the one hand, supporting the creation or expansion of design pattern libraries; on the other hand, providing numerical constraints in the form of parameter values that produce varied solutions that fit the existing context or the specific urban programme.

§ 3.5.1 Parametric rule-based design structures

The results of the proposed method can be used to extract the characteristics of local types to build parametric rule-based design structures. Such a design approach is being developed as part of the City Induction research project (Duarte et al., 2012), in which design patterns are codified into a small parametric shape grammars (Stiny and Gips, 1972) and stored in a design pattern library (Alexander et al., 1977). Each pattern grammar encodes information related to the quantitative descriptions of the corresponding type and its rules and parameters can be manipulated for applying the same type in a new design. As the quantitative description specifies ranges for the attribute values, the reuse of types in design seems a way of guaranteeing context-sensitive solutions while maintaining reasonable design flexibility.

The use of a pattern-based system for generating urban designs has been shown by Beirão et al. (2011). They propose two different design patterns based on shape grammars; one for generating street grids and another for defining urban blocks with varying sizes. These patterns are applied in sequence so that after the grid is generated, two different types of blocks are distributed according to their location on the grid. These blocks adapt to the size of the grid cells according to the parametric shape grammar rules used to encode them. The method proposed in this paper could be used to refine and extend the design pattern library by extracting accurate information regarding the context in which the blocks types can be applied, and by identifying other types from existing situations. This would help to generate more adequate and more complex designs.

§ 3.6 Conclusions and further work

In this paper a method has been described that supports the understanding of urban areas through urban typomorphological analysis and results in the description and prescription of urban types. The proposed method has the following characteristics that are important in facilitating the application of urban typomorphology to planning practice:

- Context-sensitive to geography and culture;
- Multi-dimensional, considering an array of urban form characteristics;
- Systematic, for replication in comparative studies of different urban areas and/or to be carried out by non-expert teams under expert supervision;
- Exploratory, offering a 'blind' discovery of types independent of pre-existing classifications or taxonomies of types;
- Quantitative, amenable to translation into parameters and rules.

Ultimately, it offers a method of creating urban form typologies derived from the local characteristics of a place and tailored to the objectives of a given project.

However, a consistent framework of urban form characteristics is needed to make the link between the generated types and urban environmental quality (Marshall and Gong, 2009; Osmond, 2010). Further research is required to define this framework with a more complete set of attributes related to socio-economic characteristics, such as population demographics and land use, or to the building's surface characteristics, such as entrance types and façade transparency. These types of indicators may allow us to identify relations between socio-economic data and morphological characteristics of the urban fabric.

Testing the proposed method in urban design seems to offer a promising research avenue and can be first introduced in urban design education within the context of design studios. Considering the difficulties of students during the pre-design phases of the urban design process, the proposed method could complement the urban design method described by Beirão and Duarte (2009), as it provides an enhancement of the analytical phase and complements the synthesis phase by introducing a systematic way of developing design patterns.

4 Building a Multimodal Urban Network Model Using OpenStreetMap Data for the Analysis of Sustainable Accessibility[3]

Abstract

This chapter presents the process of building a multimodal urban network model using Volunteered Geographic Information (VGI) and in particular OpenStreetMap (OSM). The spatial data model design adopts a level of simplification that is adequate to OSM data availability and quality, and suitable to the measurement of the sustainable accessibility of urban neighborhoods and city-regions. The urban network model connects a private transport system (i.e. pedestrian, bicycle, car), a public transport system (i.e. rail, metro, tram and bus) and a land use system (i.e. building land use units). Various algorithmic procedures have been developed to produce the network model, supporting the reproducibility of the process and addressing the challenges of using OSM data for this purpose. While OSM demonstrates great potential for urban analysis, thanks to the detail of its attributes and its open and universal coverage, there is still some way to go to provide the data quality and consistency required for detailed operational urban models.

3 This chapter is based on the manuscript of: Gil, J. (2015). 'Building a Multimodal Urban Network Model Using OpenStreetMap Data for the Analysis of Sustainable Accessibility', In: Jokar Arsanjani, J., Zipf, A., Mooney, P., Helbich, M. (Eds.), OpenStreetMap in GIScience: Experiences, Research, Applications, Lecture Notes in Geoinformation and Cartography. Springer, Berlin, Heidelberg, pp. 229-251.

§ 4.1 Introduction

Sustainable accessibility policy goals are concerned with all modes of travel, and give particular attention to walking and cycling for local travel, and to multimodal travel using public transport over longer distances (van Nes, 2002). Studies on the relation between land use and travel patterns have, in the past, had a series of shortcomings (Stead and Marshall, 2001; van Wee, 2002), namely the use of aggregate descriptions of urban form, low spatial resolution, a small number of case studies and the difficulty in comparing the results and methods used. These can in part be explained by data sets' reduced geographic coverage or detail, by the cost of acquiring new or existing data, and by modelling and analytical constraints imposed by both software and hardware. Advances over the last decade in open geospatial standards, data collection and distribution, and in open Geographic Information System (GIS) and spatial analysis technologies allowed some of these shortcomings to be addressed, building urban models that are disaggregated, detailed, large scale, relational and reproducible (Jiang, 2011; 2013). Recent studies measure sustainable accessibility at the city and regional level by private and public transport modes (le Clerq and Bertolini, 2003; Bertolini et al., 2005; Yigitcanlar et al., 2007; Scheurer and Curtis, 2008; Mavos et al., 2012; Hadas, 2013) using rich GIS data sets. This type of measurement suits a map view (Goodchild, 2000): a static network model requiring a high level of accuracy in the location of and relation between features, consistent coverage and rich attribute data.

GIS-based multimodal network models are data models representing the mobility infrastructure of an urban area as a network, laying out the affordances available for travel using all modes of travel. Goodchild (2000) and Miller and Shaw (2001) have highlighted the challenges and laid out the principles of developing multimodal transportation data models for GIS. Some challenges specific to multimodal network representation relate to the data availability and its multiple formats, overlapping routes of similar or different modes on the same network, the modelling of transfers between modes, and the integration of travel costs on different modes.

There are numerous examples of detailed GIS multimodal network models that include data on public transport lines, services and timetables (Friedrich, 1998; Butler and Dueker, 2001; Li, 2007; Liu, 2011; Hadas, 2013), and even the internal layout and access points of public transport stations (Chen et al., 2011). These models are usually developed for navigation and route choice modelling, and their level of detail is higher than required to understand the general structure and configuration of multimodal networks (van Nes, 2002). Nevertheless, they offer approaches to address the connection between different modes, for example adding 'abstract connectors' in a single layer (Ismail and Said, 2014), or connecting multiple layers and systems for each mode (Mouncif et al., 2006), offering a robust and flexible data model that allows the analysis of each system in isolation (Galvez-Fernandez et al., 2009). Existing studies also highlight the importance of a correctly represented pedestrian network for measuring walking affordances, and propose methods for extending existing street network representations (Kim et al., 2009; Ballester et al., 2011).

This chapter presents the process of building a multimodal urban network model using the OSM street network data set as its main structure, onto which additional public transport and land use data sets are connected, using the case of the Randstad region of the Netherlands. The following sections describe the multimodal urban network model's structure, the selection and pre-processing of the various data sets used, and the procedures developed to integrate the various elements into a topologically consistent model. It concludes with results and reflections on lessons learned from the process, highlighting some of the current challenges in building urban analytical models using OSM data.

§ 4.2 The structure and infrastructure of a multimodal urban network model

The multimodal urban network model represents the multimodal mobility infrastructure and land use, integrating a private transport system (car, pedestrian and bicycle), a public transport system (rail, tram, metro and bus), a land use system, and interfaces interlinking all three (Figure 4.1). The smallest spatial unit of each system is the street segment, the transit stop area and the individual building, respectively. The aim of this model is the analysis of the spatial characteristics of neighborhoods in the region, and of the structure of the region as a whole. This quantitative analysis aim imposes requirements on the data that, in particular regarding its attributes and topology, are different from the requirements for cartographic visualization. At the same time, there is an interest in building a platform that supports the automation of model maintenance, its reproducibility in different geographic contexts, and is accessible to all. These aims inform the subsequent choices of data set and technology stack.

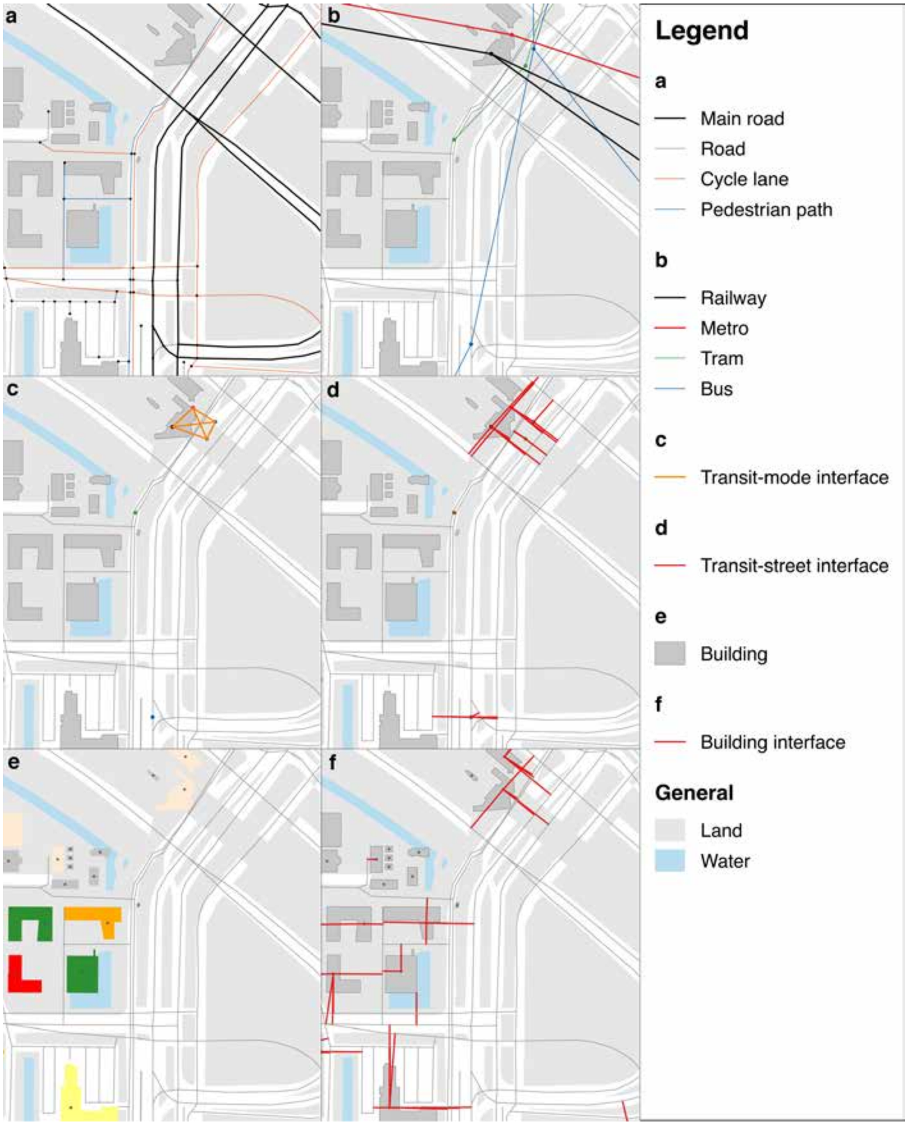


FIGURE 4.1 Structure of the multimodal urban network model's systems – a private transport system, b public transport system, and e land use system – and of the interfaces between all three (c, d, f).

§ 4.2.1 Data and software stack

The multimodal urban network model is built using various VGI and open data sources, taking advantage of the benefits, and attempting to address the issues, of integrating different data sets (Sester et al., 2014). The OSM data set forms the backbone of the model, because of its open access nature, universal coverage and standard, and rich feature set covering all modes of transport. In the case of the Netherlands, when OSM is compared with official street network data (Nationaal Wegen Bestand) according to various categories (Girres and Touya, 2010; Jokar Arsanjani et al., 2013a), it presents itself as the most appropriate choice for a multimodal urban network model. OSM offers better semantic accuracy because it includes a representation of soft modes (i.e. walking and cycling) which is essential for the analysis of the walking and cycling environment (Chin et al., 2008); OSM's positional accuracy is not substantially different from official street network data (Girres and Touya, 2010; Haklay, 2010; Neis et al., 2011; Graser et al., 2013); OSM can have a very good level of completeness: in the Netherlands a contributed road dataset was imported in early 2007 [4] and OSM contributors have been supplementing and correcting this data since. In addition, the public transport networks can be partly derived from the same OSM data. However, in the case of the Netherlands public transport data has to be complemented with data from OpenOV [5] timetable data, and verified against route maps from local network operators. Detailed land use data is still very incomplete and inconsistent in OSM (Jokar Arsanjani et al., 2013b; Estima et al., 2013; Jokar Arsanjani and Vaz, 2015), both in terms of building footprints and points of interest. In the case of the Netherlands, we used land use data extracted from the public data set Basisregister Addressen en Gebouwen (BAG) [6], which is currently in the process of being imported into the OSM data set.

In line with the chosen data sets, the multimodal urban network model described uses Free and Open Source Software (FOSS) GIS platforms. Osmosis is used to load the OSM data dump into a PostGIS database, where it is maintained together with the other datasets, the model is analyzed using pgRouting, and the results are visualized using QGIS. This software stack offers scripting capabilities in SQL, PL/SQL and Python, thus allowing the model building procedures to be reproduced and adapted to other cases.

4 For details refer to the maps on http://wiki.openstreetmap.org/wiki/WikiProject_Netherlands.

5 http://www.openov.nl/

6 http://bag.vrom.nl/

§ 4.2.2 Spatial data model

The OSM data set is composed of nodes (points) and ways (polylines), populated by a rich and open set of attribute tags, made up of keys with one or more values. It also supports relations (topologies) combining ways and nodes to describe larger entities, such as routes or named areas (polygons). Polygons can also be defined in closed ways, with a tag identifying it as an area. This data model is compact and flexible, combining all the different features based on their ids. However, this data model also makes data querying and manipulation a non-trivial task. In order to facilitate the analysis and display of the multimodal urban network model, it is based on a more conventional relational spatial data model. In the following sections we dive into the details of building the multimodal urban network model's systems, presenting the procedures for processing and integrating the various data sets, that result in the spatial data model illustrated in Figure 4.2.

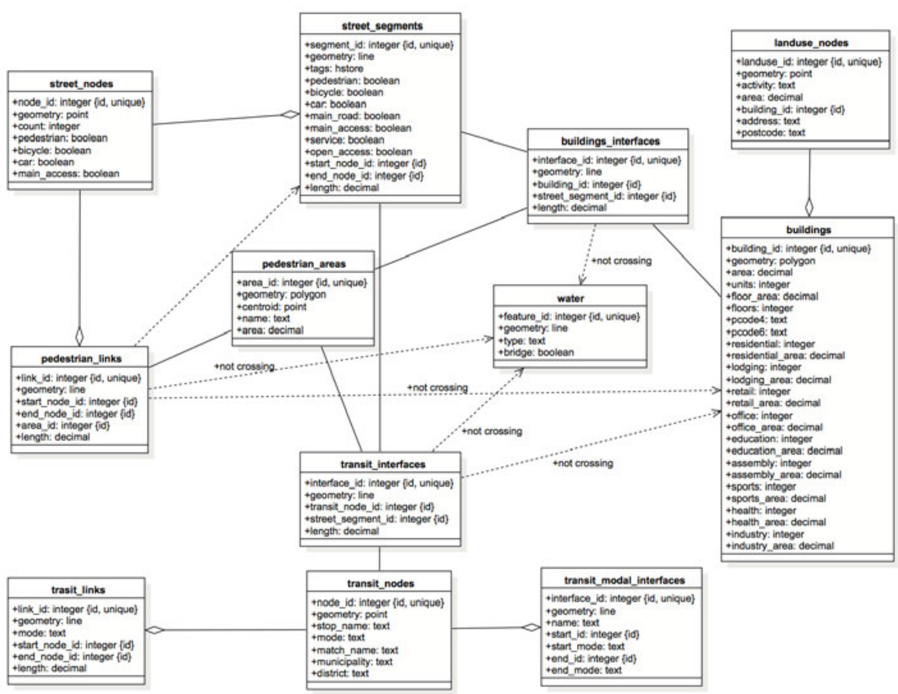


FIGURE 4.2 Diagram of the multimodal urban network spatial data model.

§ 4.3 Creating the private transport system

The private transport system is the backbone of the multimodal urban network model and, for this reason, it is the first system to be created. It defines the network of streets and paths for cars, bicycles and pedestrians onto which the public transport nodes and the land use activities are connected. The private transport system uses a standard road center line representation and data model, with a table of street segments and one of intersection nodes, populated with attribute fields defined specifically for multimodal urban network analysis (Figure 4.2). The following procedure, illustrated in Figure 4.3, describes how these features and attributes are created from the original OSM data. The main stages include the preparation of the street network segments, followed by the preparation of the street intersection nodes, concluding with the creation of pedestrian area links.

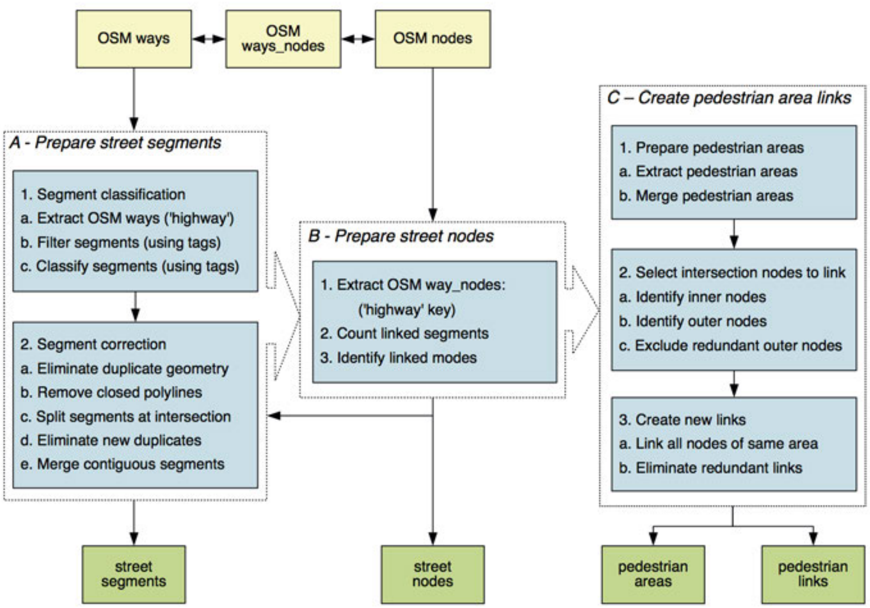


FIGURE 4.3 Procedure to create the private transport system data classes, from OSM.

§ 4.3.1 Street network segment classification and correction

There are several steps required to produce the street network segments. Firstly, the OSM ways that contain a 'highway' tag are extracted and inserted into a street segments table, keeping the complete tag contents. Secondly, the street segments are filtered and classified according to mode permissions and restrictions, and road hierarchy using the associated tags. Thirdly, the street segments need to be corrected for geometry and topology problems.

4.3.1.1 Street network segment classification

The street segments in the multimodal urban network model are assigned attributes that indicate permission or restriction of the private modes (i.e. 'car', 'bicycle' and 'pedestrian'), based on observable affordances (Scheider and Kuhn, 2009) extracted from a wide range of tags available in the OSM data set (step A1 in Figure 4.3). The level of completeness of attributes is critical to this type of network model (Neis and Zielstra, 2014), and one has to adopt a simpler model specification (e.g. ignoring turn and speed restrictions) that is consistent throughout the study area, extracting as much information from additional keys as possible.

The first step is to identify the keys and key values available in the data set, their frequency, and to define their relevance to different modes (Table 4.1), supported by examples mapped over aerial photography. The main key for classifying the street network is 'highway', with values directly related to mode (e.g. 'cycleway', 'footway', 'pedestrian', 'track', 'path', 'steps'), and to road hierarchy (e.g. 'motorway', 'trunk', 'primary', 'secondary', 'tertiary', 'residential'). In the case of the 'highway' key, the most common value is 'unclassified', which can be complemented by information in other mode related keys, namely 'motorcar', 'motor_vehicle', 'bicycle', 'cycleway', 'foot', 'footway' and 'route'. These specify if the segment is designated, accessible (e.g. yes) or restricted (e.g. no) for the given mode. Street segments with the 'construction' value should be ignored, and street segments with the 'service' value are ignored if their access is restricted (e.g. controlled by a gate), they are private, or are exclusively for public transport use. Once we have identified the relevant keys and values, we run a series of queries to populate the private mode attributes with Boolean values, where true is used when the segment is designated, false when the segment is forbidden, and null if the segment is simply accessible to that mode. The latter is the state that applies to the majority of street segments, which can be shared by all three modes.

KEY VALUE	FREQUENCY	CAR	BICYCLE	PEDESTRIAN
unclassified	652440	( )	( )	( )
cycleway	112765	F	T	
tertiary	99328			
footway	73425	F		T
residential	68182			
service	52836	(F)	(F)	(F)
secondary	47116	T		
track	34524	F		
pedestrian	31786	F		T
primary	27986	T	(F)	(F)
path	18914	F		
living_street	7566		T	T
motorway	7406	T	F	F
motorway_link	5221	T	F	F
trunk	3794	T	F	F
steps	3134	F		T
construction	1250	F	F	F
trunk_link	1030	T	F	F
primary_link	776	T	(F)	(F)
bridleway	646	F		

TABLE 4.1 Summary of relevant "highway" key values in the OSM data set, with their frequency count, and indication of the mode that they are accessible to ('T', 'F' or blank). Brackets represent states that depend on the value of additional mode-specific keys.

The open nature of the tagging system in OSM allows contributors to introduce rich detail in feature attributes, but it also adds heuristic complexity. In the data set for a given region one might find keys or values spelt differently (i.e. yes, Yes, YES, y), using regionalisms (i.e. underground, tube, metro), in different languages, or simply misspelled. One has to analyze and consider these specificities when using a data set for the first time, and develop queries to classify the segments based on a broad set of key-value pairs.

4.3.1.2 Street network segment correction

Regarding the OSM street segment geography and topology, there is a range of possible problems (Girres and Touya, 2010): duplicate segments, where geometry is exactly the same; overlapping segments, where geometry partially coincides; missing segments; closed segments, representing areas; orphans, unconnected segments from the rest of the network; segments without segmentation, where intersection nodes exist; contiguous segments, separated where no intersection nodes exist; missing intersection nodes; intersections at bridges or tunnels. One has to identify which problems are present, to what extent, how critical they are for the intended use of the data set, and ultimately decide the degree of error that is acceptable, making corrections accordingly. Considering that the aim is to produce a multimodal urban network model representing a large region, resulting from an automated procedure towards reproducibility and operationalization, we should not introduce steps that depend on the individual identification and correction of mistakes, such as missing data or incorrectly classified data. When creating a smaller network model, one should consider scanning and correcting any additional problems.

The correction steps proposed convert the OSM street segments into a standard road center line representation (A2 in Figure 4.3). Firstly, we eliminate duplicate geometry, choosing to remove the segment with greater access restrictions. Secondly, we remove closed polylines that represent pedestrian zones, and do not correspond to road center lines. Thirdly, we split segments that continue over intersections where there is an intersection node, and eliminate any new duplicates resulting from overlapping geometry. Finally, multiple contiguous segments between crossings are merged together into a single polyline.

§ 4.3.2 Street intersection node classification

The standard road center line representation uses nodes at the endpoints of street segments to indicate level crossings. Where two segments intersect without a node, this indicates the absence of a level crossing, as in the case of bridges and tunnels. The nodes layer is selected from the OSM 'nodes' data set, namely those with an id in the 'node_id' attribute of the 'way_nodes' table, whose 'way_id' is in the extracted street segments table. The intersection nodes can be used to quantify morphological characteristics of the street network, namely the typology of crossings and cul-de-sacs, and to provide this typology, each node has a 'count' attribute with the number of street segments that share it.

§ 4.3.3 Pedestrian areas links generation

The OSM street network includes pedestrian paths and cycle lanes, however some public open spaces, such as squares, parks or urban block interiors, are represented by closed polylines disconnected from the street network, with the 'highway' = 'pedestrian' value, and a 'area' key with value 'yes'. We create pedestrian area links to represent routes that pedestrians and cyclists can take across these open spaces. These are important shortcuts that affect the measurement of local neighborhood characteristics, because the routes around the perimeter of blocks and open spaces can represent a considerable increase in walking distance.

The procedure (C in Figure 4.3) generates pedestrian links in an extension of the street network, using the existing street segments, intersection nodes and open areas, without changing the street network geometry or affecting its topology. The first stage is the selection of the pedestrian area polygons, merging together pedestrian areas that intersect, are adjacent, have the same name key, or have the same OSM id. The second stage is the selection of intersection nodes to be connected, identifying 'inner nodes' that belong to street segments intersecting the pedestrian areas and are located on or inside the areas' perimeter, and 'outer nodes' that are located outside but immediately adjacent to the pedestrian areas, within a 25 m buffer. Finally, we exclude 'outer nodes' that are directly connected to 'inner nodes'. The third stage is the creation of new links between the inner and outer nodes belonging to the same pedestrian area. We simplify this procedure by ignoring the pedestrian area's shape and allowing links to cross the perimeter of concave shapes, because the link does effectively exist, albeit not so direct in terms of geometry. The final step eliminates excessive links that cross external buildings, cross external street segments, are entirely outside the pedestrian area, or are duplicates of existing street segments. The result is illustrated in Figure 4.4.

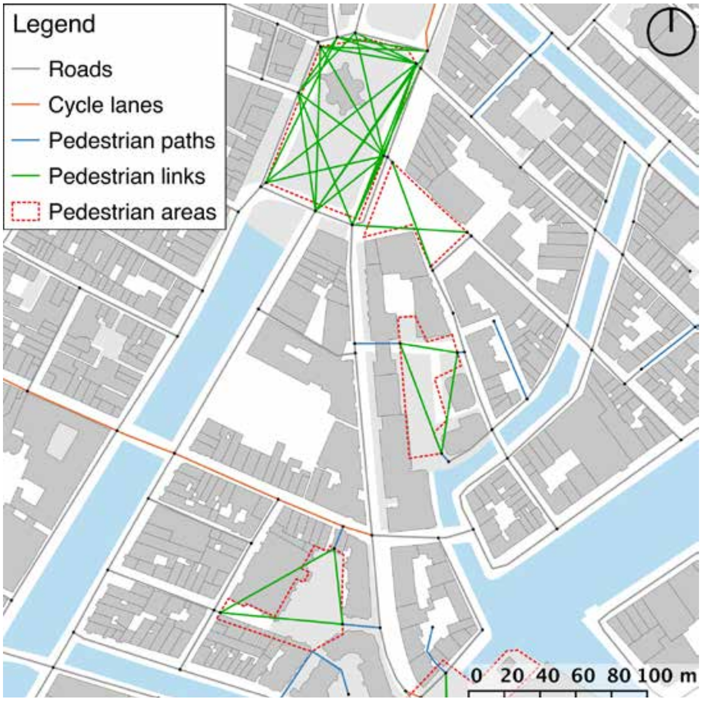


FIGURE 4.4 Map with examples of pedestrian areas, with pedestrian area links complementing the connectivity of the street network.

§ 4.4 Creating the public transport system

The next stage in building a multimodal urban network model is to build the public transport network and to connect it to the private transport network (Figure 4.5). The public transport network is also multimodal, including rail, metro (or light rail), tram, and bus networks. We have opted for a simplified representation of the network focusing on the connectivity of the infrastructure, rather than on the service provision, i.e. the lines, services, and their frequency. This simplified representation has lower data requirements, and is easier to produce, verify and explain, retaining an adequate level of detail for the measurement of multimodal accessibility and urban structure (van Nes, 2002). It is made up of nodes representing stations or stops; lines representing the links between stops of the same mode; 'transit-mode interfaces' representing the transfer between stops of different modes; and 'transit-street interfaces' connecting the stops to the streets of the private transport network (Figure 4.2).

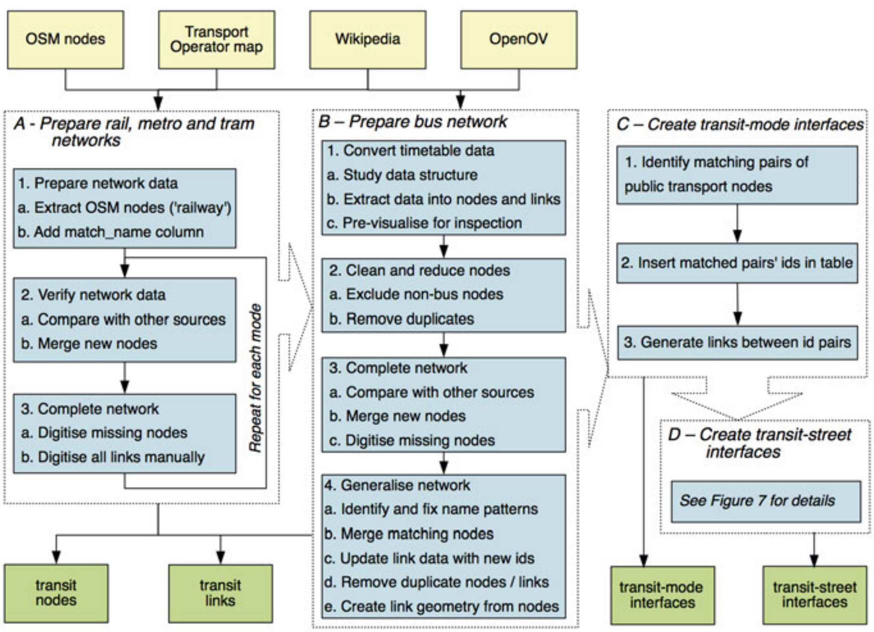


FIGURE 4.5 Procedure to create the public transport system data classes, from OSM data and other sources.

TOC

§ 4.4.1 Public transport networks preparation

The public transport networks consist of a single node of each mode at a given location, independent of the number of physical stops, platforms, or station entrances that exist; and one line segment between nodes of the same mode, where a service exists connecting them. The OSM dataset has the required tags to construct such a network, however the level of coverage and detail of the data varies across regions and across transport modes. This can lead to different approaches to produce the multimodal network model, which is less systematic than desired, but is useful to understand different methods and issues for different data scenarios.

4.4.1.1 The rail, metro and tram networks

The public transport network nodes for the modes that use rail tracks were extracted from the OSM nodes data, where the node tag has a 'railway' key. The values of the 'railway' key (Table 4.2) are used to assign the mode to each node, or to exclude nodes that are not relevant. The resulting nodes are then checked against other sources of information, mentioned in Section 4.2.2. It was found that the OSM data set could have inconsistent quality, namely missing stations, duplicate stations, inactive stations, and wrongly classified stations. In the present case, the rail network was mostly complete and correct; the metro network was mostly complete but whole segments were incorrectly classified as 'tram', and the tram network had 2% of the stations missing and had classification issues such as missing names or name inconsistencies.

NODE KEY VALUES	COUNT	MODE	WAY KEY VALUES	COUNT	MODE
tram_stop	1019	Tram	rail	12306	Railway
station	518	Railway	tram	2078	Tram
buffer_stop	184	Ignored	platform	1124	Ignored
subway_en-trance	83	Ignored	subway	388	Metro
halt	60	Metro	light_rail	309	Metro and railway
			preserved	180	Ignored
			disused	112	Ignored
			narrow_gauge	60	Ignored
			abandoned	57	Ignored

TABLE 4.2 Summary of railway key values of the nodes and ways data.

The 'match_name' attribute of the public transport network nodes table stores a lowercase and simplified version of the stop or station name, standardizing certain prefixes or suffixes that can occur differently in different modes. This attribute can be used to compare and merge data from different sources, and relate public transport nodes of different modes. When verifying station/stop names of local transport modes, such as metro, tram and bus, across a larger region, one must take care to include the municipality and/or district name in the query. Often there are general names, historical dates, or historical names, occurring in different cities or districts, raising false matches.

The public transport network links connecting the nodes are created next. The OSM data set includes ways representing the physical rail tracks, which have a railway key (see Table 4.2 for values). However, these are not necessarily complete and do not match the stations in the same way the street segments match intersection nodes. Therefore, these line segments can only be used for visual support when digitizing links between stations, or after generating links from sequences of node names. The first method was carried out in this case, as the number of links is not excessive, and it allows a careful verification of public transport nodes.

4.4.1.2 The bus network

While the semi-automated verification and manual digitization method can be adequate for rail track-based public transport modes, it is impractical to create the bus network, because it is quite extensive and is difficult to identify routes by visual inspection. The recommended approach for creating a network model of public transport modes is to use an automated and systematic procedure, and for that one requires route data and/or timetable data. The OSM data set can include the bus network, with bus stops in the nodes table identified with the key 'highway' = 'bus_stop', and routes connecting stops encoded as relations of ways with the keys 'type' = 'route' and 'route' = 'bus'. However, the relation data is often missing and only the nodes information is available. In such cases, one should look for public transit timetable data, the General Transit Feed Specification (GTFS) being a well-known standard used worldwide. In this case, the OpenOV timetable dataset was used.

Typically, public transport timetable datasets have a complex relational data structure, i.e. includes stops, links, services, cars, directions, and times. The first stage (B1, Figure 4.5) is to understand the data structure and how to extract relevant information, namely the stop name, stop id and its geographic coordinates, and the links' mode, origin stop, and destination stop. Then we extract this data into the simplified node/link public transport network data model. It is important to visualize the automatically generated public transport network to have visual feedback on the progress, and to assess its completeness and overlap with the available OSM dataset. The second stage (B2, Figure 4.5) is to clean and reduce the data, keeping only bus nodes and links, and eliminating links and stops that are exact duplicates in terms of the 'match_name' and geometry attributes. The third stage (B3, Figure 4.5) is to complete missing data, if required. In this case, the data from one of the bus network operators was missing and one had to resort to a semi-automated process similar to the rail networks. The fourth stage (B4, Figure 4.5) is to generalize the resulting bus network, merging stops around a location that correspond to different routes or different route directions.

Ideally this is done using a universal unique feature identifier, otherwise one has to use name matching, paying special attention to different naming conventions for stops used by different operators. When merging equivalent stops, using the 'match_name' together with the municipality and district attributes as recommended in section 4.4.1.1, one must limit the operation to a given distance (in this case we used 200 m) because in the case of bus networks, there are routes crossing the same street a few kilometers apart but all the stops receive the same name. The merging operation involves assigning a unique identifier to stops and links that meet the above criteria, and removing features with duplicate unique identifiers, keeping one stop for each unique identifier, and one link for each start and end node stop pair. The link's geometry is then updated based on the new start and end stops location, giving a reduced set of new generalized links (Figure 4.6).

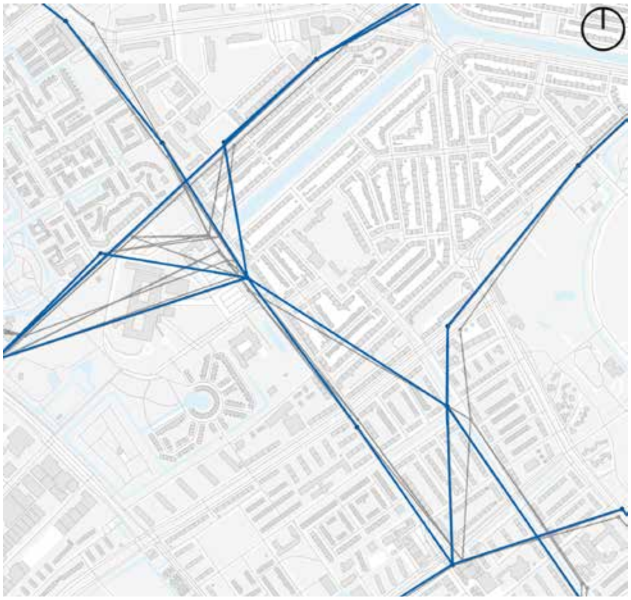


FIGURE 4.6 Map with sample result of the bus network generalization procedure, comparing the original route data set with the simplified network of single bus stops and links.

TOC

§ 4.4.2 Public transport network interfaces generation

After creating the public transport network tables, we integrate the public transport modes together and connect them to the street network of the private transport system. The 'transit-mode interfaces' (Figure 4.1c) are links connecting public transport networks between stations and stops that share the same name. Typical examples are the stops around central train stations where all modes converge, which have the same stop name. Using the 'match_name' attribute, in conjunction with the municipality and district names, we insert in the modal interfaces table pairs of nodes that share the name but belong to a different public transport mode. The 'transit-street interfaces' (Figure 4.1d) are links connecting the public transport nodes to the street network. These links allow the measurement of availability of and proximity to public transport, and the measurement of multimodal trips, e.g. where walking is combined with a longer public transport journey. Each public transport stop is connected to several of the nearest street segments, making sure that they connect to each of the private transport modes (pedestrian, bicycle and car). The procedure followed to produce these interfaces is detailed in Figure 4.7.

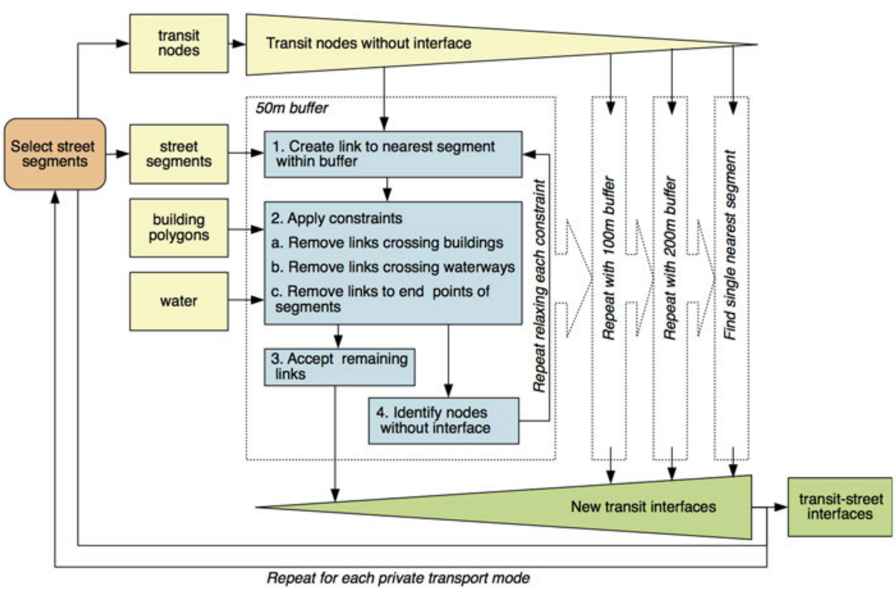


FIGURE 4.7 Procedure to create the public transport system interface with the street network.

This is a nested iterative procedure, with a sequence of steps gradually loosening restrictions to find connections, this same sequence of steps being repeated at increasing scales, and the full sequence being repeated to connect to each private transport mode. Without describing every step in detail, it is important to raise a couple of points. The relaxation of crossing buildings and water is introduced because these features come from different data sets and are not topologically consistent with the mobility networks. The restriction of connecting to endpoints of street segments aims to reduce the number of links created initially, and to obtain links perpendicular to street segments.

§ 4.5 Creating the land use system

The final stage in building the multimodal urban network model is the creation of the land use system. This system provides the origins and destinations for the journeys across the mobility infrastructure, and furthermore allows the calculation of urban form characteristics related to functional density and accessibility. The land use system is made of three components, namely the land use nodes, the building polygons and the land use–street interfaces. The procedure to produce this system is illustrated in Figure 4.8.

The first stage is to verify the quality of the data, even when it comes from official data sources, namely the attribute values' statistical and spatial distribution. In this case, it was found that 'null' values, which should be empty fields as per specification, were in certain areas recorded using numbers, e.g. 999999, 99999, 949999; and in some areas the decimal values had lost the decimal sign. In order to obtain a smaller number of nodes in the network model, the next stage is to aggregate the land use nodes information on the corresponding building polygon using a spatial join, calculating the total number of land use units and total area, and the number of units and area of each land use category. Any buildings without land use points were discarded from land use related analyses. The final stage is to create interfaces between the buildings and street segments or intersection nodes. In some data sets, the land use address attribute includes postcode, street name and door number, and can be used to define these interfaces. However, geocoding is not always an option, as the complete address is rarely available on both the land use and the OSM streets data set. Hence, one can define the interface as the (set of) line(s) from the building to the nearest the street segment(s) following a procedure largely similar to the one depicted in Figure 4.7, with the difference that each iteration uses the building centroid first, and then repeats using the building perimeter.

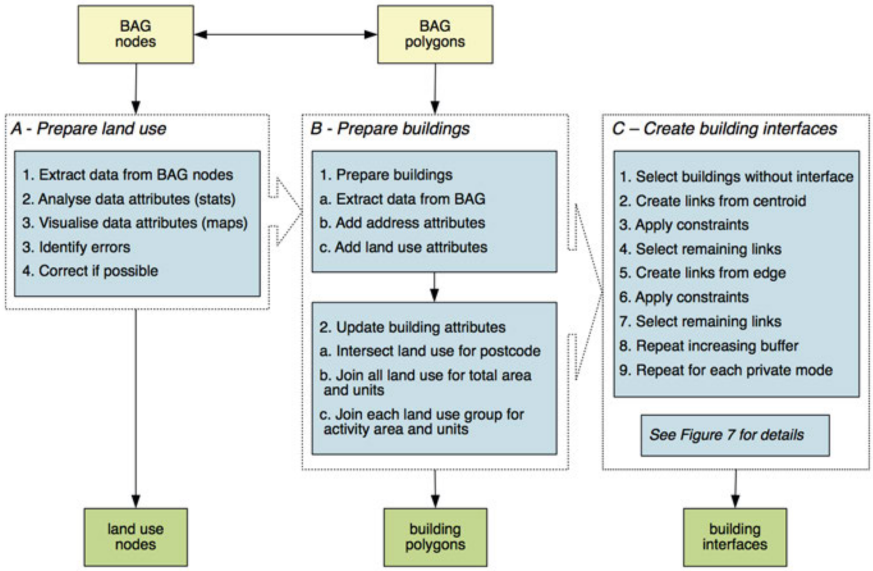


FIGURE 4.8 Procedure to create the land use system data classes.

§ 4.6 Results

Following the procedures described in Sections 3 to 5 we have produced a large-scale, detailed, multimodal transport and land use network model for the Randstad region of the Netherlands. It consists of 676,248 street segments, 462,384 street intersection nodes, 161 rail, 186 metro, 614 tram and 7680 bus nodes, and 2,430,945 building polygons (Figure 4.9). This model offers a rich representation of the region, supporting analysis of a regional scale but also goes down to the level of detail of the local neighborhoods and individual buildings.

By querying the network model to use relevant layers, e.g. pedestrian and local public transport, and to select specific sets of origins and destinations, e.g. residential buildings or education establishments, one can use network analysis and routing algorithms to calculate multimodal shortest paths and catchment areas. This is demonstrated next, with the results of shortest routes calculated around pedestrian areas, and catchment areas calculated for different transport modes.

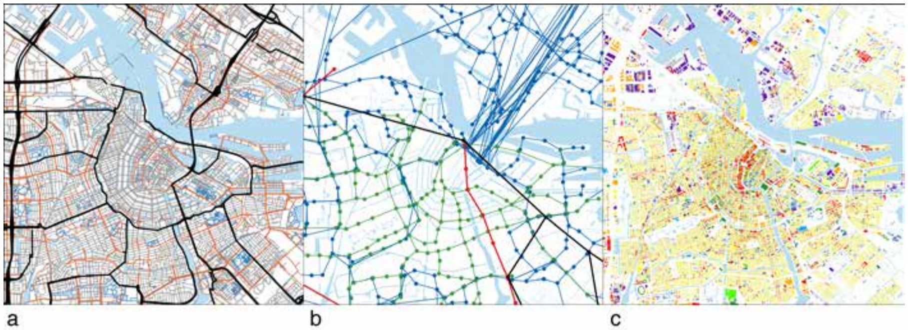


FIGURE 4.9 Maps of the three main systems of the multimodal urban network model, for a data sample around central Amsterdam: a private transport system, b) public transport system, c) land use system.)

§ 4.6.1 Multimodal network model analysis

The shortest routes were calculated between buildings in a section of the network model in central Amsterdam, which has several pedestrian-only streets and pedestrian areas (Figure 4.10).

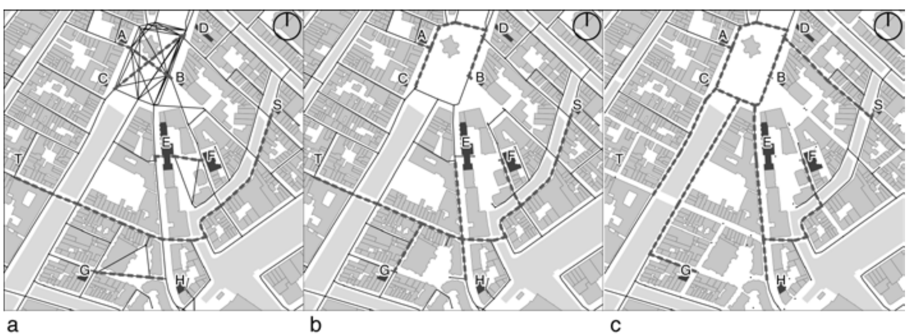


FIGURE 4.10 Shortest routes between pairs of buildings (AB, CD, EF, GH, ST) on the private transport system, a including all pedestrian links, b including pedestrian paths without pedestrian area links, and c including only car accessible links.

The calculation uses three different model filters: one that includes all pedestrian links (A), one that excludes the pedestrian area links described in Section 4.3.3 (B), and a third that does not include any exclusively pedestrian links and corresponds to the car network represented in official street network data sets (C). These results in Table 4.3 show the impact of adding pedestrian links on local shortest route calculations.

ANALYSIS	MODEL A (M)	MODEL B (M)	MODEL B (%)	MODEL C (M)	MODEL C (%)
A-B route	84	177	+109.1	177	+109.1
C-D route	121	145	+19.9	145	+19.9
E-F route	65	270	+313.2	270	+313.2
G-H route	90	174	+92.2	526	+481
C-T route	207	207	0	269	+29.9
D-T route	328	352	+7.4	379	+15.4
S-T route	407	407	0	470	+15.6
5 minutes catchment	5636	5374	-4.6	3107	-44.8
10 minutes catchment	36884	36058	-2.2	21411	-41.9

TABLE 4.3 Difference between model A and models B and C, in terms of shortest route distance between pairs of points (Figure 4.10), and in terms of catchment area.

As found by other studies (Chin et al., 2008), the pedestrian routes can be considerably shorter in model A when compared to model B and in particular with model C. This impact is obviously dependent on the quantity and location of pedestrian areas and pedestrian streets. As there are only a few pedestrian areas, certain routes in model B are not affected at all (e.g. C–T and S–T), while others are considerable affected (e.g. E–F). However, pedestrian streets are common in this urban area, hence model C gives a significant increase in distance travelled in all cases. The difference between models A, B and C is smaller in the results of the catchment area calculation for 5 and 10 minutes travel time, and this difference drops with a greater distance travelled. This seems to indicate that in aggregate calculations of many origin destination pairs including longer routes (e.g. S–T), the reduction in distance travelled from the presence of pedestrian paths and areas will have a small overall impact. From these results, it is clear that the location and concentration of pedestrian movement features will have a variable local effect on the results of network analysis. However, to draw definitive conclusions on the level of this impact on a given multimodal model, one would have to conduct a systematic study on the whole model using the full range of analyses that are required.

The results of a catchment area analysis for different travel modes are shown in Figure 4.11, where one can observe the number of buildings accessed within a 10 minute travel time: walking (Figure 4.11 a and b), comparing models A and C; using public transport (Figure 4.11 c), where pockets of buildings near public transport stops become accessible; and driving (Figure 4.11 d), with a more extensive coverage than public transport due to the fact that the central core of Amsterdam has very few public transport stops and uses a large part of the travel time budget walking to the nearest stop.

FIGURE 4.11 Catchment area maps for a 10 minutes travel time a) walking using model A, b) walking using model C, c) using public transport, and d) driving.

These results are mainly for demonstrating the use of the multimodal urban network model in basic network analysis calculations. From the calculation of shortest paths and catchment areas we can derive a wide range of analysis metrics of proximity, density and accessibility of the different mobility networks, which support the comparative assessment of sustainable accessibility of urban neighborhoods in the city-region. This is further described and developed in work by Gil and Read (2012; 2014), and Gil (2014).

§ 4.6.2 Multimodal network model reflections

At this stage we would like to reflect on aspects of the multimodal urban network model's design and lessons learned from the process of producing it. The network model is intentionally simple for the purpose of analyzing the multimodal structure and accessibility of city-regions, and this is reflected in its data model. However, the geometry of the private transport system network could be generalized to address inconsistent representation of multiple lanes, cycle lanes, pedestrian pavements and crossings, complicated intersection layouts, and to allow a correct classification of crossings typology. We opted for a general classification of the street segments using mode attributes, because the geometric generalization using OSM data is not a trivial task, and the current procedure interferes less with the original data model and facilitates update and maintenance of the network model.

If the decision goes for a more detailed model, for example in a smaller study area, the private transport system procedure from OSM data remains the same but one should add parking space information to the street network, and complete the pedestrian network with correct representations of crossings (Ballester et al. 2011). On the other hand, one should produce a more detailed public transport system using the full timetable data, including multiple stops, platforms, lines and services, as seen in other models (Friedrich, 1998; Butler and Dueker, 2001; Li, 2007; Liu, 2011; Hadas, 2013).

The network structure and level of detail of the model is also related to the type of analysis algorithm being used. In this case we use basic undirected shortest route and catchment area analysis suitable for a simpler network representation, but more detailed models would require advanced network analysis algorithms based on specific multimodal graph representations, as can be found in the works of Lozano and Storchi (2001), Bielli et al. (2006), or Ayed et al. (2011).

Data set selection and processing remains one of the biggest tasks in network model production. Some important lessons are: all data sets must be carefully verified and possibly corrected, whatever their source; data sets have strengths and weaknesses regarding the desired data model, which encourages the combination of the best available data sets from different sources; however, this can be problematic and requires workarounds, because data sets are not topologically consistent (e.g. network and building geometry), lack common unique feature identifiers, and use different naming or classification conventions (e.g. public transport attribute data).

Regarding the OSM data set, it has the potential to become a unified source for this type of urban analysis work: it is user-contributed and freely accepts updates, it is open to imports of large official datasets, it supports a wide range of features and attributes, and is based in a single geographically and topologically consistent platform. However,

TOC

it still faces many of the challenges raised by Haklay and Weber (2008). For OSM to be further used in urban analytical studies, the challenge is to improve data quality (Mooney et al., 2010; Goodchild and Li, 2012), especially of its attribute data (Neis and Zielstra, 2014), supported by software applications for data editing that are user friendly and intuitive to attract many contributors – the crowd – but sophisticated enough in the background to provide quality control – automated. For example, in order to ensure a standard street network representation, OSM could include topology processing scripts on the server side to operate on features as they are edited on the database, similar to the procedures described in Section 4.3.1.2. Furthermore, in order to facilitate data analysis and modelling based on attributes, OSM could require a minimum level of attribute classification of features. This would be supported by tools including an ontology-based data specification (e.g. Fonseca et al., 2000; Scheider and Khun, 2009; Scioscia et al., 2014) that would guide and reduce the efforts of individuals in complying with data standards.

§ 4.7 Conclusions

This chapter proposes a set of procedures to build a multimodal urban network model, including transport infrastructure and land use, for the quantitative analysis of the urban regional environment in urban design and strategic planning studies. The general scope and reproducibility of this type of model is much greater than in the past, thanks to the availability of OSM data. In addition, the level of detail afforded by crowd-sourced data sets, with the capabilities of today's open GIS and statistical analysis platforms, increase the possibilities for the analysis of complex urban regions.

OSM has great potential: its specification offers 'on paper' all the features required for this type of network models; and its open nature and worldwide standard availability can turn it into a preferred data source. But there is still some way to go before its feature classification becomes more complete and consistent and before its coverage becomes comprehensive in most geographic regions, either through individual contribution, or through the merging of open and donated official data sets.

5 Analyzing the Configuration of Multi-modal Urban Networks [7]

Abstract

This article proposes urban network models as instruments to measure urban form, structure and function indicators for the assessment of the sustainable mobility of urban areas, thanks to their capacity to describe the detail of a local environment in the context of a wider city-region. Drawing from the features of existing street network models that offer disaggregate, scalable and relational analysis of the spatial configuration of urban areas, it presents a multi-modal urban network (MMUN) model that describes an urban environment using three systems — private transport (i.e. car, bicycle and pedestrian), public transport (i.e. rail, tram, metro and bus), and land use. This model offers a unifying framework that allows the use of a range of analysis metrics and conceptions of distance (i.e. physical, topological and cognitive), and aims to be simple and applicable in practice. An implementation of the MMUN is created for the Randstad city-region in the Netherlands. This is analyzed with network centrality measures in a series of experiments, testing its performance against empirical data. The experiments yield conclusions regarding the use of different distance parameters, the choice of network centrality metrics, and the relevant combinations of multi-modal layers to describe the structure and configuration of a city-region.

7 This chapter is based on the manuscript of: Gil, J. (2014). 'Analyzing the Configuration of Multimodal Urban Networks'. Geographical Analysis 46, pp. 368–391. doi:10.1111/gean.12062

§ 5.1 Introduction

Urban areas and city regions face serious sustainability problems linked to the current car-dependent patterns of mobility, affecting the environment and the socio-economic fabric of society. The mobility trend is for increased and longer trips mostly by private car with a wide range of negative impacts. The objective of urban form and structure is to achieve a more integrated and seamless multi-modal public transport system around quality neighborhoods and vibrant city centers, with land use distribution matching the needs of population, business and institutions, shifting mobility to soft transportation modes, such as walking and cycling, and to public transport for long distance travel (Banister, 2005). To plan for and monitor progress toward these goals, a need exists to measure urban form characteristics of local neighborhoods and how these integrate into their wider city region (Ewing and Cervero, 2001; 2010).

Current practice of sustainable neighborhood design evaluation is based on urban form indicators, focusing on a wide range of sustainability dimensions (USGBC 2009; Barton, Grant, and Guise, 2010; Criterion Planners, 2011). These evaluation tools provide detailed sets of indicators relative to a local neighborhood while offering a reduced number of indicators reflecting an immediate context, not to mention its integration into a regional context (Gil and Duarte, 2013). In contrast, more extensive urban form and travel studies, focusing on regional effects or drawing from a large number of cases, resort to aggregate statistics at a neighborhood or city scale, or simplified measurements and classifications (Stead and Marshall, 2001). Finally, various authors suggest that to measure sustainable mobility in a city region, one also needs to consider measures relating to accessibility (Cheng, Bertolini, and le Clercq, 2007). To address these differentiated approaches, one should measure a range of urban form, structure and function indicators, such as those summarized in Table 5.1.

In order to describe and measure local neighborhoods integrated in the wider city region, an urban model should have three main characteristics: high resolution, relational, and holistic. It should be sufficiently high resolution in spatial and structural terms; i.e., have a small, disaggregate scale, using significant urban characteristics related to land use and street environments (Cervero and Kockelman, 1997). It also should possess a relational networked structure to integrate local elements into its wider region (Frey, 1999). Furthermore, it should be holistic, with a multi-layered structure including streets, other movement networks, and the land use activities (Dupuy, 2008), integrated together to account for the synergies and tensions between the various infrastructures (Read, 2009). With respect to these three characteristics, street network models seem to offer a useful approach, because they can be more detailed than zone, grid or area based models in describing local urban form, and lend themselves to relational accessibility and network configuration analysis at a regional scale. And to measure urban form, in terms of not only private transport but also public transport, street network models can support a multi-layered structure.

CONCEPT	MEASURE	DEFINITION	EXAMPLES
Proximity	Node Proximity	Network distance to the nearest access node or to an infrastructure element of each mode.	Distance to nearest train station, or to nearest trunk road.
Density	Network Density/ Reach	Network length or absolute number of nodes within a fixed network distance, per mode.	Street network length or number of tram stops within 10 minutes walking.
	Activity Density	Total area of activities within fixed network distance, per mode.	Total office area or number of retail units within 10 minutes cycling.
Accessibility	Network Centrality	Mean distance to or path overlap between every network node, using a specific mode.	Mean closeness centrality of street segments within 15 minutes walking.
	Activity Accessibility	Mean distance to activities, weighted by their number and size, using a specific mode.	Closeness to retail outlets within 15 minutes driving.

TABLE 5.1 Summary of main groups of urban form, structure and function metrics used for urban design and sustainable mobility evaluation.

This article describes a multi-modal urban network (MMUN) model that should allow the measurement of the various urban from, structure and function indicators proposed in Table 5.1. This model is conceived based on the principles found in existing street network and multi-modal models identified in a review of their geographic and graph representation and their analysis methods. In combining these principles into a single model, the MMUN model offers the unique opportunity of measuring the preceding indicators using different parameters relating to concepts of distance, and combining different layers of mobility infrastructure to directly compare results.

§ 5.2 Street network models and their analysis

Street network models can be used in the context of sustainable development to describe and measure the accessibility of land use, the quality of public transport provision, the characteristics of street networks, and the configuration of urban areas or cities (Clercq and Bertolini, 2003; Chiaradia et al. 2008; Porta and Latora, 2007; Sevtsuk, 2010; Chiaradia et al., 2012). These descriptive models can be disaggregate and high-resolution, but at the same time can extend to cover entire cities and city regions. They often are developed within a geographic information systems (GIS) to enable the integration of various layers of information relating to land use, transportation infrastructure, urban form, movement flows, and socio-economic characteristics, which gives them a useful operational quality. An extensive review of such models is provided in the work of Barthelemy (2010). The following subsections summarize the characteristics of existing street and multi-modal network models focusing on their analysis, geographic representation, graph representation, and concepts of distance.

§ 5.2.1 The analysis of street network models

The analysis of networks has for a long time featured in geography and related disciplines (Griffith, 2011). In transportation research, street network models usually focus on node, density and accessibility measures (Hansen, 1959; Cheng et al., 2013), where a network provides the connection between opportunities (e.g., land use units or transportation nodes). This is used to measure, from a given location, the shortest route to opportunities, the total distance to them (i.e., accessibility) and the reachable number or size below a given cutoff distance (e.g., location density). Thus, these models can be used to measure the functional affordances at a given location based on network distances.

In urban design and planning, street network models also focus on composition (Marshall, 2005; Xie and Levinson, 2007), reach (Peponis, Bafna, and Zhang, 2008) and general accessibility measures describing the characteristics of a network (Hillier and Hanson, 1984), assuming that opportunities are the same everywhere (Batty, 2009). Composition describes urban form through the typology of street network segments and intersection. Reach measures describe urban form by measuring the length of a network or the number of nodes reachable from a given location. Meanwhile, general network accessibility measures describe a network's structure based on algorithms from social networks science and mathematical graph analysis, most notably network centrality algorithms (Freeman, 1978). Thus, street network models allow the measurement of a range of urban form, structure and function indicators, as summarized in Table 5.1.

§ 5.2.2 The geographies of street network models

The most conventional geographic representation of a street network in GIS is the road centerline, with linear segments drawn along the middle of a road or of individual traffic lanes (Jiang and Claramunt, 2004). Linear street segments connect at their end nodes, which represent street crossings or junctions, and segments intersecting without nodes indicate that there is no level crossing, for example, at bridges and tunnels. These maps are readily available from official data sources at a range of scales covering whole regions and even countries. The resolution of the road centerline based models is at the level of the street segment and the crossing node. But one can split each sub-segment of curved streets between nodes into straight segments (Peponis, Bafna, and Zhang 2008; Jiang and Liu, 2011), or merge segments together at junctions based on geometry (Thomson, 2003) or named streets (Jiang and Claramunt, 2004).

The spatial network developed in space syntax theory called an axial map (Hillier and Hanson, 1984; Hillier, 1996) provides a different geographic representation. These maps are constituted with the minimal set of longest lines that cover public open space. A connection exists where lines intersect to allow a change of direction, and usually a node is used to indicate the absence of level crossings, at bridges and tunnels. These maps usually have to be produced by hand, which is not ideal for large regional models, although algorithms exist to generate small axial maps from other urban form representations (Batty and Rana, 2004; Turner, Penn, and Hillier, 2005; Jiang and Liu, 2010; Liu and Jiang, 2012). The resolution of an axial map usually is lower because a single axial line can represent several street segments or urban spaces. However, derivatives of an axial map split the lines of the map at intersections producing a segment map (Turner, 2001), or merge them into larger meaningful units, such as continuity lines (Figueiredo, 2009). These different representations correspond to a cognitive and structural description of a network, beyond its geography.

The importance of urban sustainability and sustainable mobility has created increasing interest in analyzing different modes of transport. Both the road centerline and the axial map are used to describe street networks used by private transport, i.e., pedestrians, bicycles and cars. However, the road centerline usually is more comprehensive regarding a car network, whereas an axial map usually describes in greater detail the space accessible to pedestrians. To represent other private modes, both models need to be adapted and extended. For example, the United Kingdom (UK) Ordnance Survey MasterMap road centerline data set has the urban paths layer for coverage of walking routes, whereas an axial map can adopt specific simplifications to represent road infrastructures, such as motorways and roundabouts (Chiaradia, 2007; Pereira et al., 2012).

As for the public transport networks, their representation is a standard feature in transportation network models that use the road centerline, where public transport stops are represented as nodes on a network, with segments connecting these stops along service routes or tracks. Only few examples exist of adding public transport networks to the models based on an axial map (Chiaradia, Moreau, and Raford, 2005; Gil, 2012; Law, Chiaradia, and Schwander, 2012). At present no standard way exists of representing public transport networks; sometimes these representations are determined by the possibilities of the software used for modeling and analysis.

§ 5.2.3 The graphs of street network models

In order to analyze the networks and calculate the different metrics, a graph needs to be constructed by extracting a network topology from its geographic representation using specific principles to identify the graph's vertices (or nodes) and its edges (or links). The simplest graph is a direct translation of a road centerline or public transport network representation, with vertices at the crossings and edges in place of the street segments (Crucitti, Latora, and Porta, 2006a). This graph allows the direct measurement of crossing characteristics using properties of the segments connecting them. In some network accessibility literature, this street network graph is referred to as the primal graph. An alternative graph representation, often referred to as the dual graph (Porta, Crucitti, and Latora, 2006a; Batty, 2009), considers a line or segment as a vertex, and the connection between segments (crossing) as an edge. Here the focus is on the characteristics of street segments, and the change of direction is taken into account to determine the cost of traveling between street segments (Hillier and Hanson, 1984; Hillier ,1996). For large-scale studies, and to allow the use of publicly available street databases, methods have been developed to apply the dual graph representation to road centerline networks (Dalton, Peponis, and Conroy Dalton, 2003; Turner, 2007; Jiang and Liu, 2009).

§ 5.2.4 The impedance of street network models

The notion of network distance is one of the most fundamental concepts in the analysis of street network models (Sen, 1971; Muller, 1982; Smith, 1989), and is defined by an impedance or cost parameter of graph edges. This impedance in transport studies usually is geometric/physical distance based on the length of street segments, or temporal distance if travel speed is taken into account. This impedance also can include other types of cost inherent to travel. In geographical, social network analysis and urban studies, impedance can also be simple topological distance, where every change of direction counts as one topological step, or a geometric/cognitive distance where the angle of direction change is taken into account, and a 90-degree change of direction is equivalent to one topological step (Turner, 2001; Dalton, 2001; Hillier and Iida, 2005). These topological and cognitive distances are especially made possible by the use of the previously mentioned dual graph representation, because an edge describes the change of direction between two street segments.

In the case of the public transport networks, vertices and edges are loaded with attributes that characterize the quality and performance of service, including frequency, speed, duration, waiting times or cost. However, in some experiments where the focus is on network configuration, the impedance between stops is simply topological, with network transfers representing additional topological steps (Chiaradia, Moreau, and Raford, 2005; Gil, 2012; Law, Chiaradia, and Schwander, 2012).

§ 5.3 The multimodal urban network model

From the summary on street network models, one can extract the principles for proposing a MMUN model that is large scale, functionally integrated and geographically disaggregated, to be applied to the description and measurement of urban form, structure and function in the context of a city region.

This MMUN model aims to be unifying and simple. It is unifying, combining the various analysis metrics and impedances into a single model, allowing the measurement of a wide range of urban form characteristics, and supporting a variety of theoretical approaches. This facilitates their direct comparison, and consequently the selection of the most appropriate measurement methods and distance parameters for a given urban analysis problem. This MMUN model is simple, adopting a commonly accepted geographic representation of street networks, a simplified representation of public transport networks, and a flexible graph representation that enables measurement of the various types of distance. The simplified graph representation is important for the adoption of existing data sets, and the coverage of large scale, multi-dimensional problems, while at the same time allowing deployment of the model in practice, which is a desirable outcome of GIS-based regional accessibility assessment tools (Cheng et al., 2007). In the following sections the structure and analysis features of the MMUN model are presented and explained.

§ 5.3.1 The geographic representation of the MMUN model

The MMUN model describes the topology of multi-modal mobility networks and land use units of urban areas, integrating the various mobility infrastructure networks of an urban neighborhood (i.e., pedestrian, bicycle, car, bus, tram and metro), with those of its city region (i.e., motorways and railways). This network model enables measurement of network structure and accessibility for different modes of movement. The different modes work in different ways, have specific geographic representations, and therefore need to be modeled differently. For this reason, the layers of the model are grouped into different systems, namely the private transport, the public transport, and the land use. In addition the model has a layer of elements linking the systems. Figure 5.1 illustrates each of these systems.

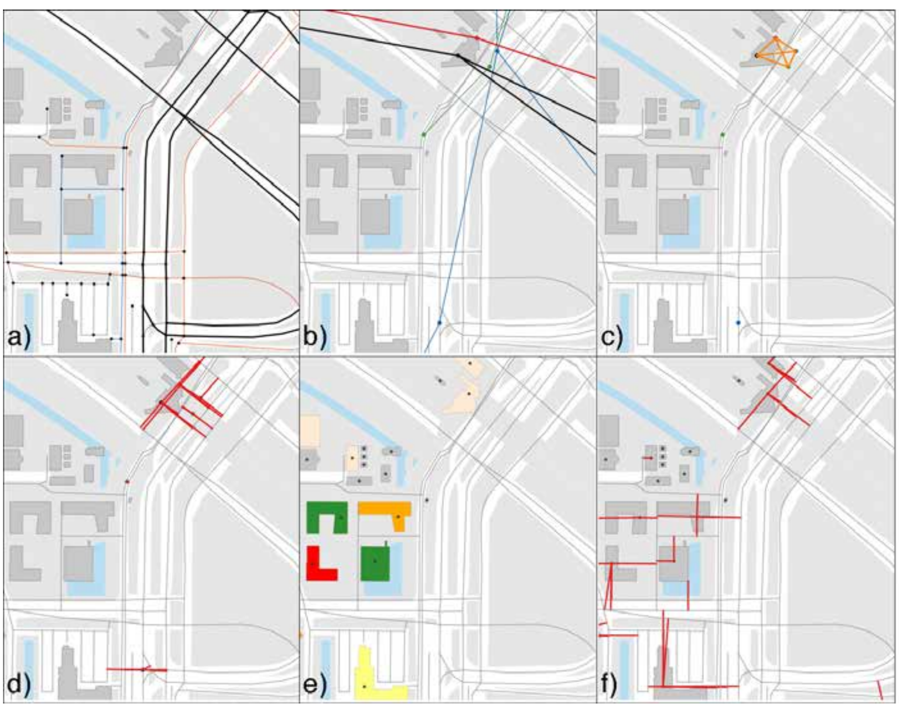


FIGURE 5.1 The systems of the MMUN model: a) private transport, b) public transport, e) land use; and, the interfaces between systems: c) multi-modal transit interfaces, d) transit and roads interfaces, f) buildings and roads interfaces

5.3.1.1 The private transport system

The private transport system is based on a street network, and caters to the free and individual movement of pedestrians, bicycles and cars that, together, share the large majority of a network. This system also constitutes the public space structure of an urban environment, and represents the main interface with other systems: one gains access to public transport and buildings through a street network. Consequently, it is the core system onto which all others must connect.

The private transport system in the MMUN model is modeled using the road centerline representation of a street network, with nodes at every level intersection or junction of two roads, and the road segments linking the nodes. By default, street segments are general and accessible to all private modes — grey segments in Figure 5.1a. However, each segment has an attribute indicating if any of the private modes are not allowed to circulate, and if a segment is designed for a specific mode — grey dotted for pedestrians, grey dashed for bicycles and black for cars in Figure 5.1a. Street segments also have impedance attributes related to their geometry, namely length and shape, and to the time of travel, depending on the speed of an associated mode (see Table 5.2). The nodes layer has attributes relating to the topology of the crossing and the number of different modes allowed to use a crossing.

5.3.1.2 The public transport system

A public transport system offers managed and collective movement of persons on rail, metro, tram and buses, most of the time using specific infrastructure for each mode. The use and the technology of each public transport mode is different, not only requiring different types of tracks to run and stops for boarding and alighting, but also offering different speeds, ranges, and different intervals between stops, increasing from bus to rail. These infrastructure networks cross and converge at particular locations where the stops of different modes share the same name, allowing interchange and multi-modal travel.

The public transport system in the MMUN model consists of a nodes layer representing the stops or stations of each public transport mode, with a single point representing the mean location of the physical access points that have the same name. A links layer connects these points, with straight lines where a service exists between two stops of the same mode — black for rail, dashed black for metro, dashed grey for tram and dotted grey for bus in Figure 5.1b. The resulting public transport networks are interconnected further by modal interfaces (Gil, 2012; Gil and Read, 2012); i.e., links connecting stops of different modes with the same name — black lines in Figure 5.1c. A more detailed representation of a public transport network could be considered, down to the level of individual services, using detailed timetable data. But the amount of error and the difficulty in extracting and building a correct topology from this information led to the decision to use a simplified and more aggregate model. This representation also is in line with the simplicity objective of the overall MMUN model.

5.3.1.3 The land use system

A land use system offers the activities that are most often at either end of travel, and that motivate travel in the first place. Although it is not strictly a layer of the multi-modal transportation system, it is an integral part of accessibility and urban form indicators, and must be included in the MMUN model. In contrast to the other systems, the land use system is composed only of a polygons layer representing the buildings, which also can be represented by nodes at the centroid of the buildings' geometry (Figure 5.1d). These buildings have land use attributes for different categories that result from the aggregation of the units and areas of each category.

§ 5.3.2 Connecting the systems

The different systems of the MMUN model need to work together as an integrated whole, requiring the need to create a feature of a different kind, different from the strict geographic representation of other elements. These features are called modal interfaces, and connect public transport nodes (Figure 5.1e) and buildings (Figure 5.1f) to adjacent street network segment(s). These modal interfaces provide direct links to a private transport system, the street network that becomes the main skeleton of the model onto which all other layers hang. Modal interfaces offer indirect links when moving between a land use and a public transport system. To create these connections, shortest lines are drawn from a public transport node, building perimeter or building centroid to all adjacent street segments of different private transport modes. This multiple linkage is to ensure that public transport and land use is accessible by every mode of a private transport network, and to allow multiple links for one node to account for the multi-lane road centerline representation. Lines crossing other buildings and/or waterways are discarded.

§ 5.3.3 From a geographic network to a graph in the MMUN model

To enable the measurement of network metrics that contribute to the urban form, structure and function indicators summarized in Table 19Error! Reference source not found., a geographic representation of the MMUN model described in the preceding section needs to be translated into a graph representation. A series of different impedances need to be calculated for its edges. The proposed MMUN model uses an undirected graph representation that tries to reflect the nature of each system, combining both a primal and a dual graph representation (Figure 5.2). Although the primal graph representation is simpler to obtain from a road centerline representation, the MMUN model uses a dual representation to enable the calculation of topological and cognitive impedances, and, as such, street segments provide the graph vertices, and crossing nodes provide the edges. In contrast, a public transport system has a more direct (primal) translation because the main spatial units of analysis are the stops or stations, which provide graph vertices, with the connections between them providing links. The land use system only has nodes that become vertices in the MMUN graph. Both public transport and land use vertices link to street segment vertices with links provided by the various modal interfaces.

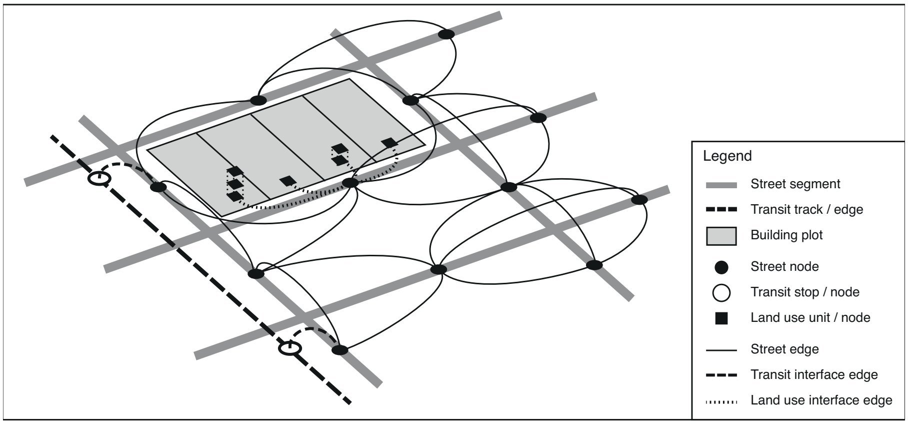


FIGURE 5.2 Diagram of the graph representation of the multi-modal network model.

§ 5.3.4 Distance in the MMUN model

A geographic representation of the MMUN model, in combination with its selected graph representation, supports a variety of network impedances related to different conceptions of distance, namely actual distance (i.e., physical/metric and temporal), topological distance (i.e., axial/turns and segment/intersections), and cognitive distance (i.e., angular/directional and continuity). This representation allows the analysis of the MMUN model from different theoretical perspectives, and a direct comparison of their features. The different distances are derived from the geometry of the network links, and the geometry and topology of the network nodes.

5.3.4.1 Distance in network links

In a first phase, the various types of distance are calculated for every street segment based on its geometry. Physical distance is simply the length of a segment in meters, whereas temporal distance multiplies a length by a factor of speed of each mode (Table 5.2). Topological segment distance takes a constant value of 1 for each segment because that is the spatial unit of the model. As for axial and cognitive distances, if a street segment is straight, then distance is zero, because there is no change of direction or turn along the segment. However, in the case of a street segment with a varying geometry, a method is used that calculates distance based not on the length, but rather on the shape of a link, a procedure first implemented in the sDNA software (Chiaradia, Webster, and Cooper, 2012).

MODE	AVG. SPEED	TOPOLOGICAL INTERFACE WITH TRANSIT	TEMPORAL INTERFACE WITH TRANSIT	TOPOLOGICAL INTERFACE WITH STREETS	TEMPORAL INTERFACE WITH STREETS
Main roads	60 km/h	-	-	-	-
Car	40 km/h	-	-	-	-
Bicycle	15 km/h	-	-	-	-
Pedestrian	5 km/h	-	-	-	-
Rail	80 km/h	2	5 min.	1	3 min.
Metro	25 km/h	2	5 min.	1	3 min.
Tram	25 km/h	2	5 min.	1	½ min.
Bus	30 km/h	2	5 min.	1	½ min.

TABLE 5.2 Network characteristics of the different modes, in terms of average speed and distance of modal interfaces

Note: Based on data from the mobility survey of the Netherlands, the mobility survey of the Netherlands Mobiliteitsonderzoek Nederland (MON) 2004-2009, by the Ministerie van Verkeer en Waterstaat. http://persistent-identifier.nl/?identifier=urn:nbn:nl:ui:13-37z-uia

Angular or directional distance is the sum of the angles between all sub-segments in a street segment (Figure 5.3a). Axial or turns distance is the count of angles, or sums of angles in the same direction, greater than or equal to +- 15 degrees (Figure 5.3b). This quantification is only an approximation of how a set of axial lines could simplify the geometry of a segment, and is not a substitute for an axial map. Continuity distance is the count of angles, or sums of angles in the same direction, greater than or equal to +- 30 degrees (Figure 5.3c). This is one of the values suggested by Figueiredo (2009). Figure 5.4 portrays the result of this method.

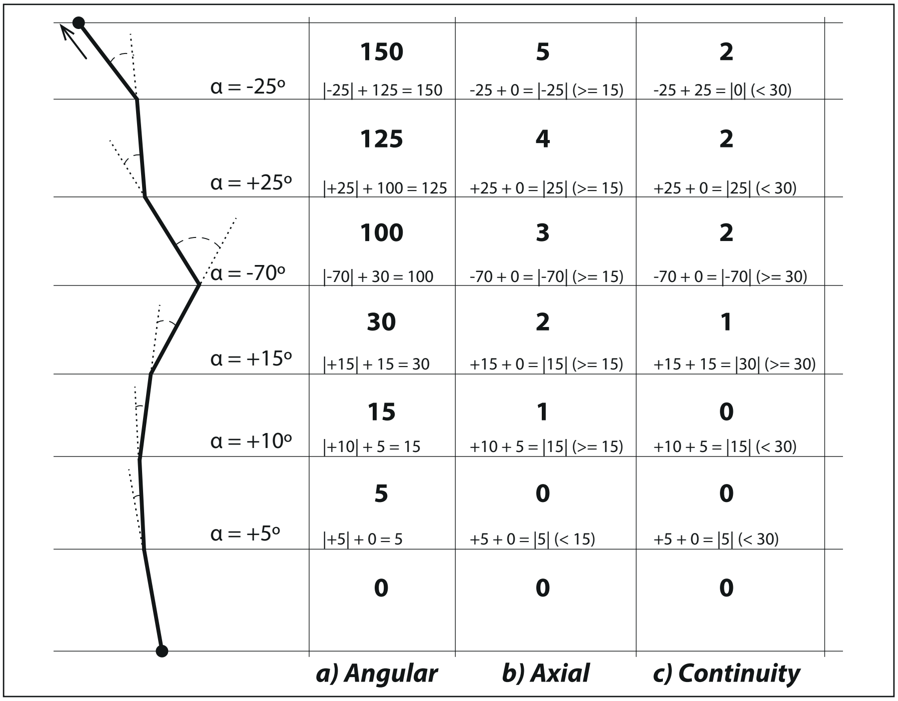


FIGURE 5.3 Calculation of cognitive distances, based on the geometry of a street segment

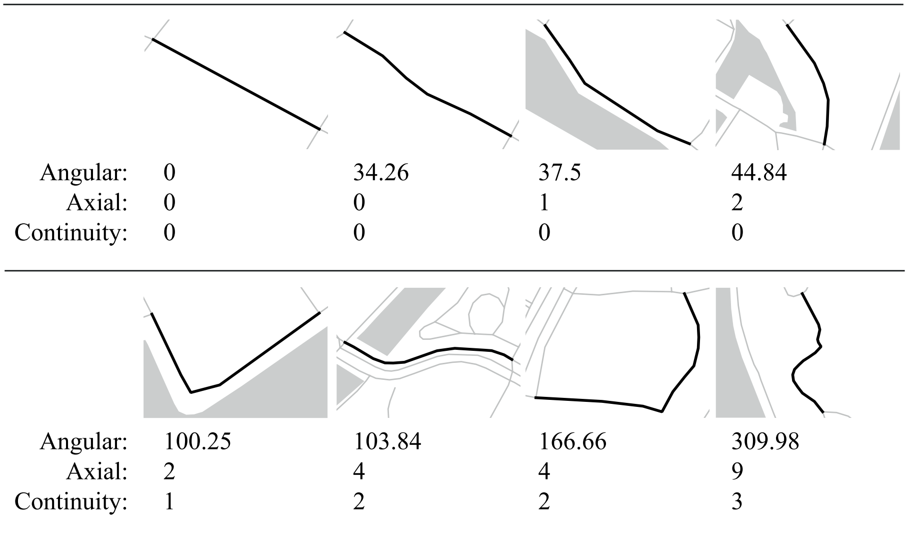


FIGURE 5.4 An example of the cognitive distance of a selection of street segments with different geometries and increasing angular cost. The length of the segments is not relevant.

5.3.4.2 Distance in graph links

In a second phase, the impedance of the dual graph edges is calculated at the moment of conversion from a network representation to a graph representation, where D is the impedance of edge e between vertices i and j, with di and dj being the impedance value of each vertex, and t is the turn cost of edge e between vertices i and j.

$$D(e_{(i,j)}) = d_i/2 + d_j/2 + t_{e(i,j)} \quad (1)$$

Graph links have the same types of distance as network links, and an impedance value results from adding half of the distance of each of the vertices together with the turn cost component of a link. The turn cost component is calculated based on the angle between two segments, and varies depending on the type of distance being calculated. Table 5.3 presents the turn cost t of an angle a between two network segments depending on the type of distance. By calculating these distances, the analysis method for the MMUN model avoids the geometric generalization of the geographic representation to obtain an alternate model, be it an axial map or a continuity map.

DISTANCE	PHYSICAL	TEMPORAL	SEGMENT	ANGULAR	AXIAL	CONTINUITY
Turn cost	t=0	t=0	t=1	t=a	if a >= 15, t=1 if a < 15, t=0	if a >= 30, t=1 if a < 30, t=0

TABLE 5.3 Turn cost added to a dual graph's edges, depending on the type of distance used.

The distances of the public transport system, whose links are straight lines, is simpler to calculate. Physical and temporal distance is based on a link's geometric length, while topological and cognitive distance have a constant value of 1. Because these network links are only represented in primal form, no further transformation is necessary. The impedance of modal interfaces is calculated as in the previous cases for physical and cognitive, distance and has pre-defined constant values for topological and temporal distance, depending on the transport mode (Table 5.3).

Finally, the multi-modal distance used when analyzing the MMUN model is, by default, temporal. This quantification accounts for the different speeds of the different modes; the network analysis algorithm chooses the shortest route accordingly. However, in order to use cognitive instead of physical distance for multi-modal analysis, the MMUN model has two additional distance types. These combine angular distance for a private transport system with topological distance for a public transport system, land use system, and the modal interfaces connecting these. New distances thus obtained can be used in the analysis of the MMUN model, as either a cut-off distance for catchment areas in density measurements, or a shortest route distance in proximity and accessibility measurements.

§ 5.4 Implementing a MMUN model of the Randstad city-region using open data

To demonstrate the MMUN model, this section introduces an implementation of the model for the Randstad city-region in the Netherlands. The Randstad city-region has a long spatial planning tradition, with a well-established multi-modal mobility network, having extensive walking and cycling infrastructure and comprehensive public transport networks. Three different open data sets have been used to build the MMUN model of the Randstad city-region (Figure 5.5): the private transport system data were extracted from the OpenStreetMap [8] (OSM) data set of the Netherlands daily dump (January 2012) [9]; the public transport system data were derived partly from OSM, and partly from the public transport time table database of the OpenOV [10] project, and then supplemented with information from route maps of the various network operators; and, the land use data were extracted from the Basisregistraties Adressen en Gebouwen [11] (BAG) data set. These three data sets were processed in PostGIS to create the various layers of the MMUN model.

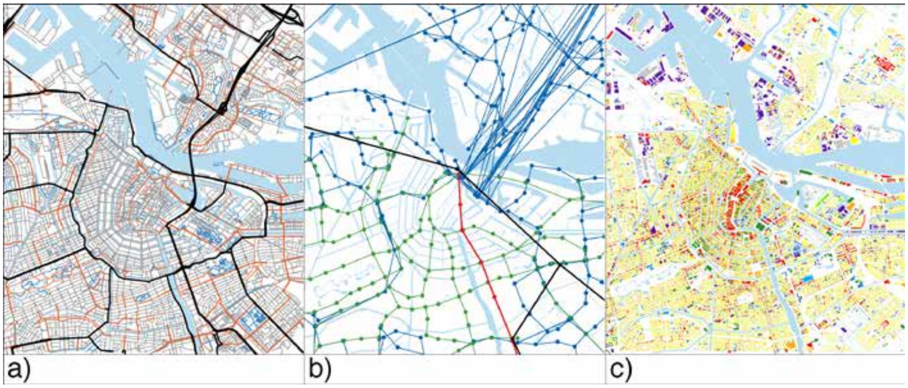


FIGURE 5.5 Overview of the three main systems of the MMUN model centered on Amsterdam: a) private transport system, b) public transport system, and c) land use system.

8 http://www.openstreetmap.org/ [Accessed 09 Nov 2013]

9 http://download.geofabrik.de/ [Accessed 09 Nov 2013]

10 http://openov.nl/ [Accessed 09 Nov 2013]

11 http://bag.vrom.nl/ [Accessed 09 Nov 2013]

The street network data of the Randstad city-region consists of 462,384 nodes and 676,264 road segments (Figure 5.5a). The OSM data initially were compared with other official data sources, and found to be at least as complete regarding the roads, and more complete in terms of pedestrian and bicycle facilities. However, its attributes had to be analyzed to determine the various modes available for each segment, excluding modes that are forbidden to circulate by law (e.g., walking or cycling on motorways). Errors in standard road centerline representations also had to be corrected to obtain the correct topology.

The public transport data consist of 161 railway, 614 tram, 186 metro, and 7680 bus nodes (Figure 5.5b). Ideally these data should be systematically extracted from a single timetable data source; however, the OpenOV database was not complete at the time the model was built. The OpenOV information was supplemented with public transport route map information from both Wikipedia and the individual network operators.

The land use data have 3,843,227 points representing each land use unit, with its category and surface area, amongst other attributes. One or more units exist inside the buildings' polygons (2,430,945), and the land use attributes are aggregated on each building (Figure 5.5c). Buildings without an associated land use point were not included in the network model. The land use data required some corrections to the area values, because of mistakes during data entry and inconsistent representation of null values across the data set.

§ 5.4.1 Some technical considerations

The OSM data structure has all of the features to support the requirements for a MMUN model, and one should expect that, over time, it will grow becoming more complete and detailed. With its worldwide coverage, it also should be the preferred data source because it can be used consistently in different countries. Any knowledge, methods and techniques developed are easily transferrable to other case studies, and the results are more easily comparable. Nevertheless, it still presents various challenges that have forced the use of supplemental data sources, and the implementation of various automated procedures to enable its use in the proposed MMUN model. While covering these issues in any detail is beyond the scope of this article, the following list is useful for future reference:

- The OSM data set requires careful extraction and consideration of the tags associated with features, which is not possible with the pre-processed data sets available for download in convenient GIS formats;
- The size of the data sets and their structure requires the use of a spatial database;

- The feature attributes suffer from problems: gaps in coverage, inconsistent application, and a wide variety of tags with subtle variations and combinations;
- The road network is not consistently represented as a road centerline, and needs to be fixed;
- OSM includes topology (relations), but these are very inconsistently and scarcely applied;
- The pedestrian network is included as paths, but squares and other areas are represented as polygons, and need processing to be included in the street segments network;
- The transit networks tend to be very incomplete;
- Streets and transit stops can have inconsistent namings, which makes data matching difficult;
- The accurate geographic location of transit stops needs to be processed when aiming for a simplified conceptual model with one stop representing a group;
- Errors and gaps in the data set exist that are impossible to check and fix in a regional model. One must accept a level of error, and only address aspects that can be corrected systematically using an algorithm.

This MMUN model of the Randstad city-region has been implemented, analysed and visualised with open source geographic information system (GIS) platforms, namely PostgreSQL/PostGIS, R, and QGIS. These platforms allow most of the steps in the process to be scripted and automated, facilitating reproducibility and generalization. The free access to both software and data ultimately supports sharing and verification of tools, methods, and results.

§ 5.5 Analysing the configuration of multi-modal urban networks

The MMUN model of the Randstad city-region provides an implementation with which one can carry out a series of experiments to identify the capabilities of the model to describe the structure and functioning of urban networks in the city region. The model is analyzed using network centrality measures (closeness and betweenness centrality), experimenting with key features of the model, namely:

- the ability to use different distance parameters, stemming from different theoretical approaches;
- the ability to select different combinations of modes of transport.

We test the performance of the model, under different distance parameters and different layer combinations, looking for significant statistical patterns in the correlation of the analysis results with empirical data, such as traffic counts, passenger numbers, and land use location. From the statistical patterns identified, one can draw conclusions about the use of different distance concepts, network centrality measures, and multi-modal layer combinations.

The first experiment uses the centrality measures of the car network to identify the urban structure and road hierarchy of the region. The second experiment correlates private transport network centrality with car traffic counts. The third correlates public transport network centrality with rail passenger counts. The fourth experiment correlates various network centrality measures with work and active land use counts.

§ 5.5.1 The urban structure and road hierarchy of the Randstad city-region

One of the roles of the urban network model is to identify the core structure of the region in terms of its urban centers and network infrastructure hierarchy. Network centrality measures can be used to identify such structures, and by calculating the network centrality of the car network of the Randstad city-region, one should expect to highlight the main urban centers of the region, and the main road infrastructure connecting them, which are illustrated in Figure 5.6 and Table 5.4.

NETWORK	LENGTH (KM)	% LENGTH	COUNT (SEGMENTS)	% COUNT
All roads	33,371,128	100	365,418	100
Motorways	2,420,148	7.25	3909	1.07
Main roads	2,491,038	7.46	15,982	4.37
Other roads	28,762,786	86.19	346,275	94.76

TABLE 5.4 Share of main roads in the car network of the Randstad city-region.

The main road network, which includes motorways and national roads, represents around 4.4% of the number of segments in the road network. With the MMUN model, one can directly compare different types of distance and measure the extent to which they correspond to such structures. The following analysis uses the car network, which excludes roads that are not accessible to motorized vehicles, and calculates closeness and betweenness centrality using different types of distance.

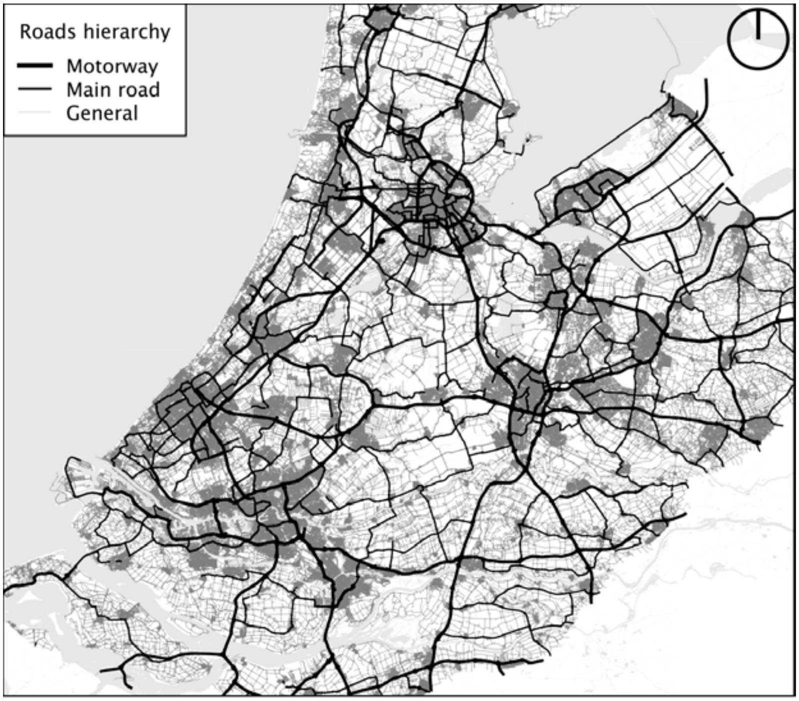


FIGURE 5.6 Map of the main road network of the Randstad city-region.

Figure 5.7 presents the results of actual (temporal) and cognitive (angular) distance for the study area. The results in the analysis buffer (dashed region) around the Randstad city-region are not shown because these are strongly affected by "edge effects" and should not be considered.

Closeness centrality analysis results imply that actual distance does not capture the main urban structure of the region Figure 5.7a. The highest closeness centrality values are concentrated in the geographic center of the region, mostly a green field area referred to as the Green Heart. Temporal distance offers some improvements over physical distance, highlighted in Figure 5.7c, with the impact of adding travel time to the analysis increasing closeness centrality in urban centers and on the main road network. This map shows the rank difference in closeness centrality between physical and temporal distance, where higher-ranking street segments in physical distance are grey, and higher-ranking street segments in temporal distance are in black. Segments with little or no rank difference are thin. However, a clearer depiction of the structure of the region comes from measures using topological and cognitive distance, here illustrated with angular distance (Figure 5.7b). The rank difference map of angular in relation to temporal distance (Figure 5.7d) shows that the angular distance closeness centrality measure identifies the main structures up to the edge of the study area.

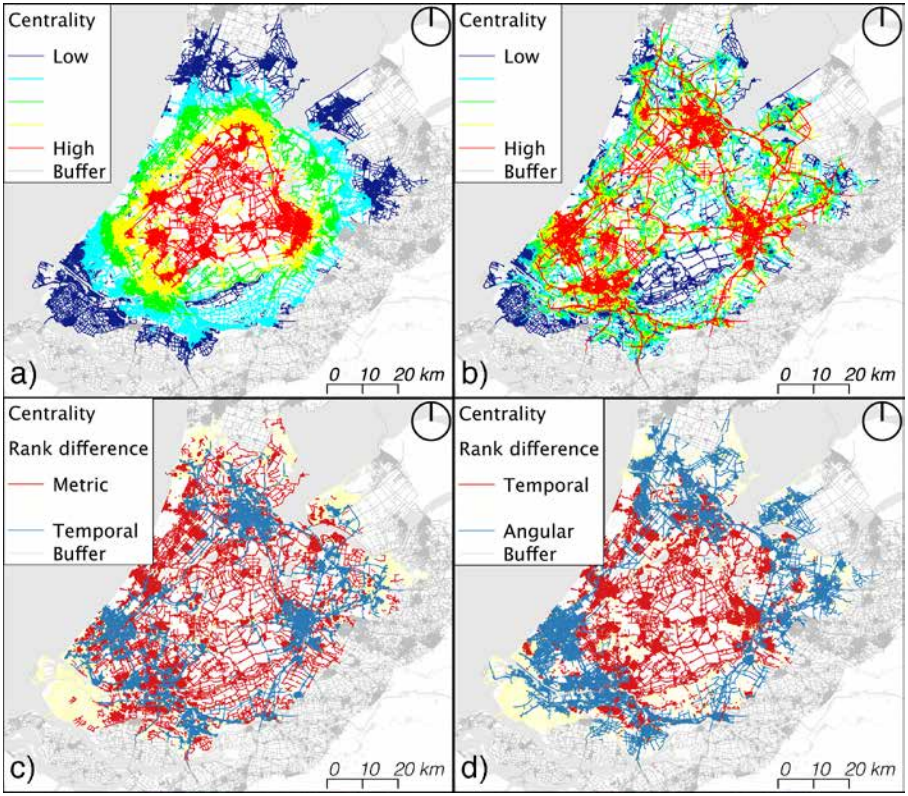


FIGURE 5.7 Closeness centrality analysis of the car network of the MMUN model for a) temporal distance, and b) angular distance, where red represents high centrality values and blue low centrality values. Centrality rank difference between c) physical (red is higher rank) and temporal (blue is higher rank) distance, and d) temporal (red is higher rank) and angular (blue is higher rank) distance.

For betweenness centrality (Figure 5.8), a measure of network flow, the top 5% rank values are expected to be found in larger proportion on segments of the main road network (Figure 5.6), because these are responsible for the majority of traffic flow (Jiang, 2009). To test the performance of this measure, one can calculate the percent share of betweenness assigned to the designated motorways and main roads of the region. The results in Table 5.5 confirm that physical distance does not assign flow preferentially to the main road network. Although temporal distance does, the classification of the network is implicit in the measure in the form of speeds. From these results, one can conclude that network centrality measures using physical distance are not adequate for regional scale analysis of urban structure, although they might be suitable for local analysis. Although temporal distance improves this result, topological and cognitive distance measures are able to identify the main road and urban centers structure of the region.

TOC

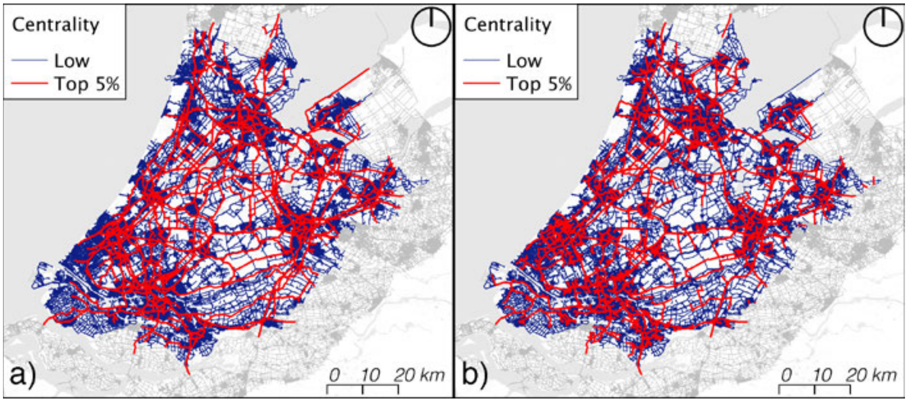


FIGURE 5.8 Betweenness centrality analysis of the car network of the MMUN model for a) metric distance, and b) angular distance, where red represents the top 5% centrality values corresponding to the long tail of the distribution, and blue represents low centrality values.

	PHYSICAL	TEMPORAL	ANGULAR	AXIAL	CONTINUITY	SEGMENT
Motorways % flow	7.42	13.46	45.67	38.33	41.14	52.8
Main roads % flow	29.12	47.2	21.39	26.11	31.26	16.87
Total % flow	36.54	60.66	67.06	64.44	72.4	69.67

TABLE 5.5 Percent share of total flow (betweenness centrality) on the main road network, for different types of distance.

§ 5.5.2 Testing private transport network flows

Next, we take the closeness and betweenness centrality measures of the private transport network of the Randstad city-region and correlate them with vehicular annual average daily traffic (AADT). The data was compiled from various sources [12], and we obtained a total of 514 traffic count locations on main roads and motorways. The map in Figure 5.9 shows the spatial distribution of traffic count measurements, whereas the histograms show the volume distribution for weekday AADT.

12 South Holland traffic intensity and measuring points (http://www.zuid-holland.nl/opendata); Utrecht traffic intensity on A and N roads (http://www.provinciaalgeoregister.nl/); Location of Dutch traffic information points (http://data.rotterdamopendata.nl/en/dataset/verkeers-informatie-locatie-database) [Accessed 09 Nov 2013]

TOC

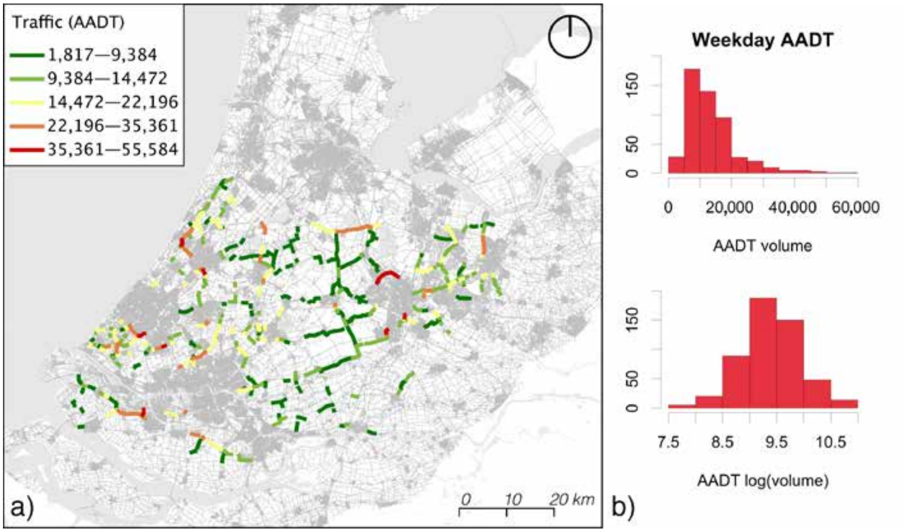


FIGURE 5.9 Map of vehicular traffic count measurement locations, and histograms of weekday AADT distribution.

The correlation with actual traffic counts presented in Table 5.6 shows that closeness and betweenness centrality using physical and temporal distance does not adequately describe the traffic volumes on the road network, compared with topological and cognitive distance measures. More surprisingly, closeness centrality gives better results than betweenness centrality, especially in the case of axial and continuity distance. These distance types encapsulate the structure of the networks by aggregating segments with minimal angular deviation into a single unit, and, as such, seem to provide a better structural description of the region.

MEASURE	CLOSENESS CENTRALITY	BETWEENNESS CENTRALITY
Car physical/metric distance	(-0.069)	0.119**
Car temporal distance	(-0.016)	(0.083)
Car angular distance	0.491***	**0.453*** **
Car axial distance	0.462***	0.271***
Car continuity distance	**0.527*** **	0.231***
Car segment distance	0.252***	0.381***
Private transport network angular distance	0.490***	0.443***
Complete network angular topological distance	0.447***	0.424***

TABLE 5.6 Correlation of private transport network centrality with vehicular AADT, using different types of distance and different MMUN model configurations

*Notes: In bold is the highest value in each column; (p > 0.05); * p < 0.05; ** p < 0.01; *** p < 0.001*

One final observation relates to the result of integrating the other private and public transport networks with the car network (the two bottom rows in Table 5.6). These results, based on angular distance, do not improve on the car network based result, which is not surprising because the vehicular counts only relate to traffic on main roads that are less related to these other networks. In addition, the public transport network introduces infrastructure at a regional scale that competes with the role of the main road network, thus not contributing to a better description of the car network structure of the region.

§ 5.5.3 Testing public transport network flows

We now focus on the structure and hierarchy of public transport networks by correlating different distance types and network configurations with rail passenger counts [13] entering and exiting the 161 railway stations of the Randstad city-region (data for 2006).

	NATIONAL		REGIONAL	
Measure	Closeness Centrality	Betweenness Centrality	Closeness Centrality	Betweenness Centrality
Rail				
Rail metric distance	(0.111)	0.377***	0.267**	0.401***
Rail topological distance	(0.170)	0.371***	0.298***	0.344***
Transit				
Transit metric distance	0.174*	0.355***	0.281**	0.366***
Transit temporal distance	0.232*	0.446***	**0.312****	0.420***
Transit topological distance	0.247*	0.479***	0.275**	0.404***
Transit topological with transfers distance	**0.265***	**0.488*****	0.276**	0.395***
Multimodal				
Non-motor temporal distance	-	-	0.259**	**0.432*****
Non-motor angular topological distance	-	-	0.262**	0.383***
Complete network temporal distance	-	-	0.248**	0.431***
Complete network angular topological distance	-	-	0.268**	0.350***

TABLE 5.7 Correlation of public transport network centrality with rail passenger counts, using different types of distance and different MMUN model configurations.

*Notes: In bold is the highest value in each column; (p > 0.05); * p < 0.05; ** p < 0.01; *** p < 0.001*

13 Rail passenger counts obtained from the rail passenger portal (http://www.treinreiziger.nl/) [Accessed 09 Nov 2013]

The coefficients presented in Table 5.7 have been calculated using Spearman's rank correlation because of the widely varying distributions of the measures and passenger count data. The rail network includes all rail stations at the national and regional levels, the transit network combines all public transport modes at the national and regional levels, the non-motor network combines the pedestrian and cycling networks with the transit network, and the complete network combines all modes of transport for the complete MMUN model.

Several patterns can be identified in the results summarized by Table 5.7:

- The betweenness centrality measures give better results than the corresponding closeness centrality measures, confirming that they are better descriptors of levels of flow;
- The national model's betweenness result performs better than the regional model's equivalent, except in the case of physical metric distance. This outcome might suggest that the analysis boundary for infrastructure networks with a reach beyond the region might have to extend to the whole country, or the analysis should be restricted to trips at a regional scale;
- For the regional model, temporal distance performs better than topological distance;
- When multiple public transport networks are integrated (i.e., the transit network), the measures that account for the multiple networks (temporal and topological with transfers) perform better than the equivalent basic measures (metric and topological);
- Integration of the various public transport networks performs better than the rail network alone;
- Integration of the non-motorized private transport network improves the description of the rail hierarchy when using physical distance, which furnishes the best overall result for the regional model;
- The addition of the motorized network has little impact on the results.

These conclusions are substantially different from what has been observed for private transport networks, and reinforces the idea that the private and public transport systems work in different ways. As such, they need to be analyzed using different parameters, and eventually perform better separately.

§ 5.5.4 The integration of networks in multi-modal configurations

In the final experiment, we focus on the integration of the different layers of the MMUN model, and compare the performance of the network centrality measures with the land use distribution of work units (i.e., office and industry) and active units (i.e., retail, leisure, and services) in the region (Figure 5.10).

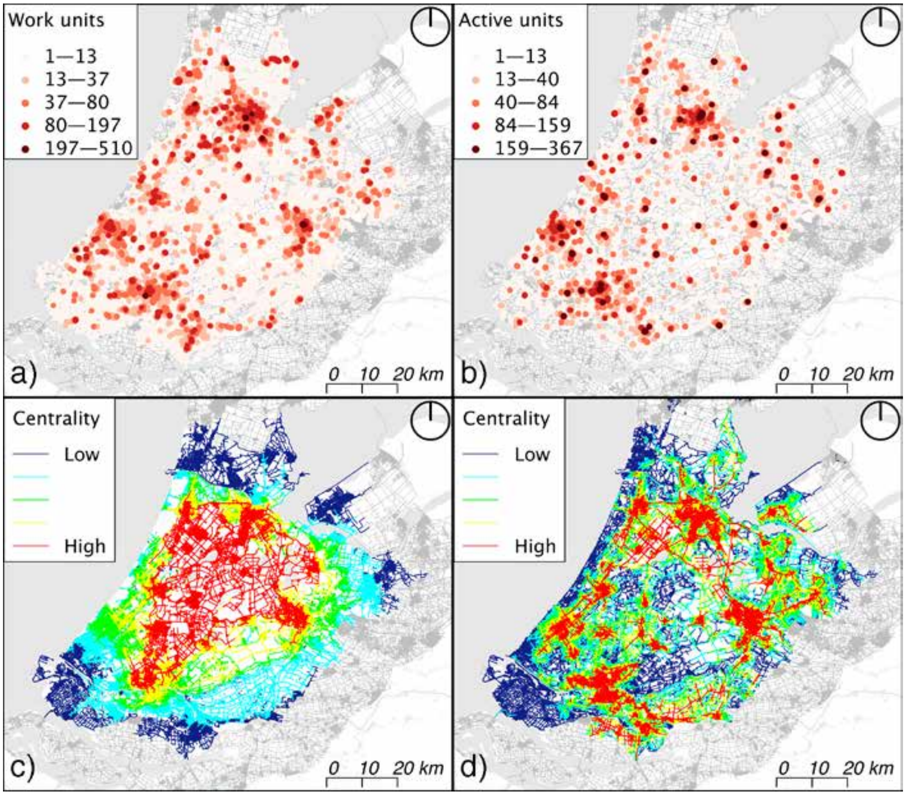


FIGURE 5.10 Maps of spatial distribution of a) work units and b) active units, and maps of closeness centrality using angular distance of the c) non-motorized network and d) transit integrated network.

This functional characteristic of the region is less related to any specific mode of transport, and is more likely to be described by an integrated MMUN model. Table 5.8 presents the results of correlating the various network centrality measures with land use units. One can identify several patterns in these results:

	WORK UNITS		ACTIVE UNITS	
Measure	Closeness Centrality	Betweenness Centrality	Closeness Centrality	Betweenness Centrality
Car network temporal distance	0.133***	(0.055)	0.016***	(0.041)
Car network angular distance	0.230***	0.052***	0.113***	0.033**
Non-motor angular distance	0.163***	0.064***	0.070***	0.042***
Private transport temporal distance	0.127***	(0.052)	0.010***	0.032**
Private transport angular distance	0.220***	0.058***	0.104***	0.037**

Transit angular topological distance	**0.261*** **	**0.061*** **	**0.187*** **	**0.051*** **
Complete network temporal distance	0.185***	0.056***	0.072***	0.034*
Complete network angular topological distance	0.260***	(0.060)	0.149***	(0.042)

TABLE 5.8 Correlation of combined multi-modal network centrality with work and active land use units.

*Notes: In bold is the highest value in each column; (p > 0.05); * p < 0.05; ** p < 0.01; *** p < 0.001*

- The closeness centrality measure always gives better results than betweenness centrality (this either has a low value, or is not statistically significant);
- Angular or topological distance always gives better results than temporal distance;
- Results improve with increased integration of the transport networks;
- The transit network model, combining non-motorized transport networks with all public transport networks, gives the overall best result.

§ 5.6 Conclusions and future work

This article presents a MMUN model to describe a region using three systems: private transport (car, bicycle and pedestrian), public transport, and building land use. This model allows the measurement of proximity, density, and accessibility characteristics of urban areas in the context of a city region to obtain urban form indicators useful in planning and urban design practice. An example of the model has been implemented for the Randstad city-region in the Netherlands using open source data and software, and a series of experiments was carried out focusing on identifying distance parameters and system integration levels that are able to capture the structural and functional characteristics of the region. These experiments imply some conclusions about the use of a MMUN model.

In the network centrality analysis of private transport networks, using physical and temporal distance does not necessarily identify the main roads and urban centers of the city-region, as opposed to the urban structures revealed when using topological and cognitive distances. This finding is confirmed when testing the model with empirical data from car traffic volumes. In contrast, for the public transport network, betweenness centrality using physical and temporal distance seems to better capture passenger numbers. This result improves as the various networks are combined progressively, except with the addition of the car network. Regarding the combination of layers into different models, the existence of meaningful combinations is confirmed when testing the analysis results against the location of work and active land uses. The land use distribution and concentration is increasingly better described with the addition of network layers to the model. However, the complete model with all layers combined, does not give the best correlation results. Indeed, the private transport system, including the car network, functions quite differently vis-a-vis the public transport network: they contribute to different phenomena in the region, and as such should be analyzed using different parameters, and eventually perform better when analyzed in meaningful layer combinations, such as the pairing of non-motorized modes and public transport.

The proposed MMUN model offers enormous possibilities to explore and describe the multi-modal urban structure of a city-region, combining different metrics, types of distance and layers of information. Experiments summarized in this article only scratch the surface, and further experimentation is required to calibrate the model's parameters in greater detail. For example, the private transport system could be tested using a directed network, with greater accuracy in the assignment of speed to segments, and even the inclusion of temporal costs at the change of direction in intersections. But one also could keep the simpler undirected graph representation, and simplify the model's geographic representation, merging roads with multiple lanes together into a single segment. The public transport's topological model would require a finer calibration of the impedance between stops, and of transfer between modes, in particular temporal cost. In addition, the level of detail of the public transport network representation also can be increased, including separating lines and services instead of the current representation of network infrastructure connectivity. However, any such modifications should be made with the main objectives, of providing a model that is unifying, to address the relational complexity of the region, while maintaining its simplicity so that it can become an operational tool in urban design and strategic planning.

Through the selective use of robust analysis measures and parameters with meaningful layer combinations, one can obtain a complex profile of urban areas integrated in a wider city region. The MMUN model seems to provide a necessary tool to conduct such an analysis.

6 Patterns of sustainable mobility and the structure of modality in the Randstad city-region [14]

Abstract

The sustainable mobility vision for city-regions proposes a more integrated and 'seamless' multi-modal public transport system around quality neighbourhoods, shifting mobility to soft transportation modes and to public transport at various scales. Existing models of sustainable urban form address this challenge focusing on the location, density and diversity of activities, on the composition of the street layout, and on the presence of transport nodes and the quality of the public transport service. In order to better understand the relation between urban form and sustainable mobility patterns we propose to additionally measure the structure of mobility networks, including network proximity, density and accessibility, for different transport modes. The analysis of a multi-modal network model of the Randstad region in the Netherlands, integrating private and public transport infrastructure networks and land use information, reveals the structures of modality in the city-region. These structures are used to identify a typology of 'modality environments' that tested against travel survey data demonstrate support for specific patterns of mobility, i.e. walking, cycling, car use, local and regional transit. This classification can contribute to a new urban form based method for evaluating the potential of neighbourhoods for sustainable mobility.

14 This chapter is based on the manuscript of: Gil, J. and Read, S. (2014). 'Patterns of sustainable mobility and the structure of modality in the Randstad city-region'. A|Z ITU Journal of the Faculty of Architecture 11 (2), pp. 231-254. (Main author, 85% contribution)

§ 6.1 Introduction

The Randstad region in the Netherlands is one of the paradigmatic polycentric city-regions in Europe (Hall and Pain, 2006), comprising the four largest cities in the country (Amsterdam, Rotterdam, The Hague and Utrecht) and a series of middle size cities (Amersfoort, Haarlem, Leiden, Dordrecht and Hilversum) that together constitute its Daily Urban Systems (DUS) against a background of suburban neighbourhoods and a mostly preserved rural and natural area at the centre called the "Green Heart" (van Eck and Snellen, 2006). The Randstad urban centres and their suburbs are served by an established multi-modal mobility network of local walking and cycling infrastructure, comprehensive road and public transport networks, and connected by rail and motorway networks. The Randstad's combination of mobility infrastructure networks with land use concentration and mix should offer the baseline conditions for sustainable mobility patterns within the local neighbourhoods and across the region (Figure 6.1).

The Randstad's current configuration is the result of a long spatial planning tradition based on carefully planned neighbourhood development since World War II (Wassenberg, 2006) that over the decades has evolved from implicit to explicit sustainable urban development (Goedman et al., 2008), reflected in policy documents since the late 1980s (Buijs, 1992; VROM, 2001; VROM 2008). The Fourth Spatial Planning Framework Extra, also known as VINEX, introduced a program of urban expansion of new residential areas focusing on the core concepts of sustainable neighbourhood development and sustainable mobility in particular. The Fifth Spatial Planning Framework, the latest spatial strategy for the Netherlands, sets as key objectives the reduction of traffic congestion, the intensification of land use and the development of the network for multi-modal transport provision (VROM, 2001; Snellen and Hilbers, 2007) with the aim of achieving a more sustainable mobility. Understanding the spatial conditions that support these policy objectives is a primary concern.

Some of the main VINEX objectives have in general not been achieved, i.e. increase in walking and cycling in the neighbourhood, use of public transport for commuting or reduction of car use. In particular, the locations in green field sites do not lead to more sustainable mobility patterns when compared to other parts of the country and continue to perform worse than new and old inner city locations (Hilbers and Snellen, 2005).

While this can in part be explained by differences in socio-economic profile between these different locations, for a particular type of location one might find a consistent trend of mobility pattern. With the aim of exploring this assumption we look at empirical evidence from a mobility survey and at network structure characteristics of the city-region within a framework of sustainable mobility indicators. This paper follows from previous research analysing public transport networks using the space syntax configurational approach (Gil and Read, 2012), which revealed the structure and hierarchy of each network and of their integrated effect, towards assessing the potential of different neighbourhoods to support sustainable mobility patterns.

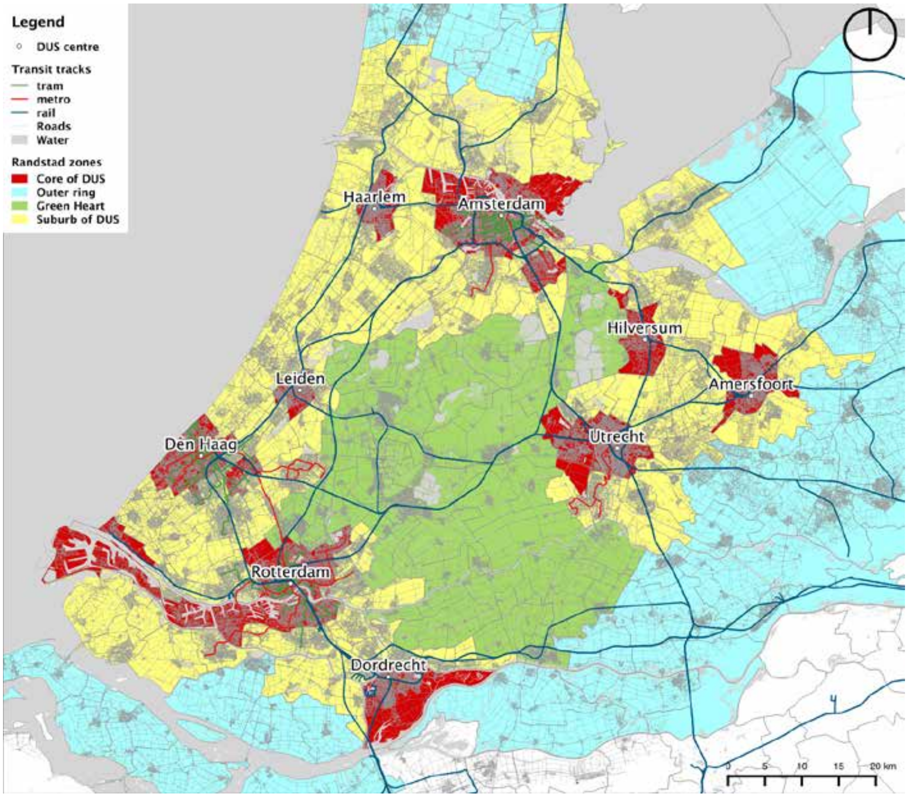


FIGURE 6.1 Map of the Randstad city-region, showing its areas, main urban centres and main mobility network infrastructure.

§ 6.2 Sustainable mobility patterns in the Randstad city-region

The general sustainable mobility vision for city-regions proposes a more integrated and 'seamless' multi-modal public transport system around quality neighbourhoods and vibrant city centres, with land use distribution matching the needs of population, business and institutions, shifting mobility to soft transportation modes such as walking and cycling and to public transport for long distance travel (Banister, 2005). These objectives can be monitored through the use of sustainable mobility indicators, like the ones found in numerous urban from and travel studies and policy documents, such as distance travelled per mode or per person, modal share and number of journeys (Cervero and Kockelman, 1997; Newman and Kenworthy, 1999; Banister 2008; Bruun, Schiller and Litman, 2012; Gilbert and Tanguay, 2000; European Commission, 2001). Using empirical data from the Netherlands Mobility Survey from the years 2004 to 2009 (MON 2004-2009) containing 282,543 individual home based journeys between the 4-digit postcodes of the Randstad city-region, one can identify the sustainable mobility patterns of the population according to a collection of sustainable mobility indicators (Table 6.1). In this table, the mean, minimum and maximum values for each indicator are given for the whole Randstad, providing baseline against which one can compare the performance of specific postcodes.

INDICATOR	SUSTAINABILITY DIRECTION	RANDSTAD		
		MEAN	MINIMUM	MAXIMUM
Share of short[1] walk journeys	+++	54.17 %	0.00	100.00
Share of walk journeys	+++	22.64 %	0.00	59.42
Share of short[1] cycle journeys	+++	30.66 %	0.00	93.75
Share of medium[2] cycle journeys	+++	33.14 %	0.00	81.82
Share of cycle journeys	+++	25.59 %	0.00	51.37
Share of short[1] car journeys	---	14.23 %	0.00	100.00
Share of medium[2] car journeys	--	52.33 %	0.00	100.00
Share of long[3] car journeys	-	78.01 %	20.00	100.00
Share of car journeys	---	44.65 %	3.42	88.71
Share of car distance	--	74.87 %	17.96	98.47
Share of car duration	--	56.16 %	6.50	93.99
Share of medium[2] local transit journeys	++	6.19 %	0.00	53.33
Share of local transit journeys	++	2.55%	0.00	20.00
Share of long[3] train journeys	++	14.82 %	0.00	65.00
Share of train journeys	++	2.13 %	0.00	17.59
Share of transit distance	++	12.64 %	0.00	65.33
Share of transit duration	+	7.91 %	0.00	41.39
Mean journey distance	-	10.2 km	2.99	28.38
Mean daily distance per person	-	34.5 km	8.70	102.01
Mean daily journeys per person	-	3.40	2.46	6.00

TABLE 6.1 Selection of sustainable mobility indicators. The 'Sustainability direction' column shows the intended direction of the indicator in relation to general sustainable mobility objectives.

Notes: 1) up to 1.5km; 2) between 1.5km and 10km; 3) longer than 10km

From the mean values in Table 6.1 one can observe certain mobility trends in this city-region. The overall number of cycle journeys share is high at 25%, even higher than walking, but this depends on the distance travelled because more than half of the short local journeys are done by walking, followed by the bicycle at 30.66%. Transit share is on average very low, which is surprising considering the extensive public transport infrastructure, however many locations away for the larger urban centres are not served by a variety public transport modes, and in urban areas public transport share can be as high as 36% of the journeys. Despite the relatively high values of some sustainable mobility indicators, the car journeys share is the highest on average 44%, approaching a 75% share when it comes to total distance travelled. For that reason, there are policies in place to reinforce the positive change towards sustainable mobility, represented in Table 6.1 by the symbols in the 'Sustainability direction' column.

One aspect that can be found in the data set is the close relation between multi-modal journeys and overall public transport journeys. While the large majority of multi-modal journeys use public transport (86%) either in one or more legs of the journey, the other legs are mostly walking (54% at origin and 71% at destination), cycling (13%) and with the car (8,5% as driver and 5% as passenger).

What is clear from the minimum and maximum values in Table 6.1 is that there is a large amount of variation for certain mobility indicators, which is suggestive of a local variation in conditions that support specific mobility patterns. We can map the sustainable mobility indicators in the region using scaled values centred on the Randstad's mean value, with red showing indicator values below the baseline and green indicator values above the baseline (Figure 6.2). Looking at the variation of indicator values on the maps, they present clear spatial patterns, further reinforcing the notion that urban form and configuration characteristics can be used as indicators of sustainable mobility especially in planning.

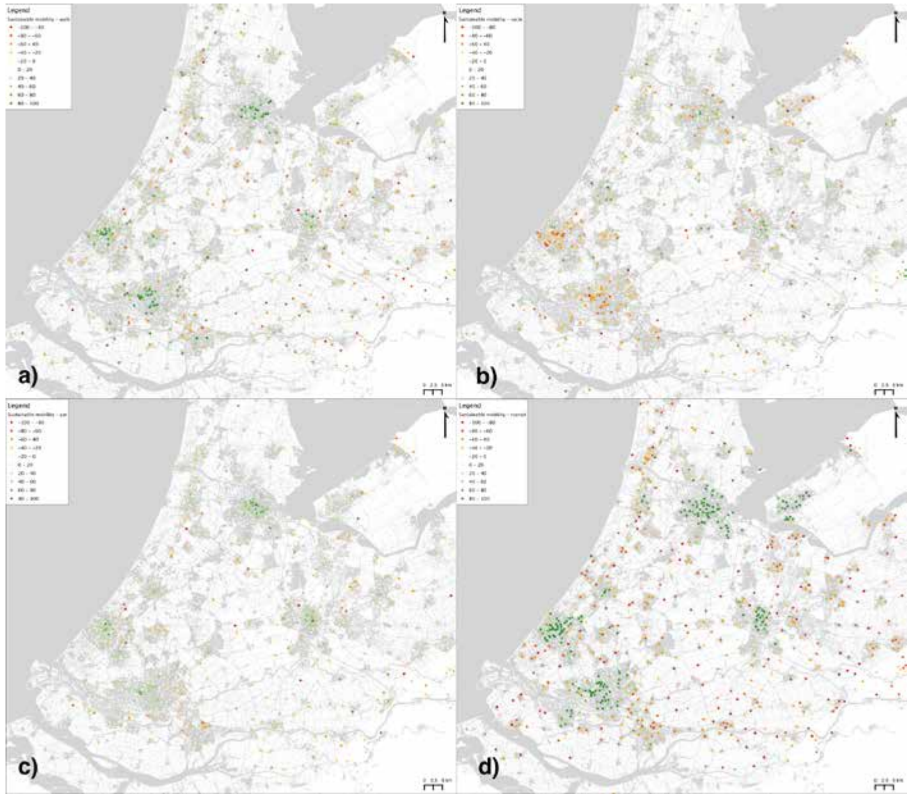


FIGURE 6.2 Maps of the spatial patterns of sustainable mobility indicators, with green for values above and red for values below the Randstad baseline mean value, for a) walking b) cycling c) car and d) public transport share.

§ 6.3 The configuration of multi-modal urban networks

Existing models of sustainable urban form, such as transit-oriented development (TOD), and of sustainable accessibility, such as 'Multi-modal urban regional development' (Bertolini and le Clercq, 2003), relate specific urban form characteristics to sustainable mobility patterns. In terms of urban form characteristics, these models focus on the presence of transport nodes, on the public transport's network size and service quality, and on the location, density and diversity of activities. They use node, density and accessibility measures (Cheng et al., 2012) where the network provides the connection between opportunities (land use units or transportation nodes) and is used to measure the distance to them (accessibility) and their number or size (density) reachable from a given location.

Other urban form models focus on the characteristics of the street network itself, measuring the composition of the street layout (Marshall, 2005b), network reach (Peponis et al., 2008) and network centrality (Hillier and Hanson, 1984), providing the network affordances of all locations assuming that the opportunities are the same everywhere in a general form of accessibility (Batty, 2009). These street network models are used in the context of sustainable development to describe and measure the configuration of urban areas and can extend to cover entire cities and city-regions.

In order to better understand the complex relation between urban form and sustainable mobility patterns it is proposed that the city-region needs to be measured according to the configuration characteristics of its mobility infrastructure networks, and for that we need integrated urban network models. These models can address the organising role of the mobility infrastructure networks, where these whole, integrated structures define the relational condition of urban areas in a city-region (Read et al., 2007; Read and Gil, 2012).

§ 6.3.1 Multimodal network models in space syntax research

The spatial network developed in space syntax theory most used in urban and regional studies is the 'axial map' (Hillier and Hanson, 1984; Hillier, 1996), and its derivatives that split the lines of the map into smaller segments producing the 'segment map' (Turner, 2001; Hillier and Iida, 2005) or merging lines based on their angular connectivity producing the 'continuity map' (Figueiredo and Amorim, 2005). The most conventional geographic representation of the street network in GIS is the road centre line, with linear segments drawn along the middle of the street or of the individual traffic lanes. The resolution of the 'road centre line' based models is at the level of the street segment and the crossing node. In large-scale studies, and to allow the use of publicly available street databases, methods have been developed to apply space syntax centrality analysis to road centre line networks (Dalton, Peponis, and Conroy Dalton, 2003; Turner, 2007; Peponis, Bafna, and Zhang, 2008; Chiradia et al., 2008; Jiang and Liu, 2009). Both the road centre line and the axial map representations are used to describe the street networks used by private transport, i.e. pedestrian, bicycles and cars.

As for the public transport networks, their representation is a standard feature in transportation network models, where the public transport stops are represented as nodes on the network with the links connecting these stops along the service routes or tracks. There are some examples of adding public transport networks to the models based on the 'axial map' (Chiaradia, Moreau, and Raford, 2005; Gil, 2012; Law, Chiaradia, and Schwander, 2012), most of the times opting for a simplified topological representation linking the stops and stations directly, and considering additional topological links for transfer between modes. The power of these street and multimodal network models can be further increased by integrating the activity and land use information using the buildings or building plots and connecting these to the nearest street (Ståhle et al., 2005; Marcus, 2005; Sevtsuk, 2010).

Beyond aspects of network representation, the analysis of network models uses the concept of network distance, which can take different forms (Hillier et al., 2010). This can be physical distance based on the length of the street segment, topological distance where every change of direction counts as one topological step, or angular distance where the angle of direction change is taken into account and a 90-degree change of direction is equivalent to one topological step (Turner, 2001; Dalton, 2001; Hillier and Iida, 2005). In the case of the public transport network, the focus is on the network structure and the impedance is simply topological, with network transfers representing additional topological steps. However, when one starts working with multi-modal networks where flows happen at different speeds, one should also consider temporal distance where physical distance takes travel speed into account.

§ 6.3.2 Measuring multi-modal network models

Table 6.2 provides a summary of different network metrics that can be calculated to characterise the mobility conditions of local urban areas using a multi-modal network model.

CONCEPT	MEASURE	DEFINITION	EXAMPLES
Proximity	Node Proximity	Network distance to the nearest access node or to an infrastructure element of each mode.	Distance to nearest train station, or to nearest trunk road.
Density	Network Density/ Reach	Network length or absolute number of nodes within a fixed network distance, per mode.	Street network length or number of tram stops within 10 minutes walking.
	Activity Density	Total area of activities within fixed network distance, per mode.	Total office area or number of retail units within 10 minutes cycling.
Configuration	Network Centrality	Mean distance to or path overlap between every network node, using a specific mode.	Mean closeness centrality of the street segments within 15 minutes walking.
Accessibility	Activity Accessibility	Mean distance to activities, weighted by their number and size, using a specific mode.	Closeness to retail within 15 minutes driving.

TABLE 6.2 Summary of five types of urban network measures calculated on the multi-modal network model.

Proximity is the distance to the nearest element of the mobility network infrastructure of each mode, e.g. distance to the nearest train station or trunk road, and allows assessing the local network in terms of availability or convenience of a given mode.

Density measures provide an assessment of the availability and intensity of a given mobility mode (network reach) or land use activity (location density) in the local network. Network reach (Peponis et al., 2008) gives the amount of elements of the mobility network infrastructure within a given distance from a source location, e.g. number of crossings, total street length or cycle lanes length. Location density (Ståhle et al., 2005; Marcus, 2005) gives the amount of activities available within a given distance from a source location, e.g. number of shops or total area of office space. It can be calculated for a variety of activities, such as offices, retail or education.

Accessibility is a more abstract concept that measures the relative importance of a location based on the distance to other locations on the network and to opportunities associated with activities (Batty, 2009). Network centrality is a general type of accessibility that uses measures from network theory to describe the configuration of networks based on their topological relations (Freeman, 1978). It calculates the mean distance of shortest routes to (closeness) and the frequency of shortest routes through (betweenness) a location. In space syntax closeness is called 'integration' and described as 'to movement', and betweenness is called 'choice' and described as 'through movement'. The results are the hierarchy, attraction and flow potential of individual elements of the network, e.g. junctions, street segments or rail stations. Activity closeness is the 'classic' accessibility, combining the mobility infrastructure networks with land use. It calculates the physical distance to locations on the network, weighed by the size or number of activities at those destinations, and uses a negative quadratic distance decay factor (Hansen, 1959).

In a multi-modal network model, these urban network metrics can be calculated for the different mobility modes - walking, cycling, car, local public transport (tram, metro and bus) and rail - because each mode is based on different infrastructure elements, and must be calculated differently because each mode has different principles of use, e.g. reach, purpose or integration with other modes.

§ 6.4 The multi-modal urban network model of the Randstad

The multi-modal network model of the Randstad integrates the various mobility infrastructure networks of the urban neighbourhood, i.e. pedestrian, bicycle, car, bus, tram and metro, with those of the city-region, i.e. motorways and railways, together with land use units. This is a disaggregate model with the smallest spatial units being respectively the street segments, the public transport stops and the individual buildings. Three different data sets have been used to build the model (Figure 6.3).

The private transport system data was extracted from the OpenStreetMap (OSM) data set of the Netherlands (dump from January 2012) (http://www.openstreetmap.org/); the public transport system data was partly derived from OSM, partly from the public transport time table database of the OpenOV project (http://openov.nl/), and complemented with information from route maps of the various network operators; the land use data was extracted from the Basisregister Addressen (BAG) data set (http://bag.vrom.nl/).

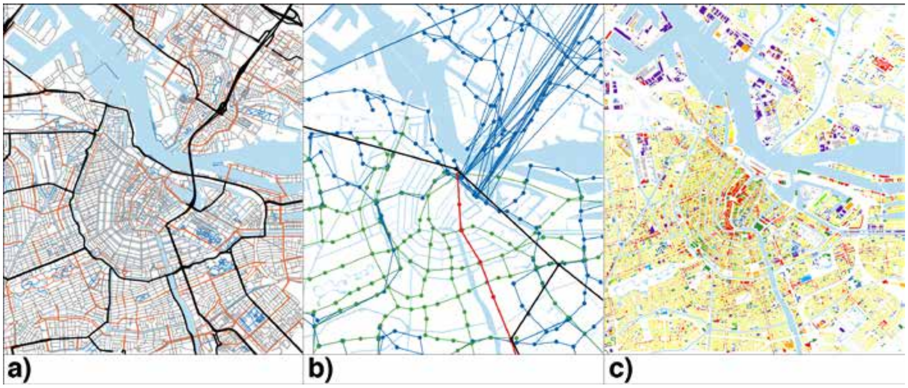


FIGURE 6.3 Overview of the three main systems of the multi-modal network model: a) private transport system (blue – pedestrian routes, orange – cycle routes, black motorways, grey – general roads), b) public transport system (black – rail, red – metro, green – tram, blue – bus), and c) land use system (LBCS classification).

§ 6.4.1 The structure of the model

The different modes work in different ways, have specific geographic representations and need to be modelled differently. For this reason the components of the model are grouped in different systems, namely the private transport system, the public transport system and the land use system. In addition, the model has a layer of components connecting the systems together. Each of these systems is illustrated in Figure 6.4, and described next.

The private transport system is based on the street network and caters for the free and individual movement of pedestrians, bicycles and cars that together share the large majority of the network. This system also constitutes the public space structure of the urban environment and represents the main interface to the other systems: it is through the street network that one gains access to public transport and buildings. For that reason it is the core system onto which all others must connect.

The private transport system is modelled using the road centre line representation of the street network, with nodes at every level intersection or junction of two roads and the road segments linking the nodes. By default the street segments are general and accessible to all private modes - grey segments in Figure 6.4a. However, each segment has an attribute indicating if any of the private modes is not allowed to circulate and if the segment is specifically designed for a specific mode - blue for pedestrians, orange for bicycles and black for cars in Figure 6.4a. The street segments also have attributes related to their geometry, namely length and shape, and to the time of travel dependent on the speed of the associated mode. The nodes layer has attributes relating to the topology of the crossing and the number of different modes allowed to use the crossing.

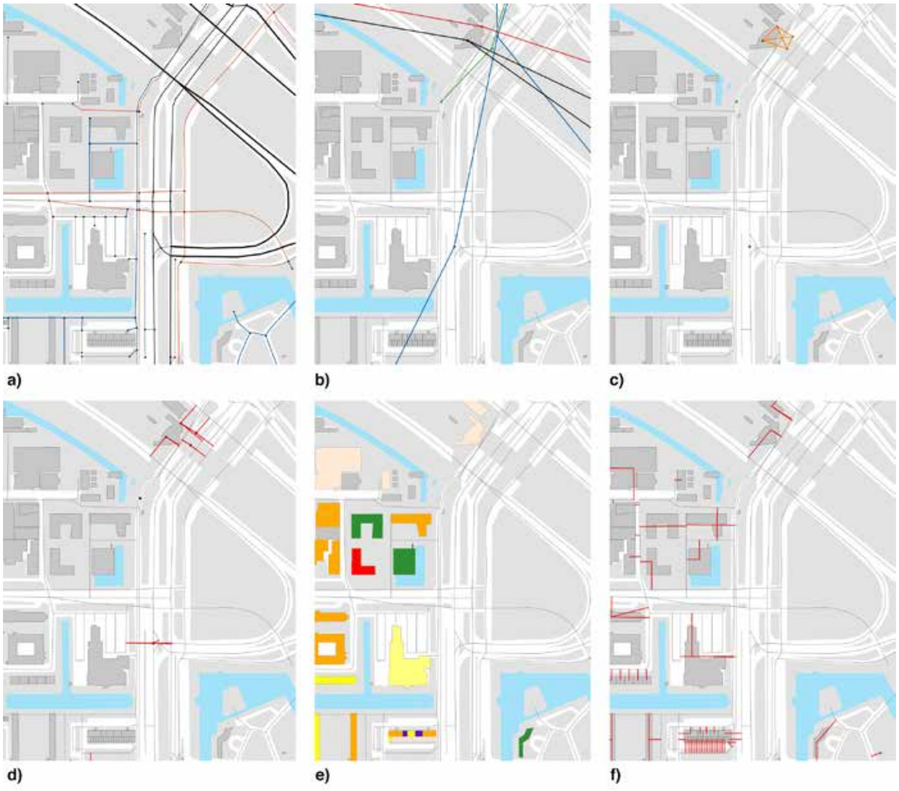


FIGURE 6.4 The systems of the multi-modal network model: a) private transport, b) public transport, e) land use; and the interfaces between systems: c) multi-modal transit interfaces, d) transit and roads interfaces, f) buildings and roads interfaces.

The public transport system offers managed and collective movement of persons on metro, tram, buses and rail, most of the time using specific infrastructure for each mode. The technology and use of each public transport mode is different, not only requiring different types of tracks to run and stops for boarding and alighting, but also offering different speeds, ranges of movement and consequently different intervals between stops, increasing from bus to rail. These infrastructure networks cross and converge at particular locations where the stops of different modes share the same name, to allow interchange and multi-modal travel.

The public transport system consists of a nodes layer representing stops or stations of each public transport mode, and a links layer connecting these where a service exists between two stops of the same mode – black for rail, red for metro, green for tram and blue for bus in Figure 6.4b. The resulting public transport networks are further interconnected by 'modal interfaces' (Gil, 2012; Gil and Read, 2012), i.e. links connecting stops of different modes with the same name – orange links in Figure 6.4c.

The land use system offers the activities that are most often at either end of travel and that motivate travel in the first place. For this reason, although it is not strictly a component of the multi-modal transportation system, it is an integral part of mobility, accessibility and urban form and is therefore included in the model.

Contrary to the other systems, the land use system is composed only of a polygons layer representing the buildings, which can also be represented by nodes at the centroid of the buildings' geometry (Figure 6.4d). These buildings have land use attributes for different categories that result from the aggregation of the units and areas of each category in the building.

For multi-modal network analysis, the different systems of the model need to work together as an integrated whole and therefore there are 'modal interfaces' connecting the public transport nodes to the street network segments (Figure 6.4e) and the buildings to the adjacent street segment(s) (Figure 6.4f). These 'modal interfaces' provide direct links to the private transport system, and indirect links to the land use system and public transport system respectively.

To create these connections, links are drawn from the node, building perimeter or building centroid to all adjacent street segments of different private transport modes. Only links crossing other buildings and/or waterways are discarded. It is thus possible to have multiple links for one node, to account for the multi-lane road centre line representation and to the variety of options in reaching those nodes.

§ 6.4.2 The analysis of the model

The geographic representation of the multi-modal network model, described in the previous section, needs to be translated into a graph representation for analysis. Here, the option of creating a primal or a dual graph is available. The proposed model uses an undirected graph that tries to reflect the nature of each system, and combines both dual and primal graph representations (Figure 6.5).

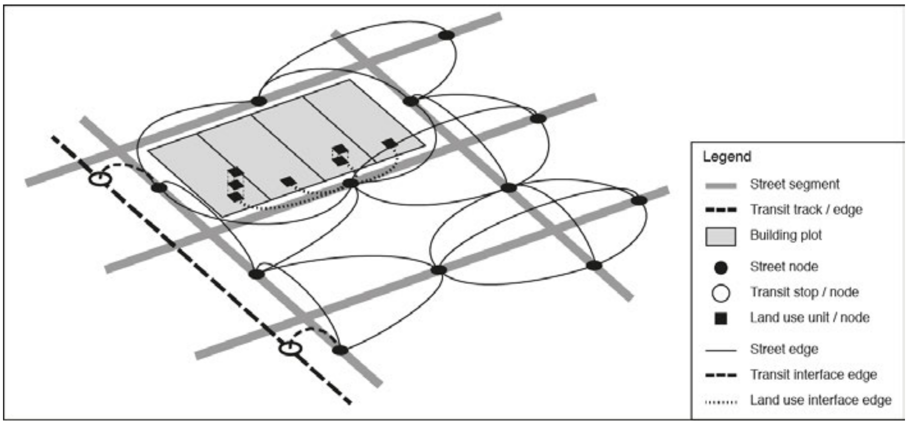


FIGURE 6.5 Diagram of the graph representation of the multi-modal network model.

On the one hand, in the private transport system, while the primal graph is simpler to obtain from a road centre line, the model uses a dual graph with the street segment as the main spatial unit of analysis providing the graph vertices, and the crossing nodes providing the edges. On the other hand, the public transport system has a more direct translation because the main spatial unit of analysis are the stops or stations, and these provide the graph vertices, with the connections between them providing the edges. The land use system only has nodes that become vertices in the graph. Both public transport and land use vertices are then linked to the street segment vertices with the various 'modal interfaces' edges.

The geographic representation of the model, in combination with the selected graph representation, supports different conceptions of distance, namely actual distance (physical and temporal), topological distance (segment, axial and directional) and angular distance.

In a first phase, the various types of distance are calculated for every street segment based on its geometry. Physical distance is simply the length of the segment in metres, while temporal distance multiplies the length by a factor of speed based on the averages taken from the mobility survey, for different modes and types of street segment, e.g. normal roads and main roads/motorways have different values (see Table 6.3). Topological distance is a constant value of 1 (one) in the case of segment distance, and a multiple of 1 depending on the number of changes of direction along the segment that are greater than a specific threshold, e.g. 15 degrees, in the case of axial and directional distance (Ozbil et al., 2011; Peponis et al., 2008). Angular distance is the sum of the angles between all sub-segments in a street segment, a method implemented in the sDNA software (Chiaradia, Webster, and Cooper, 2012).

MODE	AVG. SPEED	TOPOLOGICAL INTERFACE WITH TRANSIT	TEMPORAL INTERFACE WITH TRANSIT	TOPOLOGICAL INTERFACE WITH STREETS	TEMPORAL INTERFACE WITH STREETS
main roads	60 km/h	-	-	-	-
car	40 km/h	-	-	-	-
bicycle	15 km/h	-	-	-	-
pedestrian	5 km/h	-	-	-	-
rail	80 km/h	2	5 min.	1	3 min.
metro	25 km/h	2	5 min.	1	3 min.
tram	25 km/h	2	5 min.	1	½ min.
bus	30 km/h	2	5 min.	1	½ min.

TABLE 6.3 Network characteristics of the different modes, in terms of average speed and distance of 'modal interfaces'.

Notes: Based on data from the mobility survey of the Netherlands (Ministerie van Verkeer en Waterstaat, Rijkswaterstaat, and Dienst Verkeer en Scheepvaart, 2011)

In a second phase, the impedance of the dual graph edges is calculated at the moment of conversion from network representation to graph representation

$$D_{(e(i,j))} = d_i/2 + d_j/2 + t_{e(i,j)} \qquad (1)$$

where D is the impedance of edge e between vertices i and j, with di and dj being the impedance value of each vertex and t the turn cost of edge e between vertices i and j. The graph links have the same types of distance as the network links, and the impedance results from adding half of the distance of each of the vertices together with the turn cost component of the link. The turn cost component t is calculated based on the angle between two segments and varies depending on the type of distance. In physical and temporal distance t has a value of 0 (zero), in topological distance a value of 1 (one), and in angular distance the angle's value.

In the public transport system, with links that are straight lines, physical or temporal distance is based on the link's geometric length, while topological and angular distance have a constant value of 1 (one). Because these network links are only represented in primal form there is no further transformation. The impedance of 'modal interfaces' is calculated as in the previous cases for physical and cognitive distance and has pre-defined constant values for topological and temporal distance, depending on the transport mode (Table 6.3).

§ 6.5 The structure of modality of the Randstad

§ 6.5.1 Network proximity structure

The Randstad region has a comprehensive public transport network comprised of railway, metro (or light rail), tram and bus networks. If we map the shortest distance of every street segment to the nodes of each of the public transport networks we obtain the network proximity structure of the region. Proximity can be calculated using any of the concepts of distance mentioned earlier, but here we adopt the concept of physical distance, which is simpler and frequently used to define the walking catchment area from a location. The resulting maps in Figure 6.6 give the availability of each public transport mode at every location, or conversely the physical reach of every mode within the city-region. This reveals the environment of possible movement afforded by different mobility infrastructure networks.

While the railway clearly has reach across the whole city-region, linking its various centres and sub-centres, the tram and metro networks are contained in the four main urban centres, and the bus network is a local presence throughout the city-region. The three latter networks have a complementary role in their coverage, converging in the mobility hubs of the main urban centres where they also interface with the railway.

This analysis can be synthesised in a map of the public transport environment of the Randstad (Figure 6.6d), showing a different hue for the different combinations of public transport covering a location, a bright white colour where all these modes overlap, and black where there is no public transport reaching the location.

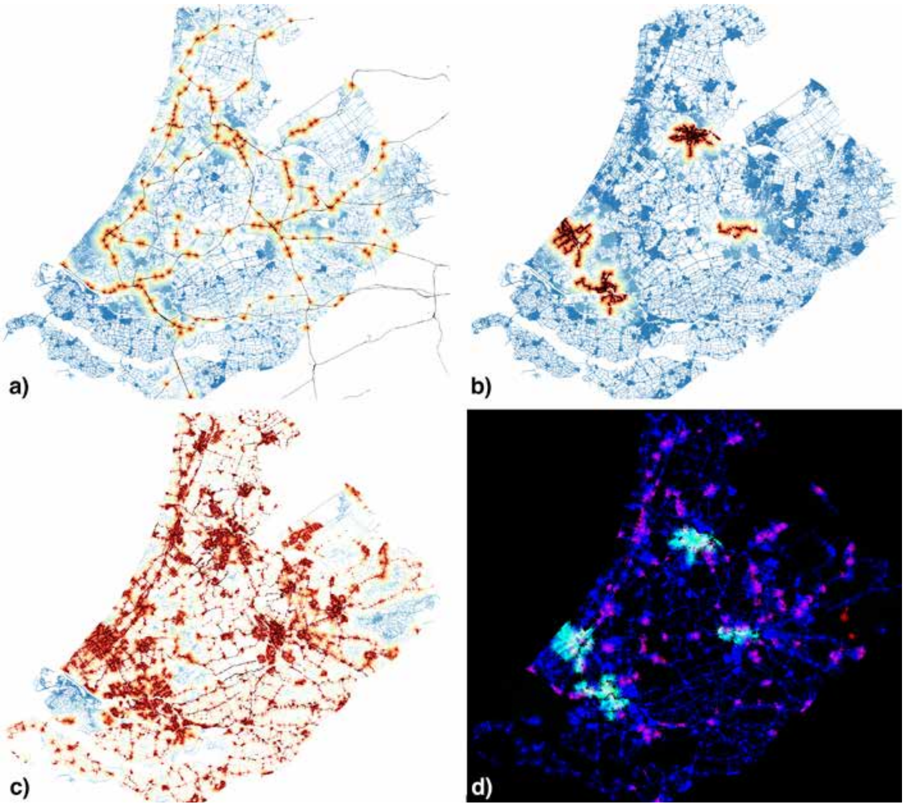


FIGURE 6.6 Public transport modality in the Randstad region. Maps of proximity to public transport, showing the physical distance of every street segment to a a) rail station, b) tram stop and c) bus stop. The red to orange colour range corresponds to a 'walkable' distance of 400 to 1600m. Map d) shows a composite image where each colour highlights one mode, white indicating a concentration of modes and black the absence of public transport.

TOC

§ 6.5.2 Network centrality structure

Network centrality analysis reveals the hierarchy of places and the hierarchy of routes in an urban area, city or region. It is usually carried out on a complete model that does not differentiate between mobility modes, eventually using varying radii to capture different grains or scales of this hierarchy. However, the different modes are an essential aspect of measuring sustainable mobility (Table 6.1), and for that reason it is useful to explicitly measure the centrality structure of models representing different modes. Figure 6.7 shows angular closeness analysis of the region at the global (radius N) scale. The grey area represents the buffer of the study area that is part of the calculations but for which the results are 'hidden'.

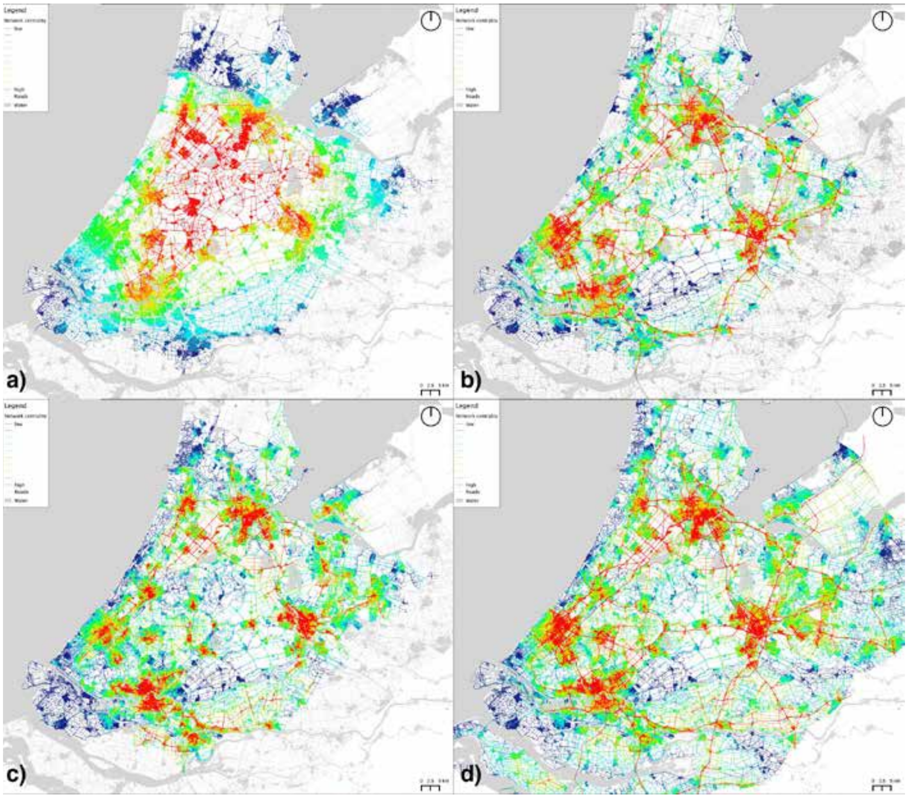


FIGURE 6.7 Network centrality analysis of angular closeness at radius N, for different modes: a) non-motorised, b) private transport, c) public transport, d) all modes combined.

If we only consider the network of roads and paths accessible to pedestrians, which excludes the motorways, angular closeness analysis reveals a pattern with the integration core concentrated in the 'Green Heart' of the Randstad, instead of its urban centres (Figure 6.7a). Of course, this analysis of pedestrian movement is not realistic, as no pedestrians would walk the distances required to traverse the region. A solution to capture 'walkable' centralities would be to constraint the analysis to 'local' radii.

However, what this map also shows is that there have been other mobility infrastructures, or modes (i.e. canals, ports, roads for horse and carriage), that allowed the region to historically form in the polycentric structure that we find today, otherwise the analysis would be 'correct'. If we run the same analysis integrating the present day mobility networks of car (Figure 6.7b) and public transport (Figure 6.7c) a new hierarchy emerges that already highlights local centralities. In the case of the car it captures the urban peripheries and out of town retail parks, while with public transport it captures the more traditional urban centres and suburbs. The final analysis (Figure 6.7d) is a composite of all non-motorised and motorised modes.

In these multi-modal centrality analyses, we have used angular distance with the private transport networks and topological distance with the public transport networks, the land use system and the 'modal interfaces' connecting these. Other combinations have been tried, however there should be a relation between the different concepts of distance being combined, as is the case with a topological turn equating to a 180 degree angle change, otherwise a complex process of calibration is required. On the other hand, temporal distance should be used as the cut-off distance for radius and catchment areas in multi-modal analysis measurements because this accounts for the different speeds of the different modes.

§ 6.5.3 The relation between modality and mobility in the Randstad

Given the measurements proposed in Table 6.2, we can calculate a range of modality characteristics for the Randstad region using the multi-modal network model demonstrated so far. As the previous analyses have shown, there are several parameters for each measurement, such as network layers used, network distance type, catchment distance or modal interface costs. This opens the door to a potentially endless list of possible measures. In order to identify a set of urban form indicators that is relevant to sustainable mobility assessment we have calculated the modality characteristics of 839 postcode locations of the MON survey, and correlated these with the mobility indicators from Table 6.1.

The first step was to reduce the set of possible indicators to a set of meaningful indicators. This was achieved by identifying and eliminating co-variant measures of the same type, and selecting those that also showed greater inequality with the Gini

TOC

coefficient, as they are more differentiating. The second step was to correlate the modality characteristics with the mobility patterns summarised in Table 6.1, in order to identify the most relevant urban form indicators. This resulted in the set of urban form indicators, summarised in Table 6.4.

			RANDSTAD POSTCODE LOCATIONS			
MEASURE	DISTANCE	RANGE	MEAN	MINIMUM	MAXIMUM	GINI
Network Proximity						
Cycle network metric distance	Metric	-	274	0	3388	0.5901
Main road segment distance	Metric	-	1542	0	8611	0.4548
Motorway distance	Metric	-	3262	0	17396	0.3731
Rail station distance	Metric	-	4181	102	30416	0.4703
Local transit stop distacne	Metric	-	503	0	17800	0.6336
Network Density / Reach						
Pedestrian network length	Metric	800m	2826	0	18393	0.5632
Cycle network length	Metric		4221	0	18469	0.4334
Cul-de-sacs count	Metric		14.36	0	50	0.4290
Crossings (X and T) count	Metric		148	1	523	0.3570
Local transit stops	Metric		5.23	0	24	0.4300
Rail stations	Metric	1600m	0.34	0	3	0.7355
Non-motor network reach	Angular	180°	6615	62	70947	0.5134
Car network reach	Angular		4725	62	102226	0.5512
Location Density						
Residential area	Metric	800m	254,880	164	966,080	0.3897
Activity area	Metric		29,429	0.00	467,770	0.6079
Work area	Metric		40,971	0.00	934,775	0.6779
Education area	Metric		13,877	0.00	335,879	0.6416
Network Centrality						
Car closeness mean	Angular	800m	0.000206	0.00	0.000240	0.0502
Non-motor closeness mean	Angular / topologic		0.000312	0.000001	0.0003137	0.0027
Local transit closeness mean	Angular / topologic		0.000274	0.00	0.0003139	0.1248
Rail closeness mean	Angular / topologic	1600m	0.000093	0.00	0.0003141	0.7028
Location accessibility						
Car activity accessibility	Angular	-	2,034,127	88,363	226,490,500	0.7653
Car work accessibility	Angular	-	9,249,206	3,904,583	622,935,100	0.8008
Transit activity accessibility	Angular / topologic	-	722,325	32,173	40,776,020	0.6321
Transit work accessibility	Angular / topologic	-	243,9811	35,321	63,318,680	0.5909

TABLE 6.4 List of selected urban form measures used to characterise the modality of urban areas in the Randstad

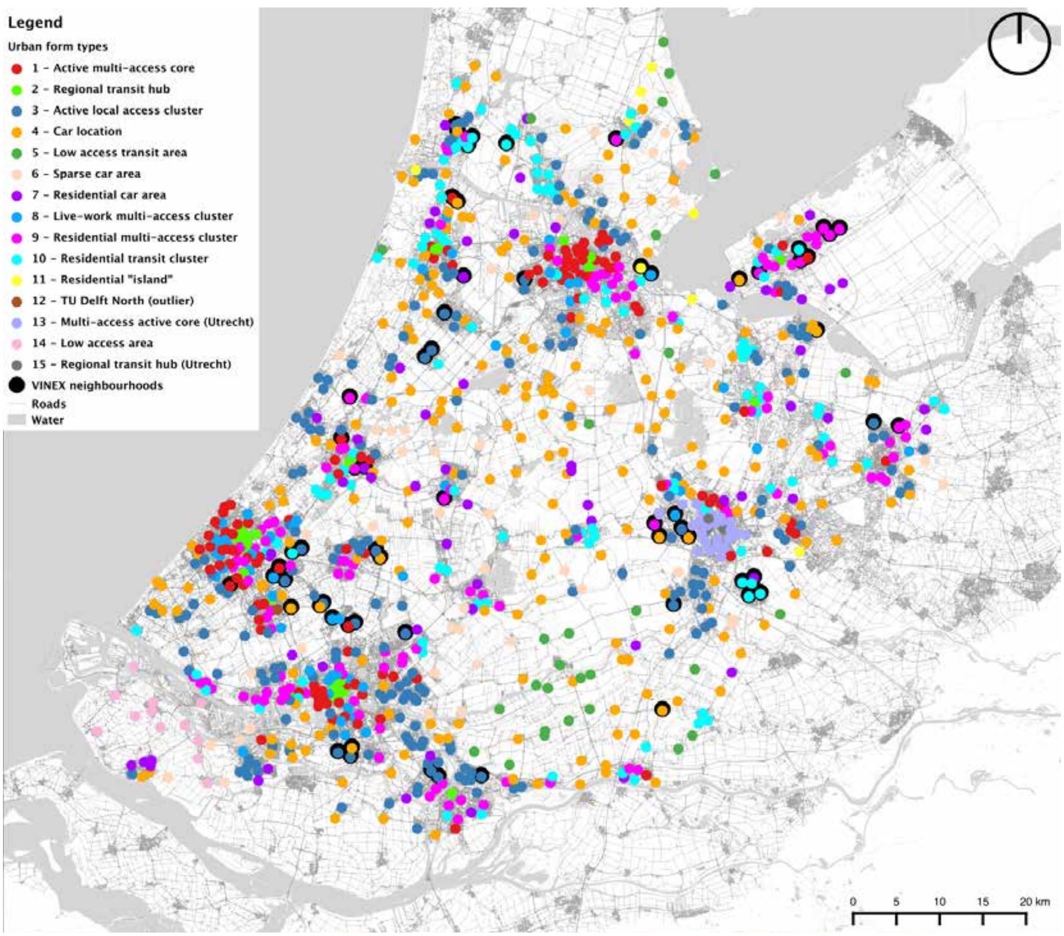
The result of simple bivariate correlation between modality and mobility characteristics (Table 6.5) shows that twelve of the modality indicators have medium correlation with one or more of ten sustainable mobility indicators. From these results one can confirm some well known relations, such as higher density is an indicator of more walking and public transport use, and less driving. However, the rest of the mobility indicators remain unexplained, namely those relating to cycling, and urban form indicators do not show a sizeable nor significant correlation. One should not forget that each mobility indicator represents a complex mobility pattern influenced by many factors and it would be impossible to get a single urban form characteristic to explain all that happens.

MEASURE	SHARE OF SHORT WALK JOURNEYS	SHARE OF WALK JOURNEYS	SHARE OF MEDIUM CAR JOURNEYS	SHARE OF CAR JOURNEYS	SHARE OF CAR DISTANCE	SHARE OF MEDIUM TRANSIT JOURNEYS	SHARE OF TRANSIT JOURNEYS	SHARE OF LONG TRANSIT JOURNEYS	SHARE OF TRAIN JOURNEYS	SHARE OF TRANSIT DISTANCE
Rail station distance	-0.142	-0.187	*0.311*	*0.354*	*0.355*	-0.236	*-0.32*	*-0.39*	***-0.565***	*-0.384*
Cycle network length	*0.332*	*0.301*	*-0.321*	*-0.354*	*-0.324*	*0.441*	*0.477*	*0.345*	0.233	*0.37*
Crossings count	0.182	*0.339*	*-0.39*	*-0.466*	*-0.359*	*0.345*	*0.344*	*0.317*	0.213	*0.343*
Local transit stops	*0.322*	*0.405*	*-0.39*	*-0.447*	*-0.368*	*0.473*	*0.437*	0.293	0.122	*0.362*
Residential area	*0.309*	*0.429*	*-0.432*	***-0.511***	*-0.421*	*0.477*	*0.489*	*0.423*	0.254	*0.452*
Activity area	0.244	*0.463*	*-0.444*	***-0.543***	*-0.386*	*0.344*	*0.322*	*0.31*	0.223	*0.339*
Work area	0.236	*0.368*	*-0.404*	*-0.492*	*-0.379*	*0.308*	*0.308*	0.294	0.244	*0.324*
Education area	0.275	*0.344*	*-0.452*	*-0.471*	*-0.407*	*0.451*	*0.493*	*0.403*	*0.343*	*0.448*
Non-motor closeness	0.296	*0.331*	*-0.369*	*-0.416*	*-0.33*	*0.405*	*0.428*	*0.34*	*0.32*	*0.382*
Rail closeness	0.218	0.289	*-0.346*	*-0.374*	-0.199	*0.308*	*0.329*	0.189	(0.102)	0.223
Car activity accessibility	0.203	*0.31*	*-0.358*	*-0.42*	-0.299	*0.35*	*0.324*	0.256	0.239	*0.321*
Transit activity accessibility	0.178	0.229	*-0.343*	*-0.379*	-0.293	*0.324*	*0.338*	0.297	*0.372*	*0.347*

TABLE 6.5 Correlation between modality characteristics of postcode areas and sustainable mobility indicators of the same area. In bold are correlations of large size, with r >= 0.5, and in italic correlations of medium size, with 0.5 > r >= 0.3. For all values p < 0.01, except the value in brackets with p = 0.089.

§ 6.5.4 The modality environments of the Randstad

As a next step, one could use multivariate regression models to explore the combined influence of urban form characteristics in determining each mobility indicator, considering the many possible combinations of urban form variables. But only some of these combinations correspond to recognisable urban forms on the terrain, and given the spatial diversity one should not expect to find a unique statistical model that is capable of explaining the mobility patterns that occur throughout the region. For this reason, it is proposed to identify a set of modality profiles in the region that correspond to the different urban areas based on the modality indicators from Table 6.4. This is achieved applying unsupervised data classification methods, in particular k-medoid clustering, used in previous urban morphology studies (Gil et al., 2012; Serra, Gil and Pinho, 2012). In this case, the method has led to the identification of 15 different modality environment types, summarised in Table 6.6. Their urban form profile provides a composite, multivariate description of each location. Their spatial distribution, illustrated in Figure 6.8, confirms the location and concentration of different types, highlighting the differentiated urban form and structure affordances of the different areas of the region.



TOC

FIGURE 6.8 Map of the location of the 15 different modality environment types described in Table 6.6. Each of these environments has specific urban form and structure affordances that are expected to support different types of mobility

ID	NAME	SUMMARY DESCRIPTION
1	Active multi-access core	High non-motorised network density, reach and centrality, proximity to main roads, dense local transit network, high mixed-use density and accessibility.
2	Regional transit hub	Highest non-motorised network density, reach and centrality, regional car and rail accessibility, high mixed-use density, with focus on non-residential activity.
3	Active local access cluster	Non-motorised network present with interrupted layout, average car and local transit access, but no rail, high residential and active land use density.
4	Car location	Average private transport presence and network density, but no rail and basic local transit, low residential and education densities.
5	Low access transit area	Low non-motorised and car infrastructure availability in sparse and segregated network, without rail but close to local transit, low active land use density.
6	Sparse car area	Low non-motorised and car infrastructure availability in sparse network without crossings, reduced presence of public transport, low active land use density.
7	Residential car area	Low non-motorised and car infrastructure availability, but high regional centrality, in sparse network of limited reach, reduced presence of public transport, mostly residential land use.
8	Live-work multi-access cluster	High non-motorised network density, reach and centrality, close to motorways with high car centrality and regional accessibility, high residential and work density and high regional accessibility to active land uses.
9	Residential multi-access cluster	High non-motorised network availability close to motorways, high public transport availability and centrality, dense residential and educational street network, with high regional accessibility to other land uses.
10	Residential transit cluster	Average private transport availability in structured network, presence of rail, high residential density and high regional accessibility to other land uses.
11	Residential island	Segregated private and public transport network, some presence of rail, mostly residential land use with low active land use density.
12	TU Delft North (outlier)	Available but segregated non-motorised network, many cul-de-sacs and high density of education land use.
13	Multi-access active core (Utrecht)	High street network density, reach, and centrality, local transit availability and centrality, high mixed-use density and highest regional accessibility.
14	Low access area	Sparse and segregated private and public transport network, lowest local density and lowest regional accessibility to active and work land uses.

15	Regional transit hub (Utrecht)	High non-motorised network density and centrality but low reach, far from car network infrastructure, high public transport availability and centrality, high residential density, with high regional accessibility to other land uses.

TABLE 6.6 Summary description of the 15 modality environment types identified for the Randstad region based on the modality characteristics of Table 6.4

By charting, for each of these modality environment types, the mean value of the sustainable mobility variables from Table 6.1, one can clearly identify how the different modality types support different mobility patterns (Figure 6.9).

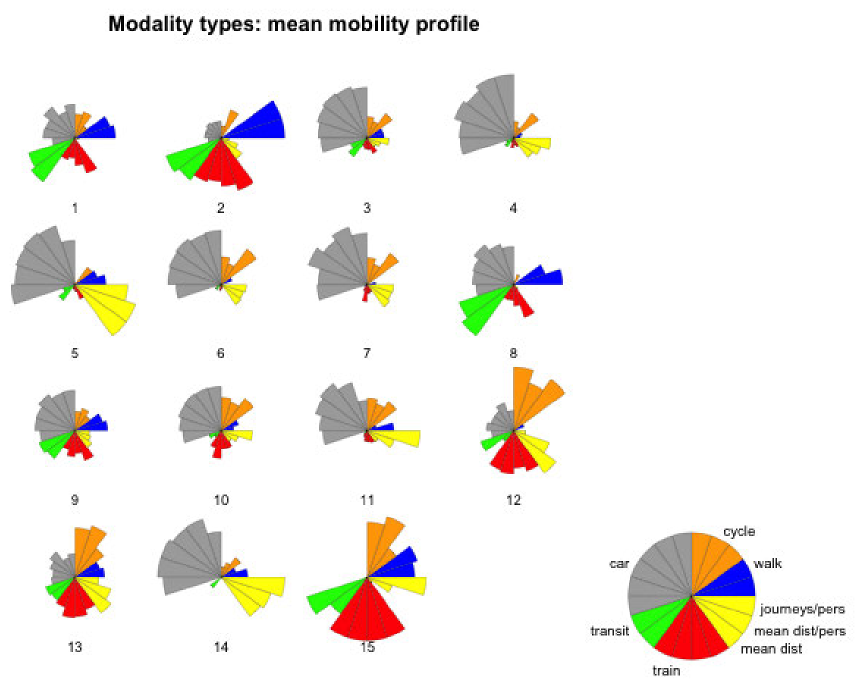


FIGURE 6.9 Mobility profile of each of the 15 modality environment types described in Table 6.6 and located in Figure 6.8, using the sustainable mobility variables identified in Table 6.1.

Types 2 and 15 clearly show a reduced use of the car, with a high level of walking and use of public transport. In types 1, 8, 9, 12 and 13 the car doesn't dominate, with transit (in the first three) and the bicycle (in the last two) taking higher prominence. Types 4, 6 and 7 show the average pattern of the Randstad dominated by the car, followed by the bicycle, while the similar types 3, 10 and 11 show some use of public transport and increased levels of walking. Types 5 and 14 are absolutely dominated by the car with an increased distance and frequency travelled. These mobility patterns are consistent with the location of the neighbourhoods and what would be expected from their modality environment description.

The affordances of the different modality environment types enable or constraint the use of specific modes, at varying travel distances and journey frequency. Each of these mobility patterns defines the potential of a location, of a given modality type, to fulfil sustainable mobility objectives.

This approach can be used as an evaluation method of the sustainable mobility potential of neighbourhoods in this region, for ex-ante decision support during planning stages of new neighbourhoods, or ex-post decision support for monitoring performance and propose policy and planning interventions on existing neighbourhoods. Further work is required to explore the performance potential of each sustainable mobility dimension, namely walking, cycling, transit and driving, in relation to each individual modality type, and identify trends and similarities between these types with regards to specific mobility performance.

§ 6.6 Conclusion

In this paper we introduce a multi-modal network model to explore the relation between urban form characteristics of urban areas that relate to different modes of movement. The relational network model is high-resolution, and integrated, combining three systems (private transport, public transport, and land use), differentiating the network links that are accessible to each mode of transport. Using this model we were able carry out analyses and measurements of the infrastructure network of the different modes, namely, the proximity to access nodes, the network density of infrastructure, the activity density within reach, regional accessibility to work and active land uses, and the regional network centrality of nodes. These analyses reveal the structures and hierarchies of urban form in the city-region that support the different modes of mobility.

From the large set of resulting measurements, we proceed to identify a reduced set of urban form indicators that are independent, and can describe the urban areas in the region based on a variety of proximity, density and accessibility dimensions. Upon correlation with empirical mobility data, we were able to confirm some of the accepted urban form principles of sustainable mobility, such as the relation between high network and active land use density and higher pedestrian movement and lower car use. However, these bivariate relations are not sufficient to explain the full range of mobility patterns. Using a k-medoids clustering algorithm on the same dataset of urban form indicators, we obtain a typology of urban areas in the region, which we call modality environments because they have specific signatures in terms of the mobility patterns that they support. This typology of urban areas can contribute to new a relational and multi-scale urban form based method for evaluating the sustainable mobility potential of neighbourhoods in the city-region.

7 The Sustainable Travel Performance of Urban Areas: Context-sensitive Evaluation for Strategic Planning Support

Abstract

To achieve sustainable mobility objectives within urban areas and city-regions it is important to develop strategic planning support instruments for local and regional governments to evaluate urban development plans (ex-ante) and outcomes (ex-post). This study proposes a quantitative method to evaluate the performance of urban areas with regards to the sustainability of the multimodal travel patterns of their residents (walk, cycle, car and transit travel at different distances), applied to the travel performance of VINEX neighbourhoods in the Randstad region of the Netherlands. The evaluation is contextual, calculating the sustainable mobility performance of urban areas against those that in the region share a common baseline of spatial and socio-economic characteristics, based on typologies obtained from unsupervised classification techniques. Using the multimodal travel patterns of urban areas of the same types, we determine their sustainable mobility potential for ex-ante assessment of development locations. The mobility potential ranges are then used to normalise the travel outcomes for performance evaluation of individual urban areas (ex-post). The evaluation results allow the identification of negative cases that should be the focus of policy intervention and positive cases that can provide lessons for effective policy transfer.

§ 7.1 Introduction

One of the key objectives of today's city and regional governments is to achieve sustainable mobility (Banister, 2008), concerned with problems related to CO_2 emissions, congestion, traffic accidents, energy consumption, and the dominance of the private car in daily journeys. And one of the means to achieve this objective is to change travel patterns, reducing overall distance travelled and, more importantly, shifting from the car to active modes (walking and cycling) and transit, not only within urban areas but also in longer distance travel across city-regions. Strategic planning is a key instrument to achieve successful urban regions with more sustainable travel patterns (Curtis, 1996; Newman, 2009; Reconnecting America, 2011), and the evaluation of alternatives to support decision making is fundamental in land use planning because its legacy is long lasting, resistant, slow and very costly to change (Van Wee and Handy, 2016). At the regional scale the concept of accessibility helps understand the spatial structure of the region, and differentiate its urban areas by modes of transport, assessing their accessibility and mobility potential for sustainable travel (le Clerq and Bertolini, 2003; Bertolini and le Clerq, 2003; Bertolini et al., 2005; Straatemeier, 2008; Silva and Pinho, 2010; Silva et al., 2014). Hence, to achieve sustainable travel patterns one needs to carefully consider the location and spatial distribution of urban areas within this regional accessibility structure, because simply conforming to local urban design principles will not necessarily lead to the desired outcomes (Ewing and Cervero, 2010).

In the evaluation of strategic plans towards sustainable travel patterns, it is not only the built environment's spatial characteristics that need to be taken into consideration, because the socio-economic fabric of the region and the individual characteristics of the population also play an important role (Stead, 2001; Bagley and Mokhtarian, 1999; Geurs and Van Wee, 2004, Schwanen et al., 2004; Handy et al. 2006). The interdependent relationship between these factors is summarised in the conceptual framework of travel patterns of Figure 7.1 (based on Stead et al., 2000). The complexity of the influences on travel patterns suggests a strategic planning process that incorporates flexibility, is iterative and reflexive, based on operational decisions, and including ex-ante and ex-post evaluation stages (Alexander and Faludi, 1989). Given the role of strategic planning for sustainable mobility and accessibility, it is necessary to develop tools to support the decision making process and the implementation of plans, and measure their performance in achieving the stated goals (Mastop and Faludi, 1997; May et al., 2008; Curtis, 2008).

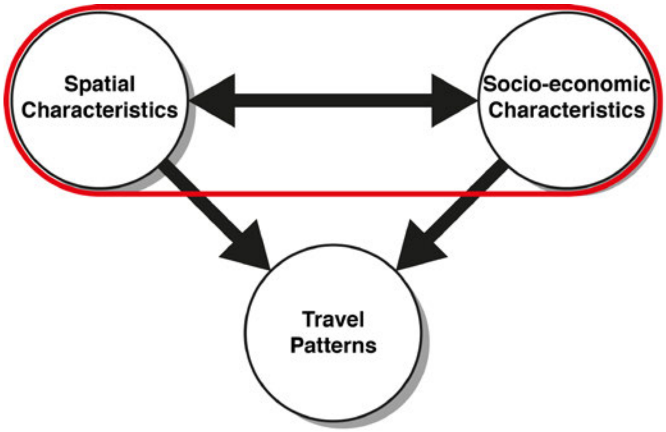


FIGURE 7.1 Conceptual framework of the relations between spatial characteristics, socio-economic characteristics and travel patterns (based on Stead et al., 2000). The red outline indicates a common baseline required for a contextual evaluation of mobility performance of urban areas.

The aim of this study is to develop a quantitative method that evaluates the performance of urban areas in terms of sustainable mobility objectives (i.e. modal share and distance travelled), and integrates ex-ante (potential) and ex-post (performance) evaluation stages, to offer a decision support framework for strategic planning of sustainable mobility that is pragmatic and rewarding for planners and agencies (Laurian et al., 2010). Furthermore, the evaluation is performed within the context of urban areas that share a common baseline of spatial and socio-economic characteristics (Figure 7.1). One should expect that urban areas with a different baseline perform rather differently, and one can plan urban areas (ex-ante) to have the baseline conditions with greater potential for sustainable travel patterns. However, in existing urban areas (ex-post), one can identify within each baseline context the cases of exceptional travel patterns (positive or negative) that deserve planning and policy attention. These results can be aimed at prioritising areas of intervention, selecting appropriate policy and planning actions, or studying successful policies that can be transferred to equivalent urban areas.

With its context-sensitive nature, the proposed method is not specific to a single location or urban development model, but rather general and transferable following a typological approach (Oppenheim, 1975). The contextual baseline is composed of spatial and socio-economic types identified using unsupervised classification (clustering) techniques applied to a regions geographic data. The urban form and socio-economic typologies cover all urban areas in the region and are used to define an objective sustainable mobility potential of type pairs, calculated for each multimodal travel dimension. The performance of an existing urban area is the actual observed travel outcome normalised within the mobility potential ranges for that location.

This approach does not follow a-priori, reductionist, subjective, or theoretical classifications of urban areas, and introduces multi-level evaluation in considering urban areas within groups of related areas. It differs from the comparison of urban areas with contrasting spatial characteristics of binary classification, such as pedestrian versus automobile neighbourhoods (Cervero and Radisch, 1996) or TOD versus non-TOD areas (Nasri and Zhang, 2014), aiming to test the effectiveness of those concepts, demonstrate causal relations between spatial characteristics and travel patterns, and the size of this influence, in order to develop theory (Van Wee and Handy, 2016).

The performance evaluation method is detailed in the next section, followed by its application to the Randstad region in the Netherlands in sections 7.3 and 7.4, where the baseline data is presented and classified, and the mobility potential and performance results of VINEX neighbourhoods are presented.

§ 7.2 Methodology

The present study evaluates the performance of urban areas based on a context sensitive approach that compares urban areas possessing a common baseline of spatial and socio-economic characteristics. This performance evaluation is suited to obtain results that support case specific decision-making, thus suitable for the aim of supporting strategic planning. It is a quantitative methodology, that goes from the very general measurement of the spatial, socio-economic and travel characteristics for all urban areas in the entire region, i.e. the components of the conceptual framework represented in Figure 7.1; through the extraction of urban form and socio-economic typologies and the calculation of the mobility potential of each baseline condition of identical urban form and socio-economic type pairs; to the performance assessment of individual urban areas putting the observed travel patterns in relation to the areas' baseline potential, identifying those with positive or negative performance traits.

The first step is the measurement of travel patterns, spatial characteristics and socio-economic characteristics of urban areas. One may define urban areas using census tracks of different levels of detail, grid cells, or any other meaningful spatial unit for which there is data available. In this case, the three types of data have been aggregated at the 4-digit postcode area because it was the finest commonly available spatial unit. The travel patterns of the residents of each urban area are defined by a selection of mobility variables related to modal share, distance, and duration of travel, which are relevant performance indicators of sustainable mobility. The spatial characteristics of the urban areas are measured using variables related to the 5D's (Ewing and Cervero, 2010), but is extended to measurement of the various mobility infrastructure networks and includes the regional configuration of each location measured using their multimodal network centrality. This extended description includes the distance to the nearest infrastructure of a given mode (bicycle, main road or transit); the density of network infrastructure (soft modes, car and transit) within a given distance; the design of the network layout in terms of crossings (3-way, and 4-way), cul-de-sacs and directness (soft modes and car); the density of different activities (residential, commercial or service activities, office or industry work places, education institutions) within a 800m walking distance, the recommended radius of walkable neighbourhoods; the closeness centrality of the network (soft modes, car and transit) within a 800m walking distance; and the accessibility to work and activities within a 20 minute journey by car or transit, which is the median commute travel time in the Randstad. The socio-economic characteristics of the urban areas include aspects of age, gender, household composition and size, income, education, and car ownership, which have been frequently associated with travel patterns.

After measuring the spatial and socio-economic characteristics, one extracts the urban form and the socio-economic typologies of urban areas in the region. First, one uses bivariate correlation to reduce these characteristics to a set of variables that are not collinear and are significantly related to travel patterns. Then, one applies an unsupervised classification method to this reduced set of variables, in this case the partition around medoids (PAM) or k-medoids clustering algorithm, and plots various cluster validation indices (i.e. sum of squared errors, average within cluster distance, average between cluster distance, Goodman Kruskal index, and Dunn's index) to select the appropriate number of clusters. The resulting typologies are context sensitive (Gil et al. 2012), and are not based on pre-defined classes or on all possible combinations of a small number of categories and variables.

The next step is the calculation of the mobility potential for the baseline conditions of urban areas, i.e. the specific pairs of socio-economic and urban form types. All urban areas sharing the same baseline conditions have similar invariants that define the affordance (Gibson, 1979) for multimodal mobility of its residents, thus the areas' multimodal travel patterns can be used to calculate the mobility potential of the given baseline condition. The mobility potential *Pot* is defined by two limits for each mobility variable *V*, an upper $Pot_{up}(V)$ [7.2] and a lower $Pot_{low}(V)$ [7.4] limit . These limits are calculated based on the inter-quartile range $IQR(V)=Q3(V)-Q1(V)$ added to the upper quartile *Q3* for the upper limit *up* [7.1] and subtracted from the lower quartile *Q1* for the lower limit *low* [7.3], but are never above the maximum *max* or below the minimum *min* values of the mobility variable *V*.

$$up(V) = Q3(V) + (1.5 * IQR(V))$$

[7.1]

$$Pot_{up}(V) = \begin{cases} up(V), & \text{if } up(V) < max(V) \\ max(V), & \text{otherwise} \end{cases}$$

[7.2]

$$b(V) = Q1(V) - (1.5 * IQR(V))$$

[7.3]

$$Pot_b(V) = \begin{cases} b(V), & \text{if } b(V) > min(V) \\ min(V), & \text{otherwise} \end{cases}$$

[7.4]

The value of *1.5*IQR(V)* used in equations [7.1] and [7.3] is a known robust method of outlier identification (Tukey, 1977) typically used in boxplots. It is deemed a reasonable value for defining the limits of a mobility variable potential, and to identify performance outliers in the evaluation of urban areas.

The final step is the evaluation of the performance of urban areas, relative to the context of their baseline mobility potential. For every mobility indicator *i*, the performance *Per* [7.5] is calculated taking the absolute mobility value m_i of an urban area and normalising it by the potential limits (Pot_t and Pot_b) of the corresponding mobility variable V_i.

$$Per_i(m_i) = \frac{m_i - Pot_{low}(V_i)}{Pot_{up}(V_i) - Pot_{low}(V_i)}$$

[7.5]

The mobility performance Per is in the [0,1] range if the result is within the potential range, with a low performance being close to 0 and a high performance close to 1. If the performance value is outside the [0,1] range, that means it is above the upper limit or below the lower limit of potential, and indicates that the urban area is an outlier for the given mobility indicator, under- or over-performing.

These performance results are analysed against an evaluation framework of sustainable mobility indicators based on travel patterns. In light of the goal of reducing private car use, the assessment criteria consider the level of soft modes share in local journeys and of transit share in longer distance journeys, against the mode share of the car. High values in the soft mode and transit indicators represent a positive performance and low values a negative one, while high values in the car indicators represent a negative performance and low values a positive one. The framework takes into account the adoption of different travel modes at different scales of travel by assessing them at the local (up to 1500m), medium (from 1500m to 10km) and long distance (above 10km), as well as overall mode and distance travelled share. In all cases, low performing urban areas should be selected for intervention to improve their performance, and outliers should be identified and further investigated.

§ 7.3 Travel patterns and the typologies of urban areas

The methodology presented in Section 7.2 is here applied to the Randstad region of the Netherlands, to evaluate the performance of its VINEX neighbourhoods. These are mostly suburban residential areas adjacent to the main urban centres developed since the mid 1990's, based on policy aiming to achieve sustainable mobility in the region (see Chapter 1, Section 1.5). This case study offers the opportunity to compare a number of urban areas that have been developed under the same policy framework, and in the same geographic, cultural and temporal context, but nevertheless present local and regional spatial implementation differences, and different outcomes in terms of travel patterns. This section presents the characteristics and typologies of the urban areas of the Randstad, and situates the VINEX neighbourhoods in this regional context, according to the components of the conceptual framework in Figure 7.1, namely travel patterns, spatial characteristics and socio-economic characteristics.

The data on travel patterns and socio-economic characteristics comes from the Mobility Survey of the Netherlands (MON) (http://persistent-identifier.nl/?identifier=urn:nbn:nl:ui:13-37z-uia), combining the years 2004 to 2009 in order to obtain a larger sample. This data set is available at the 4-digit postcode level, which defines the spatial unit of analysis and the aggregation for spatial characteristics of urban areas. Each postcode is represented by the residential units weighted centroid of the area, which identifies the location of its densest residential nucleus. In rural areas this is particularly important as it identifies the actual urbanised area instead of an abstract location in the middle of fields. In total there are 832 urban areas with complete data, of which 63 have been developed under the VINEX program. The spatial characteristics are measured on a multimodal urban network model (Gil, 2014; Gil, 2015) that uses OpenStreetMap data (http://download.geofabrik.de/europe.html), OpenOV public transport data (http://data.openov.nl/), and Basisregistraties Adressen en Gebouwen (BAG) for building address and land use data (http://data.nlextract.nl/bag/postgis/). The measurements are aggregated at the residential units weighted centroid of each 4-digit postcode area. The data set with the aggregate results for travel patterns, spatial characteristics, socio-economic characteristics, and typological classification will be provided as supplementary material to this article. With it is possible to reproduce the maps and statistical analyses for the Randstad case study.

In the following maps the urban areas are represented as points because in this study the important dimension is the location and spatial distribution of types instead of their areal coverage. Additionally this avoids giving unduly visual importance to the large polygons of rural areas, and to make visible the typology in urban centres where postcodes have very small surface area.

§ 7.3.1 Travel patterns

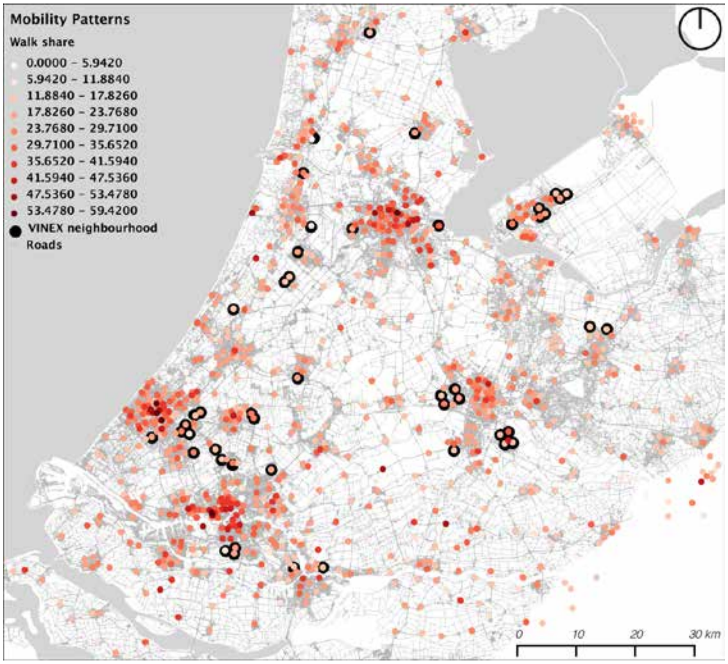
The travel patterns result from the aggregate journeys of the residents of urban areas, with at least 60 outgoing and incoming journeys recorded and a mean of 100 unique individuals per area. In total there are 279,744 recorded journeys by 82,780 unique individuals, including all journey purposes and all days of the week. It is acknowledged that origin and destination characteristics, as well as purpose and day of the week, play a role in individual travel behaviour and choice, however the aim here is to capture the aggregate travel patterns resulting at a given location for an evaluation of that area's overall performance. The characteristics of the travel patterns are the mode share of walking, cycling, driving, local transit and rail. Furthermore, these mode shares are calculated for different ranges of travel namely, short distance (up to 1500m), medium distance (from 1500m to 10km) and long distance (above 10km). These distances are derived from the journey distance frequency distribution of specific modes, where 85% walking and less than 4% local transit journeys are below 1500m; 95% cycling and 65% local transit journeys are below 10km, and 92% of rail journeys are above 10km.

Table 7.1 presents summary statistics of the travel patterns for the Randstad and the set of VINEX neighbourhoods. Looking at the split of mode share by range of travel shows the specific role and complementarity of soft modes and transit across scales, with walking dominating in the short distance, bicycle the medium distance and transit the long distance. However, car journeys span all distances with a clear dominance in medium (51%) and long (77%) distance journeys, reaching nearly 74% of distance travelled in the Randstad. This might seem surprising given the extensive and integrated transit network in the region, and the level of cycling that the Netherlands is known for. In relation to the VINEX neighbourhoods their travel patterns in Table 7.1 are not significantly different from the Randstad average. The share of soft and transit modes is lower than the Randstad average as we consider longer distance journeys, and the car share in terms of journeys and distance travelled is higher than the Randstad average. From these results we could conclude that their performance is worse than expected and their role in changing the travel patterns of the region a failure, as found in previous studies (Snellen and Hilbers, 2007). However, the residents' travel patterns have a spatial variation across the region that is linked to the socio-economic and spatial characteristics of the different urban areas and highlight the importance of location in influencing travel patterns and the outcomes of sustainable mobility policy.

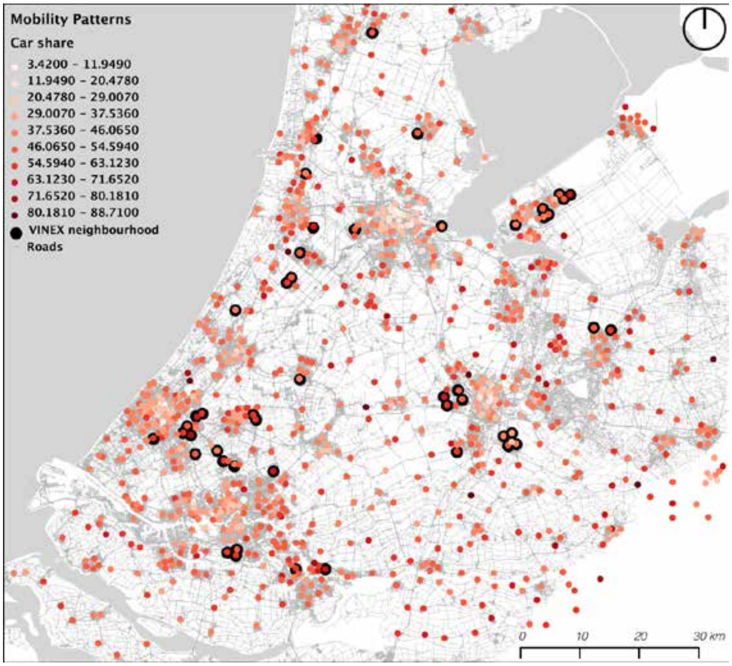
TRAVEL PATTERNS		All distances % mode share				Short distances (< 1.5 km)			Medium distances (1.5 - 10km)			Long distances (> 10km)		% distance share	
		Walk	Cycle	Public transport	Car	Walk	Cycle	Car	Cycle	Public transport	Car	Public transport	Car	Public transport	Car
RAND-STAD	Mean	23.69	24.88	3.85	43.73	56.31	28.86	13.82	32.92	7.32	51.32	15.69	77.23	13.24	73.99
VINEX	Mean	19.04	22.24	3.17	51.82	55.58	28.69	15.10	29.30	5.58	58.86	12.55	81.62	10.62	79.39
SPATIAL TYPES	1*	28.63	25.6	6.77	34.91	63.51	24.7	10.28	35.81	13.31	40.8	20.64	71.46	18.69	66.42
	2	37.4	22.19	6.56	26.97	73.17	19.73	5.35	36.73	15.46	35.12	33.94	60.58	30.1	56.87
	3*	21.84	24.84	3.45	46.88	53.51	30.63	15.27	31.46	5.49	55.1	12.51	80.52	10.25	77.45
	4*	19.52	23.55	2.11	51.81	49.49	30.65	19.11	28.47	3.05	60.7	9.82	82.37	7.65	80.43
	5	24.12	18.92	3.08	51.86	59.57	27.03	13.31	23.56	4.25	59.57	9.81	85.3	7.72	84.04
	6	20.33	26.62	1.71	47.81	46.67	35.41	16.28	33.27	2.3	54.77	8.29	81.16	5.81	79.76
	7*	16.54	26.36	0.99	52	50.07	33.56	15.48	32.87	1.67	58.79	11.69	80.16	8.9	77.41
	8*	27.44	19.78	7.79	41.43	67	19.36	11.5	28.18	15.32	48.79	16.88	77.1	15.46	72.37
	9*	26.08	24.28	4.68	40.19	60.28	26.13	12.29	33.95	10.49	47.53	19.06	74.96	16.29	71.53
	10*	22.58	28.22	1.82	42.47	51.89	34.01	13.38	36.99	4.27	50.32	17.73	75.38	13.83	72.66
	11*	19.61	28.01	1.42	47.9	57.72	32.54	9.35	36.2	1.71	53.43	11.34	82.25	9.85	76.37
SOCIO-ECONOMIC TYPES	1*	19.79	25.28	2.02	49.82	51.71	31.68	16.14	31.96	3.13	57.09	10.34	82.54	8.33	80.03
	2*	19.65	24.18	2.55	50.15	51.33	32.21	15.76	30.65	4.30	58.51	11.57	82.45	9.33	79.98
	3*	21.93	27.00	3.44	43.81	51.95	32.70	14.45	34.25	5.13	52.47	14.67	76.42	11.53	73.85
	4*	20.35	26.90	2.04	47.01	48.12	32.97	18.14	32.27	4.38	54.97	14.36	79.23	11.53	76.02
	5	27.81	21.94	5.40	40.76	63.88	22.19	12.65	30.66	10.51	49.33	18.54	74.70	15.86	70.82
	6*	34.23	22.96	9.43	28.29	71.10	19.91	6.76	34.68	20.76	34.72	27.58	65.52	25.59	59.99
	7	30.13	33.06	5.72	25.31	63.11	30.04	5.37	51.31	12.12	26.24	29.10	63.38	26.59	57.66
	8*	22.20	22.69	2.49	49.41	55.83	28.46	14.80	28.91	4.17	57.98	10.42	81.66	8.06	79.86

TABLE 7.1 Mean travel patterns of the Randstad, setting overall regional values against those of the VINEX neighbourhoods', the spatial types, and the socio-economic types of urban areas. It shows the distinctive travel signature of each type.

*Notes: * Types that are present in the set of VINEX neighbourhoods.*
Spatial types 12 to 15 are not included as they are outliers (12, 14) or are equivalent to types 1 and 2 (13 and 15).



1



2

FIGURE 7.2 Spatial distribution of walk (top) and car (bottom) mode share in the Randstad region.

The maps in Figure 7.2 clearly show that this spatial variation is not random, with highest levels of walking share and inversely the lowest levels of car share occurring in the larger urban areas. A complete set of maps and statistics related to the travel patterns of the Randstad can be found in Appendix E.

Given the specific location of VINEX neighbourhoods at the periphery of larger urban centres, one must take a closer look at the specific characteristics of those locations and evaluate their performance in this context. . Based on the conceptual model in Figure 7.1, these travel patterns should correspond to equivalent patterns of spatial and socio-economic characteristics.

§ 7.3.2 Spatial characteristics

The spatial characteristics of urban areas are described using indicators that measure their urban form, function, and configuration, both at the local and at the regional scales. As concluded in chapter 6, the Randstad region has urban areas with differentiated spatial characteristics, and these show a statistically significant correlation coefficient with the multimodal travel patterns of urban areas, hence they can be used as indicators of sustainable mobility. Using these spatial characteristics, I extract an urban form typology of the Randstad region obtaining 15 different types, defined by specific sets of spatial characteristics (Table 7.2), illustrated in Figure 7.3.

A description of every urban form type can be found in Chapter 6, Table 6.6, page 177, but here it is worth highlighting key differences between the most common types and especially the ones related to VINEX neighbourhoods. The large urban centres (Amsterdam, Utrecht, Rotterdam and the Hague) are predominantly composed of types 1 and 2 in their denser, active land use and multi-modal accessibility cores, and of types 3, 8 and 9 in other mixed use and residential areas, also characterised by high levels of multi-modal accessibility. Types 13 and 15 are equivalent to types 1 and 2 respectively, but correspond to the Utrecht area, which has the highest regional accessibility due to its central position in the region. Despite large urban centres having common types, it is noticeable how their mix varies spatially, providing a more refined and specific description of those cities than simple density, core/periphery or distance to city centre classifications. Types 7 and 10 identify other suburban residential neighbourhoods in the region, which are respectively supported by car infrastructure or also have regional transit infrastructure. The rural locations are mostly represented by types 4, 5 and 6, with a low density and predominantly supported by car infrastructure, with some transit availability in type 5. Types 11 and 14 have overall low regional accessibility, as they have sparse mobility infrastructures and are located in the most peripheral areas of the region.

SPATIAL CHARACTERISTIC	RAND-STAD	URBAN FORM TYPOLOGY									
	All	1	2	3	4	5	6	7	8	9	10
Bicycle dist.	166	110	83	132	278	1468	590	264	45	113	211
Main road dist.	1023	658	842	1228	1120	1727	2520	1552	545	1387	886
Motorway dist.	2529	2196	1740	2530	3654	9499	7217	3372	2349	1676	2553
Local transit dist.	237	206	192	214	282	157	3491	967	143	188	260
Rail dist.	2465	2201	932	4295	5263	10737	7364	3451	2171	958	1002
Pedestrian network (m)	2320	4371	6213	2665	859	551	331	1324	3376	2822	1409
Bicycle network (m)	4363	7513	7637	4748	1660	0	611	2970	6707	6210	3229
Cul-de-sac count	15	7	12	22	13	13	7	14	10	17	14
Crossings count	163	225	280	172	87	52	40	98	252	203	149
Local transit count	5	9	12	6	3	3	0	0	9	7	4
Rail count	0	0	1	0	0	0	0	0	0	1	1
Soft network reach (m)	4655	6804	10292	3821	2466	3312	2623	3216	23731	5556	3100
Car network reach (m)	3010	4537	6451	2569	1950	3160	2559	2009	16807	3752	1978
Residential area (x1000 m^2)	284	429	605	297	159	75	60	171	430	342	246
Active area (x1000 m^2)	20	43	201	19	8	5	3	10	34	30	22
Work area (x1000 m^2)	17	42	231	15	6	4	3	9	31	18	24
Education area (x1000 m^2)	9	20	37	7	3	2	0	3	18	20	7
Soft closeness mean ($x10^{-3}$)	0.313	0.313	0.314	0.313	0.313	0.313	0.313	0.313	0.313	0.313	0.313
Car closeness mean ($x10^{-3}$)	0.211	0.22	0.225	0.207	0.207	0.184	0.19	0.203	0.223	0.214	0.209
Transit closeness mean ($x10^{-3}$)	0.313	0.313	0.314	0.313	0.313	0.313	0	0	0.313	0.314	0.313
Rail closeness mean ($x10^{-3}$)	0	0	0.314	0	0	0	0	0	0	0.314	0.314
Activity car accessibility (x1000)	549	826	1939	463	376	287	270	367	1008	671	565
Activity transit access. (x1000)	314	372	706	261	226	198	165	257	391	400	369
Work car accessibility (x1000)	1713	2311	4287	1396	1759	1276	1195	1639	2060	1750	1946
Work transit access. (x1000)	1147	1192	1424	1013	1004	930	371	968	1098	1339	1470

TABLE 7.2 Median values of the spatial characteristics for the Randstad region, and for the types in the urban form typology of urban areas.

Notes: Types 11 to 15 are not included. Types 11 and 14 are exteme cases, type 12 is an outlier, and types 13 and 15 are equivalent to types 1 and 2 with the exception of much higher regional accessibility values..For the complete the of values please refer to appendix I.

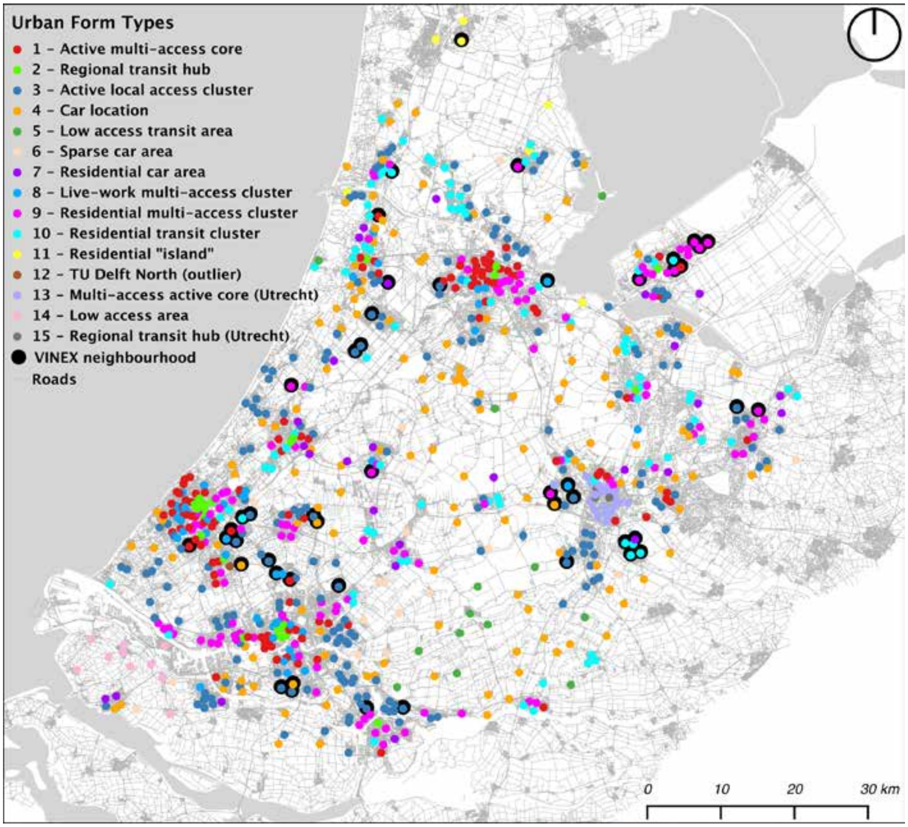


FIGURE 7.3 Spatial distribution of the urban form typology of the Randstad region.

This urban form typology confirms the idea that urban areas have a 'modality' and they support specific modes of travel, i.e. walk-ability, cycle-ability, transit-ability and drive-ability. The different urban form types show characteristic travel patterns, summarised in the mean mobility indicator values of Table 7.1. The urban form types of urban centres (1, 2, 8, and 9) have higher than average walking and transit share, and below average car and short distance cycle share, especially in types 2 and 8. In contrast, modes 4, 5, 6 and 7 have above average car and short cycle distance share, and below average walking and transit share, with the exception of type 5 that has better local transit support.

With regards to the VINEX neighbourhoods, one can conclude that despite the common policy principles they cover a range of different urban form types, with predominance of type 3 followed by type 9 (Figure 7.3). VINEX neighbourhoods do not represent the least sustainable types, i.e. little support for walking and transit and/or highly car oriented, but neither do they result in the types found in urban cores that more strongly support soft modes and transit. VINEX neighbourhoods are ultimately new forms of suburban development that do not reproduce the urban qualities of dense, active and car-free urban areas. Furthermore, it is also of note that the larger VINEX developments combine different neighbourhoods with different 'modality' types, and one can expect differentiated mobility performance levels within the same development. Are these different neighbourhoods catering for different populations?

§ 7.3.3 Socio-economic characteristics

The MON data set contains the socio-economic profile of the individuals taking the recorded journeys. The socio-economic data of the residents of each postcode area was used to define the urban area's socio-economic characteristics, including gender, age, household composition, income, car ownership, and level of education (Table 7.3).

SOCIO-ECONOMIC CHARACTERISTIC	RANDS-TAD	SOCIO-ECONOMIC TYPOLOGY							
	All	1	2	3	4	5	6	7	8
Male %	49.12	50	50.82	50	48.13	47.98	48.39	47.05	48.47
Female %	50.88	50	49.18	50	51.88	52.03	51.61	52.95	51.53
Age 0-14 %	16.67	16.36	24.32	17.07	20	13.04	13.25	12.37	12.73
*Age 15-24 %	9.23	9.84	8.76	14.12	5.81	8.2	11.11	3.67	7.27
*Age 25-44 %	27.91	25.9	34.21	25.64	25.1	27.16	37.31	44.75	19.7
*Age 45-64 %	30.19	35.78	23.4	31.14	30.97	29.29	23.81	27.37	35.16
*Age 65-74 %	8.25	8.23	4.11	7.52	10	11.95	6.25	5.77	16.36
*Age 75 or more %	4.72	3.45	1.98	3.9	7.42	9.56	3.9	3.77	7.89
Household (HH) size	2.38	2.46	2.75	2.64	2.32	2.06	2.04	1.75	2.22
*One person HH %	23.53	19.51	15.87	17.74	27.77	36.06	42.65	47.14	22.92
*No children HH %	43.48	49.61	37.21	45.9	41.94	40.95	32.35	37.18	54.55
*With children HH %	30.3	30.39	45.45	36.36	30.6	22.45	25	16.57	21.52
*Low income HH %	32.63	31.76	29.02	37.88	26.64	34.01	37.04	22.05	35.14
*High income HH %	13.64	15.98	14.8	9.33	23.78	10.39	10.94	25.11	13.33
*Cars per HH	1.18	1.28	1.37	1.23	1.21	0.88	0.65	0.73	1.17
Workers HH %	46.48	48.61	49.62	45.83	44.44	43.6	47.83	60.14	39.68
*Car ownership %	48.84	53.09	50	47.52	51.7	45.16	35.78	41.55	52.76
Driver's licence %	65.79	69.86	63.77	63.64	67.21	63.12	56.6	69.89	70.87
*Primary education %	11.11	9.3	10.53	14.29	9.59	13.46	13.79	5.86	12.82
*Middle educ. %	23.85	25	19.28	28.57	13	28.09	18.75	9.63	28.18
*Secondary educ. %	26.47	28.85	27.27	28.13	21.64	25.63	22.22	17.3	26.42
*Higher educ. %	19.81	20.35	18.78	11.96	35.56	17.15	25.51	52.53	17.39

TABLE 7.3 Median values of the socio-economic characteristics for the Randstad region, and for each of the eight types in the socio-economic typology of urban areas.
Note: * Variable used in the clustering algorithm to produce the socio-economic typology

These socio-economic characteristics are used to define a socio-economic typology of the urban areas of the Randstad region, following the methodology described in section 7.2. The characteristics with an asterisk in Table 7.3 have been included in the clustering algorithm, leaving out those that are strongly correlated with another or have minimal variation across urban areas. The socio-economic typology includes eight distinctive types, summarised in Table 7.3: Type 1, working couples with car; Type 2, young middle class families, with cars; Type 3, working class families with car; Type 4, rich, educated older couples with car; Type 5, retired people, few cars; Type 6, younger people, low income, no car; Type 7, rich educated young adults, few cars; Type 8, retired couples with car. The socio-economic types' names reflect distinctive characteristics that dominate above or below the Randstad average, and do not necessarily correspond to all the individuals or households in an urban area, nor include characteristics that are simply average. The spatial distribution of these socio-economic types is presented in Figure 7.4.

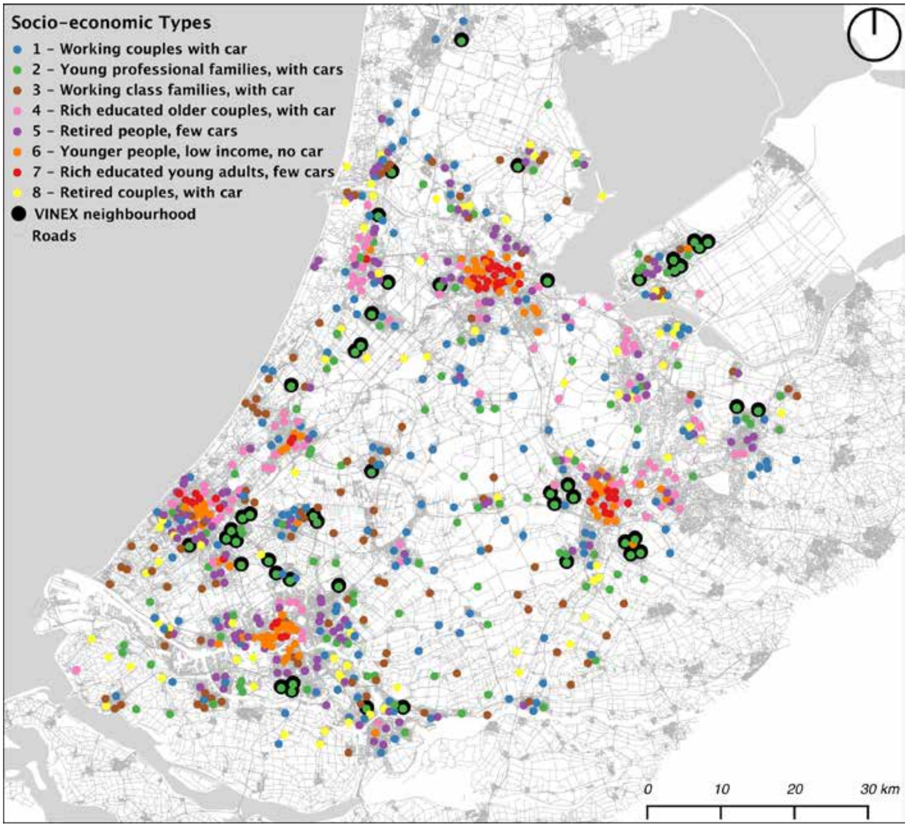


FIGURE 7.4 Spatial distribution of socio-economic types in the Randstad region.

Figure 7.4 shows the spatial distribution of the socio-economic typology, with concentrations of types 5, 6 and 7 in larger urban areas, and the remaining types distributed across suburban and rural areas. This spatial pattern is indicative of residential self-selection, i.e. that specific population groups move to or concentrate in specific types of urban area, thus confirming the bi-directional relation between spatial characteristics and socio-economic characteristics illustrated in Figure 7.1. The socio-economic typology is also related with travel patterns, which is summarised in Table 7.1. Types 6 and 7 have above average walking and transit share, and below average car share, being different in the higher cycling share of type 7. Type 5 also has a high walking share, but has below average cycling and average transit, resulting in higher car share. The remaining socio-economic types have a similar travel pattern of low walking and transit shares, compensated by higher short distance cycle and overall car shares.

The distribution of socio-economic types among VINEX neighbourhoods is highlighted in Figure 7.4. There is a clear dominance of socio-economic type 2, present in 79% of VINEX neighbourhoods. This dominance is not in line with the share of socio-economic type 2 in the Randstad (17%), revealing that these new suburban neighbourhoods were particularly attractive for a sector of the population looking for a new home at the time they were being developed. Type 2 population's travel pattern does not show a sustainable tendency, with the highest levels of car share and the lowest levels of walking and transit shares. Despite the different urban modality types across VINEX neighbourhoods, the socio-economic profile of their population seems to constraint the possibilities of achieving sustainable mobility outcomes. This potential and performance is evaluated next.

§ 7.4 The travel performance of VINEX neighbourhoods

In this section we present the results of evaluating the travel performance of VINEX neighbourhoods with regards to sustainable mobility outcomes. The socio-economic and urban form typologies of the Randstad provide the baseline conditions for travel in the region and, combined, each pair of types at any given location defines the location's mobility potential: the conditions for specific modes of travel. The spatial distribution of urban form and socio-economic types has shown (Figures 7.3 and 7.4 respectively) that this mobility potential varies systematically across the region and corresponds to specific travel patterns. For this reason, evaluating the travel performance of VINEX neighbourhoods against the city centre locations yields a negative result, and against low accessibility rural areas a positive one (Snellen and Hilbers, 2007). But the contextual evaluation of the travel performance of VINEX neighbourhoods against typologically similar urban areas gives an objective indication of their individual success.

§ 7.4.1 The relation between urban form and socio-economic types

Each pair of urban form and socio-economic types defines one baseline condition for travel patterns. But because of the residential preferences of different population groups not all baseline combinations occur: socio-economic types have a correspondence with certain urban form types (Table 7.4). While urban areas with urban form types 2, 13 and 15 (intense and mixed use regional cores) would provide the ideal compact urban development model towards achieving sustainable mobility objectives, they have a strong association with socio-economic types 6 and 7, of a generally younger population. Urban areas of type 1 (mixed-use multi-access area) and types 8 and 9 (multi-access residential areas) have a broad socio-economic appeal, in particular to socio-economic type 5 of older residents without car. But despite their presence in these urban areas, population types 1 to 3 (families and working couples) dominate more often urban areas of types 3, 4 (car dependent suburbs) and 10 (transit suburbs). Population with a higher share of older couples, types 4 and 8, share this preference for urban types 10 and 3 respectively. Low access car dependent urban areas (urban form types 5 to 7) appeal primarily to families and working couples, and in some cases older couples.

		SOCIO-ECONOMIC TYPE							
		1	2	3	4	5	6	7	8
URBAN FORM TYPE	1	6	11	8	12	29	27	16	2
	2	1	0	0	2	2	9	10	0
	3	53	41	35	11	35	3	0	32
	4	47	32	17	16	10	2	0	18
	5	3	3	3	0	1	0	0	3
	6	4	3	9	0	0	0	0	0
	7	6	6	5	7	0	0	0	3
	8	3	6	3	6	14	6	5	1
	9	14	20	10	9	32	18	6	5
	10	13	13	11	22	15	7	0	8
	11	2	2	1	1	1	0	0	0
	13	0	0	0	2	2	8	9	0
	14	0	4	1	1	0	0	0	4
	15	0	0	0	0	0	2	1	0

TABLE 7.4 Contingency table with the frequency of each socio-economic type for each urban form type.

§ 7.4.2 Defining the mobility potential of VINEX neighbourhoods

In oder to define the mobility potential of VINEX neighbourhoods, first, we must identify their different baseline conditions, by examining their urban form and socio-economic types. The dominance of socio-economic type 2 (SET2) in VINEX neighbourhoods (Figure 7.4) provides the opportunity to focus the rest of the study on SET2 urban areas, of which there are 141 in the entire Randstad (Table 7.4) and 48 VINEX neighbourhoods. Next, we calculate the mobility potential for each VINEX SET2 urban form type (types 1, 3, 4, 7, 8, 9, 10) using the travel patterns of Randstad SET2 urban areas, and finally we assess the performance of individual VINEX SET2 neighbourhoods within their specific (context-sensitive) potential.

The mobility potential of SET2 urban form types is made of a top and a bottom value calculated according to the equations in Section 7.2, and the values for each multimodal travel pattern are presented in Table 7.5. The range for each travel pattern can be very wide when considering all of the Randstad's SET2 urban areas, however, specific urban form types display a much narrower range, where urban areas are expected to achieve a specific score. For example: urban areas of urban form type 8 should have a high short distance walking share, above 44%; type 10 should have the highest cycle share (more than 15% and no more than 46%), as opposed to the lowest in type 8 areas (no more than 20%); while in type 4 areas a high level of car use should not be surprising. It is against this mobility potential range that each VINEX SET2 neighbourhood is evaluated.

MOBILITY POTENTIAL	RANDS-TAD	URBAN FORM TYPOLOGY							VINEX
(TOP AND BOTTOM %)	SET2 (N=141)	1 (N=11)	3 (N=41)	4 (N=32)	7 (N=6)	8 (N=6)	9 (N=20)	10 (N=13)	SET2 (N=48)
Walk share	35.21	28.87	27.34	30.53	34.56	33.71	32.64	26.17	34.56
	4.64	17.27	8.06	5.88	4.76	14.05	13.47	7.625	3.9
Cycle share	46.53	34.67	45.65	42.44	33.93	20.11	36.4	46.53	46.27
	1.42	15.7	4.35	5.56	15.09	4.57	5.95	15.79	1.42
Transit share	8.86	9.72	7.92	6.24	0.63	20	7.69	5.08	20
	0	0	0	0	0	0	0	0	0
Car share	75.51	57.23	71.29	80.26	69.81	70.25	66.92	63.16	73.04
	31.61	31.61	32.92	36.03	35.78	40.59	38.17	31.93	35.78
Short distance walk	91.78	79.57	89.19	84.62	79.55	92.59	82.35	62.98	89.19
	12.97	44.74	19.38	11.11	12.9	44.74	29.48	15.81	15.79
Short dist. cycle	69.8	48.45	59.69	62.32	52.66	39.47	52.59	63.16	63.16
	0	10.98	5.41	0	15.15	0	11.76	22.52	0

Short dist. car	38.51	30.59	32.14	42.86	45.95	28.57	21.39	21.05	45.95
	0	3.09	3.96	4.88	5.06	3.51	0	1.79	0
Medium dist. cycle	56.54	38.66	54.67	54.26	46.6	32.99	42.05	59.82	56.79
	5.52	25.9	7.14	4.26	22.64	7.55	8.7	25.64	0
Medium dist. transit	14.98	18.96	11.81	12.44	7.77	52.83	17.39	11.88	52.83
	0	0	0	0	0	0	0.65	0	0
Medium dist. car	87.14	62.53	82.09	90.91	70.37	91.49	74.19	67.19	92.19
	28.99	39.78	38.89	38.46	35.92	28.3	46.44	30.86	28.3
Long dist. transit	31.82	31.82	22.13	25	27.27	11.11	28.23	30.68	30.68
	0	0	0	0	0	0	2.27	0	0
Long dist. car	100	87.5	99.14	100	85	97.94	95.45	93.94	95.45
	61.98	67.86	69.18	66.15	72.73	84.21	67.69	67.73	61.98
Transit dist. share	25.46	21.95	20.13	21.49	21.88	12.2	21.7	25.46	25.46
	0	0	0	0	4.13	0	2.27	0	0
Car dist. share	96.2	85.89	95.21	95.85	85.32	96.2	95.95	87.44	95.95
	59.91	64.96	65.93	65.13	63.9	71.45	66.14	59.91	65.31

TABLE 7.5 Mobility potential of the urban form types, calculated based on the travel patterns of the Randstad SET2 neighbourhoods. The VINEX SET2 values refer to the maximum and minimum multimodal travel values in the group of neighbourhoods that is being evaluated.

§ 7.4.3 Contextual evaluation of mobility performance

The first conclusion to draw from the evaluation of VINEX SET2 neighbourhoods in the Randstad is that their performance is not systematically better than that of other Randstad SET2 urban areas, with the same potential. The VINEX SET2 multimodal travel outcome spreads over the full mobility potential range rather than concentrating near the top values for soft modes and transit or the bottom values for car travel (Table 7.5).

But every VINEX neighbourhood has a perfomance value for each of the sustainable mobility indicators. The contextual evaluation of VINEX neighbourhood's sustainable mobility performance is obtained by first calculating the value of each urban area's travel characteristics in the context of the potential for the area, according to Equation 7.5, and then converting those results to sustainable mobility evaluation indicators, where the values of car mode share are considered to be negative performance.

Next, we focus our attention on the VINEX neighbourhoods that have outlier performance evaluation results (positive and negative) in particular in relation to private car use (Table 7.6), which is the main concern of sustainable mobility policy.

POST CODE	VINEX NAME	NEIGHBOURHOOD NAME	URBAN TYPE	POSITIVE PERFORMANCE	NEGATIVE PERFORMANCE
2548	Wateringse Veld	Parkbuurt Oost-einde	1	-	medium distance car; car share.
1328	Almere-Stad	Tussen de Vaarten Zuid	1	short distance walk; train; transit distance share.	medium cycle; cycle share.
3059	Nesselande	Nesselande	3	walk share.	cycle; medium distance car share.
2642	Pijnacker-Zuid	Klapwijk	3	cycle; long distance car share.	medium distance transit share.
2498	Ypenburg	De Bras	3	-	walk; medium distance car; car; car distance share.
2721	Oosterheem	Oosterheem-Noor-doost	4	far distance transit; transit; medium distance car share.	short distance cycle; cycle; medium distance transit; short distance car share.
2994	Carnisselande	Vrijenburg	4	short distance walk; transit share.	train share.
1087	IJburg	IJburg West	8	walk; transit share (all modes and distances); medium distance car share.	medium distance cycle; cycle; train share.
3452	Vleuterweide	Vleuterweide	9	short distance walk; medium distance transit; short distance car share.	medium distance cycle; cycle; far transit; train; transit distance; far distance car; car share; car distance share.
1336	Almere-Buiten	Stripheldenbuurt	9	-	car share.
1948	Broekpolder	Wijkerbroek	10	short distance cycle share.	walk; medium distance cycle; short distance car share.
1318	Almere-Stad	Tussen de Vaarten Noord	10	short distance walk; transit (all modes and distances); far distance car share.	short distance cycle share.
2493	Leidschenveen	De Lanen	10	-	transit (all modes and distanc-es); far distance car; car share.

TABLE 7.6 Performance results for selected VINEX neighbourhoods, with positive and negative outlier performance in their mobility potential context.

The contextual evaluation provides a detailed screening of success and failure of individual mobility performance aspects of VINEX neighbourhoods. For example, Wateringse Veld Oosteinde (post code 2548) fails in terms of medium distance and overall car share, indicating a need to improve the take up of local transit and cycling, which is within the average of other urban areas of the same type. Examples can be taken from other VINEX and non-VINEX urban areas that share the same baseline type 1. Such a case, Almere-Stad Tussen de Vaarten Zuid (post code 1328), is not a good example because its cycling share (overall and at the medium distance) is low and this could work as a substitute for car use. This neighbourhood, however, is exceptional in terms of level of walking for short journeys and level of rail use in long distance journeys, which in turn boosts the share of transit in the total distance travelled. Such an example can be studied in greater detail to inform other urban areas of urban baseline type 1 that are interested in improving one of those sustainable mobility goals.

IJburg West (post code 1087), with urban type 8, is another example achieving a high level of walking and transit use, effectively reducing the level of medium distance car travel. It only stands out negatively with regards to cycle and train share. However, in this case these aspects are not critical, as they do not result in shifts to the car mode, but instead to sustainable alternatives. That is not the case with Vleuterweide (post code 3452) of urban type 9, with a problem of high overall car share, especially for long distances, which is reflected in the low level of long distance use of public transport.

Almere-Stad Tussen de Vaarten Noord (post code 1318) shows a positive performance in terms of walking and transit use, contributing to a positive (low) level of long distance car share. This contrasts with another VINEX location of urban form type 10, Leidschenveen de Lanen (post code 2493) that presents a negative performance in all types of transit journeys, reflected in negative long distance as well as overall car use. In this case, one can look at the transit service quality and frequency of post code 1318, and see to what extent it differes from what is on offer in post code 2493.

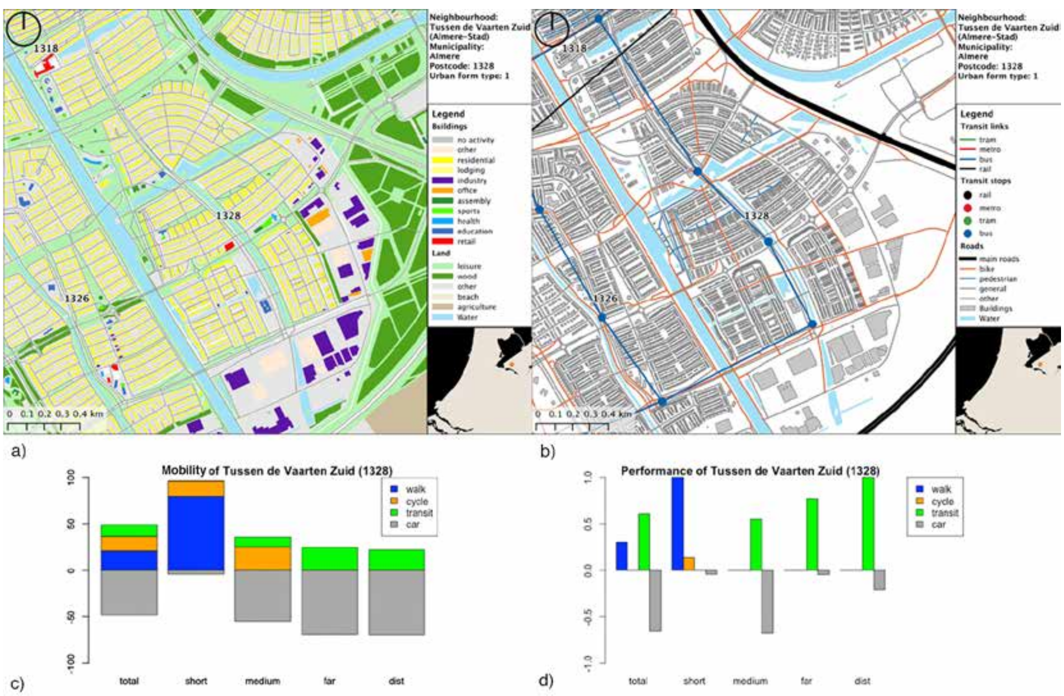


FIGURE 7.5 Example performance evaluation of a VINEX neighbourhood, comparing c) absolute mobility and d) performance relative to the context of the same socio-economic and urban form typologies.

One can synthesise these performance evaluation results in charts to make them more accessible and get an overview of a neighbourhood (Figure 7.5). In this case, the charts group the sustainable mobility indicators by range of movement (local to regional), and oppose the car values in a negative direction against all other modes.
These charts demonstrate the relevance of context sensitive evaluation, highlighting the difference between the absolute mobility levels usually considered (Figure 7.5c), and the normalised performance levels based on the mobility potential (Figure 7.5d). For example, the overall cycle share in medium distance travel at 25% represents a very poor performance, indicated on the performance chart by a 0 (zero) score; while the transit distance share of 20% might seem low when compared to that of the car, but it is actually outstanding in terms of the specific urban form and socio-economic type.

§ 7.5 Conclusions

The empirical data on travel in the Randstad region shows strong spatial distribution patterns that are aligned with the spatial distribution of socio-economic and spatial characteristics, translated into regional typologies. These regularities highlight the role of location in influencing travel patterns and the outcomes of sustainable mobility policy. These regularities also highlight the interaction between all those factors, and the socio-economic and urban form typologies can form a level of baseline conditions to determine the sustainable mobility potential of urban areas. Urban areas under different baseline conditions have different mobility potential, hence the travel performance of urban areas should be evaluated against others with baseline conditions.

This chapter proposed a context-sensitive evaluation method to support the strategic planning of sustainable mobility in a given region or country. The method defines quantitatively the mobility potential of urban areas based on their spatial and socio-economic profile, taking into acount empirical evidence on travel patterns. The mobility potential provides ranges of possible travel outcomes, with which one can identify locations for successful development within the region. In addition, the evaluation method assesses the performance of individual urban areas in this regional context, highlighting each area's strengths and weaknesses in relation to its sustainable mobility potential. This evaluation approach can be applied ex-ante, to evaluate alternative plans early on using the existing data from the region and to guide development to locations or plans with greater sustainable mobility potential, or ex-post, to evaluate the performance of plans based on actual travel outcomes and identify underperformers to set priority areas for intervention using regulatory and soft measures.

The sustainable mobility potential of an urban area can be realised or not, as the evaluation of VINEX neighbourhoods has shown. In identifying low or underperforming neighbourhoods, with greater room for improvement to reach their potential, one can define planning priorities. To fullfill this potential one can intervene at the spatial level, ensuring all spatial characteristics are well within the expected values. But we acknowledge that other factors play a role in influencing the travel performance of urban areas, such as transport technology, service frequency and cost, parking regulations or personal attitudes and preferences. By identifying examples of success, where the sustainable mobility potential is reached or even surpassed, one can select relevant policies and initiatives to be transfered to other locations in the region that share identical baseline conditions.

A change in mobility potential can only be achieved by retrofitting an urban area. On the one hand, it requires costly intervention at the level of mobility infrastructure and land use, aiming to transform the spatial characteristics of the area into a different 'urban modality' type. On the other hand, it has to wait for a progresive shift or exert a direct influence on the socio-economic composition of the urban area. Such changes are not only expensive and slow, but sometimes very difficult to implement ex-post for technical reasons and public opposition. For these reasons, one should first assess the actual performance of an urban area within its current mobility potential, and intervene with regulatory and soft measures with the aim of maximising its sustainable mobility performance.

8 Conclusions

This thesis has presented an integrated urban network model that offers a detailed description of the multimodal mobility infrastructure and land use of a city-region as a whole and of its urban areas. This model was analysed to produce a collection of urban form and structure indicators, including measures of multimodal accessibility and network configuration. The indicators describe the different urban areas in the region and are used to classify them according to their 'urban modality'. 'Urban modality' is the affordance of each urban area for travelling by particular modes of transport, i.e. its walk-ability, cycle-ability, drive-ability and transit-ability. In this work, it has been shown that there is a relation between the 'urban modality' typology of urban areas and the travel patterns of their residents, measured as a set of sustainable mobility indicators related to mode share and distance. For this reason, 'urban modality' offers a context for the ex-ante evaluation of sustainable mobility potential, and the ex-post evaluation of sustainable mobility performance. The context-sensitive evaluation of the sustainable mobility of urban areas was demonstrated with the case study of the VINEX neighbourhoods of the Randstad city-region of the Netherlands.

Section 8.1 proposes an expanded conceptual framework of urban form and travel towards a multi-level approach for sustainable mobility policy and planning practice. The remainder of the chapter brings together the conclusions of the various chapters together in an attempt to answer the research questions put forward in Chapter 1, but also reflecting on their initial formulation in light of the research outcomes. In addition, the conclusion looks at aspects of the present work that deserve further research, in particular relating to the multimodal urban network model and its analysis, and concludes poiting to new directions of research that could be taken from this thesis.

§ 8.1 A multi-level framework for sustainable mobility policy and practice

To achieve sustainable mobility goals across a region, policy makes and planners need support instruments to guide their decisions. Policy transfer in this field often resorts to international prescriptive models, which are difficult to translate to the local context and end up being used as source of inspiration and discourse, or resorts to 'best practice' examples, based on case studies that have not been really tested and are expected to work equally well everywhere. These are rarely a source of technical expertise and the use of local experts is frequent (Pojani and Stead, 2014). The proposed evaluation method aims to support policy and practice by offering an instrument that reflects the local context and provides objective indication of the potential success of local areas and identification of local best practice.

The mobility potential range of urban areas with similar spatial and socio-economic characteristics, defined in Chapter 7, suggests that the conceptual model by Stead et al. (2000) on the factors that influence travel patterns (Chapter 1, Figure 1.1) can be extended with additional factors into a multi-level framework for decision making. The baseline characteristics that are known to afford specific travel patterns (level 1), namely spatial and socio-economic characteristics, should be supplemented with additional aspects that have been shown to impact on travel patterns (level 2), namely transport service and regulations (Priemus, 1995; Cervero et al., 2004; Beirão and Sarsfield Cabral, 2007; Banister, 2008; Redman et al., 2013) and individual attitudes and preferences (Beirão and Sarsfield Cabral, 2007; Ewing and Cervero, 2010; Van Acker et al., 2010; Olaru et al., 2011; De Vos et al., 2014). These additional aspects have an influence on travel outcomes, within the range of sustainable mobility potential values defined by the baseline factors (Table 7.5). They also have an influence on the other characteristics of the travel patterns conceptual model, creating a highly interdependent and complex system (Van Acker et al., 2010). This extended model (Figure 8.1) can be used as a multi-level framework for sustainable mobility policy, with the different factors that influence travel patterns being subject of specific planning and policy measures (Banister, 2008) at different stages, depending on their level and on the current state of the hierarchically higher level. Namely, land use and infrastructure plans being higher level measures (A), transport policy and planning on transportation technologies, on regulations affecting access, parking, and travel cost, or on public transport service route, reliability and frequency (B) and policy measures to inform, educate and promote the use of alternative transport modes (C) as lower level measures.

In this multi-level framework, the higher level of planning and policy addresses spatial characteristics (A), be it at the local or regional scales, as these define the baseline conditions for travel patterns. One should remember that the urban form typology defining this baseline is composed of sets of interrelated spatial characteristics, and in order to obtain a different mobility potential the plan must seek a different urban form type, only achievable by modifications to these sets. These are hard measures with strong path dependency, involving the mobility infrastructure, property subdivision and buildings. Interventions on spatial characteristics (A) are therefore more challenging ex-post, and if a given urban area has a baseline level with potential to reach some of the desired mobility targets, one should prioritise policy and planning intervention on the lower level. If this urban area is perceived as having a low performance for its baseline, it has greater potential for change in mobility, and policy on transport service and regulations (B) or attitudes and preferences (C) can be effective in changing travel patterns in the desired direction. If areas are at the peak of mobility performance, and aligned with the overall sustainable mobility objectives, one should study these success cases to identify the particular policies of types B or C addressing travel patterns. These policies can be considered for transfer into other areas of identical or similar baseline context (higher level conditions) that may be struggling to achieve their sustainable mobility objectives. This multi-level approach has the potential to make policy intervention on sustainable travel more effective as it is sensitive and tailored to the local context, but at the same time derived from proven cases and supported by a general quantitative analytic method.

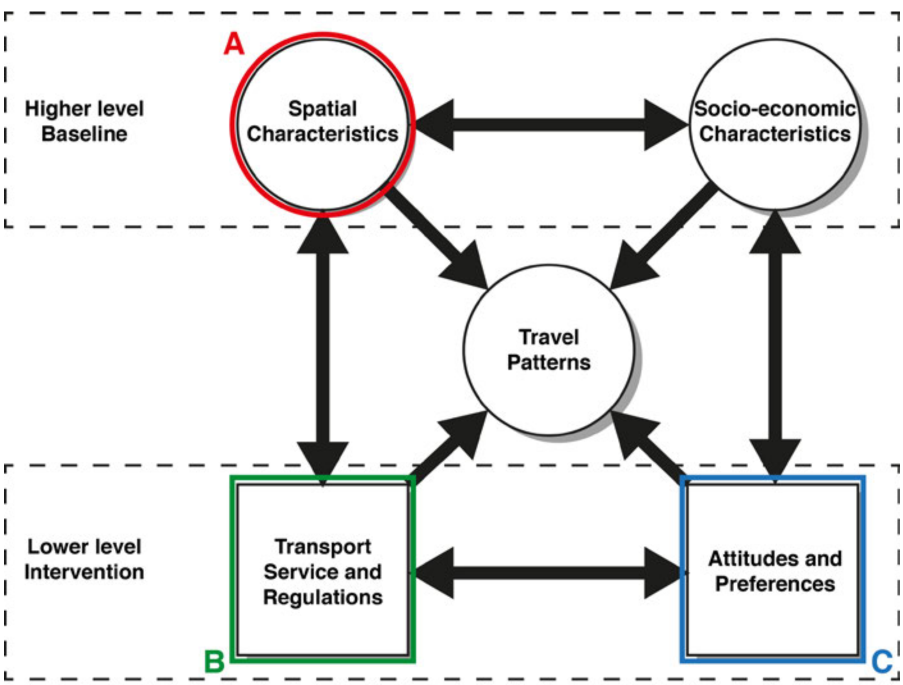


FIGURE 8.1 Proposed conceptual model for sustainable mobility policy multi-level framework, where spatial planning decisions (A) impact the higher level baseline, and policy and planning decisions on transport services (B) and population attitudes (C) represent opportunities for intervention at the lower level, dependent on the context provided by the higher level baseline.

§ 8.2 Research questions revisited

What are the types of urban areas that support or constrain sustainable travel patterns?

From the analysis of the MON dataset and the mapping of sustainable mobility indicators for the Randstad (Chapters 6 and 7, Appendix E), it is clear that the most sustainable travel patterns are concentrated in larger urban centres, while the most unsustainable travel patterns are found scattered in different rural and/or less dense urban areas. The suburban areas adjacent to larger cities show partial positive trends, where there are positive levels of walking, cycling or public transport use, but higher levels of car use for different journey distances, depending on local infrastructural and regional structural conditions. In these suburban centres, local differences can correspond to different sustainable travel patterns, e.g. urban areas with a higher concentration of local amenities and public transit services have travel patterns similar to that of urban centres, as opposed to purely residential areas in the same suburb.

In urban centres, one can witness a much lower car use by its residents and a stronger share of walking and public transport use, as well as shorter overall travel distances. In residential suburbs, cycling is generally prevalent over walking and local public transport, and the use of the car for shorter distances varies from place to place. Car is the main mode of transport in rural areas at all scales of movement, although cycling has a large travel share at short and medium distances (up to 10km), more so than in the fringes of large urban centres, where walking and public transport provide for those distances. In these larger urban centres cycling is mostly used for medium distance journeys, but this pattern is more prevalent in Amsterdam and Utrecht than the Hague and Rotterdam. Long distance public transport use is clearly linked to the urban areas served by important rail infrastructure. All this is hardly surprising, given that these different urban environments have been historically constructed to support particular modes of transport, and evolved along with specific cultures of movement, that today we can grade as sustainable (walking and cycling) or not (car).

The quantitative classification of urban areas presented in Chapter 6, based on their multimodal urban form, accessibility and configuration characteristics, is a general method that can objectively differentiate 'urban modality' types. The typology identified in the Randstad region (Section 6.5.4, Table 6.6) is composed of the following types:

1. Active multi-access core
2. Regional transit hub
3. Active local access cluster
4. Car location
5. Low density transit area
6. Low density car area

7 Residential car area
8 Live-work multi-access cluster
9 Residential multi-access cluster
10 Residential transit cluster
11 Residential island
12 TU Delft North (outlier)
13 Multi-access active core (Utrecht)
14 Low density inaccessible area
15 Regional transit hub (Utrecht)

While these 'urban modality' types can reappear (at least partially) in different regions, with the exception of types 12, 13 and 15 that are reion specific, this should be tested to assess their general applicability and use as contemporary urban development models for regional design and planning. In addition, given regional differences certainly different types will emerge with spatial parameters beyond the values found in the Randstad region. Nevertheless, the method is general, and from the example of the Randstad one can draw conclusions for given 'urban modality' types.

To select a relevant urban development model(s) one must take into account the travel patterns associated with the different 'urban modality' types. There is variation in the travel patterns of each 'urban modality' type, but each presents a unique signature regarding specific travel modes. Urban areas of types 1, 2, 13 and 15, that are found in larger urban centres with intensive activities and integrated public transport infrastructure, have a distinctive multimodal and diverse travel pattern with low car use. As opposed to areas of types 4, 5, 6, 7, 11 and 14 clearly dominated by the car and long travel distances and times, with no available alternatives other than local cycling. Urban areas of types 3, 8, 9 and 10 present a more balanced picture, where an average car share is closely followed by transit or cycling shares. With this classification, instead of looking for a direct influence of urban form on travel and calculating an exact travel outcome, one can extract the limits imposed on travel by an urban modality type, in the form of a sustainable mobility potential (Chapter 7). There are lower and upper sustainable mobility indicator limits beyond which that travel pattern is not observed in a given urban modality type, and should not be expected in urban areas of that same type. Given clear sustainable mobility objectives, one can select the urban modality type that more closely, and with a greater margin, meets those objectives.

Finally, from the 'urban modality' classification we should select multiple urban development models, given the wide range of sustainable mobility goals that can be met by different types of urban area, e.g. some have high levels of cycling but low levels of walking or transit and vice-versa; and given the range of differences in population and functions in a city-region that must be provided for by different environments.

What are the urban environment characteristics necessary to (re)produce the best preforming urban areas?

The multimodal urban network model offers a description of urban areas based on a set of urban form, accessibility and configuration characteristics, and we have calculated how individual characteristics correlate with the sustainable mobility indicators of the same urban areas, giving us the overall relevance of the urban form characteristics as indicators of specific travel patterns. The results presented in Chapter 6 and Appendix I confirm the strength of known indicators of sustainable urban form, and introduce new ones:

- Increasing distance to the rail station is a negative indicator of rail and local transit shares, and positive indicator of car share;
- Density of street network, crossings, public transport stops and land use of all kinds, are positive indicators of walking and local transit shares, and negative indicators of car share and distance travelled;
- Density but also regional centrality of the rail stations in an area are positive indicators of rail share;
- Accessibility to active land uses (by street or transit) is a positive indicator of walking and local transit share, and a negative indicator of car share;
- Configuration of the transit network is a positive indicator of rail usage.

Other results are more surprising and contradict the expected role of urban form indicators. For example, regional accessibility does not show a significant correlation with distance travelled in general, and accessibility to work locations shows weak correlations with all modes of travel. This can partly be imputed to necessary improvements to the multimodal network model and its measurement (see Section 8.3), but can also raise the question if distance based attraction is an important characteristic in itself or needs to be combined with configuration and other structural characteristics. The definition of 'urban modality' types attempts such a combination, but other approaches are possible (see Section 8.3). Another surprising result is that urban form indicators show little correlation with cycling mode share, or even a small negative correlation in the most 'walkable' areas. This can be explained by the widespread use of the bicycle in the Netherlands, including for local travel in rural areas, making the case for developing sustainable urban form and mobility indicators adapted to the regional context. But it also demonstrates that urban modality is an affordance from a complex set of invariants representing different modes and does not determine outcome. The mode share in an urban area is influenced by the take up of alternative modes of travel that use the same infrastructure, have the same range, or benefit from a similar range of local conditions.

At this stage, I would like to reflect on the formulation of the research question, and highlight some aspects regarding the interpretation and application of systems of indicators.

The first reflection is the notion that urban areas have complex and interdependent collections of characteristics. The 'urban modality' affordance identified in this study results from a combination of urban form, accessibility and configuration characteristics, and their indicator values provide a quantitative description of the specific mix for each 'urban modality' type. Different 'urban modality' types have different outcomes in terms of travel patterns, and to achieve a specific travel pattern the urban environment characteristics must exist approximately in that combination, because they work in tandem. One should not take the values of individual urban form indicators as reference to replicate a specific travel pattern out of the context of the 'urban modality' type where they feature.

The second reflection is that urban form and structure indicators are useful for evaluation because they allow us to quantify, describe, compare and assess different urban areas, but they do not necessarily represent the only ingredients for (re) production of an urban area's performance. It is important to understand that to produce urban environments with specific travel performance, spatial characteristics and other ingredients are at play (technology, regulations, individual preferences). And the spatial characteristics described by the indicators are as much part of the process as its product, because the urban development process is dynamic and complex. The urban form indicators are a snapshot to monitor progress towards the desired sustainable mobility goals, but to produce the best performing environments we need to learn more about the process, i.e. its ingredients, quantities, relations, eventually through longitudinal studies (see Section 8.4).

How do we integrate the mobility infrastructure of different modes in a regional urban network model?

One of the main challenges in building a regional urban network model arises from the fact of it being multi-modal, i.e. composed of different systems, as well as multi-level, i.e. a coupling of systems that do not necessarily operate on the same level or scale (Marshall, 2006). This requires a correct representation for each system but also making different levels of representation across systems compatible. The answer to this depends on the purpose and use of the model, and the proposed network model is designed for the size of the regional territory represented and type of indicators being measured, as described in Chapter 4. It is possible to have alternative representations of the individual modes and their integration, but these remain to be tested in future work, as discussed in section 8.3.1.

Regarding the private transport system, we recommend having a single level to represent the private transport modes (i.e. pedestrian, bicycle and car), because there is largely a shared general infrastructure for all modes. There are differences with mode specific infrastructure, such as motorways, cycle lanes and pedestrian paths and areas. These differences can be established by attributes specifying the access and impedance of each mode on every link, which avoids a large amount of data duplication. In this model, the street network topology was expanded to incorporate the pedestrian areas and paths that are important in the measurement of local scale indicators. Further separation of levels is only recommended if the mode specific infrastructure networks are largely separate, and one has access to their complete and detailed representation.

Regarding the public transport system, the opposite approach is recommended. Each mode should be represented in a separate and complete level based on their individual infrastructure networks because these are largely separate, and the levels are connected by interface links. Nevertheless, in strategic planning and configuration studies one should resort to a simplified representation of the network that is equivalent to the private transport system, using a single node at general stop locations and links between those stops that have a service connecting them. This representation contrasts with a more detailed timetable-based representation of the topology of individual services and times, which is more suitable for detailed public transport service planning or route planning instead of strategic regional infrastructure planning.

Because the private transport system has the widest coverage in the region, it should be treated as the base level, onto which the other levels are linked by additional interface elements. This includes the buildings representing the land use system.

How can we analyse this model to produce meaningful descriptions of urban modality?

The multi-modal and multi-level physical network representation is a geographic representation that needs to be translated into a graph for network analysis (Chapter 5). In this case an undirected graph with the nodes representing the segments of the street network is recommended. On the one hand, the integrated model results in a non-planar graph because of its multiple levels and therefore there is no reason to attempt a graph representation that matches the geographic representation. On the other hand, using the street segments as nodes facilitates the calculation and usage in a consistent graph data structure of additional impedance attributes other than physical impedance along the segment. Namely temporal, topological and geometric impedance of the transitions between segments, i.e. changes of direction at intersection. This expanded list of distances enables the analysis of the model adopting different approaches and theories of urban form and accessibility, and as a result compare but also combine them. It was found that to describe the centrality of the regional structure of mobility infrastructure it was more appropriate to use geometric and topological distance than the traditional metric and temporal distances. However, the same type of distance is not necessarily the best to describing the structure of all modes, as the tests with the public transport network have shown (Section 5.5). An outstanding challenge is to find a suitable combination of distance types with compatible units to represent the different modes, or develop improved methods incorporating temporal distance, as this is one unified distance easily available for all modes.

The analysis of the model runs on a subset of nodes and links of the integrated multimodal graph, based on the chosen modes of travel. Two main combinations stand out as meaningful: car network, versus the public transport and soft modes networks combined. The analysis of these sub-graphs can be based on simple network shortest routes and service areas, and standard algorithms of network centrality and accessibility. However, the fully integrated network model, based on a street network 'backbone', should allow the development and implementation of truly multimodal analysis algorithms (Section 8.3.2). These should give improved results, especially in the way of handling the transitions between modes.

How can we evaluate the sustainable mobility performance of urban areas to support strategic planning?

The answer to this question is largely covered in Chapter 7, where an evaluation method is proposed and demonstrated for the case of the VINEX neighbourhoods of the Randstad. The main principle behind this evaluation is to consider performance in the context of urban areas of a similar type. This approach acknowledges that the urban environment defines affordances and the socio-economic characteristics establish demand, which influence the sustainable mobility performance of urban areas. The calculation of the mobility potential, based on the observed movement patterns of similar urban areas, sets the range of expected outcomes. In this study, the 'urban modality' and socio-economic typologies of the region have been used to identify urban areas with identical pairs of types, and for these one calculates the upper and lower mobility potential limits for each sustainable mobility indicator.

The mobility potential range can be used to support strategic planning in different ways: the selection of locations for new urban area development, the ex-ante evaluation of urban development proposals, and the ex-post evaluation of urban areas. In the first case, one identifies the locations with a potential that more closely matches the strategic mobility objectives for the region; in the second case, one determines the urban development proposals' type based on their urban form characteristics and identifies the corresponding potential from similar types in the region, choosing a proposal whose potential more closely matches the sustainable mobility objectives; in the third case, one determines the urban area's type based on urban form and socio-economic characteristics and evaluates the observed travel patterns against the type's potential, choosing appropriate policies based on the relative performance. These can be softer actions to boost an unrealised potential for specific modes of transportation, or harder measures to retrofit an urban area and upgrade its urban form type, in the face of a fully realised potential or an inadequate potential for the current strategic mobility objectives.

In this evaluation process, it is important to clearly define the sustainable mobility objectives in relation to the various modes of transport, and take into account that not all indicators need to be aligned in the same direction, as there is competition and compensation between sustainable transport modes, e.g. walking versus cycling, cycling versus local transit, cycling combined with rail. In this case, the sustainable mobility indicators have been split by scale of movement (i.e. short, medium and long distance of travel) and by mode, with the sustainable transport modes at each scale being pitted against the car (e.g. walking and cycling at short distance).

How do VINEX neighbourhoods compare to traditional inner city areas? And to other suburban neighbourhoods?

One can easily be critical of the performance of VINEX neighbourhoods when comparing them with the older traditional inner city areas of the region. From the analysis of the empirical data of the Randstad region, the traditional urban areas stand out from all other urban areas with a unique profile, not only in terms of travel patterns (Appendix E) but also in terms of urban from (Appendix G) and socio-economic characteristics. This has been confirmed by the typologies developed for those characteristics (Chapters 6 and 7). The difference to the rest of the region is such that any comparison seems unfair, and setting as development target to replicate their performance is a tall order. These traditional inner city areas have a sustainable movement culture around soft modes and public transport that is designed into the environment over centuries, and adhered to by the residents attracted to the particular local culture. Urban areas are developed for specific modes of transport, in a specific historical time, reflecting the specific culture of that time. Despite the best intentions of sustainable urban development and sustainable transportation agendas, replicating today the places of the past is impossible (Marshall, 2005, p.10). There are fundamental principles and rules today that need to be accommodated when making places, which are driven by specific transport modes and their infrastructure, and make the environment better suited for those modes and less for others. In addition, new urban developments are attractive to young families looking for a new home, bringing with them specific lifestyle preferences and also practical requirements.

It was found that VINEX neighbourhoods have different urban modality types and larger VINEX developments are composed of urban areas with diverse types. Some areas have higher density and mixed use and are served by a variety of public transport modes, while others have an exclusively residential character with weak presence of transit infrastructure. For this reason one can observe varying sustainable mobility performance across VINEX neighbourhoods. The mobility performance result is influenced by the strategic location and accessibility conditions in the region of these out of town urban areas. Since the socio-economic type of VINEX neighbourhoods is the same in most areas (80% are dominated by younger families with car), one can conclude that their urban modality type plays a role in supporting different sustainable mobility outcomes. Furthermore, if we compare VINEX neighbourhoods with other non-VINEX urban areas of the same urban modality type, VINEX neighbourhoods do not stand out as performing systematically better or worse. For this reason, the general criticism of VINEX neighbourhoods should be targeted at specific implementations, to address problems that are also found in similar non-VINEX neighbourhoods. In order to draw further conclusions and provide concrete examples on policy interventions and lessons, one would have to conduct a more detailed local study of a selection of urban areas (VINEX and non-VINEX) sharing the same typologies.

§ 8.3 Other findings

§ 8.3.1 Limitations of SUD evaluation tools

The review of sustainable urban development (SUD) evaluation tools (Chapter 2) revealed some of their current limitations: the lack of explicit evidence base, the need for regional adaptation, and the limited spatial scope of the indicator systems. Many SUD evaluation tools and standards present collections of indicators and benchmark values, but lack explicit references to the evidence base that supports those metrics. They are generated from a consensus on 'ideal-normative' best practice by a group of experts, sometimes open to wider public consultation, but without a single reference to research, case studies, or regulations. This is the case with LEED-ND, one of the most well known neighbourhood development standards. Indicators and benchmarks must be supported by evidence to give credibility to the tools, but also to provide a reference point for review and confirmation of their adequacy to a given regional context or the need for adaptation based on different local evidence. For example, how are recommended levels of density or acceptable walking distances defined?

There are different strategies to deal with regional localisation: some tools are region specific based on local regulations and studies, some tools offer different versions adapted to different regions with different indicator weights and benchmark values, finally others leave the specific definition of parameters open to be defined by those carrying out the evaluation. Even in the case of the LEED-ND rating system, it is acknowledged that the indicator system is US specific and not necessarily relevant to Europe or Asia. The indicator system should be revised and new versions created before applying it in these other locations, eventually creating new local standards and rating systems.

Finally, in most cases, these systems impose a hard spatial boundary on the analysis, around or close to a pre-defined neighbourhood boundary. In doing so, they ignore the surrounding context and its characteristics, as well as the wider regional context and the strategic location of the neighbourhood. In the present study, the neighbourhood is defined by a walking range from the individual address, as everything within walking distance is part of that addresses' local neighbourhood, even if located outside the official administrative boundary of the neighbourhood or limit of the development plan. Furthermore, the regional accessibility and configuration characteristics provide a differentiating factor between neighbourhoods that share similar local characteristics. In the present case study of the Randstad region, the regional accessibility of the city of Utrecht sets it apart from other important cities like Amsterdam or Rotterdam.

§ 8.3.2 The challenge of combining different data sets

Regarding the construction of a MMUN model, using the OSM data set certainly offers an adequate street network base for the model and compares well with standard official data sets: it provides detailed information regarding the local area and soft modes, usually absent from official data. Nevertheless, the OSM data can be incomplete and inconsistent in terms of represented features and their attributes. In this case, the land use and public transport information had to be complemented with other data sets, either from official open data repositories or from additional VGI sources. While this combination of different data sets allows the production of a more comprehensive model, it also raises problems. The geometric representations between the different sources are not topologically compatible, resulting in incorrect spatial relations being identified. Furthermore, it is difficult to relate features and identify duplicates between data sources because they rarely share unique identifiers, and the attributes using names such as streets or rail stations often use different spelling or naming conventions. For this reason, one has to develop heuristics, custom algorithms and routines to process these data sets and make them compatible. And these are far from reaching 100% accuracy.

§ 8.3.3 Transport mode's distance patterns

There is competition and complementarity between transport modes at different distances. Competition can be seen where two modes are suitable for the same distance, and complementarity where different modes integrate to form a multimodal journey covering a longer distance. This can be observed in the chart of Figure 8.1, showing the frequency distribution of journey distances for the different transport modes, i.e. walking, cycling, car, local transit and rail. Where there is a larger overlap between curves, one can observe stronger competition, unless one of the modes is not locally or personally viable. This is the case between the car and cycling, cycling and local transit, or walking and cycling. Where the curves dip coinciding with where another mode is rising, one can expect multimodal complementarity. This is the case between walking and local transit, and cycling and the rail.

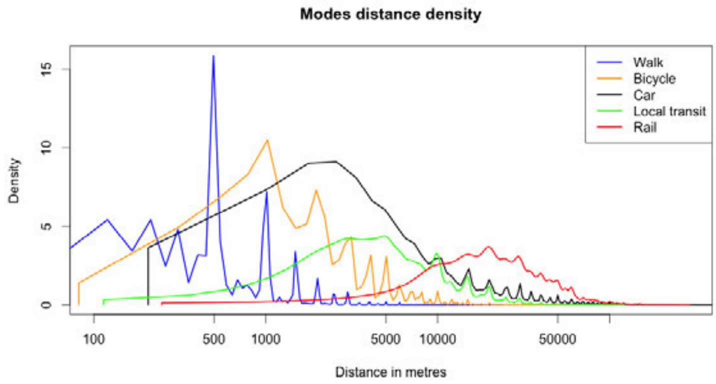


FIGURE 8.2 Density plots of the distribution of journey distance using different modes of transport in the Randstad. This plot shows the overlap and complementarity between transport modes, but also the discrete recording of journey distances in the travel survey.

For example, urban areas with high levels of cycling tend to show lower levels of local public transport use, or urban areas with high levels of walking do not present equally high levels of cycling over short distances. In fact, one can observe strong negative correlations between mode shares at different scales (Appendix I). For this reason, when evaluating sustainable mobility objectives, one should not expect an equal increase in all alternatives to the car, and rather consider an integrated strategy where different soft and public transport modes complement each other.

Another observation from Figure 8.1 are the spikes in the curves at regular intervals. These coincide with round numbers equally spaced, such as 500m, 1000m, 1500m, etc. Although the mobility survey asks respondents to record the exact journey distance and duration, with a 100m and 1 minute resolution respectively, respondent mostly provide an approximate value. This shows that individuals perceive and simplify travel impedance using discrete steps rather than continuous values, and consequently distance does not have a linear and exact cost. Such step values can be taken into consideration when determining travel ranges, catchment areas, and the utility of destinations, albeit with fuzzy edges to accommodate destinations close to either side of the range limit.

§ 8.4 Considerations on the multimodal urban network model

The work presented in this thesis is largely based on the spatial description of a city-region using a multimodal network model, and the work explores the results from a range of network analysis metrics. Throughout this study, decisions made under time, data or personal experience constraints have determined the characteristics and quality of the network model and its analysis. The quality of the results and generalisation of the findings are very much dependent on these characteristics, and it is appropriate to highlight, in retrospect, some of the alternative routes that could be taken and aspects that could be improved in building and analysing the MMUN model. An improved network model and analysis method can increase the quality of the urban form and accessibility indicators, and the general relevance of the urban modality typology developed in the study.

§ 8.4.1 Alternative approaches to network representation

Starting with the representation of the street network, as explained in Chapter 4, the decision was to keep the original road centre line data unchanged, and only make automatic corrections to the street segment topology where it was inconsistent with the general representation in the rest of that data set. There are however missing features and missing attributes, in particular in the cycle and pedestrian networks (Appendix C, Figures C-1 and C-3), namely many missing segments of cycle lane, missing polygons of pedestrian areas, hardly any pedestrian pavements or road crossing locations, inconsistent description of multi-lane roads, and of their characteristics for all modes. The individual mode's network topology is fragmented, affecting in particular the network analysis of local metrics of soft transport modes. In light of this, one can follow one of two routes: adopt a simplified representation, or correct and maintain a detailed representation of the street network. The current model does not pursue completely either approach.

In the simplified representation, all road segments must be part of the cyclist and pedestrian networks as long as this mode of travel is permitted. The MMUN model in this study takes this approach. But in this case one should also generalise the street network, collapsing the geometry of multiple car lanes and cycle lanes running parallel to roads, as well as simplifying complex junctions and roundabouts. At the same time the simplified segments would receive attributes describing the characteristics of the infrastructure for each mode in the given segment. The urban form and accessibility indicators calculated in this study would then give more reliable results. For example, the crossings typology and number of crossings is incorrect in roads represented by multiple lanes (see Appendix C, Figure C-2) even if roads inaccessible to pedestrians are not considered. And the shortest route algorithms might select one of several parallel lanes giving a higher hierarchy value to one of them in detriment of all others, instead of a similar value to all lanes, affecting aggregate statistics of network configuration. However, the generalisation process requires sophisticated and non-trivial algorithms, extensive manual verification, and for the best result it depends on the availability of attributes describing the original street network, which unfortunately are not consistently present in the OSM data set.

The alternative approach is to have a detailed street network representation, and the MMUN model keeps the original street network segments. However, to obtain reliable results one should correct mistakes, add the missing features and attributes listed above, and complement the data set with additional information, e.g. turn restrictions and travel directions for the car network, and pedestrian connections across public open spaces. Even if some automatic procedures have been developed (Section 4.3.3 shows an algorithm to connect pedestrian paths across public squares), it is difficult to ensure the consistency of the results for an entire region or country. This task requires the concerted effort of a group of individuals, probably in an organised OSM mapping event. If relevant for a given purpose, one could focus on correcting specific neighbourhoods or urban areas of interest, as this improves local metrics and is not expected to have a great impact on the results of the regional model.

One element that could be included in the MMUN model is the location of car parking spaces and parking restrictions. The car parking locations, number of spaces and types of parking are seen as useful indicators for the estimation or evaluation of sustainable mobility patterns of urban areas, as they directly influence the choice of car travel. The OSM data includes most of the larger exterior parking lots, but it does not give any indication of the smaller residential parking lots, roadside car parking spaces or car park silos (above or under ground), nor the numbers of residential parking spaces in buildings. Depending on the street network modelling approach taken, one would either use an additional data source on parking numbers and types, or conduct a local survey and contribute this detailed information to the OSM data set.

When it comes to the representation of the public transport network, the MMUN model adopts a simplified approach, aggregating equivalent public transport stops and stations on a location and representing single routes between stops rather than multiple services. To achieve this simplification the network was digitised from scratch (rail, metro and tram) or extracted from timetable data and generalised (bus). However, the metric and temporal impedances on the network links are only approximations based on the length of the simplified straight links, which is acceptable when using topological impedance or doing strategic analysis. But in order to use temporal cost, one should extract the physical impedances from the timetable data to reflect the actual travel distance and duration.

When using timetable data as the source to generate the public transport network model, instead of OSM data, one could also consider the representation of different services along the network, as the travel time and the number of stops varies greatly between local and regional or even high-speed services. This differentiation is important for accurate multimodal route calculations when the focus of the analysis is on route planning or route choice modelling. With timetable data, one also has the possibility of building a detailed model representing every stop, station platform and service in the public transport network. If in addition on includes the location of station entrances (above or underground), the resulting representation will allow a more accurate measurement of transfer between modes and onto the street network, as opposed to the abstract links used in the present version of the model. However, this will also increase the complexity of the model, with more types of nodes and links, and require more sophisticated multimodal analysis algorithms. And, as with every other data set, there will be mistakes and inconsistencies in timetable data that one will also have to systematically address, instead of working on simplification and generalisation.

Ultimately, the approach taken for the representation of the street network and the public transport network should be consistent and have an equivalent level of abstraction, so that similar analysis algorithms and equivalent theoretical concepts can be applied. The choice of modelling approach must be adequate for the purpose of the study and the type of urban form indicator being calculated. While aggregate structural measurements can use simplified representations, disaggregate individual behaviour or local scale measurements require detailed representations of the multimodal network. In any case, it is important to run systematic sensitivity tests for different network representations to assess to what extent they affect the specific network analysis results. In these tests one would have to build alternative models, e.g. using different levels of aggregation, and different model boundary conditions (size and shape), make pilot runs of the analyses, and finally select one type of representation or calibrate it if possible. This is a time consuming task and was only carried out to assess the impact of creating pedestrian area links in the street network (Section 4.6.1), thus the model representation does require further testing for the alternatives suggested above.

§ 8.4.2 Alternative approaches to network analysis

The construction of the model and its analysis are interdependent, and when the analysis algorithms and their parameters are also being developed and selected, sensitivity testing becomes extremely complex. To obviate this complexity, the model developed supports different types of impedance along network links and turns, in the transfer between public transport nodes and the street network, and between the buildings and the street network. Some tests were carried out to select the most appropriate type of impedance on network links for configuration indicators (Section 5.5). However, more tests would be required on all analysis parameters and on alternative analysis algorithms to calibrate the urban form and accessibility indicators. Even if in the end to conclude that changes produce little effect on the results, or the effect is identical in all urban areas and therefore the comparative results remain unchanged. The following list suggests alternative approaches to the analysis of the network model:

- include a temporal impedance value for turns of car and cycling modes, as this is likely to further improve the analysis results in relation to simple metric distance;
- improve the shortest route calculation with topological and geometric distance, ignoring short street segments that do not represent significant urban elements but result from (excessive) digitisation rigour of the road centre line representation;
- constrain the shortest topological and cognitive route search using a metric or temporal cut-off limit, with some tolerance;
- develop alternative algorithms for determining the street crossings typology, possibly based on a simplified graph representation of complex street and road junctions;
- improve the multimodal shortest route calculation, to give realistic travel behaviour patterns in terms of mode changes and mode sequences, namely only using buildings at both ends of the journey,, and not using pedestrian paths en route when on car or transit journeys;
- use the actual distance to building entrances along a street segment, calculated using linear referencing, instead of locating all buildings at the segment's centroid or nearest end node;
- test alternative distance decay functions in regional accessibility indicators, for different modes and different types of distance;
- introduce cut-off distance in network configuration indicators, equivalent to the one of regional accessibility indicators;
- expand the set of network centrality and configuration metrics used, beyond closeness and betweenness;
- calculate network configuration using buildings as origin and destination nodes;
- constrain the analysis parameters based on the size and shape of the buffer around the study area (the analysis boundary);
- explore aggregation methods for network configuration results of an area, beyond simple mean and maximum.

The above alternative approaches can be considered for improving the analysis results of specific urban form indicators, and their introduction in the model should involve a systematic comparison taking into consideration data requirements, computing performance, and output improvements. It is expected that some of these changes to the analysis make the multimodal model more robust to problems of network representation, such as lack of generalisation or missing data. They can provide "soft" solutions without the need for building separate models or for modifying the original data sources' geometry.

§ 8.5 Future research

In the course of this study, questions have arisen suggesting alternative and further research paths that could not be carried out in the timeframe of the PhD. Seven of these topics are mentioned next, as pointers to future research and application of the work.

National and trans-national typologies

This study has developed a context-sensitive evaluation method based on regional typologies, using the Randstad region as case study. However, this could be extended to the whole Netherlands. To extract relevant spatial and socio-economic typologies, one might want to consider the largest possible territory that is cohesive and consistent in terms of governance, planning policy, culture, and data availability, which might be a country's political borders or include neighbouring countries. Technical practicalities aside, the effort will result in a general typology that is comprehensive and contains a complete set of best practice cases that are relevant across the entire territory. These results can then be used to inform national planning policy for sustainable mobility.

Network edge effect

The edge effect in network analysis is a topic that deserves further research (Okabe and Sugihara, 2012, pp.41-42), especially when dealing with metrics of network structure and configuration. Network models are in most cases partial models, representing a subset of a larger network, and therefore have an artificial boundary. The current approach to obtain reliable analysis results is to create a large enough buffer around the study area and to constraint the analysis distance. However, the increase in model size is extremely costly for certain algorithms, e.g. betweenness centrality, and the distance constraint cannot be the same for all types of impedance (e.g. metric, temporal, angular, or topological) required in the multimodal analysis of the network. It would be important to assess how different boundary shapes and sizes affect different network analysis metrics, i.e. measure the size and spatial distribution of the error, and possibly identify different strategies to minimise this error.

Disaggregate typologies

The typologies identified in this study are tied to the definition of postcode areas, however this is an administrative level of aggregation that has little to do with the characteristics of the built environment, of the population, or of the travel patterns being studied. The MMUN model presented in this thesis supports the disaggregate measurement of neighbourhood characteristics at the level of the individual building, i.e. each building has a specific neighbourhood surrounding it that is different from the neighbourhoods of other buildings in the same postcode area. This enables the definition of disaggregate neighbourhood typologies of urban form and accessibility characteristics. These typologies provide a more detailed description of the built environment and a more accurate measurement of its relation with empirical data sets, provided these data sets are also available at a higher level of detail. In addition, the disaggregate typologies can lead to the definition of new neighbourhood limits composed of clusters of identical or similar neighbourhood types, or lead to the description of the region by the contours of the field of neighbourhood types.

Origin and destination pairs

Regarding the subject of sustainable mobility, it is known that travel patterns depend on the built environment characteristics at the origin of the journey as well as on those at the destination. Rather than focusing on the sustainable mobility potential of urban areas, one could instead look at the sustainable mobility potential of urban area pairs, i.e. of the origin's neighbourhood type and destination's neighbourhood type. This approach is more aligned with the complexity of the problem stated in Chapter 1 because the sustainable mobility performance of urban areas is interdependent, i.e. it is not determined by the area's characteristics alone, but also by those of the surrounding neighbourhoods. This approach would also allow the extension of the study to all journeys happening in and out of an urban area, not only of its residents.

This line of research would investigate if certain sustainable mobility patterns are dominant between specific urban type pairs, and identify collections of urban types that together contribute to a more sustainable functioning of the region. The planning strategy would then be to promote a select variety of urban area types that accommodate the different needs and preferences of individuals, families and businesses, rather than to focus on a single development model.

Longitudinal research

In order to support strategic planning and evaluation, it would be important to carry out a longitudinal study of the typological description of the city-region. Some urban form and socio-economic types observed in the present cross-sectional study might be strongly related and represent stages of a changing process, instead of different kinds of urban area. As urban development proceeds, the resident population ages, and households restructure, will some urban area types transform into others? Are associations between urban form and socio economic types consistent over time? Do these changes result in new urban types?

Comparative studies of local policies and regulations

The sustainable mobility performance evaluation exemplified in Chapter 7 results in the identification of urban areas that are doing well in some aspects, and others that are underperforming. This information could be used to select sets of urban areas with identical potential and baseline conditions but divergent mobility outcomes, to form the basis of comparative studies. One can then carry out indepth analysis of each urban area, looking at factors not contemplated in the baseline conditions (spatial and socio-economic characteristics) that might be exceptional in boosting or hindering sustainable mobility practice. In particular, studying local policies and regulations directly related to mobility, such as parking restrictions, location and cost, traffic calming measures or public transport frequency and cost.

Planning support systems

The findings from research on the built environment and sustainable mobility should be incorporated in user-friendly evaluation and planning support systems, accessible to practitioners. In this case, such a system would require functionality to streamline the process of building the multimodal network model, and interactive tools to run the spatial analysis and evaluation, producing both quantitative and graphic outputs. In addition, it would require the ability to localise the model to other regional realities, in terms of the indicators calculated and the analysis parameters. Such an interactive and flexible system is, however, more likely to thrive if developed as a community effort with a transparent and open source base. The availability of open source GIS solutions and the increasing availability of open and volunteered geographic data sets make this a real possibility. And the source code produced in this study, available in the Github repository (Appendix M), is a small contribution to the future development of such a system.

Glossary

accessibility	In planning, it is a measure of the capacity of a location to reach, or be reached by, a set of destinations within a given time frame or distance.
affordance	A concept introduced by Gibson (1979) that represents an action supported by the environment, available to an individual.
AADT	Annual Average Daily Traffic, unit for summarising traffic flow on a network link.
betweenness centrality	A centrality measure in network analysis, giving the number of shortest paths passing through a node from the paths between all pairs of nodes.
buurt	Neighbourhood unit, lowest level administrative area in the Netherlands.
closeness centrality	A centrality measure in network analysis, giving them mean shortest distance of a node to all other nodes in the graph.
cognitive distance	see geometric distance.
data mining	Exploratory statistical methods and analytic algorithms to identify patterns and relationships in multivariate data.
descriptive model	A theoretical model that is used to profile and quantify the actual characteristics and performance of a location.
descriptive statistics	Statistical analysis of a data set to quantitatively describe and summarise its basic features, e.g. mean, maximum, range, or standard deviation.
euclidean distance	Straight-line distance, on a plane, between two points, also known as "as crow flies" distance.
gemeente	Municipality, administrative area in the Netherlands.
geometric distance	A graph distance that takes into account the geometry of street segments, and sets the link weight as the angle between segments.
Gini coefficient	or Gini index, is a measure of statistical dispersion commonly used to represent inequality in the distribution of a variable.
GIS	Geographic Information System.
graph	Mathematical representation of a set of objects (nodes) where some pairs are connected by links (edges).

index of impedance	The weight or cost assigned to the links of a graph used to calculate the distance of traversing the graph.
Inter Quartile Range (IQR)	Value of the range between the 1st and 3rd quartiles of a variable.
k-means clustering	Unsupervised classification method that partitions the data into k clusters minimising the within cluster difference, assigning observations to the cluster with the nearest mean.
k-medoids clustering	Clustering method derived from k-means, where the centre of the cluster is one of the data points, the exemplar. This method is more robust to noise and outliers.
land use	Classification of the activities that take place in buildings, in this study it is not the same as land cover.
metric distance	Distance between nodes in a graph, where the unit of measurement is the physical length of the links.
mobility	Ability or capacity to move and travel.
mobility infrastructure	Infrastructure that supports mobility, by different modes.
mobility performance	Actual (observed or recorded) travel of persons, in terms of mode, purpose, distance, duration, etc.
mobility potential	Possible or expected travel pattern of persons, derived from environmental and socio-economic conditions.
modality	Ability to travel by different modes: walk-ability, cycle-ability, transit-ability or car-ability.
multimodal network	Graph representing the integrated networks of multiple transport modes.
network analysis	Measurement of properties of the nodes and links of a graph representation of a network.
normative model	A theoretical model setting precise standards, principles and guidelines for planning and urban design.
PAM	Partition Around Medoids (PAM) is a clustering method also known as k-medoids.
point density	or location density, is a measure of density calculated from a point location for a given distance, instead of calculated for a predefined and fixed polygonal boundary.
predictive model	A theoretical model that is used to simulate and quantify the future performance of a location, for example in terms of mobility.
Randstad	Region of the Netherlands that comprises the provinces of Noord Holland, Zuid Holland, Utrecht and Flevoland, including its four largest cities: Amsterdam, Rotterdam, Utrecht and The Hague.
space syntax	An architectural and urban theory and method that analyses the relational properties of graphs representing the spatial topological connections between spaces.
SUD	Sustainable urban development.
temporal distance	Distance between nodes in a graph, where the unit of measurement is the time of traversing the links.
TOD	Transit-oriented development.
topological distance	The distance between nodes of an unweighted graph, where each link represents one step.
topology	The structure of a geometric or network construct defined by the relations between its elements.

travel behaviour	The choices and actions of an individual in relation to travel.
travel patterns	The aggregate travel outcomes of a population.
urban form indicator	Indicator based on the built environment characteristics of urban areas.
VGI	Volunteered Geographic Information, geographic data set created on a voluntary basis by its contributors, such as OpenStreetMap.
VINEX	Common name of the Fourth memorandum on spatial planning of the Netherlands, a policy document that identified locations in proximity of urban centres for the development of new large residential districts. Became a name associated with those districts: VINEX wijk.
wijk	District, higher-level administrative area in the Netherlands, aggregating a collection of neighbourhoods (see buurt).

References

Van Acker, V., Van Wee, B., and Witlox, F., 2010. When Transport Geography Meets Social Psychology: Toward a Conceptual Model of Travel Behaviour. Transport Reviews, 30 (2), 219–240.

Alexander, D., Lannon, S., and Linovski, O., 2009. The identification and analysis of regional building stock characteristics using map based data. In: Building Simulation 2009. Presented at the Eleventh International IBPSA Conference, Glasgow, Scotland, 1421–1428.

Alexander, E.R., 1997. A mile or a millimeter? Measuring the 'planning theory – practice gap'. Environment and Planning B: Planning and Design, 24 (1), 3–6.

Alexander, E.R., 2000. Rationality Revisited: Planning Paradigms in a Post-Postmodernist Perspective. Journal of Planning Education and Research, 19 (3), 242–256.

Alexander, E.R., 2006. Problems and Prospects: Dilemmas in Evaluation and Directions for the Future. In: Evaluation in Planning: Evolution and Prospects. Ashgate Publishing, Ltd., 267–276.

Alexander, E.R. and Faludi, A., 1989. Planning and plan implementation: notes on evaluation criteria. Environment and Planning B: Planning and Design, 16 (2), 127 – 140.

Ambiente Italia Research Institute, 2003. European Common Indicators: Towards a Local Sustainability Profile. Milano, Italy: European Commission.

Anderson, P., Levinson, D.M., and Parthasarathi, P., 2011. Accessibility Futures. University of Minnesota: Nexus Research Group, Working Paper No. 000088.

Archibugi, F., 2006. Pitfalls in Planning and Plan-evaluation. In: Evaluation in Planning: Evolution and Prospects. Ashgate Publishing, Ltd., 73–83.

Ascher, F., 2003. Multi-mobility, multispeed cities: a challenge for architects, town planners and politicians.

Ayed, H., Galvez-Fernandez, C., Habbas, Z., and Khadraoui, D., 2011. Solving time-dependent multimodal transport problems using a transfer graph model. Computers & Industrial Engineering, 61 (2), 391–401.

Bagley, M.N. and Mokhtarian, P.L., 1999. The Role Of Lifestyle and Attitudinal Characteristics in Residential Neighborhood Choice. Presented at the 14th International Symposium on Transportation and Traffic Theory, 735–758.

Bagley, M.N. and Mokhtarian, P.L., 2002. The impact of residential neighborhood type on travel behavior: A structural equations modeling approach. The Annals of Regional Science, 36 (2), 279–297.

Bagley, M.N., Mokhtarian, P.L., and Kitamura, R., 2002. A Methodology for the Disaggregate, Multidimensional Measurement of Residential Neighbourhood Type. Urban Studies, 39 (4), 689–704.

Ballester, M.G., Pérez, M.R., and Stuiver, J., 2011. Automatic pedestrian network generation. Presented at the Proceedings 14th AGILE International Conference on GIS, 1–13.

Banister, D., 2005. Unsustainable Transport: City transport in the new century. 1st ed. Routledge.

Banister, D., 2008. The sustainable mobility paradigm. Transport Policy, 15 (2), 73–80.

Banister, D. and Marshall, S., 2000. Encouraging Transport Alternatives: good practice in reducing travel. Stationery Office Books.

Banister, D., Watson, S., and Wood, C., 1997. Sustainable cities: transport, energy, and urban form. Environment and Planning B: Planning and Design, 24 (1), 125 – 143.

Barthelemy, M., 2011. Spatial networks. Physics Reports, 499 (1–3), 1–101.

Barton, H., Grant, M., and Guise, R., 2003. Shaping neighbourhoods: a guide for health, sustainability and vitality. London, UK: Spon Press.

Barton, H., Rice, L., Grant, M., Horswell, M., and Breeze, M., 2009. SOLUTIONS - London Local Case Study - Final Report. Bristol. UK: University of the West of England, Final Report.

Batty, M., 2009. Accessibility: in search of a unified theory. Environment and Planning B: Planning and Design, 36 (2), 191–194.

Batty, M. and Rana, S., 2004. The automatic definition and generation of axial lines and axial maps. Environment and Planning B: Planning and Design, 31 (4), 615 – 640.

Becker, J., 2004. Making sustainable development evaluations work. Sustainable Development, 12 (4), 200–211.

Behnisch, M. and Ultsch, A., 2009. Urban data-mining: spatiotemporal exploration of multidimensional data. Building Research & Information, 37 (5), 520–532.

Beirão, G. and Sarsfield Cabral, J.A., 2007. Understanding attitudes towards public transport and private car: A qualitative study. Transport Policy, 14 (6), 478–489.

Beirão, J.N. and Duarte, J.P., 2007. Urban Design with Patterns and Shape Rules: Devising a Methodology to Create Solutions. In: Model Town: Using Urban Simulation in New Town Planning. Amsterdam, The Netherlands: Uitgeverij SUN, 148–165.
Beirão, J.N., Duarte, J.P., and Stouffs, R., 2011. Creating Specific Grammars with Generic Grammars: Towards Flexible Urban Design. Nexus Network Journal, 13 (1), 73–111.
Bentivegna, V., Curwell, S., Deakin, M., Lombardi, P., Mitchell, G., and Nijkamp, P., 2002. A vision and methodology for integrated sustainable urban development: BEQUEST. Building Research and Information, 30 (2), 83–94.
Van den Berg, A.E., Vlek, C.A.J., and Coeterier, J.F., 1998. Group Differences in the Aesthetic Evaluation of Nature Development Plans: a Multilevel Approach. Journal of Environmental Psychology, 18 (2), 141–157.
Berghauser-Pont, M. and Haupt, P., 2004. Spacemate: the spatial logic of urban density. Delft, The Netherlands: Delft University Press Science.
Berghauser-Pont, M. and Haupt, P., 2010. Space Matrix: Space, Density and Urban Form. Netherlands: NAi Publishers.
Bertolini, L., 1999. Spatial Development Patterns and Public Transport: The Application of an Analytical Model in the Netherlands. Planning Practice and Research, 14 (2), 199–210.
Bertolini, L. and le Clercq, F., 2003. Urban development without more mobility by car? Lessons from Amsterdam, a multimodal urban region. Environment and Planning A, 35 (4), 575 – 589.
Bertolini, L., Clercq, F. le, and Kapoen, L., 2005. Sustainable accessibility: a conceptual framework to integrate transport and land use plan-making. Two test-applications in the Netherlands and a reflection on the way forward. Transport Policy, 12 (3), 207–220.
Bertolini, L. and Dijst, M., 2003. Mobility Environments and Network Cities. Journal of Urban Design, 8, 27–43.
Betsky, A., 2006. Islands in Suburbia: Ypenburg as a Model for Sprawl. a+u, (06), 89–97.
Bielli, M., Boulmakoul, A., and Mouncif, H., 2006. Object modeling and path computation for multimodal travel systems. European Journal of Operational Research, 175 (3), 1705–1730.
BioRegional, 2009. BedZED seven years on - The impact of the UK's best known eco-village and its residents. Wallington, UK: BioRegional, Post occupancy evaluation.
Black, W.R., 2010. Sustainable transportation: problems and solutions. New York, USA: Guilford Press.
Blum, A. and Grant, M., 2004. Sustainable Neighbourhoods: Assessment tools for renovation and development. HQE2R, No. DEL16.
Brandes, U., 2001. A faster algorithm for betweenness centrality. Journal of Mathematical Sociology, 25, 163–177.
Brandon, P. and Lombardi, P., 2010. Evaluating Sustainable Development in the Built Environment. John Wiley and Sons.
Briassoulis, H., 2001. Sustainable Development and its Indicators: Through a (Planner's) Glass Darkly. Journal of Environmental Planning and Management, 44 (3), 409–427.
Bruun, E., Schiller, P.L.L., and Litman, T., 2012. An Introduction to Sustainable Transportation: 'Policy, Planning and Implementation'. Earthscan.
BSV Büro für Stadt- und Verkehrsplanung, 2005. Qualitätsziele und Indikatoren für eine nachhaltige Mobilität - Anwenderleitfaden. Dessau: Umweltbundesamt Dessau.
Buijs, S., 1992. Urbanisation alternatives in the fourth report on physical planning. Journal of Housing and the Built Environment, 7 (2), 209–211.
Bulkeley, H. and Betsill, M., 2005. Rethinking Sustainable Cities: Multilevel Governance and the 'Urban' Politics of Climate Change. Environmental Politics, 14 (1), 42–63.
Butler, J.A.. and Dueker, K.J., 2001. Implementing the enterprise GIS in transportation database design. Journal of the Urban and Regional Information Systems Association, 13 (1), 17–28.
Calthorpe, P., 1993. The next American metropolis: ecology, community, and the American dream. New York: Princeton Architectural Press.
Calthorpe, P., 2002. The Urban Network: A new framework for growth.
Calthorpe, P. and Fulton, W., 2001. The Regional City. Island Press.
Camagni, R., Gibelli, M.C., and Rigamonti, P., 2002. Urban mobility and urban form: the social and environmental costs of different patterns of urban expansion. Ecological Economics, 40 (2), 199–216.
Cao, X., Handy, S., and Mokhtarian, P., 2006. The Influences of the Built Environment and Residential Self-Selection on Pedestrian Behavior: Evidence from Austin, TX. Transportation, 33 (1), 1–20.
Cao, X., Mokhtarian, P.L., and Handy, S.L., 2009. Examining the Impacts of Residential Self-Selection on Travel Behaviour: A Focus on Empirical Findings. Transport Reviews: A Transnational Transdisciplinary Journal, 29 (3), 359–395.

Carmona, M., 2003. An international perspective on measuring quality in planning. Built Environment, 29 (4), 281–287.
Carmona, M. and Sieh, L., 2008. Performance measurement in planning—towards a holistic view. Environment and Planning C: Government and Policy, 26 (2), 428–454.
Centre for Sustainable Transportation, 2002. Definition And Vision Of Sustainable Transportation. Toronto, Canada: The Centre for Sustainable Transportation, Mission statement.
Cervero, R., 1998. The Transit Metropolis: A Global Inquiry. Island Press.
Cervero, R. and Duncan, M., 2003. Walking, Bicycling, and Urban Landscapes: Evidence From the San Francisco Bay Area. Am J Public Health, 93 (9), 1478–1483.
Cervero, R. and Gorham, R., 1995. Commuting in Transit Versus Automobile Neighborhoods. Journal of the American Planning Association, 61 (2), 210–225.
Cervero, R. and Kockelman, K., 1997. Travel demand and the 3Ds: Density, diversity, and design. Transportation Research Part D: Transport and Environment, 2 (3), 199–219.
Cervero, R., Murphy, S., Ferrell, C., Goguts, N., Tsai, Y.-H., Arrington, G.B., Boroski, J., Smith-Heimer, J., Golem, R., Peninger, P., Nakajima, E., Chui, E., Dunphy, R., Myers, M., and McKay, S., 2004. Transit-oriented Development in the United States: Experiences, Challenges, And Prospects. Transportation Research Board, TRCP No. 102.
Cervero, R. and Radisch, C., 1996. Travel choices in pedestrian versus automobile oriented neighborhoods. Transport Policy, 3 (3), 127–141.
Cervero, R. and Wu, K.-L., 1997. Polycentrism, commuting, and residential location in the San Francisco Bay area. Environment and Planning A, 29 (5), 865 – 886.
Cheng, J., Bertolini, L., and le Clercq, F., 2007. Measuring Sustainable Accessibility. Transportation Research Record: Journal of the Transportation Research Board, 2017, 16–25.
Cheng, J., Bertolini, L., Clercq, F. le, and Kapoen, L., 2013. Understanding urban networks: Comparing a node-, a density- and an accessibility-based view. Cities, 31, 165–176.
Chen, S., Tan, J., Claramunt, C., and Ray, C., 2011. Multi-scale and multi-modal GIS-T data model. Journal of Transport Geography, 19 (1), 147–161.
Chiaradia, A., 2007. Emergent Route Choice Behaviour, Motorway and Trunk Road Network: the Nantes conurbation. In: A.S. Kubat, ed. Proceedings of the 6th International Space Syntax Symposium. Presented at the 6th International Space Syntax Symposium, Istanbul, Turkey: Istanbul Technical University.
Chiaradia, A., Hillier, B., Schwander, C., and Wedderburn, M., 2012. Compositional and urban form effects on centres in Greater London. Proceedings of the ICE - Urban Design and Planning, 165 (1), 21–42.
Chiaradia, A., Moreau, E., and Raford, N., 2005. Configurational Exploration of Public Transport Movement Networks: A Case Study, The London Underground. In: A. van Nes, ed. Proceedings of the 5th International Space Syntax Symposium. Presented at the 5th International Space Syntax Symposium, Delft, The Netherlands: TU Delft, 541–552.
Chiaradia, A., Schwander, C., Gil, J., Friedrich, E., and Gosset, A., 2008. Mapping the intangible value of urban layout (i-VALUL): Developing a tool kit for the socio-economic valuation of urban areas, for designers and decision makers. In: H. Timmermans and B. DeVries, eds. 9th International Conference on Design & Decision Support Systems in Architecture and Urban Planning. Presented at the DDSS 2008, Eindhoven, The Netherlands: Eindhoven University of Technology.
Chiaradia, A., Webster, C., and Cooper, C., 2012. sDNA - A software for spatial design network analysis. Cardiff, UK: Cardiff University.
Chin, G.K.W., Van Niel, K.P., Giles-Corti, B., and Knuiman, M., 2008. Accessibility and connectivity in physical activity studies: The impact of missing pedestrian data. Preventive Medicine, 46 (1), 41–45.
Le Clercq, F. and Bertolini, L., 2003. Achieving Sustainable Accessibility: An Evaluation of Policy Measures in the Amsterdam Area. Built Environment, 29 (1), 36–47.
Van de Coevering, P. and Schwanen, T., 2006. Re-evaluating the impact of urban form on travel patternsin Europe and North-America. Transport Policy, 13 (3), 229–239.
Colantonio, A., 2008. Measuring Social Sustainability: Best Practice from Urban Renewal in the EU. European Investment Bank, Working Paper No. 2008/02.
Cole, R.J., 1999. Building environmental assessment methods: clarifying intentions. Building Research & Information, 27 (4-5), 230–246.
Cole, R.J., 2005. Building environmental assessment methods: redefining intentions and roles. Building Research & Information, 33 (5), 455–467.
Collison, P., 1954. Town Planning and the Neighbourhood Unit Concept. Public Administration, 32 (4), 463–469.

Commission of the European Communities, 1990. Green Paper on the Urban Environment. Luxembourg: Office for Official Publications of the European Communities.
Communities and Local Government, 2001. Planning Policy Guidance 13: Transport. UK: Communities and Local Government, Legislation and policy, Good practice and guidance No. 13.
Conzen, M.P., 2010. The elusive common denominator in understanding urban form. Urban Morphology, 14 (1), 55–58.
Cooper, I., 1999. Which focus for building assessment methods – environmental performance or sustainability? Building Research & Information, 27 (4-5), 321–331.
Cormier, A. and Gilbert, R., 2005. Defining Sustainable Transportation. Toronto, Canada: The Centre for Sustainable Transportation, No. T8013-4-0203.
Costa, M. da S., 2008. Um índice de mobilidade urbana sustentável. PhD. Universidade de Sao Paulo, Sao Carlos, Brazil.
Crane, R., 2000. The Influence of Urban Form on Travel: An Interpretive Review. Journal of Planning Literature, 15 (1), 3–23.
Criterion Planners, 2011. INDEX PlanBuilder User Notebook. USA: Criterion Planners.
Crucitti, P., Latora, V., and Porta, S., 2006a. Centrality in networks of urban streets. Chaos: An Interdisciplinary Journal of Nonlinear Science, 16 (015113), 1–9.
Crucitti, P., Latora, V., and Porta, S., 2006b. Centrality measures in spatial networks of urban streets. Physical Review E, 73 (3), 036125:1–036125:5.
Csardi, G. and Nepusz, T., 2006. The igraph Software Package for Complex Network Research. InterJournal, Complex Systems, 1695.
Curtis, C., 1996. Can strategic planning contribute to a reduction in car-based travel? Transport Policy, 3 (1–2), 55–65.
Curtis, C., 2008. Planning for sustainable accessibility: The implementation challenge. Transport Policy, 15 (2), 104–112.
Curtis, C., 2011. Integrating Land Use with Public Transport: The Use of a Discursive Accessibility Tool to Inform Metropolitan Spatial Planning in Perth. Transport Reviews, 31 (2), 179–197.
Curtis, C., Renne, J.L., and Bertolini, L., 2009. Transit Oriented Development: Making it Happen. Surrey, UK: Ashgate Publishing, Ltd.
Curtis, C. and Scheurer, J., 2010. Planning for sustainable accessibility: Developing tools to aid discussion and decision-making. Progress in Planning, 74 (2), 53–106.
Curtis, C., Scheurer, J., and Burke, M., 2013. Using New Accessibility Tools to Guide Policy Innovation. Built Environment, 39 (4), 454–472.
Curwell, S. and Cooper, I., 1998. The implications of urban sustainability. Building Research & Information, 26 (1), 17–28.
Cutsinger, J. and Galster, G., 2006. There is No Sprawl Syndrome: A New Typology of Metropolitan Land Use Patterns. Urban Geography, 27 (3), 228–252.
Dalton, N., 2001. Fractional configurational analysis and a solution to the Manhattan problem. In: J. Peponis, J. Wineman, and S. Bafna, eds. Proceedings of the 3rd International Space Syntax Symposium. Presented at the 3rd International Space Syntax Symposium, Atlanta, Georgia, USA: Georgia Institute of Technology, 26.1–26.13.
Dalton, N., Peponis, J., and Conroy Dalton, R., 2003. To tame a TIGER one has to know its nature: extending weighted angular integration analysis to the description of GIS road-centerline data for large scale urban analysis. In: J. Hanson, ed. Proceedings of the 4th International Space Syntax Symposium. Presented at the 4th International Space Syntax Symposium, London, UK, 65.1–65.10.
Deakin, M., Huovila, P., Rao, S., Sunikka, M., and Vreeker, R., 2002. The assessment of sustainable urban development. Building Research & Information, 30 (2), 95–108.
Defra, 2009. Sustainable development indicators in your pocket - 2009 Edition. London, UK: Defra Publications, No. PB13265.
Dempsey, N., Brown, C., Raman, S., Porta, S., Jenks, M., Jones, C., and Bramley, G., 2010. Elements of Urban Form. In: Dimensions of the sustainable city. Springer Netherlands, 21–51.
Department for Communities and Local Government (DCLG), 2005. Planning Policy Statement 1: Delivering Sustainable Development. UK: Communities and Local Government, Legislation and policy.
Department for Communities and Local Government (DCLG), 2009. Planning Policy Statement: eco-towns - A supplement to Planning Policy Statement 1. London, UK: Communities and Local Government, Legislation and policy No. 09SCG06036/pps.
Department for Transport, 2009. Low Carbon Transport: A Greener Future. Other.

Dieleman, F.M., Dijst, M.J., and Spit, T., 1999. Planning the compact city: The randstad Holland experience. European Planning Studies, 7 (5), 605–621.
Dijst, M., 1997. Spatial policy and passenger transportation. Journal of Housing and the Built Environment, 12 (1), 91–111.
Dijst, M.J., Jayet, H., and Thomas, I., 2002. Transportation and Urban Performance: Accessibility, Daily Mobility and Location of Households and Facilities. In: Governing cities on the move : functional and management perspectives on transformations of European urban infrastructures. Ashgate, 19–41.
Ding, G.K.C., 2008. Sustainable construction—The role of environmental assessment tools. Journal of Environmental Management, 86 (3), 451–464.
Dittmar, H. and Ohland, G., 2003. The New Transit Town: Best Practices In Transit-Oriented Development. Island Press.
Duarte, J.P., Beirão, J.N., Montenegro, N., and Gil, J., 2012. City Induction: A Model for Formulating, Generating, and Evaluating Urban Designs. In: S.M. Arisona, G. Aschwanden, J. Halatsch, and P. Wonka, eds. Digital Urban Modeling and Simulation. Springer Berlin Heidelberg, 73–98.
Ducruet, C., Ietri, D., and Rozenblat, C., 2011. Cities in Worldwide Air and Sea Flows: A multiple networks analysis. Cybergeo : European Journal of Geography, 2011 (528).
Dupuy, G., 2008. Urban Networks - Network Urbanism. Amsterdam, The Netherlands: Techne Press.
Van Eck, J.R. and Snellen, D., 2006. Is the Randstad a city network? Evidence from commuting patterns. In: European Transport Conference 2006. Presented at the European Transport Conference, Strasbourg, France: Association for European Transport, 14.
Erath, A., Löchl, M., and Axhausen, K.W., 2009. Graph-Theoretical Analysis of the Swiss Road and Railway Networks Over Time. Networks and Spatial Economics, 9 (3), 379–400.
Estima, J. and Painho, M., 2013. Exploratory Analysis of OpenStreetMap for Land Use Classification. In: Proceedings of the Second ACM SIGSPATIAL International Workshop on Crowdsourced and Volunteered Geographic Information. New York, NY, USA: ACM, 39–46.
European Commission, 1998. Sustainable urban development in the European Union: A framework for action. European Commission, Communication.
European Commission, 2001. White paper – 'European transport policy for 2010: time to decide'. Luxembourg: Office for Official Publications of the European Communities, White Paper No. COM(2001)370.
European Commission, 2007. Green Paper - Towards a new culture for urban mobility. Brussels, Belgium: European Commission, Legislation and policy No. SEC(2007) 1209.
European Commission, 2011. White Paper - Roadmap to a Single European Transport Area – Towards a competitive and resource efficient transport system. Brussels, Belgium: European Commission, White Paper No. COM(2011) 144 final.
European Council, 2007. Leipzig Charter.
European Council, 2010. Strategy For Integrating Environment And Sustainable Development Into The Transport Policy.
European Environment Agency, 2011. Laying the foundations for greener transport — TERM 2011: transport indicators tracking progress towards environmental targets in Europe. Copenhagen, Denmark: European Environment Agency, EEA Report No. 7/2011.
Ewing, R., 1995. BEYOND DENSITY, MODE CHOICE, AND SINGLE-PURPOSE TRIPS. Transportation Quarterly, 49 (4), 15–24.
Ewing, R. and Cervero, R., 2001. Travel and the Built Environment: A Synthesis. Transportation Research Record: Journal of the Transportation Research Board, 1780, 87–114.
Ewing, R. and Cervero, R., 2010. Travel and the Built Environment: A Meta-Analysis. Journal of the American Planning Association, 76 (3), 265–294.
Ewing, R., Pendall, R., and Chen, D., 2002. Measuring sprawl and its impact. Washington, D.C., USA: Smart Growth America.
Falk, N., 2007. Learning from Dutch New Towns and Suburbs. London, UK: URBED.
Figueiredo, L., 2009. Continuity Lines - An investigation of urban form through street networks. PhD. University College London, London, UK.
Figueiredo, L. and Amorim, L., 2005. Continuity lines in the axial system. In: Proceedings of the 5th International Space Syntax Symposium. Presented at the Space Syntax Symposium, Delft, The Netherlands: TU Delft.
Figueiredo, L. and Amorim, L., 2007. Decoding the urban grid: or why cities are neither trees nor perfect grids. In: Proceedings of the 6th International Space Syntax Symposium. Presented at the International Space Syntax Symposium, Istanbul, Turkey: Istanbul Technical University.
Foletta, N. and Field, S., 2011. Europe's Vibrant New Low Car(bon) Communities.

Fonseca, F.T., Egenhofer, M.J., Davis, C.A., and Borges, K.A.V., 2000. Ontologies and knowledge sharing in urban GIS. Computers, Environment and Urban Systems, 24 (3), 251–272.

Frank, L. and Pivo, G., 1994. Impacts of mixed use and density on utilization of three modes of travel: single-occupant vehicle, transit, and walking. Transportation research record, (1466), 44–52.

Freeman, L.C., 1978. Centrality in social networks conceptual clarification. Social Networks, 1 (3), 215–239.

Frey, H., 1999. Designing the City: Towards a More Sustainable Urban Form. 1st ed. Oxon, UK: Spon Press.

Frey, H.W., Ferguson, N.S., Bagaeen, S.G., and Woods, L., 2006. Suburbs Reconsidered: Form, Mobility and Sustainability. Built Environment, 32 (3), 250–266.

Friedrich, M., 1998. A Multi-modal Transport Model for Integrated Planning. Presented at the 8th World Conference on Transport Research, Antwerpen, Belgium: World Conference on Transport Research Society, 1–14.

Galle, M., Modderman, E., Galle, M., and Modderman, E., 1997. Vinex: National Spatial Planning Policy in the Netherlands during the nineties. Journal of Housing and the Built Environment, 12 (1), 9–35.

Galvez-Fernandez, C., Khadraoui, D., Ayed, H., Habbas, Z., and Alba, E., 2009. Distributed Approach for Solving Time-Dependent Problems in Multimodal Transport Networks. Advances in Operations Research, 2009, e512613.

Garrison, W.L., 1960. Connectivity of the Interstate Highway System. Papers in Regional Science, 6 (1), 121–137.

Garrison, W.L. and Marble, D.F., 1962. The Structure Of Transportation Networks.

Gasparatos, A., El-Haram, M., and Horner, M., 2009. The argument against a reductionist approach for measuring sustainable development performance and the need for methodological pluralism. Accounting Forum, 33 (3), 245–256.

Geertman, S.C.M. and Ritsema Van Eck, J.R., 1995. GIS and models of accessibility potential: an application in planning. International journal of geographical information systems, 9 (1), 67–80.

George, C., 2001. Sustainability appraisal for sustainable development: integrating everything from jobs to climate change. Impact Assessment and Project Appraisal, 19 (2), 95–106.

Geurs, K.T. and van Wee, B., 2004. Accessibility evaluation of land-use and transport strategies: review and research directions. Journal of Transport Geography, 12 (2), 127–140.

Geurs, K.T. and van Wee, B., 2006. Ex-post evaluation of thirty years of compact urban development in the Netherlands. Urban Studies, 43 (1), 139–160.

Gibson, J.J., 1979. The theory of affordances. In: The Ecological Approach To Visual Perception. Hillsdale, USA: Lawrence Erlbaum Associates, 127–143.

Gibson, R.B., 2001. Specification of sustainability-based environmental assessment decision criteria and implications for determining' significance' in environmental assessment. University of British Columbia.

Gilbert, R., Irwin, N., Hollingworth, B., and Blais, P., 2002. Sustainable Transportation Performance Indicators (STPI). In: TRB 2003 Annual Meeting CD-ROM. Presented at the TRB 2003, Transportation Research Board.

Gilbert, R. and Tanguay, H., 2000. Sustainable Transportation Performance Indicators. Brief review of some relevant worldwide activity and development of an initial long list of indicators. Toronto, Canada: The Centre for Sustainable Transportation, Final Report No. Phase 1.

Gil, J., 2012. Integrating public transport networks in the axial model. In: Proceedings: 8th International Space Syntax Symposium. Presented at the 8th International Space Syntax Symposium, Santiago, Chile: Pontificia Universidad Catolica de Chile, 8103:1–8103:21.

Gil, J., 2014. Analyzing the Configuration of Multimodal Urban Networks. Geographical Analysis, 46, 368–391.

Gil, J., 2015. Building a Multimodal Urban Network Model Using OpenStreetMap Data for the Analysis of Sustainable Accessibility. In: J. Jokar Arsanjani, A. Zipf, P. Mooney, and M. Helbich, eds. OpenStreetMap in GIScience: Experiences, Research, Applications. Berlin, Heidelberg: Springer, 229–251.

Gil, J., Almeida, J., and Duarte, J.P., 2011. The backbone of a City Information Model (CIM): Implementing a spatial data model for urban design. In: Respecting fragile places - 29th eCAADe Conference Proceedings. Presented at the 29th eCAADe Conference, Ljubljana, Slovenia: University of Ljubljana, Faculty of Architecture, 143–151.

Gil, J., Beirão, J.N., Montenegro, N.C., and Duarte, J.P., 2010. Assessing computational tools for urban design: Towards a 'City Information Model'. In: Future Cities. Presented at the 28th eCAADe Conference, Zurich, Switzerland: ETH Zurich, 361–369.

Gil, J., Beirão, J.N., Montenegro, N., and Duarte, J.P., 2012. On the discovery of urban typologies: data mining the many dimensions of urban form. Urban Morphology, 16 (1), 27–40.

Gil, J. and Duarte, J.P., 2008. Towards an Urban Design Evaluation Framework. In: Architecture in Computro. Presented at the 26th eCAADe Conference, Antwerpen, Belgium, 257–264.

Gil, J. and Duarte, J.P., 2013. Tools for evaluating the sustainability of urban design: a review. Proceedings of the ICE - Urban Design and Planning, 166 (6), 311–325.
Gil, J. and Read, S., 2012. Measuring sustainable accessibility potential using the mobility infrastructure's network configuration. In: Proceedings: 8th International Space Syntax Symposium. Presented at the 8th International Space Syntax Symposium, Santiago, Chile: Pontificia Universidad Catolica de Chile, 8104:1–8104:19.
Gil, J. and Read, S., 2014. Patterns of sustainable mobility and the structure of modality in the Randstad city-region. A|Z ITU Journal of the Faculty of Architecture, 11 (2), 231–254.
Girres, J.-F. and Touya, G., 2010. Quality Assessment of the French OpenStreetMap Dataset. Transactions in GIS, 14 (4), 435–459.
Goedman, Houtsma, and Zonneveld, W., 2008. Dutch Spatial Planning: From implicit towards explicit sustainable urban development. In: 44th ISOCARP Congress. Presented at the 44th ISOCARP.
Goodchild, M.F., 2000. GIS and Transportation: Status and Challenges. GeoInformatica, 4 (2), 127–139.
Goodchild, M.F. and Li, L., 2012. Assuring the quality of volunteered geographic information. Spatial Statistics, 1, 110–120.
Gordon, P., Kumar, A., and Richardson, H.W., 1989. The influence of metropolitan spatial structure on commuting time. Journal of Urban Economics, 26 (2), 138–151.
Grant, J., 2001. The dark side of the grid: power and urban design. Planning Perspectives, 16 (3), 219–241.
Graser, A., Straub, M., and Dragaschnig, M., 2014. Towards an Open Source Analysis Toolbox for Street Network Comparison: Indicators, Tools and Results of a Comparison of OSM and the Official Austrian Reference Graph. Transactions in GIS, 18 (4), 510–526.
Griffith, D.A., 2011. Geography, Graph Theory, and the New Network Science. Geographical Analysis, 43 (4), 345–346.
Habraken, J., 1988. Type as a social agreement. Presented at the Asian Congress of Architects, Seoul.
Hacking, T. and Guthrie, P., 2008. A framework for clarifying the meaning of Triple Bottom-Line, Integrated, and Sustainability Assessment. Environmental Impact Assessment Review, 28 (2–3), 73–89.
Hadas, Y., 2013. Assessing public transport systems connectivity based on Google Transit data. Journal of Transport Geography, 33, 105–116.
Haggag, M.A. and Ayad, H.M., 2002. The urban structural units method: a basis for evaluating environmental prospects for sustainable development. Urban Design International, 7 (2), 97–108.
Haggett, P. and Chorley, R.J., 1969. Network Analysis in Geography. Hodder & Stoughton Educ.
Haklay, M., 2010. How good is volunteered geographical information? A comparative study of OpenStreetMap and Ordnance Survey datasets. Environment and Planning B: Planning and Design, 37 (4), 682 – 703.
Haklay, M. and Weber, P., 2008. OpenStreetMap: User-Generated Street Maps. IEEE Pervasive Computing, 7 (4), 12–18.
Halden, D., 2002. Using accessibility measures to integrate land use and transport policy in Edinburgh and the Lothians. Transport Policy, 9 (4), 313–324.
Hall, A.C., 2008. Bridging the Gap: applying urban morphology to successful planning practice. Urban Morphology, 12 (1), 54–57.
Hall, P. and Pain, K., 2006. The Polycentric Metropolis: Learning from Mega-city Regions in Europe. First. Earthscan Ltd.
Handy, S.L., 1992. Regional versus local accessibility: neo-traditional development and its implications for non-work travel. Built Environment, 18 (4), 253–267.
Handy, S.L., 1993. Regional versus Local Accessibility: Implications for Nonwork Travel. Transportation Research Record: Journal of the Transportation Research Board, 1400, 58–66.
Handy, S.L., 1996. Understanding the Link Between Urban Form and Nonwork Travel Behavior. Journal of Planning Education and Research, 15 (3), 183–198.
Handy, S.L., 2005. Smart Growth and the Transportation-Land Use Connection: What Does the Research Tell Us? International Regional Science Review, 28 (2), 146–167.
Handy, S.L., Cao, X., and Mokhtarian, P., 2005. Correlation or causality between the built environment and travel behavior? Evidence from Northern California. Transportation Research Part D: Transport and Environment, 10 (6), 427–444.
Handy, S.L., Cao, X., and Mokhtarian, P.L., 2006. Self-Selection in the Relationship between the Built Environment and Walking: Empirical Evidence from Northern California. Journal of the American Planning Association, 72 (1), 55–74.
Handy, S.L. and Clifton, K.J., 2001. Evaluating neighborhood accessibility: Possibilities and practicalities. Journal of Transportation and Statistics, 4 (2/3), 67–78.

Handy, S.L. and Niemeier, D.A., 1997. Measuring accessibility: an exploration of issues and alternatives. Environment and Planning A, 29 (7), 1175 – 1194.
Hanna, S., 2007. Automated Representation of Style by Feature Space Archetypes: Distinguishing Spatial Styles from Generative Rules. International Journal of Architectural Computing, 5 (1), 2–23.
Hansen, W.G., 1959. How Accessibility Shapes Land Use. Journal of the American Institute of Planners, 25 (2), 73–76.
Hanson, M.E., 1986. Modeling For Forecasting Versus Modeling for Understanding: Observations from Energy Planning. Journal of Planning Education and Research, 6 (1), 50 –59.
Healey, P., 2006. Place development in a relational world. Town and Country Planning, 75 (11), 318–321.
Hilbers, B., 2008. The influence of the spatial planning on bicycle use and health: Comparison between Houten and Leidsche Rijn. Bilthoven, The Netherlands: Planbureau voor de Leefomgeving.
Hilbers, H.D., Wilmink, I.R., and Droppert-zilver, M.N., 1999. Evaluatie mobiliteitseffecten vinex-locaties: eindrapport. Delft, The Netherlands: TNO, Final Report No. TNO 99/NV/182 InroVervoer/1999-19.
Hilbers, H. and Snellen, D., 2005. Evaluation of the mobility impacts of the Dutch Vinex policy. In: 45th Congress of the European Regional Science Association. Presented at the 45th Congress of the European Regional Science Association, Amsterdam, The Netherlands: European Regional Science Association.
Hillier, B., 2007. Space is the machine: a configurational theory of architecture. 2nd ed. London, UK: Space Syntax.
Hillier, B. and Hanson, J., 1984. The Social Logic of Space. Cambridge, UK: Cambridge University Press.
Hillier, B. and Iida, S., 2005. Network and Psychological Effects in Urban Movement. In: A.G. Cohn and D.M. Mark, eds. Spatial Information Theory. Berlin, Heidelberg: Springer, 475–490.
Hillier, B., Penn, A., Hanson, J., Grajewski, T., and Xu, J., 1993. Natural movement: or, configuration and attraction in urban pedestrian movement. Environment and Planning B: Planning and Design, 20, 29–66.
Hillier, B., Turner, A., Yang, T., and Tae-Park, H., 2010. Metric And Topo-Geometric Properties Of Urban Street Networks: Some convergences, divergences and new results. Journal of Space Syntax, 1 (2), 258–279.
Hunt, D., Lombardi, D., Rogers, C., and Jefferson, I., 2008. Application of sustainability indicators in decision-making processes for urban regeneration projects. Engineering Sustainability, 161 (1), 77–91.
Independent Commission on Transport, 1974. Changing Directions: the Report of the Independent Commission on Transport. Coronet.
Ingram, D.R., 1971. The concept of accessibility: A search for an operational form. Regional Studies, 5 (2), 101–107.
Institute for Transportation and Development Policy, 2014. TOD Standard.
Ismail, M.A. and Said, M.N., 2014. Integration of geospatial multi-mode transportation Systems in Kuala Lumpur. IOP Conference Series: Earth and Environmental Science, 20 (1), 012–027.
Jacobson, J. and Forsyth, A., 2008. Seven American TODs: Good Practices for Urban Design in Transit-Oriented Development Projects. Journal of Transport and Land Use, 1 (2), 51–88.
Jacques, C. and El-Geneidy, A., 2014. Does travel behavior matter in defining urban form? A quantitative analysis characterizing distinct areas within a region. Journal of Transport and Land Use, 7 (1), 1–14.
Jiang, B., 2009. Street hierarchies: a minority of streets account for a majority of traffic flow. International Journal of Geographical Information Science, 23 (8), 1033–1048.
Jiang, B., 2011. A Short Note on Data-Intensive Geospatial Computing. In: V.V. Popovich, C. Claramunt, T. Devogele, M. Schrenk, K. Korolenko, W. Cartwright, G. Gartner, L. Meng, and M.P. Peterson, eds. Information Fusion and Geographic Information Systems. Springer Berlin Heidelberg, 13–17.
Jiang, B., 2013. Volunteered Geographic Information and Computational Geography: New Perspectives. In: D. Sui, S. Elwood, and M. Goodchild, eds. Crowdsourcing Geographic Knowledge. Springer Netherlands, 125–138.
Jiang, B. and Claramunt, C., 2004. Topological analysis of urban street networks. Environment and Planning B: Planning and Design, 31 (1), 151–162.
Jiang, B. and Liu, C., 2009. Street-based topological representations and analyses for predicting traffic flow in GIS. International Journal of Geographical Information Science, 23 (9), 1119–1137.
Jiang, B. and Liu, X., 2010. Automatic generation of the axial lines of urban environments to capture what we perceive. International Journal of Geographical Information Science, 24 (4), 545–558.
Jiang, B. and Liu, X., 2011. Computing the fewest-turn map directions based on the connectivity of natural roads. International Journal of Geographical Information Science, 25 (7), 1069–1082.
Jokar Arsanjani, J., Barron, C., Bakillah, M., and Helbich, M., 2013. Assessing the Quality of OpenStreetMap Contributors together with their Contributions. Presented at the 16th AGILE International Conference on Geographic Information Science, Leuven.

Jokar Arsanjani, J., Helbich, M., Bakillah, M., Hagenauer, J., and Zipf, A., 2013. Toward mapping land-use patterns from volunteered geographic information. International Journal of Geographical Information Science, 27 (12), 2264–2278.

Jokar Arsanjani, J. and Vaz, E., 2015. An assessment of a collaborative mapping approach for exploring land use patterns for several European metropolises. International Journal of Applied Earth Observation and Geoinformation, (35), 329–337.

Jones, C., Jenks, M., and Bramley, G., 2008. Complementarities and Contradictions. In: Sustainable City Form. Springer Netherlands, 239–256.

Jones, P. and Patterson, J., 2007. The Development of a Practical Evaluation Tool for Urban Sustainability. Indoor and Built Environment, 16 (3), 255–272.

Ben-Joseph, E., 2004. Future of Standards and Rules in Shaping Place: Beyond the Urban Genetic Code. Journal of Urban Planning and Development, 130 (2), 67–75.

Kamruzzaman, M., Baker, D., Washington, S., and Turrell, G., 2014. Advance transit oriented development typology: case study in Brisbane, Australia. Journal of Transport Geography, 34, 54–70.

Kansky, K.J., 1963. Structure of transportation networks : relationships between network geometry and regional characteristics.

Kapelan, Z., Savic, D.A., and Walters, G.A., 2005. Decision-support tools for sustainable urban development. Engineering Sustainability, (ES3), 135–142.

Karimi, H.A. and Kasemsuppakorn, P., 2012. Pedestrian network map generation approaches and recommendation. International Journal of Geographical Information Science, 27 (5), 947–962.

Karol, E. and Brunner, J., 2009. Tools for Measuring Progress towards Sustainable Neighborhood Environments. Sustainability, 1, 612–627.

Kasperczyk, N. and Knickel, K., 2006. Sustainability A-Test. Amsterdam, The Netherlands: VU University Amsterdam, Final Report No. D15.

Kelbaugh, D., 1989. The pedestrian pocket book: A new suburban design strategy. Princeton Architectural Press.

Kelbaugh, D., 1996. Typology - An Architecture of Limits. Architectural Theory Review, 1 (2), 33–52.

Kenworthy, J.R., 2006. The eco-city: ten key transport and planning dimensions for sustainable city development. Environment and Urbanization, 18 (1), 67–85.

Kenworthy, J.R., 2008. Energy Use and CO_2 Production in the Urban Passenger Transport Systems of 84 International Cities: Findings and Policy Implications. In: P. Droege, ed. Urban Energy Transition. Amsterdam: Elsevier, 211–236.

Kenworthy, J.R. and Laube, F.B., 1996. Automobile dependence in cities: An international comparison of urban transport and land use patterns with implications for sustainability. Environmental Impact Assessment Review, 16 (4-6), 279–308.

Kenworthy, J.R. and Laube, F.B., 1999. Patterns of automobile dependence in cities: an international overview of key physical and economic dimensions with some implications for urban policy. Transportation Research Part A: Policy and Practice, 33 (7-8), 691–723.

Kerry, J.F., Cardin, B.L., and Durbin, R., 2010. Sustainable Urban Development Act of 2010.

Khakee, A., 2003. The Emerging Gap Between Evaluation Research and Practice. Evaluation, 9 (3), 340–352.

Kim, J., yong Park, S., Bang, Y., and Yu, K., 2009. Automatic derivation of a pedestrian network based on existing spatial data sets. Presented at the ASPRS /MAPPS 2009 Fall Conference, San Antonio, Texas.

Knowles, R.D., 2012. Transit Oriented Development in Copenhagen, Denmark: from the Finger Plan to Ørestad. Journal of Transport Geography, 22, 251–261.

Kolars, J. and Malin, H.J., 1970. Population and Accessibility: An Analysis of Turkish Railroads. Geographical Review, 60 (2), 229–246.

Kroeze, P., 2008. Planological differences between Vinex neighbourhoods Veldhuizen and Houten. Den Haag, The Netherlands: Ministerie van Verkeer en Waterstaat.

Kurant, M. and Thiran, P., 2006. Layered Complex Networks. Physical Review Letters, 96 (13), 138701:1–138701:4.

Lara, J.J., 2009. Sustainable Phoenix: Lessons from the Dutch Model. In: Visualizing Sustainable Planning. Springer Berlin Heidelberg, 231–243.

Laskari, A., Hanna, S., and Derix, C., 2008. Urban identity through quantifiable spatial attributes: coherence and dispersion of local identity through the automated comparative analysis of building block plans. In: Proceedings of the Third International Conference on Design Computing and Cognition. Presented at the Design Computing and Cognition '08, Dordrecht, The Netherlands: Springer Netherlands, 615–634.

Laurian, L., Crawford, J., Day, M., Kouwenhoven, P., Mason, G., Ericksen, N., and Beattie, L., 2010. Evaluating the outcomes of plans: theory, practice, and methodology. Environment and Planning B: Planning and Design, 37 (4), 740 – 757.

Law, S., Chiaradia, A., and Schwander, C., 2012. Towards a multi-modal space syntax analysis. A case study of the London street and underground network. In: Proceedings: 8th International Space Syntax Symposium. Presented at the 8th International Space Syntax Symposium, Santiago, Chile: Pontificia Universidad Catolica de Chile, 8021:1–8021:20.

Lee, C.C. and Jacoby, S., 2011. Typological Urbanism and the Idea of the City. Architectural Design, 81 (1), 14–23.

Lee, C. and Moudon, A.V., 2006. The 3Ds+ R: Quantifying land use and urban form correlates of walking. Transportation Research Part D: Transport and Environment, 11 (3), 204–215.

Lee, C., Moudon, A.V., and Courbois, J.-Y.P., 2006. Built Environment and Behavior: Spatial Sampling Using Parcel Data. Annals of Epidemiology, 16 (5), 387–394.

Leitmann, J., 1999. Can city QOL indicators be objective and relevant? Towards a participatory tool for sustaining urban development. Local Environment, 4 (2), 169–180.

Litman, T., 2007. Developing Indicators for Comprehensive and Sustainable Transport Planning. Transportation Research Record: Journal of the Transportation Research Board, 2017 (-1), 10–15.

Litman, T., 2008. Sustainable Transportation Indicators: A Recommended Research Program for Developing Sustainable Transportation Indicators and Data. In: TRB 2009 Annual Meeting. Presented at the Transportation Research Board 88th Annual Meeting, Transportation Research Board.

Litman, T. and Burwell, D., 2006. Issues in sustainable transportation. International Journal of Global Environmental Issues, 6 (4), 331–347.

Liu, L., 2011. Data model and algorithms for multimodal route planning with transportation networks. PhD. TECHNISCHE UNIVERSITÄT MÜNCHEN, Munich, Germany.

Liu, X. and Jiang, B., 2012. Defining and Generating Axial Lines from Street Center Lines for better Understanding of Urban Morphologies. International Journal of Geographical Information Science, 26 (8), 1521–1532.

Li, Z.-C., Huang, H.-J., Lam, W.H.K., and Wong, S.C., 2007. A Model for Evaluation of Transport Policies in Multimodal Networks with Road and Parking Capacity Constraints. Journal of Mathematical Modelling and Algorithms, 6 (2), 239–257.

Lo, C., 2007. The application of geospatial technology to urban morphological research. Urban Morphology, 11 (2), 81–90.

Lörzing, H., 2006. Reinventing Suburbia in The Netherlands. Built Environment, 32 (3), 298–310.

Lozano, A. and Storchi, G., 2001. Shortest viable path algorithm in multimodal networks. Transportation Research Part A: Policy and Practice, 35 (3), 225–241.

Maller, A., 1998. Emerging urban form types in a city of the American Middle West. Journal of Urban Design, 3 (2), 137–150.

Marcus, L., 2005. Plot Syntax - a configurational approach to urban diversity. In: Proceedings of the 5th International Space Syntax Symposium. Presented at the Space Syntax Symposium, Delft, the Netherlands: TU Delft.

Marshall, A., 2003. A Tale of Two Towns Tells a Lot about this Thing called New Urbanism. Built Environment, 29 (3), 227–237.

Marshall, S., 2005. Streets and Patterns. Oxon, UK: Spon Press.

Marshall, S., 2006. Un réseau viaire favorable aux transports collectifs. Flux, 4 (66-67), 96–110.

Marshall, S. and Gong, Y., 2009. SOLUTIONS - WP4 Deliverable Report: Urban Pattern Specification. London, UK: Bartlett School of Planning, UCL, Final Report.

Marshall, W.E. and Garrick, N.W., 2010. Effect of Street Network Design on Walking and Biking. Transportation Research Record: Journal of the Transportation Research Board, 2198 (-1), 103–115.

Marshall, W.E. and Garrick, N.W., 2012. Community design and how much we drive. Journal of Transport and Land Use, 5 (2), 5–21.

Massey, D., 1991. A global sense of place. Marxism today, 35 (6), 24–29.

Mastop, H. and Faludi, A., 1997. Evaluation of strategic plans: the performance principle. Environment and Planning B: Planning and Design, 24 (6), 815–832.

Mavoa, S., Witten, K., McCreanor, T., and O'Sullivan, D., 2012. GIS based destination accessibility via public transit and walking in Auckland, New Zealand. Journal of Transport Geography, 20 (1), 15–22.

May, A.D., Page, M., and Hull, A., 2008. Developing a set of decision-support tools for sustainable urban transport in the UK. Transport Policy, 15 (6), 328–340.

Meadows, D.H., Meadows, D.L., Randers, J., and Behrens, W., 1972. The Limits to growth. A report for the Club of Rome's project on the predicament for mankind. New York, USA: Universe Books.

Mensink, J. and Boeijenga, J., 2008. Vinex Atlas. 010 Uitgeverij.

Miller, H.J. and Shaw, S.-L., 2001. Geographic information systems for transportation: principles and applications. Oxford, UK: Oxford University Press.

Ministerie van Volkshuisvesting, Ruimtelijke Ordening en Milieubeheer (VROM), 2001. Making space, sharing space. Fifth National Policy Document on Spatial Planning 2000/2020 - Summary. The Hague, The Netherlands: Ministry of Housing, Spatial Planning and the Environment Communications Directorate, Policy Statement No. vrom 00.0698/h/06-01 15564/179.

Ministerie van Volkshuisvesting, Ruimtelijke Ordening en Milieubeheer (VROM), 2008. Randstad 2040 - Summary of the structural vision. The Hague, The Netherlands: VROM.

Ministerie van Volkshuisvesting Ruimtelijke Ordening en Milieubeheer (VROM), 2008. Gezonde plannen. Netherlands: Rijksoverheid, rapport.

Ministerio de Medio Ambiente, y Medio Rural y Marino (MMAMRM) and Agencia de Ecologia Urbana de Barcelona (BCN), 2010. Sistema de indicadores y condicionantes para ciudades grandes y medianas. Madrid, Spain: Ministerio de Medio Ambiente.

Mitchell, G., 1996. Problems and Fundamentals of Sustainable Development Indicators. Sustainable Development, 4 (1), 1–11.

Mooney, P., Corcoran, P., and Winstanley, A.C., 2010. Towards Quality Metrics for OpenStreetMap. In: Proceedings of the 18th SIGSPATIAL International Conference on Advances in Geographic Information Systems. New York, NY, USA: ACM, 514–517.

Moudon, A., 1997. Urban morphology as an emerging interdisciplinary field. Urban Morphology, 1 (1), 3–10.

Moudon, A.V., 1994. Getting to know the built landscape: typomorphology. In: A. Franck, ed. Ordering space: types in architecture and design. New York, USA: Van Nostrand Reinhold, 289–314.

Mouncif, H., Boulmakoul, A., and Chala, M., 2006. Integrating GIS-Technology for Modelling Origin-Destination Trip in Multimodal Transportation Networks. The International Arab Journal of Information Technology, 3 (3), 256–264.

Muller, J.-C., 1982. Non-Euclidean Geographic Spaces: Mapping Functional Distances. Geographical Analysis, 14 (3), 189–203.

Munda, G., 2006. Social multi-criteria evaluation for urban sustainability policies. Land Use Policy, 23 (1), 86–94.

Nasri, A. and Zhang, L., 2014. The analysis of transit-oriented development (TOD) in Washington, D.C. and Baltimore metropolitan areas. Transport Policy, 32, 172–179.

Neis, P. and Zielstra, D., 2014. Generation of a tailored routing network for disabled people based on collaboratively collected geodata. Applied Geography, 47, 70–77.

Neis, P., Zielstra, D., and Zipf, A., 2011. The Street Network Evolution of Crowdsourced Maps: OpenStreetMap in Germany 2007–2011. Future Internet, 4 (1), 1–21.

Van Nes, R., 2002. Design of multimodal transport networks. PhD. Civil Engineering, Delft Technical University, Delft, The Netherlands.

Newman, M., 2010. Networks: An Introduction. OUP Oxford.

Newman, P., 2009. Planning for Transient Oriented Development: Strategic Principles. In: C. Curtis, J.L. Renne, and L. Bertolini, eds. Transit Oriented Development: Making it Happen. USA: Ashgate Publishing, Ltd., 13–22.

Newman, P. and Kenworthy, J.R., 1999. Sustainability and cities: Overcoming Automobile Dependence. Island Press.

Newman, P. and Kenworthy, J.R., 2000. The ten myths of automobile dependence. World Transport Policy & Practice, 6 (1), 15–25.

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

NL Milieu en Leefomgeving, 2010. Informatie voor duurzaam inkopen van Stedenbouwkundig Ontwerp. Netherlands: Ministerie van VROM, Policy Statement.

Okabe, A. and Sugihara, K., 2012. Spatial Analysis Along Networks: Statistical and Computational Methods. John Wiley & Sons.

Olaru, D., Smith, B., and Taplin, J.H.E., 2011. Residential location and transit-oriented development in a new rail corridor. Transportation Research Part A: Policy and Practice, 45 (3), 219–237.

Oliveira, V. and Pinho, P., 2010. Evaluation in Urban Planning: Advances and Prospects. Journal of Planning Literature, 24 (4), 343–361.

Oppenheim, N., 1975. A typological approach to individual urban travel behavior prediction. Environment and Planning A, 7 (2), 141–152.
Osmond, P., 2010. The urban structural unit: towards a descriptive framework to support urban analysis and planning. Urban Morphology, 14 (1), 5–20.
Ozbil, A., Peponis, J., and Stone, B., 2011. Understanding the link between street connectivity, land use and pedestrian flows. Urban Design International, 16 (2), 125–141.
Parish, Y.I.H. and Müller, P., 2001. Procedural modeling of cities. In: Proceedings of the 28th annual conference on Computer graphics and interactive techniques. New York, NY, USA: ACM Press, 301–308.
Parliament of the State of Victoria, 2010. Transport Integration Act 2010.
Penn, A., Hillier, B., Banister, D., and Xu, J., 1998. Configurational modelling of urban movement networks. Environment and Planning B: Planning and Design, 25, 59–84.
Peponis, J., Allen, D., Haynie, D., Scoppa, M., and Zhang, Z., 2007. Measuring the configuration of street networks. In: Proceedings of the 6th International Space Syntax Symposium. Presented at the Space Syntax Symposium, Istanbul, Turkey: Istanbul Technical University, 002–1–002–16.
Peponis, J., Bafna, S., and Zhang, Z., 2008. The connectivity of streets: reach and directional distance. Environment and Planning B: Planning and Design, 35 (5), 881 – 901.
Pereira, R.H.M., Holanda, F.R.B. de, Medeiros, V.A.S. de, and Barros, A.P.B.G., 2012. The use of Space Syntax in urban transport analysis: limits and potentials. In: Proceedings: 8th International Space Syntax Symposium. Presented at the International Space Syntax Symposium, Santiago, Chile: Pontificia Universidad Catolica de Chile, 8214.1–8214.25.
Pflieger, G. and Rozenblat, C., 2010. Urban Networks and Network Theory: The City as the Connector of Multiple Networks. Urban Studies, 47 (13), 2723–2735.
Pojani, D. and Stead, D., 2014. Dutch planning policy: The resurgence of TOD. Land Use Policy, 41, 357–367.
Pojani, D. and Stead, D., 2015. Transit-Oriented Design in the Netherlands. Journal of Planning Education and Research, 35 (2), 131–144.
Pope, J., Annandale, D., and Morrison-Saunders, A., 2004. Conceptualising sustainability assessment. Environmental Impact Assessment Review, 24 (6), 595–616.
Porta, S., Crucitti, P., and Latora, V., 2006a. The Network Analysis of Urban Streets: A Dual Approach. Physica A: Statistical Mechanics and its Applications, 369 (2), 853–866.
Porta, S., Crucitti, P., and Latora, V., 2006b. The Network Analysis of Urban Streets: A Primal Approach. Environment and Planning B: Planning and Design, 33 (5), 705 – 725.
Porta, S. and Latora, V., 2007. Multiple centrality assessment: mapping centrality in networks of urban spaces. In: K. Thwaites, S. Porta, O. Romice, and M. Greaves, eds. Urban Sustainability Through Environmental Design: Approaches to Time-people-place Responsive Urban Spaces. Oxon, UK: Routledge, 101–108.
Priemus, H., 1995. Reduction of car use: instruments of national and local policies—a Dutch perspective. Environment and Planning B: Planning and Design, 22 (6), 721 – 737.
Priemus, H. and Spaans, M., 1992. Fourth report on physical planning extra (VINEX) and the randstad. Journal of Housing and the Built Environment, 7 (2), 133–134.
PRP, URBED, and Design for Homes, 2008. Beyond Eco-towns: Applying the Lessons from Europe. London, UK: PRP Architects Ltd, No. 978-0-9560622-0-8.
Rapoport, A., 1990. History and Precedent in Environmental Design. New York, USA: Plenum Press.
Read, S., 2009. Another Form: From the 'Informational' to the 'Infrastructural' City. Footprint Delft Architecture Theory Journal, (5), 5–22.
Read, S., 2013. Intensive urbanisation: Levels, networks and central places. The Journal of Space Syntax, 4 (1), 1–17.
Read, S. and Bruyns, G., 2007. The Form of a Metropolitan Territory: the case of Amsterdam and its periphery. In: Proceedings of the 6th International Space Syntax Symposium. Presented at the International Space Syntax Symposium, Istanbul, Turkey: Istanbul Technical University, 10.1–10.18.
Read, S., Bruyns, G., van den Hoogen, E., and Plomp, M., 2007. Constructing Metropolitan Landscapes of Actuality and Potentiality. In: Proceedings 6th International Space Syntax Symposium. Presented at the International Space Syntax Symposium, Istanbul, Turkey: Istanbul Technical University, 14.1–14.18.
Read, S. and Gil, J., 2012. Amsterdam and its region as a layering of socio-technical systems. In: 8th International Space Syntax Symposium. Presented at the International Space Syntax Symposium, Santiago, Chile: Pontificia Universidad Catolica de Chile, 8119:1–8119:16.
Read, S. and Sulis, P., 2010. Infrastructure as world-building. In: Infrastructure as Architecture. JOVIS Verlag, 124–135.

Reconnecting America, 2007. Transit-Oriented Development And Why Now?. Washington D.C., USA: Center for Transit-Oriented Development, Best Practice Guidance No. TOD 101.
Reconnecting America, 2011. Planning for TOD at the Regional Scale: the Big Picture. Washington D.C., USA: Center for Transit-Oriented Development, Best Practice Guidance No. TOD 204.
Redman, L., Friman, M., Gärling, T., and Hartig, T., 2013. Quality attributes of public transport that attract car users: A research review. Transport Policy, 25, 119–127.
Reffat, R., 2008. Investigating Patterns of Contemporary Architecture using Data Mining Techniques. In: Proceedings of the 26th Conference on Education of Computer Aided Architectural Design in Europe. Presented at the eCAADe, Antwerpen, Belgium, 601–608.
Renne, J., 2009. Evaluating Transit-Oriented Development Using a Sustainability Framework: Lessons from Perth's Network City. In: Planning Sustainable Communities. Calgary, Canada: University of Calgary, 115–148.
Rossi, P.H., Lipsey, M.W., and Freeman, H.E., 2004. Evaluation: a systematic approach. Sage.
Rydin, Y., Holman, N., Hands, V., and Sommer, F., 2003. Incorporating sustainable development concerns into an urban regeneration project: how politics can defeat procedures. Journal of Environmental Planning and Management, 46 (4), 545–561.
Samuels, I., 1999. A typomorphological approach to design: The plan for St Gervais. Urban Design International, 4 (3), 129–141.
Samuels, I., 2008. Typomorphology and urban design practice. Urban Morphology, 12 (1), 58–62.
Samuels, I. and Pattacini, L., 1997. From description to prescription: Reflections on the use of a morphological approach in design guidance. Urban Design International, 2 (2), 81–91.
Scheider, S. and Kuhn, W., 2010. Affordance-based categorization of road network data using a grounded theory of channel networks. International Journal of Geographical Information Science, 24 (8), 1249–1267.
Scheurer, J. and Curtis, C., 2008. Spatial Network Analysis of Multimodal Transport Systems: Developing a Strategic Planning Tool to Assess the Congruence of Movement and Urban Structure. Perth, Australia: Curtin University of Technology, Monograph.
Scheurer, J., Curtis, C., and Porta, S., 2007. Spatial network analysis of public transport systems. Presented at the Australasian Transport Research Forum, Melbourne, Australia, 19.
Scheurer, J. and Porta, S., 2006. Centrality and connectivity in public transport networks and their significance for transport sustainability in cities. Presented at the World Planning Schools Congress, Mexico City, Mexico.
Schianetz, K., Kavanagh, L., and Lockington, D., 2007. Concepts and Tools for Comprehensive Sustainability Assessments for Tourism Destinations: A Comparative Review. Journal of Sustainable Tourism, 15 (4), 369–389.
Schreffler, E.N., 2000. State of the Practice: Mobility Management Monitoring and Evaluation in the United States. Aachen, Germany: Institut für Stadtbauwesen, No. Work Package 3, D3.
Schwander, C., 2007. Network Analysis Applied: the railway network in South East England. In: Proceedings of the 6th International Space Syntax Symposium. Presented at the 6th International Space Syntax Symposium, Istanbul, Turkey: Istanbul Technical University, 076:1–076:17.
Schwanen, T., Dieleman, F.M., and Dijst, M., 2004. The Impact of Metropolitan Structure on Commute Behavior in the Netherlands: A Multilevel Approach. Growth and Change, 35 (3), 304–333.
Schwanen, T., Dijst, M., and Dieleman, F.M., 2004. Policies for Urban Form and their Impact on Travel: The Netherlands Experience. Urban Studies, 41 (3), 579–603.
Schwanen, T. and Mokhtarian, P.L., 2005. What affects commute mode choice: Physical neighborhood structure or preferences toward neighborhoods? Journal of Transport Geography, 13 (1), 83–99.
Scioscia, F., Binetti, M., Ruta, M., Ieva, S., and Di Sciascio, E., 2014. A Framework and a Tool for Semantic Annotation of POIs in OpenStreetMap. Procedia - Social and Behavioral Sciences, 111, 1092–1101.
Sen, L., 1971. The Geometric Structure of an Optimal Transport Network in a Limited City—Hinterland Case. Geographical Analysis, 3 (1), 1–14.
Serra, M., Gil, J., and Pinho, P., 2014. Unsupervised classification of evolving metropolitan street patterns. In: New urban configurations. Presented at the EAAE/ISUF international conference, Delft, The Netherlands: IOS Press, 160–167.
Sester, M., Jokar Arsanjani, J., Klammer, R., Burghardt, D., and Haunert, J.-H., 2014. Integrating and Generalising Volunteered Geographic Information. In: D. Burghardt, C. Duchêne, and W. Mackaness, eds. Abstracting Geographic Information in a Data Rich World. Springer International Publishing, 119–155.
Sevtsuk, A., 2010. Path and Place: A Study of Urban Geometry and Retail Activity in Cambridge and Somerville, MA. PhD. Massachusetts Institute of Technology, Cambridge, Massachusetts, USA.
Shane, D.G., 2011. Transcending Type: Designing for Urban Complexity. Architectural Design, 81 (1), 128–134.

Silva, C. and Pinho, P., 2010. The Structural Accessibility Layer (SAL): revealing how urban structure constrains travel choice. Environment and Planning A, 42 (11), 2735 – 2752.
Silva, C., Reis, J.P., and Pinho, P., 2014. How urban structure constrains sustainable mobility choices: comparison of Copenhagen and Oporto. Environment and Planning B: Planning and Design, 41 (2), 211 – 228.
Smith, T.E., 1989. Shortest-Path Distances: An Axiomatic Approach. Geographical Analysis, 21 (1), 1–31.
Snellen, D., Borgers, A., and Timmermans, H., 2002. Urban form, road network type, and mode choice for frequently conducted activities: a multilevel analysis using quasi-experimental design data. Environment and Planning A, 34 (7), 1207 – 1220.
Snellen, D. and Hilbers, H., 2005. Evaluation of the mobility impacts of the Dutch Vinex policy. Association for European Transport.
Snellen, D. and Hilbers, H., 2007. Mobility and congestion impacts of Dutch VINEX policy. Tijdschrift voor economische en sociale geografie, 98 (3), 398–406.
Song, Y. and Knaap, G.-J., 2007. Quantitative Classification of Neighbourhoods: The Neighbourhoods of New Single-family Homes in the Portland Metropolitan Area. Journal of Urban Design, 12 (1), 1–24.
Southworth, M., 2005. Designing the Walkable City. Journal of Urban Planning and Development, 131 (4), 246–257.
Ståhle, A., Marcus, L., and Karlström, A., 2005. Place Syntax- Geographic Accessibility with Axial Lines in GIS. In: Proceedings of the 5th International Space Syntax Symposium. Presented at the 5th International Space Syntax Symposium, Delft, The Netherlands: TU Delft, 131–144.
Stead, D., 2001. Relationships between land use, socioeconomic factors, and travel patterns in Britain. Environment and Planning B: Planning and Design, 28 (4), 499 – 528.
Stead, D. and Marshall, S., 2001. The relationships between urban form and travel patterns. An international review and evaluation. European Journal of Transport and Infrastructure Research, 1 (2), 113–141.
Stead, D., Williams, J., and Titheridge, H., 2000. Land use, transport and people: identifying the connections. In: Achieving sustainable urban form. 174–186.
Steinemann, A., 2001. Improving alternatives for environmental impact assessment. Environmental Impact Assessment Review, 21 (1), 3–21.
Straatemeier, T., 2005. Potential accessibility: an interesting conceptual framework to address strategic planning issues in the Amsterdam region? Presented at the ERSA conference papers, Vienna, Austria: European Regional Science Association.
Straatemeier, T., 2008. How to plan for regional accessibility. Transport Policy, 15 (2), 127–137.
TCPA, 2009. TCPA study tour: The Netherlands.
Thomas, I., Frankhauser, P., Frenay, B., and Verleysen, M., 2010. Clustering patterns of urban built-up areas with curves of fractal scaling behaviour. Environment and Planning B: Planning and Design, 37 (5), 942 – 954.
Thomson, R.C., 2003. Bending the axial line: smoothly continuous road centre-line segments as a basis for road network analysis. In: J. Hanson, ed. Proceedings of the Fourth International Space Syntax Symposium. London, UK: University College London, 50.1–50.10.
Timmermans, H., 2007. Transit-oriented urban environments reduce travel – a fairytale?/! In: G.-J. Knaap, ed. Incentives, regulations and plans: the role of states and nation-states in smart growth planning. Edward Elgar Publishing, 168–189.
Trache, H., 2001. Promoting urban design in development plans: typo-morphological approaches in Montreuil, France. Urban Design International, 6 (3), 157–172.
Transport for London, 2010. Measuring Public Transport Accessibility Levels PTALs. London, UK: Transport for London, Technical Report.
Tukey, J.W., 1977. Exploratory Data Analysis. Reading, Massasuchets: Addison-Wesley Publishing.
Turner, A., 2001. Angular analysis. In: 3rd International Space Syntax Symposium. Presented at the International Space Syntax Symposium, Atlanta, GA: Georgia Institute of Technology, 30.1–30.11.
Turner, A., 2007. From axial to road-centre lines: a new representation for space syntax and a new model of route choice for transport network analysis. Environment and Planning B: Planning and Design, 34 (3), 539–555.
Turner, A., Penn, A., and Hillier, B., 2005. An algorithmic definition of the axial map. Environment and Planning B: Planning and Design, 32 (3), 425–444.
UK Government, 1999. A better quality of life - a strategy for sustainable development for the United Kingdom. London, UK: UK Government, White Paper.
United Nations, 1992. Agenda 21. Rio de Janeiro, Brazil: United Nations Division for Sustainable Development, Agenda.
Urban Task Force, 1999. Towards an Urban Renaissance. 1st ed. Routledge.

Urban Task Force, 2005. Towards a Strong Urban Renaissance [online]. Rogers Stirk Harbour + Partners. Available from: http://www.richardrogers.co.uk/theory/urban_task_force [Accessed 29 Jun 2009].
Urhahn, G. and Bobic, M., 1994. A pattern image: a typological tool for quality in urban planning. Rijksplanologische Dienst Netherlands. Bussum, The Netherlands: Thoth Publishers.
USGBC, 2009. LEED 2009 for Neighborhood Development Rating System.
Victoria Transport Policy Institute, 2014. Online TDM Encyclopedia [online]. Victoria Transport Policy Institute. Available from: http://www.vtpi.org/tdm/tdm12.htm [Accessed 22 Dec 2009].
De Vos, J., Van Acker, V., and Witlox, F., 2014. The influence of attitudes on Transit-Oriented Development: An explorative analysis. Transport Policy, 35, 326–329.
Waddell, P., 2002. Urbansim: Modeling Urban Development for Land Use, Transportation, and Environmental Planning. Journal of the American Planning Association, 68 (3), 297–314.
Wagner, R., 2008. On the metric, topological and functional structures of urban networks. Physica A: Statistical Mechanics and its Applications, 387 (8–9), 2120–2132.
Walton, J., El-Haram, M., Castillo, N., Horner, R., Price, A., and Hardcastle, C., 2005. Integrated assessment of urban sustainability. Engineering Sustainability, 158 (2), 57–65.
Wassenberg, F., 2006. The Netherlands: Adaptation of the Carefully Planned Structure. Built Environment, 32 (1), 12–31.
Van Wee, B., 2002. Land use and transport: research and policy challenges. Journal of Transport Geography, 10 (4), 259–271.
Van Wee, B. and Handy, S., 2016. Key Research Themes on Urban Space, Scale and Sustainable Urban Mobility. International Journal of Sustainable Transportation, 10 (1), 18–24.
Van Wee, B., Holwerda, H., and van Baren, R., 2002. Preferences for Modes, Residential Location and Travel Behaviour The Relevance of Land-Use Impacts on Mobility. European Journal of Transport and Infrastructure Research, 2 (3/4), 305–316.
Van Wee, B. and Maat, K., 2003. Land-use and transport: a review and discussion of Dutch research. European Journal of Transport and Infrastructure Research, 3 (2), 199–218.
Wegener, M., 1994. Operational Urban Models State of the Art. Journal of the American Planning Association, 60, 17–29.
Wegener, M., 2007. After the Oil Age: Do we have to rebuild our cities?.
Witten, I.H. and Frank, E., 2005. Data Mining: Practical Machine Learning Tools and Techniques, Second Edition. 2nd ed. San Francisco, CA, USA: Morgan Kaufmann Publishers Inc.
Wong, C., 2006. Indicators for Urban and Regional Planning. 1st ed. London, New York: Routledge.
World Business Council for Sustainable Development (WBCSD), 2001. Mobility 2001 - World mobility at the end of the twentieth century and its sustainability. Geneva, Switzerland: WBCSD, Publication.
World Commission on Environment and Development and Brundtland Commission, 1987. Our Common Future. UN, Communication No. A/42/427.
Xie, F. and Levinson, D., 2007. Measuring the Structure of Road Networks. Geographical Analysis, 39 (3), 336–356.
Yigitcanlar, T., Sipe, N., Evans, R., and Pitot, M., 2007. A GIS-based land use and public transport accessibility indexing model. Australian Planner, 44 (3), 30–37.

Biography

Jorge Gil, born in Lisbon, Portugal, 1972

e-mail:
- j.a.lopesgil@tudelft.nl
- jorge.gil@ucl.ac.uk

web:
- www.linkedin.com/pub/jorge-gil/2/17a/40a
- tudelft.academia.edu/jorgegil

Jorge is an architect and urban designer, graduated in 1996 at the Faculty of Architecture, TU Lisbon. He worked several years in architecture practice in Portugal (for bquadrado and Paulo David), before moving to London in 1999. He earned in 2000 an MSc in Built Environment: Virtual Environments with Distinction from the Bartlett, UCL. Following this research period, when he developed generative design, programming and 3D interaction design skills, he worked as interaction designer and front-end developer for on-line content, financial data visualisation and edutainment.

Between 2004 and 2009 Jorge was Associate for R&D at Space Syntax Limited, in London. His main responsibility was the development of GIS tools for spatial analysis and visualisation of architectural and urban scale projects. He worked in projects involving the assessment of large complex buildings, such as offices, museums, shopping malls and hospitals, and urban design interventions of various scales, from the individual public space to the city district and the entire city.

In 2009 Jorge earned an individual research grant from the Portuguese Science and Technology Foundation to conduct PhD research at the Department of Urbanism, TU Delft. He has been conducting his research, under supervision of Prof. Vincent Nadin and Dr. Stephen Read, on the topic of urban form and sustainable mobility patterns, developing multi-modal network models for measuring and evaluating the sustainable mobility potential of urban areas, using spatial analysis and data mining methods.

In parallel Jorge has been involved in additional academic research and professional activities. Between 2007 and 2011 Jorge was a member of the "City Induction" research project, coordinated by Prof. José Pinto Duarte and hosted at ICIST, TU Lisbon, being responsible for prototyping an urban design evaluation module for City Information Modeling. Between August 2013 and July 2015 he was research associate at the Space Syntax Laboratory, the Bartlett, UCL, developing software to integrate space syntax methods with the open source QGIS platform. He has been reviewer for a number of international academic journals and conferences.

Since 2009 Jorge has been providing professional consultancy on sustainable mobility planning; pedestrian accessibility and visibility analysis; data analysis, visualisation and user interaction for decision support; and development of custom GIS solutions. In this role he was a member of several prize-winning teams in architecture and urban design competitions.

Awards

- 03 / 2014 – 1st Prize in Architecture competition (FPM41, Lisbon), with Barbas Lopes Arquitetos.
- 09 / 2012 – 1st Prize in Architecture competition for l'Université Toulouse II – Le Mirail campus, with Valode & Pistre architectes
- 12 / 2011 – 2nd Prize in EUROPAN 11 competition (NEST – Allerod), with Openlab Architects

Selected Publications

- Gil, J. (2015) "Examining 'Edge Effects': Sensitivity of Spatial Network Centrality Analysis to Boundary Conditions", in: Proceedings of the 10th International Space Syntax Symposium, University College London, London, UK.

- Gil, J. (2015) "Building a Multimodal Urban Network Model Using OpenStreetMap Data for the Analysis of Sustainable Accessibility", in: Jokar Arsanjani, J., Zipf, A., Mooney, P., Helbich, M. (Eds.), OpenStreetMap in GIScience: Experiences, Research, Applications, Lecture Notes in Geoinformation and Cartography. Springer, pp. 229–251

- Gil, J. and Read, S. (2014) "Patterns of sustainable mobility and the structure of modality in the Randstad city-region". A|Z ITU Journal of the Faculty of Architecture 11 (2), pp. 231–254.

- Gil, J. (2014) "Analyzing the Configuration of Multimodal Urban Networks". Geographical Analysis 46, pp. 368–391. doi:10.1111/gean.12062

- Gil, J. and Duarte, J. P. (2013) "Tools for Evaluating the Sustainability of Urban Design: a Review." Proceedings of the ICE - Urban Design and Planning 166 (6), pp. 1–15. doi:10.1680/udap.11.00048.

- Gil, J., Beirão, J. N., Montenegro, N., Duarte, J. P. (2012) "On the discovery of urban typologies: data mining the many dimensions of urban form", Urban Morphology 16 (1), pp. 27-40

- Gil, J., Almeida, J. and Duarte, J.P. (2011) “The backbone of a City Information Model (CIM): Implementing a spatial data model for urban design”, in Proceedings of the 29th eCAADe Conference 2011, Ljubljana, Slovenia, pp. 143-151

- Gil, J., Beirão, J., Montenegro, N., Duarte, J. P. (2010) “Assessing computational tools for urban design: Towards a ‘City Information Model’” in Proceedings of the 28th Conference on Education in Computer Aided Architectural Design in Europe, eCAADe 2010, Zurich, Switzerland

- Gil, J., Tobari, E., Lemlij, M., Rose, A., Penn, A. (2009) ”The Differentiating Behaviour of Shoppers: Clustering of Individual Movement Traces in a Supermarket”, in Proceedings of the 7th International Space Syntax Symposium, KTH Stockholm, Sweden

- Chiaradia, A., Schwander, C., Gil, J., Friedrich, E., Gosset, A. (2008) “Mapping the intangible value of urban layout (i-VALUL): Developing a tool kit for the socio-economic valuation of urban areas, for designers and decision makers”, in Timmermans, H. and de Vries, B. (eds.) 9th International Conference on Design & Decision Support Systems in Architecture and Urban Planning, Eindhoven University of Technology, The Netherlands

- Gil, J. and Duarte, J. P. (2008) “Towards an Urban Design Evaluation Framework”, in Architecture in Computro, Antwerpen, Belgium, pp. 257–264

- Gil, J. and Steinbach, P. (2008), “From flood risk to indirect flood impact: evaluation of street network performance for effective management, response and repair”, in Flood Recovery, Innovation and Response (Wessex Institute of Technology Press, London, UK), pp. 335–345

- Raford, N., Chiaradia, A., Gil, J. (2005) “Critical Mass: Emergent cyclist route choice in central London”, in Proceedings of the 5th International Space Syntax Symposium, TU Delft, Faculty of Architecture, The Netherlands

Profile and Skills

- Urban data analysis for sustainable urban development and mobility assessment
- Development of design and decision support methods based spatial data modelling, analysis and visualisation
- GIS use and automation (QGIS, MapInfo and ArcGIS)
- Open source geo databases (PostgreSQL/PostGIS and SQLlite/Spatialite)
- Data mining and statistical analysis (R, SQL and JMP)
- Front-end software development (UI, UX) in Python, javascript, C++ and VB
- Interactive graphic design and development (2D and 3D)
- Parametric design, genetic algorithms and agent based systems

TOC

Appendix A SUD assessment criteria

DIMENSIONS / ISSUES	ID	ASSESSMENT CRITERIA	NOTES	%
Environment				
Environment	1.1.1	Water	Presence, area	46%
	1.1.2	Green space	Presence, area	31%
	1.1.3	Biodiversity	Index	62%
	1.1.5	Landscape	Consideration, protect	46%
	1.1.6	Topography	Consideration of	15%
Resources	1.2.1	Water management		69%
	1.2.2	Energy	Efficiency, reduction	77%
	1.2.3	Food production		15%
	1.2.4	Land	Re-use, coverage	85%
	1.2.5	Raw Materials		77%
Hazards & Pollution	1.3.1	Flood risk		15%
	1.3.2	Air pollution	Amount, reduction	77%
	1.3.3	Noise	Amount, reduction	54%
	1.3.4	Soil pollution		31%
	1.3.5	Waste	Reduction, management	46%
	1.3.6	Odour nuisance		8%
Transport & Mobility	1.4.1	Public transport networks	Presence, size	62%
	1.4.2	Car parking	Reduction, management	31%
	1.4.3	Slow modes	Network quality	77%
	1.4.4	Traffic management	Reduction, calming	62%
Society				
Access	2.1.1	Local services	Proximity, quantity	85%
	2.1.2	Education	Proximity, quantity	69%
	2.1.3	Public transport	Proximity	31%
	2.1.4	Culture	Proximity, quantity	8%
	2.1.5	Recreation/Leisure	Proximity, quantity	23%
	2.1.6	Sports	Proximity, quantity	15%
	2.1.7	Green areas	Proximity, area	46%
	2.1.8	Health	Proximity, quantity	31%
	2.1.9	Social services	Proximity, quantity	38%
	2.1.10	City centre	Distance	8%
Equality & Justice	2.2.1	Inclusive community	Age, income, education	92%
	2.2.2	Inclusive design		15%

Diversity	2.3.1	Housing types	Quantity, mix	31%
	2.3.2	Housing ownership		15%
	2.3.3	Mixed use	Residential and other	54%
Identity	2.4.1	Cultural Heritage	Respect	54%
	2.4.2	Vistas	Consideration, protect	23%
Health & Safety	2.5.1	Personal safety		31%
	2.5.2	Property safety		15%
	2.5.3	Traffic safety		31%
	2.5.4	Outdoor comfort		31%
Economy				
Viability	3.1.1	Business investment		31%
	3.1.2	Employment		77%
	3.1.3	Profitability		38%
	3.1.4	Low cost places for non-profit organisations		8%
	3.1.5	Competition/Cooperation		8%
Flexibility	3.2.1	Function flexibility		23%
	3.2.2	Building re-use		23%
Vitality	3.3.1	City centre		15%
	3.3.2	Frontage/Entrance		15%
Layout & Design				
Form	4.1.1	Compact	Density	38%
	4.1.2	Polycentric		15%
	4.1.3	Connected	To surroundings	15%
	4.1.4	Project location	Type of site	23%
	4.1.5	Passive solar design		38%
Open space	1.5.1	Public space	Size, quality	92%
	1.5.2	Surface materials	Type	31%
	1.5.3	Urban furniture		8%
Building quality	4.2.1	Housing quality		31%

TABLE APP.A.1 List of SUD evaluation criteria covered by the tools reviewed in Chapter 2, indicating the percentage (%) of tools that include each criterion. There might be one or more performance indicators assigned to each assessment criterion, but these tend to be specific to the individual tools.

Appendix B Spatial data model

The following diagrams represent the tables and attributes of the PostGIS spatial database, including the dependencies between tables through shared attributes and spatial relations.

FIGURE APP.B.1 Data model of the multimodal urban network geography classes.

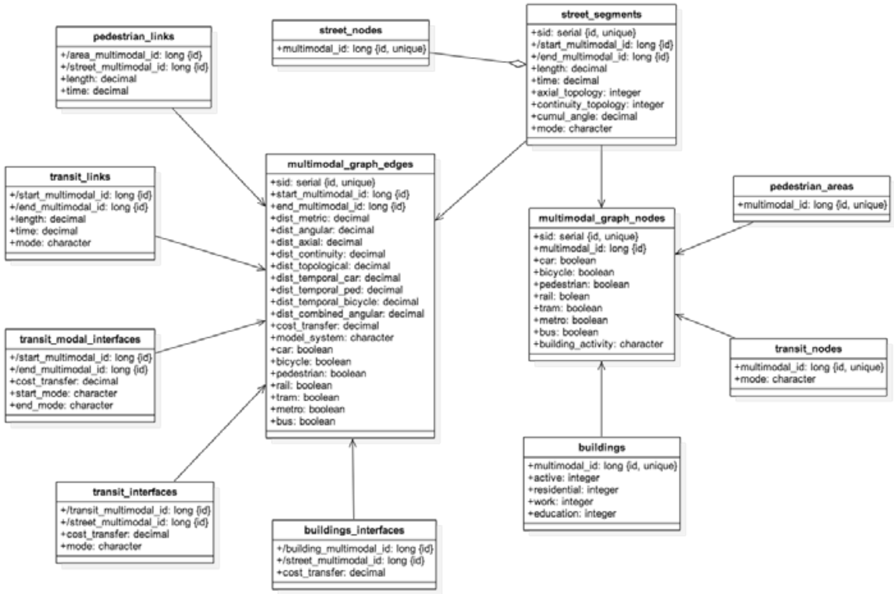


FIGURE APP.B.2 Data model of the multimodal urban network graph classes (edges and nodes), including the geography classes that are combined to produce them.

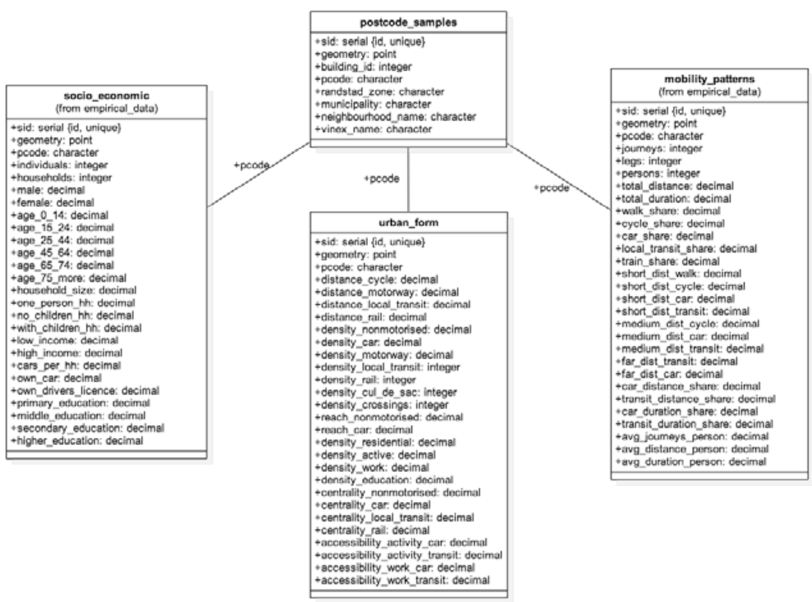


FIGURE APP.B.3 Data model of the empirical data classes that characterise urban areas, all linked by the common postcode. The urban form class results from the analysis of the multimodal urban network model.

Appendix C Spatil database layers

The following maps present the layers of the GIS database, to illustrate each of the classes of the spatial data model and their main attributes, centring on Delft.

FIGURE APP.C.1 Thematic map of the street segments table, classified according to the main mode.

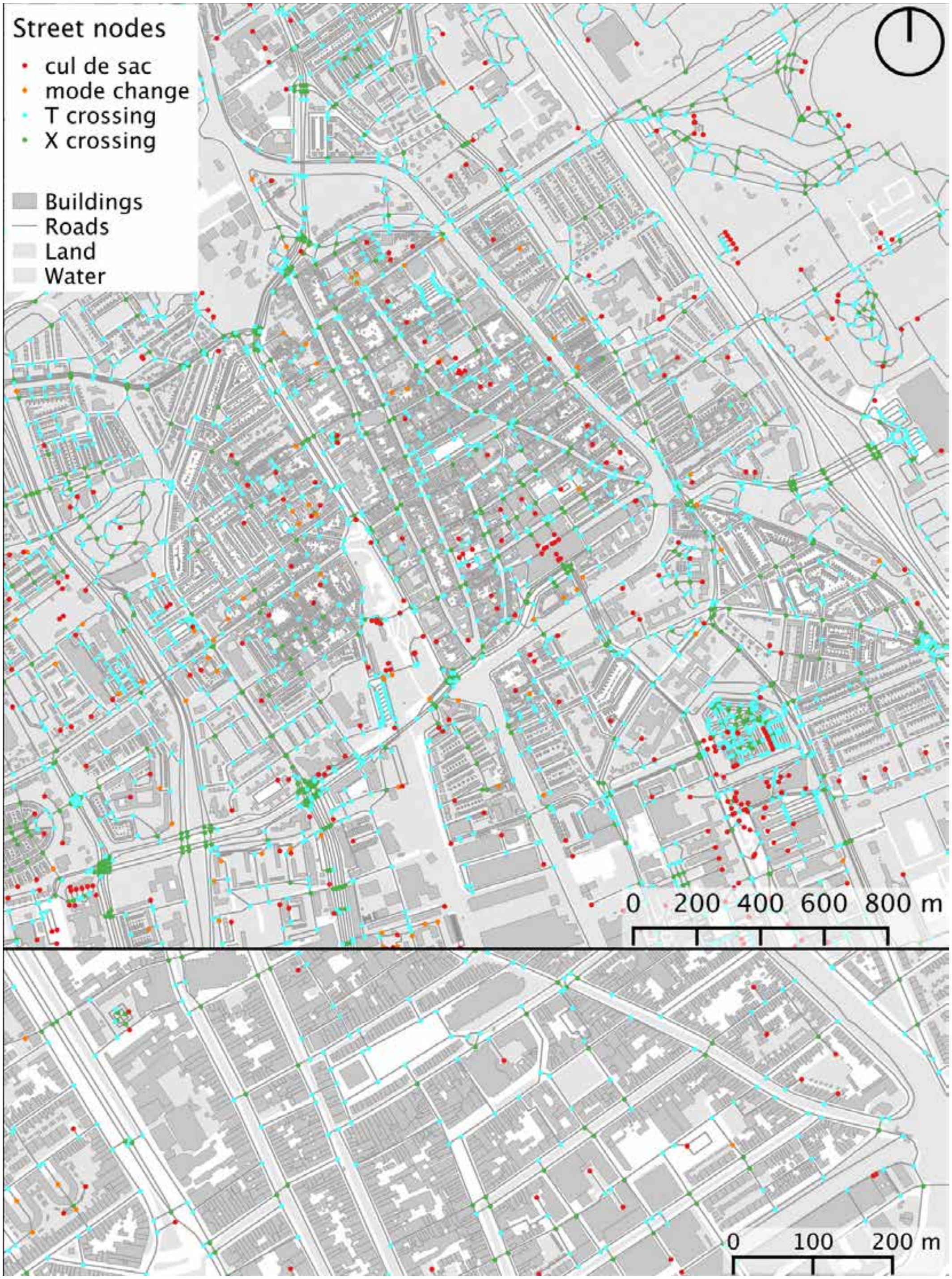


FIGURE APP.C.2 Thematic map of the street nodes table, classified according to the typology of intersections. The mode change class is where there is a cul-de-sac for one mode (e.g. the car) but the street continues for other modes (e.g. walking and cycling).

FIGURE APP.C.3 Thematic map of the pedestrian areas table. From this map it is clear that not all public open pedestrian spaces are included, e.g. Delft's central market square.

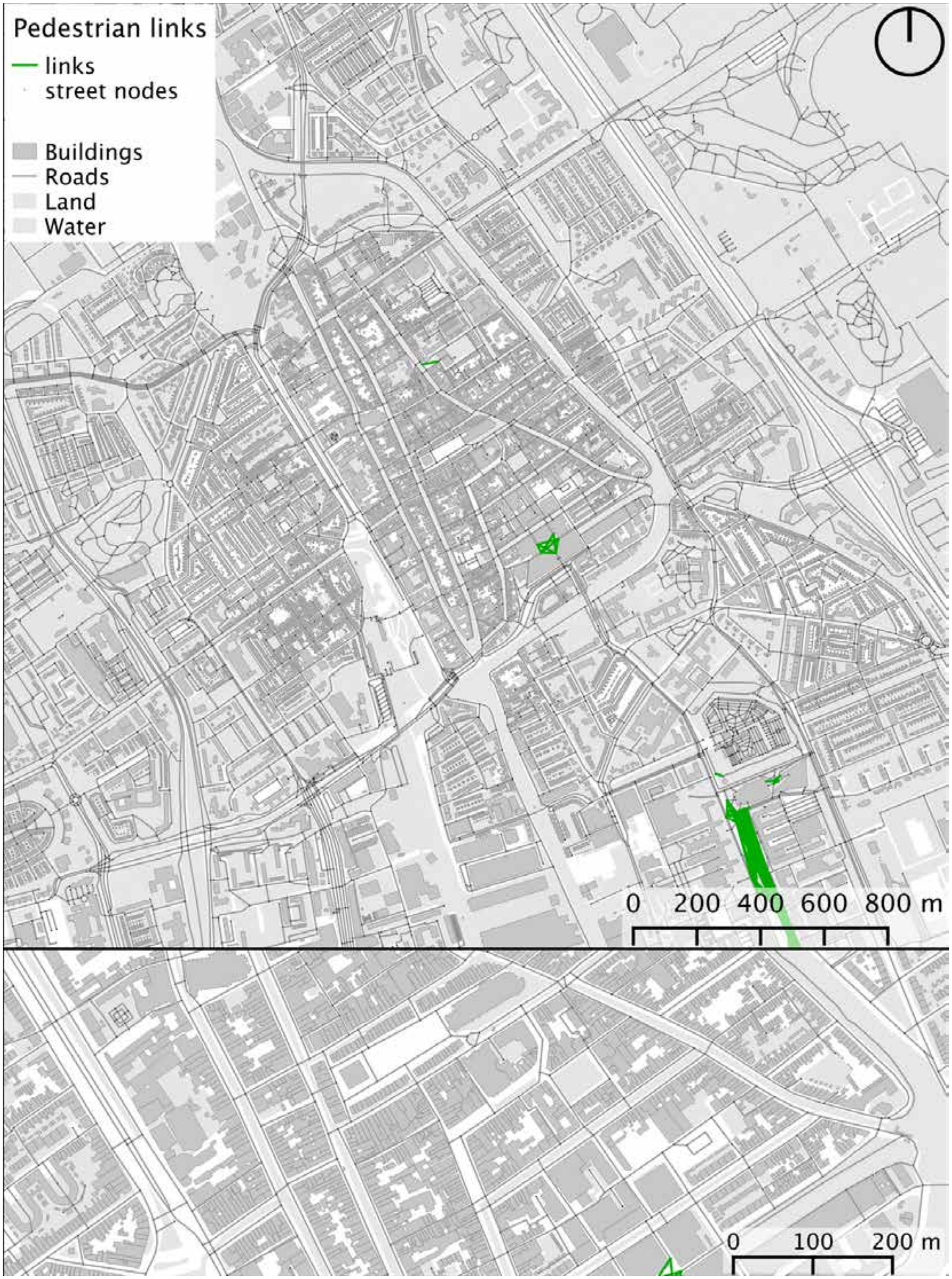


FIGURE APP.C.4 Thematic map of the pedestrian links table.

FIGURE APP.C.5 Thematic map of the public transit stops table, classified by transport mode.

TOC

FIGURE APP.C.6 Thematic map of the public transit links table, classified by transport mode.

FIGURE APP.C.7 Thematic map of the transit mode interfaces table.

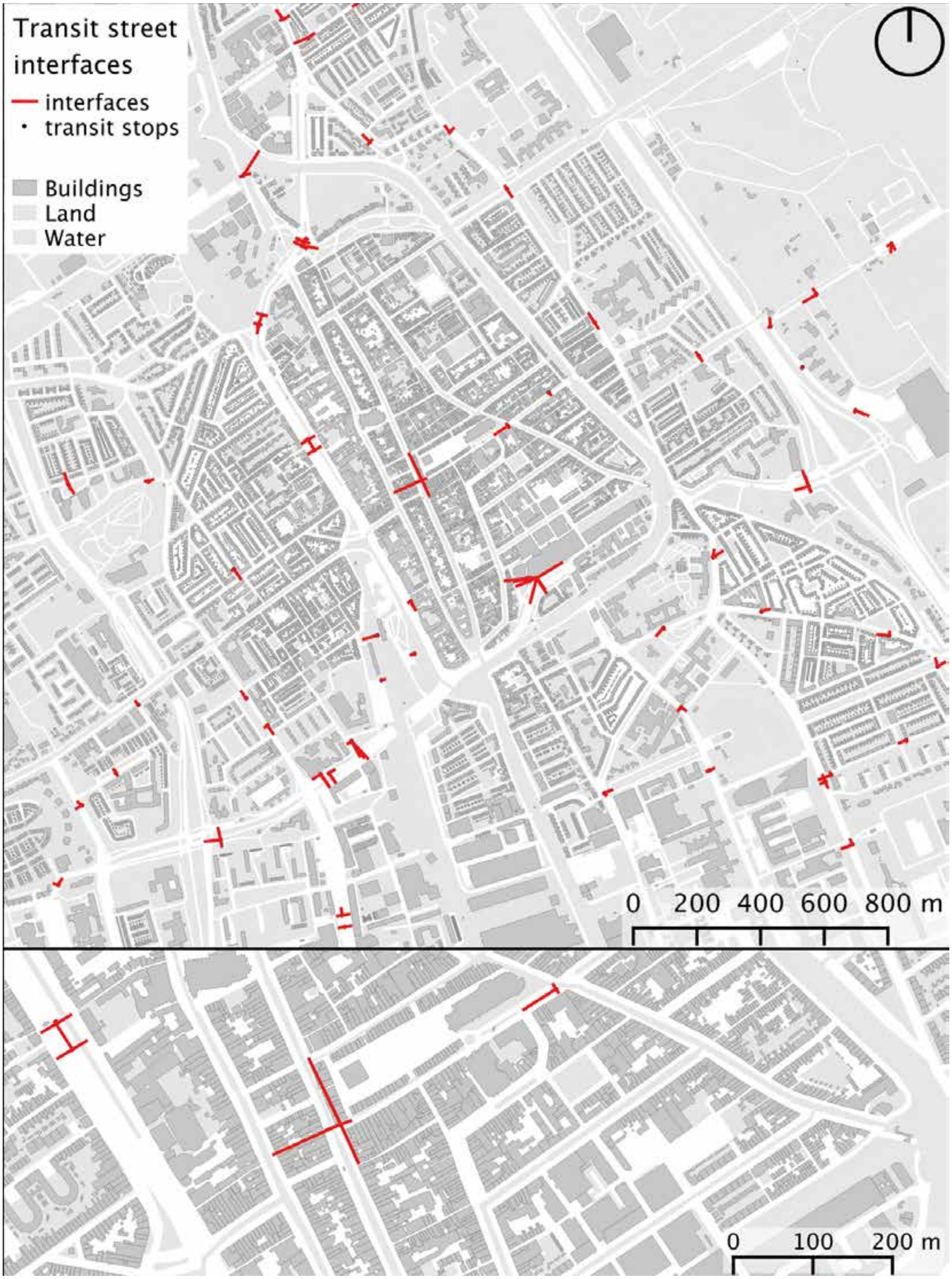


FIGURE APP.C.8 Thematic map of the transit street interfaces table.

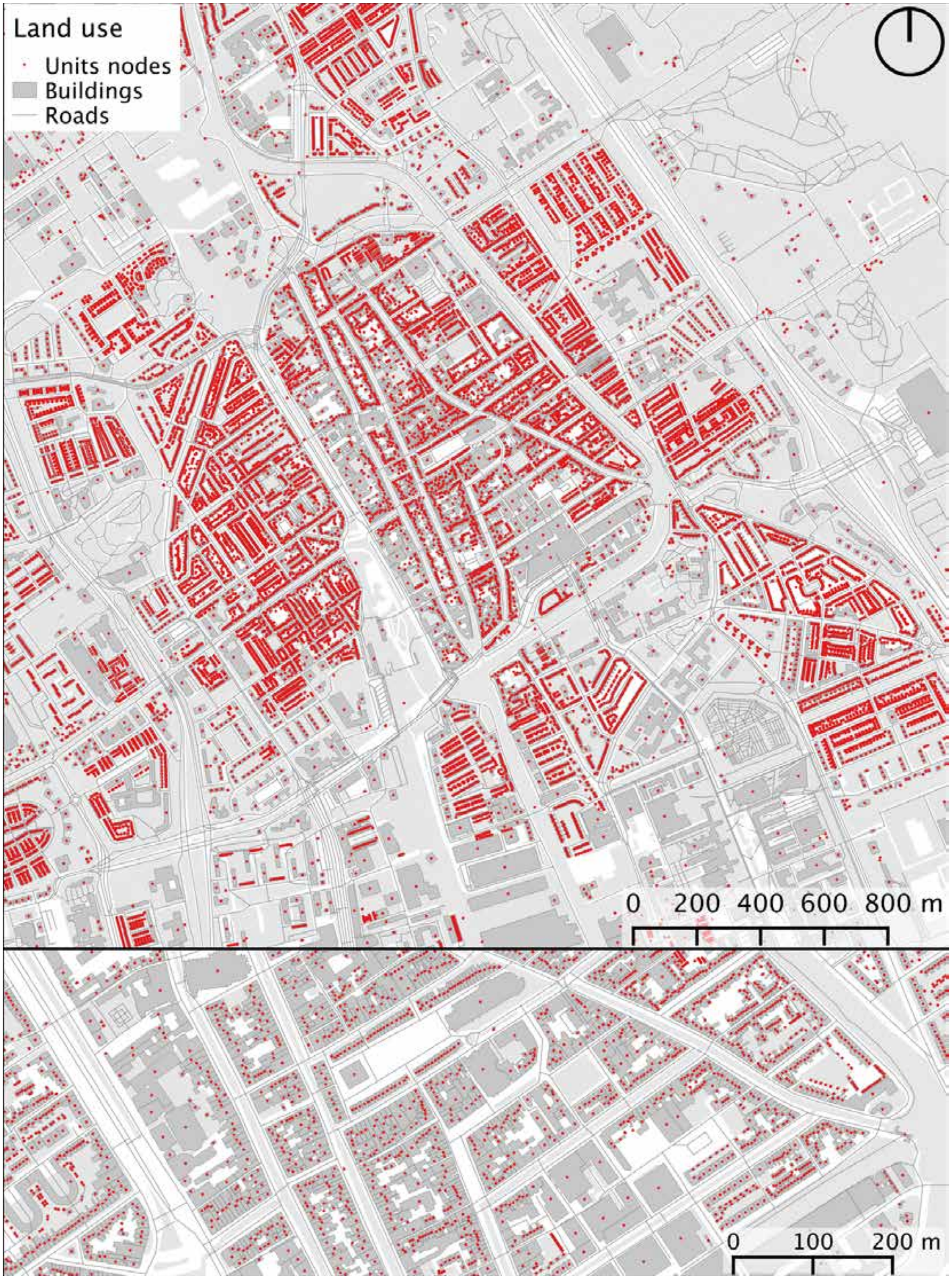


FIGURE APP.C.9 Thematic map of the land use nodes table. The bottom map shows that there can be multiple units per building.

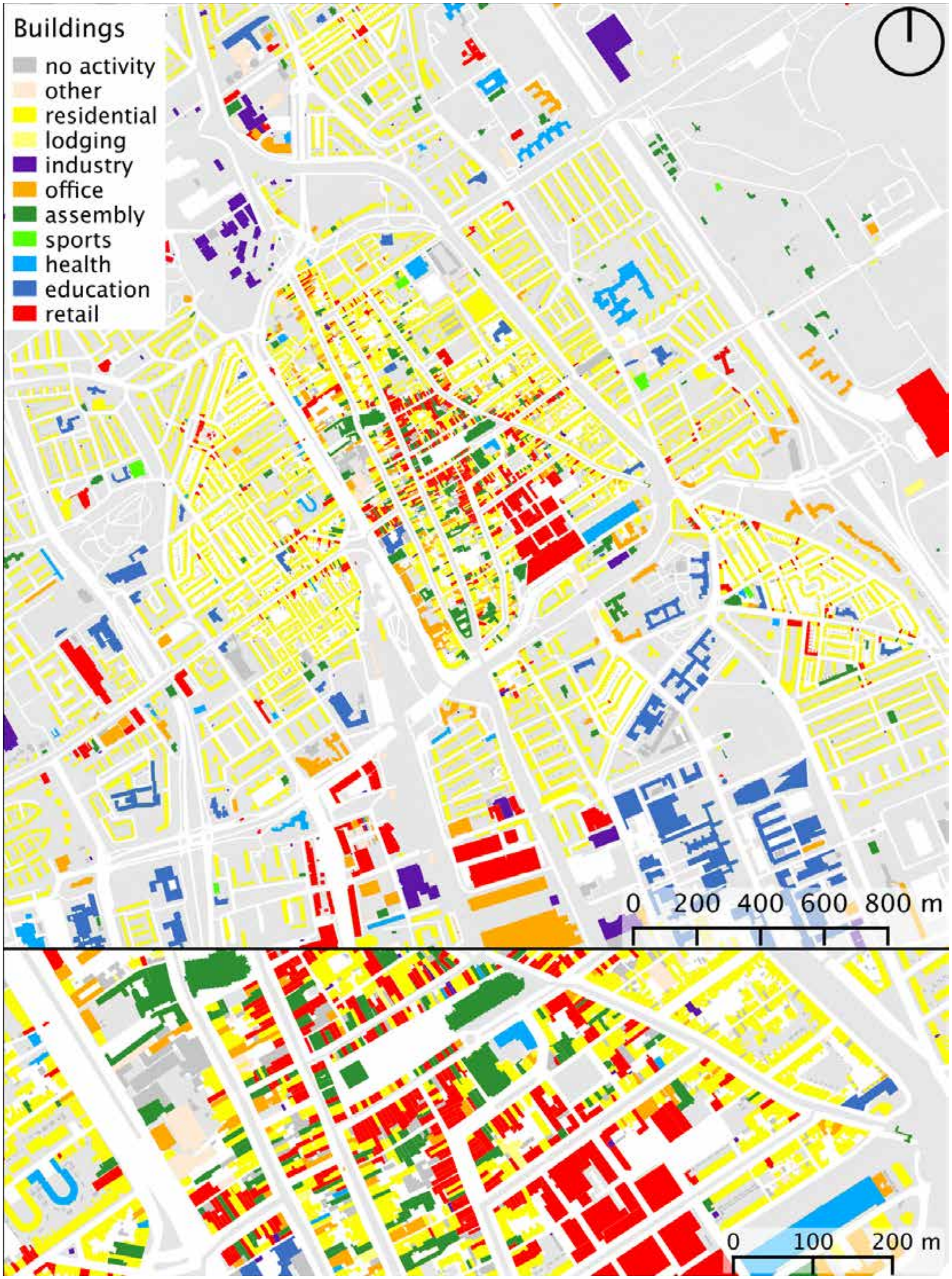


FIGURE APP.C.10 Thematic map of the buildings table, classified by the ground floor unit use.

FIGURE APP.C.11 Thematic map of the building street interfaces table.

TOC

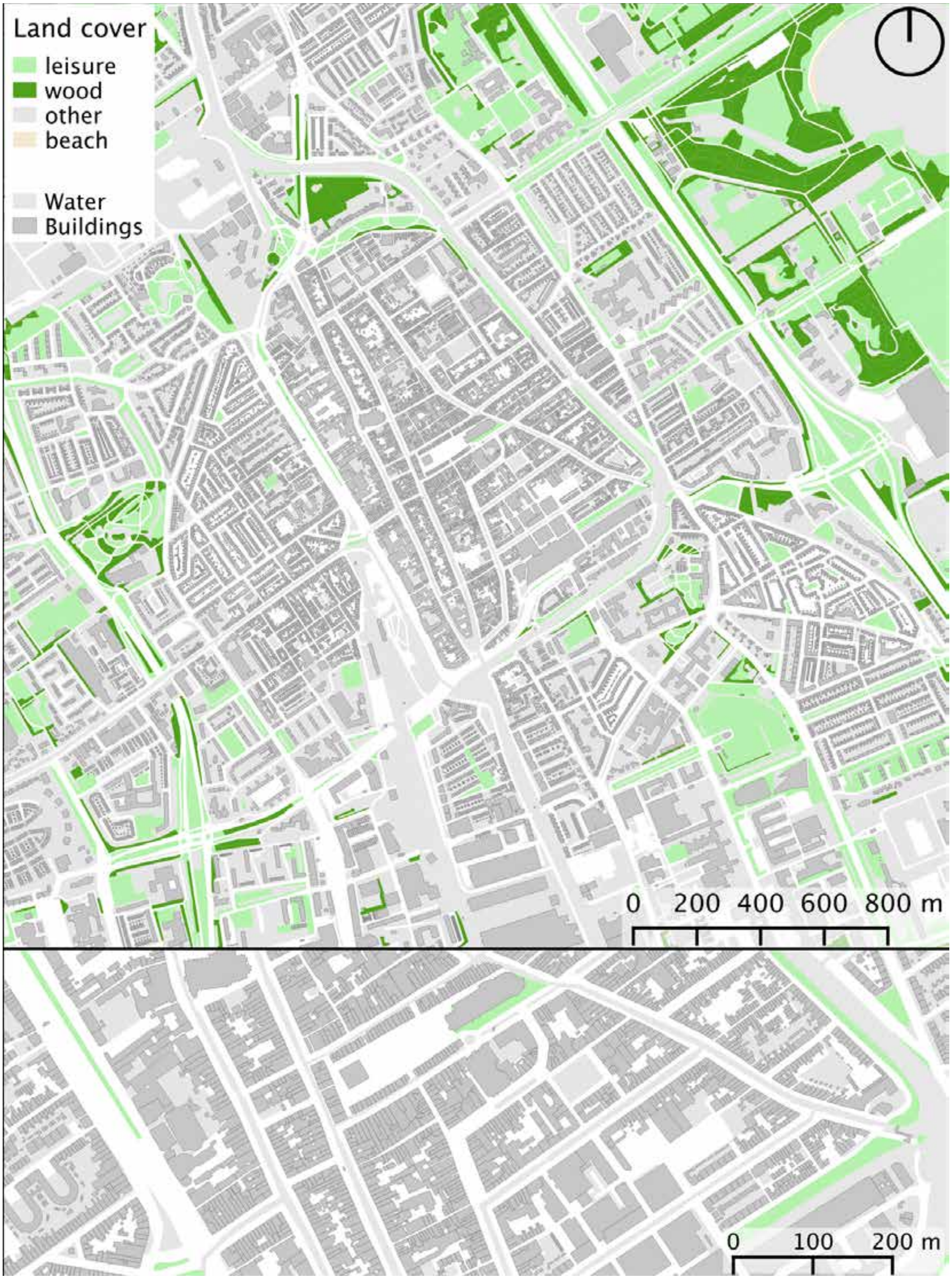


FIGURE APP.C.12 Thematic map of the land cover table, classified by type of surface coverage.

FIGURE APP.C.13 Thematic map of the water table, classified to indicate the location of bridges.

FIGURE APP.C.14 Thematic map of the multimodal graph nodes table, classified according to the type of node: transit stop, street centroid, pedestrian area centroid, and building centroid.

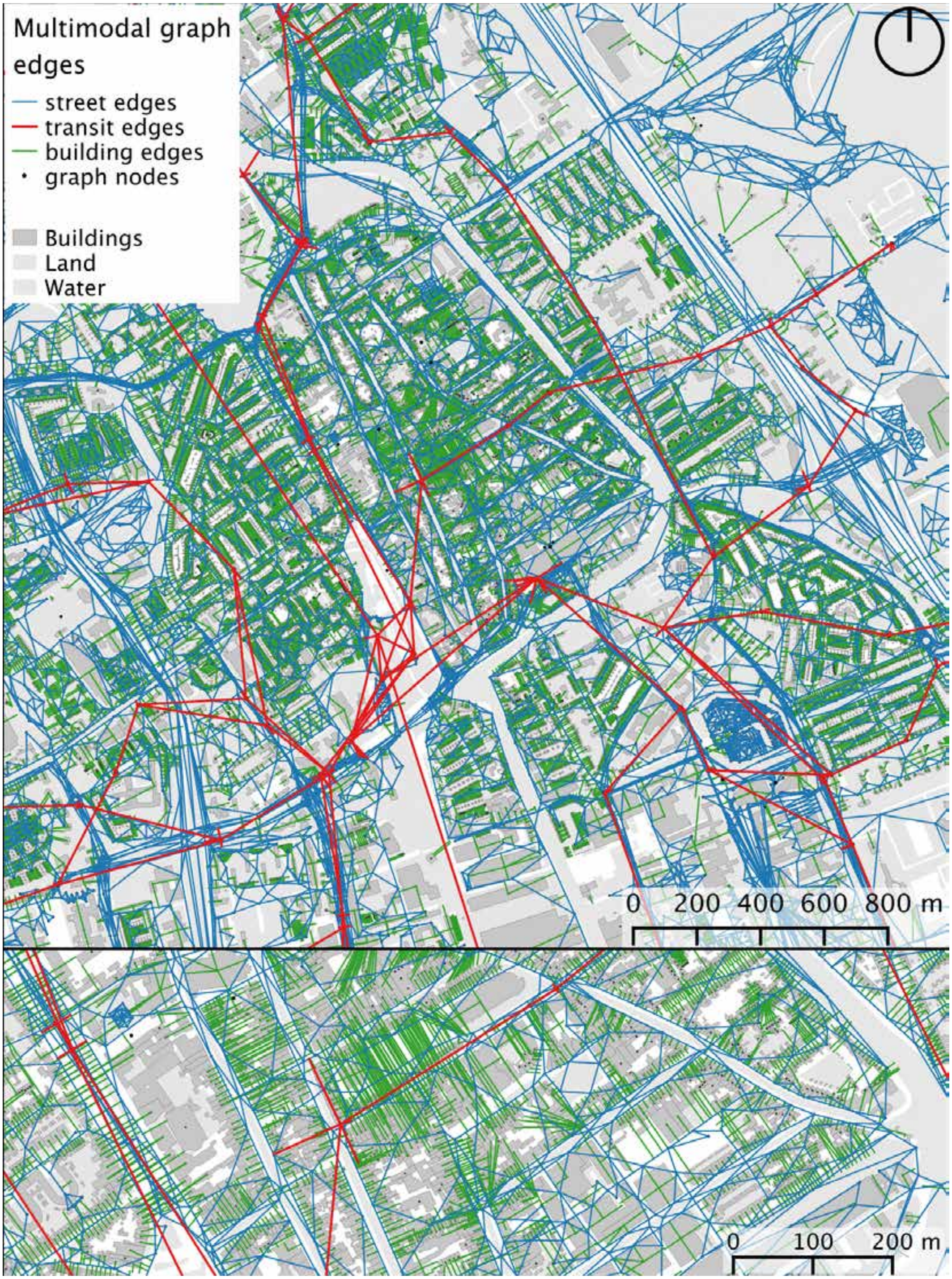


FIGURE APP.C.15 Thematic map of the multimodal graph edges table, classified according to the type of edge: transit, streets, or buildings.

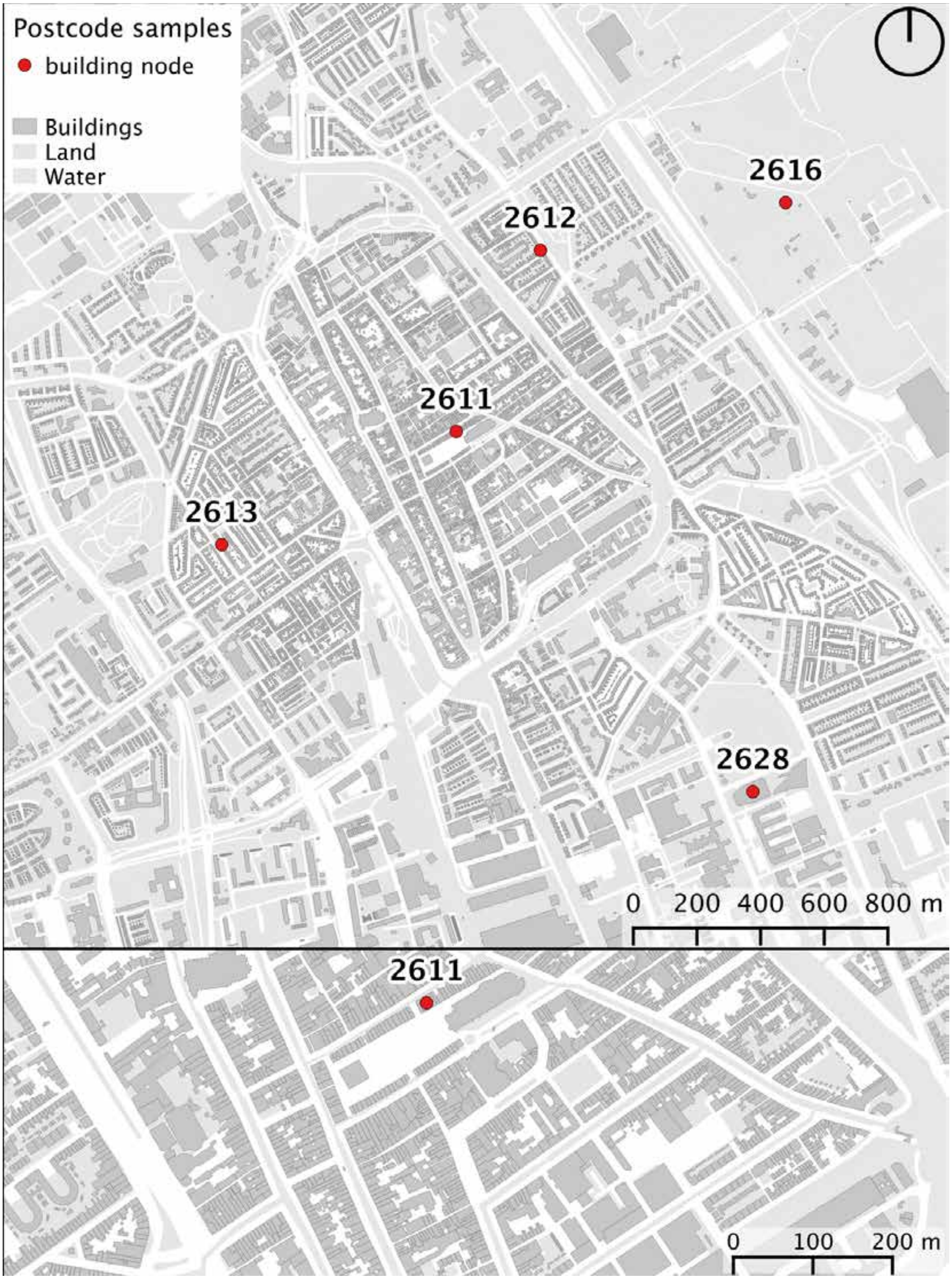


FIGURE APP.C.16 Thematic map of the postcode samples table, labelled with the respective number. These are located on the residential building nearest to the residential unit weighted centroid of the postcode area.

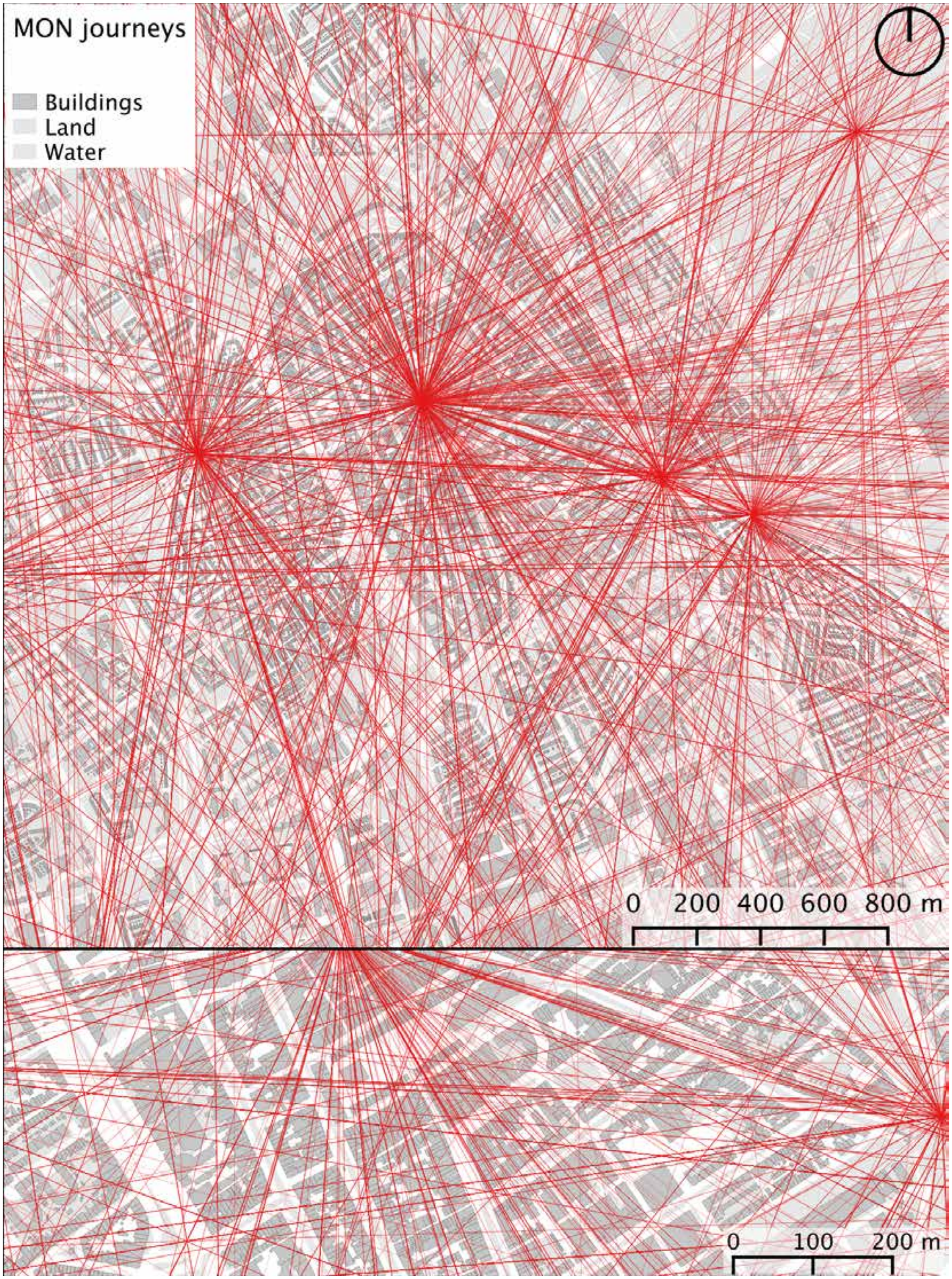


FIGURE APP.C.17 Thematic map of the mobility survey journeys table, with individual journeys between postcodes represented as lines. These were initially mapped on the non-weighted centroid of the postcode area.

Appendix D Network impedance comparison

The following maps provide a comparison of the different network impedance (distance) types available in the multimodal urban network model, as introduced in Chapter 5: metric, temporal, angular (geometric), axial, continuity (cognitive) and segment (topologic). The maps show shortest routes, catchment areas, and network centrality results.

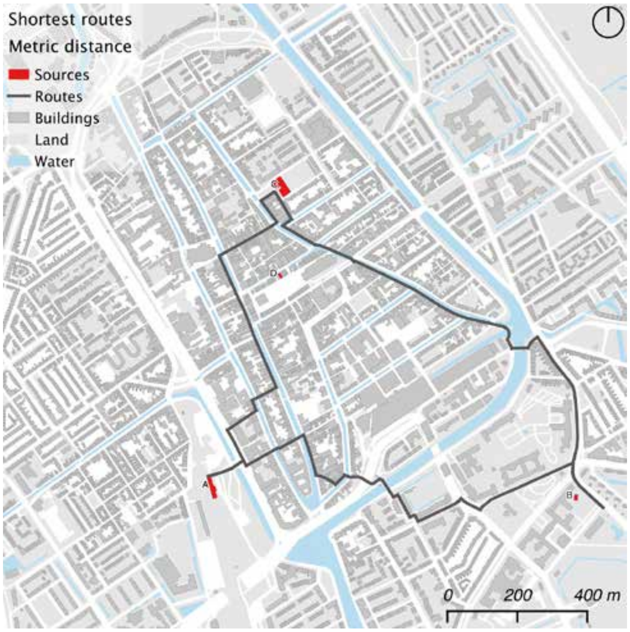


FIGURE APP.D.1 Shortest routes (A-B, B-C, C-A) using metric distance.

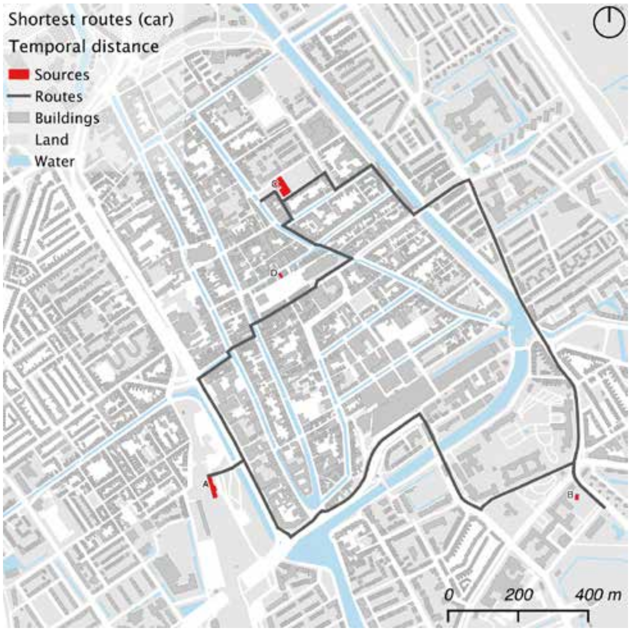


FIGURE APP.D.2 Shortest routes (A-B, B-C, C-A) using temporal distance on the car network, with route and speed constraints.

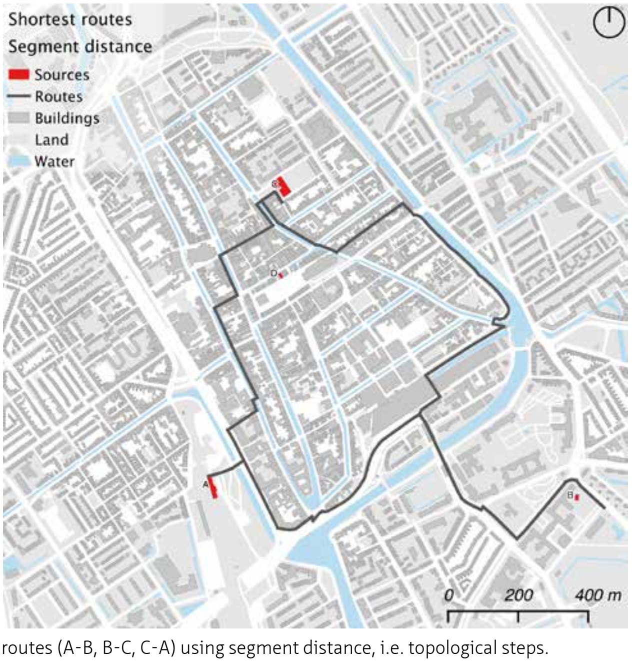


FIGURE APP.D.3 Shortest routes (A-B, B-C, C-A) using segment distance, i.e. topological steps.

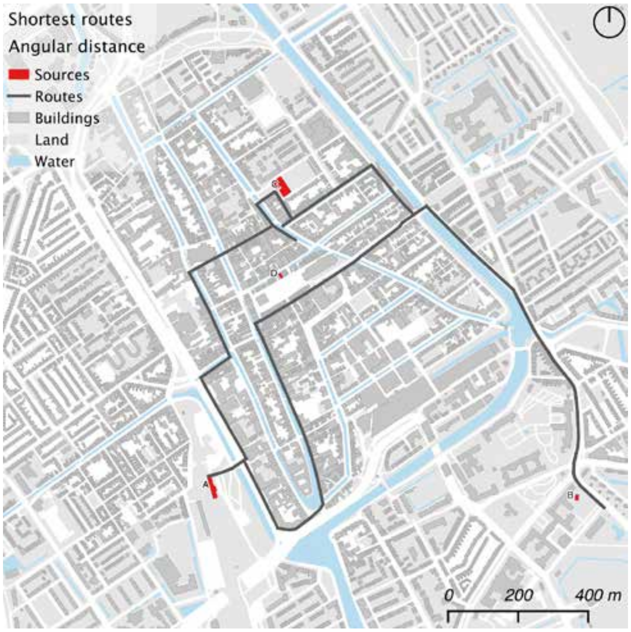


FIGURE APP.D.4 Shortest routes (A-B, B-C, C-A) using angular distance.

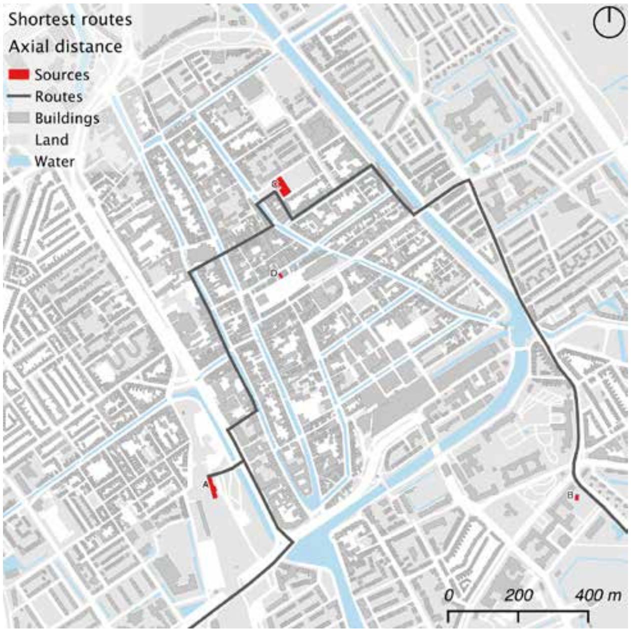


FIGURE APP.D.5 Shortest routes (A-B, B-C, C-A) using axial distance.

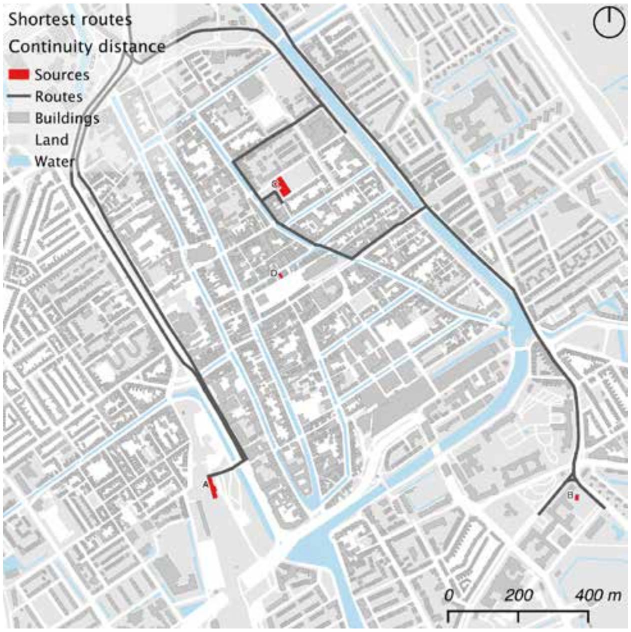


FIGURE APP.D.6 Shortest routes (A-B, B-C, C-A) using continuity distance.

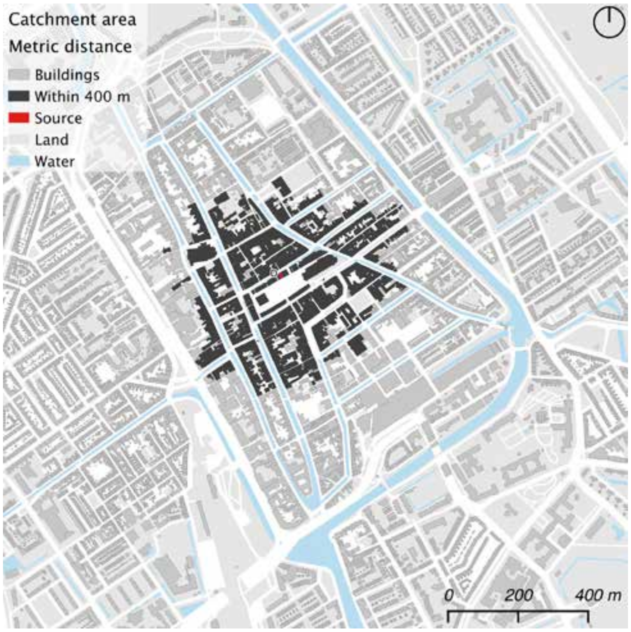


FIGURE APP.D.7 Catchment area from source D, for 400 meters of metric distance.

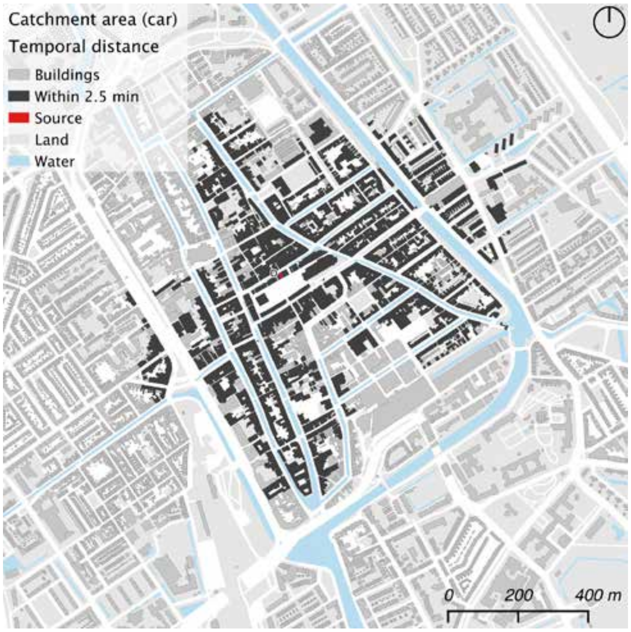


FIGURE APP.D.8 Catchment area from source D, for 2.5 minutes of temporal distance.

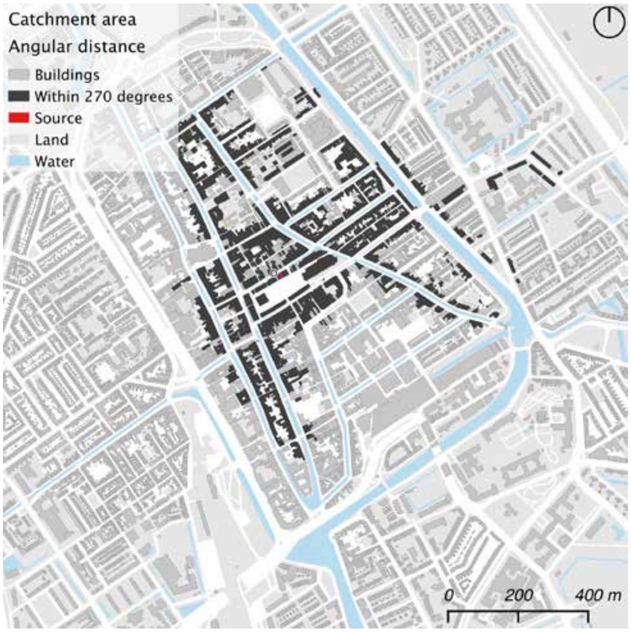


FIGURE APP.D.9 Catchment area from source D, for 270 degrees of angular distance.

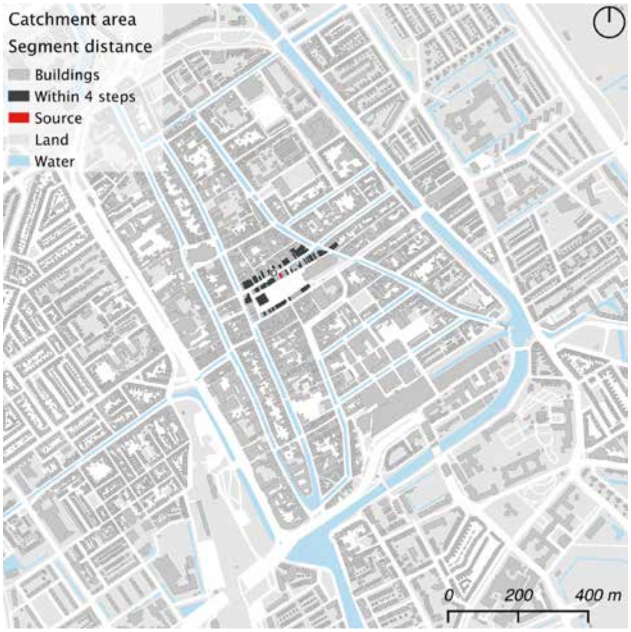


FIGURE APP.D.10 Catchment area from source D, for 4 steps of segment distance.

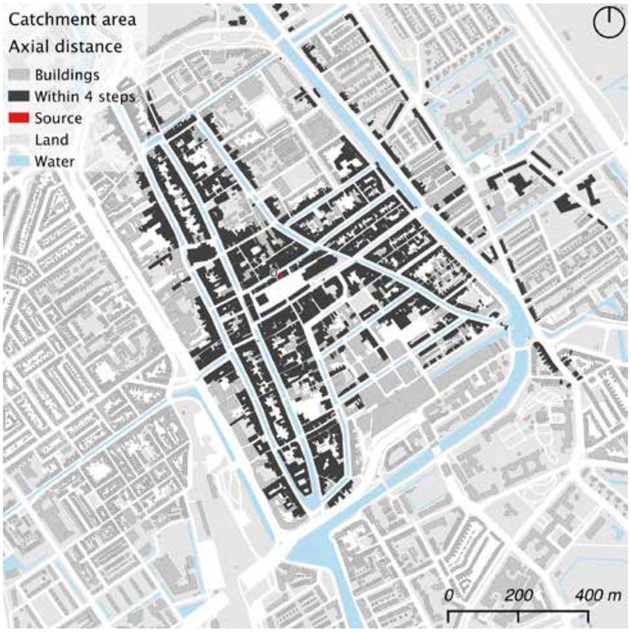


FIGURE APP.D.11 Catchment area from source D, for 4 steps of axial distance.

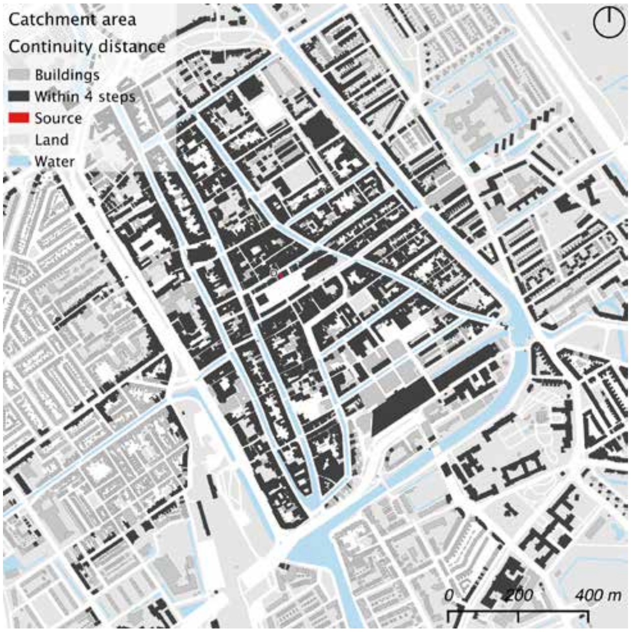


FIGURE APP.D.12 Catchment area from source D, for 4 steps of continuity distance.

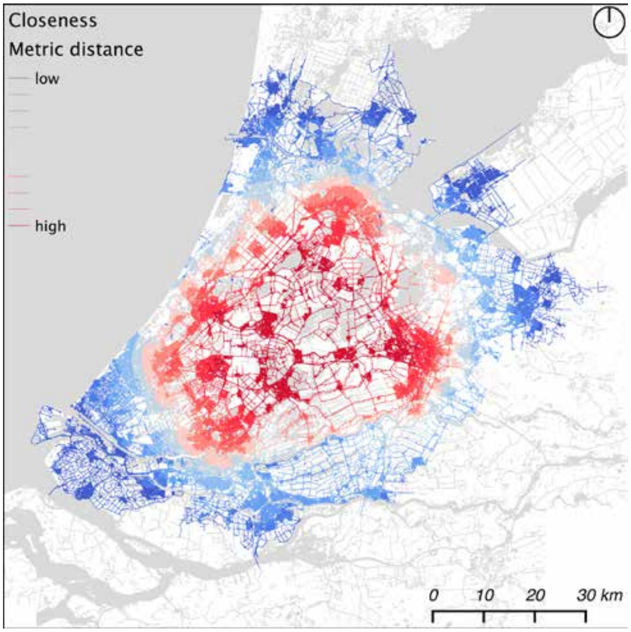


FIGURE APP.D.13 Regional configuration of closeness centrality for metric distance.

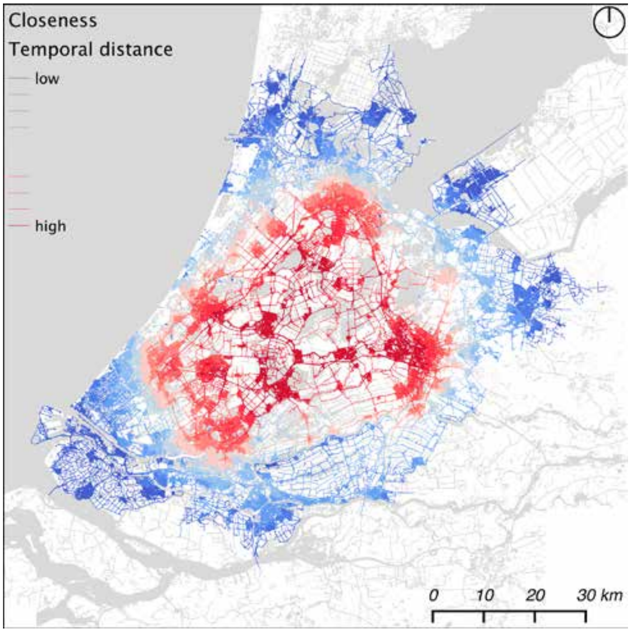


FIGURE APP.D.14 Regional configuration of closeness centrality for temporal distance.

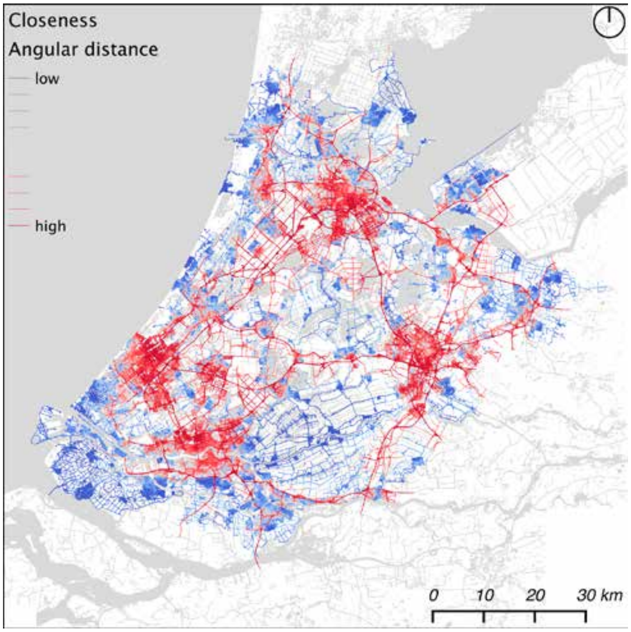


FIGURE APP.D.15 Regional configuration of closeness centrality for angular distance.

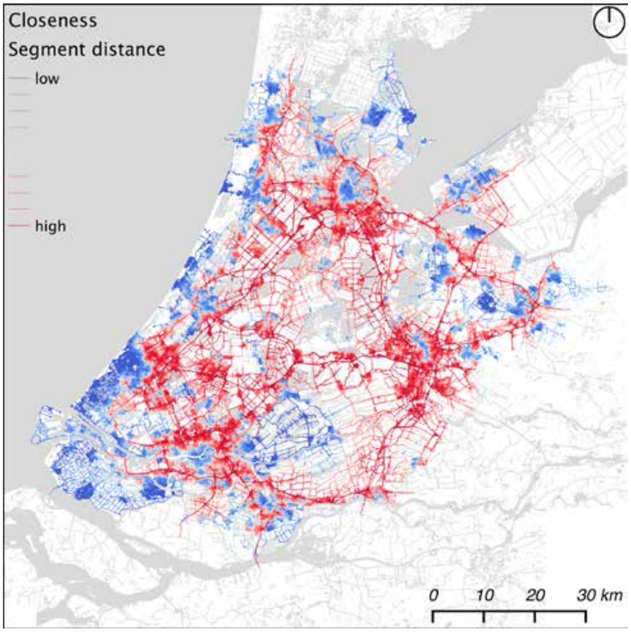


FIGURE APP.D.16 Regional configuration of closeness centrality for segment distance.

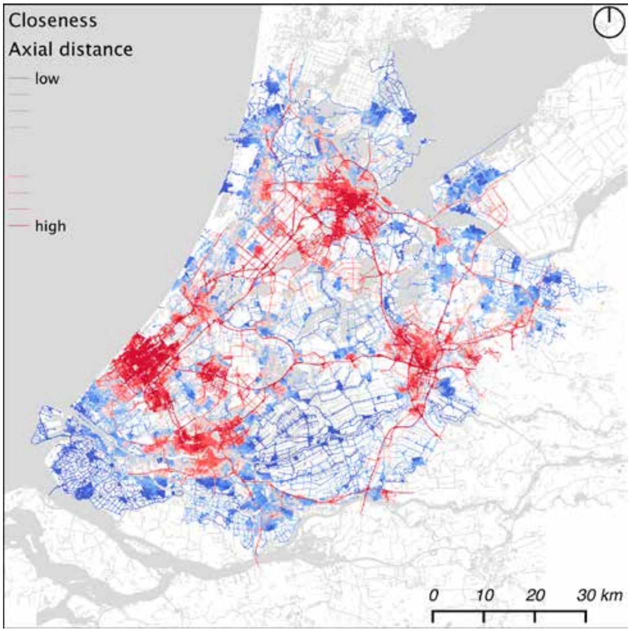


FIGURE APP.D.17 Regional configuration of closeness centrality for axial distance.

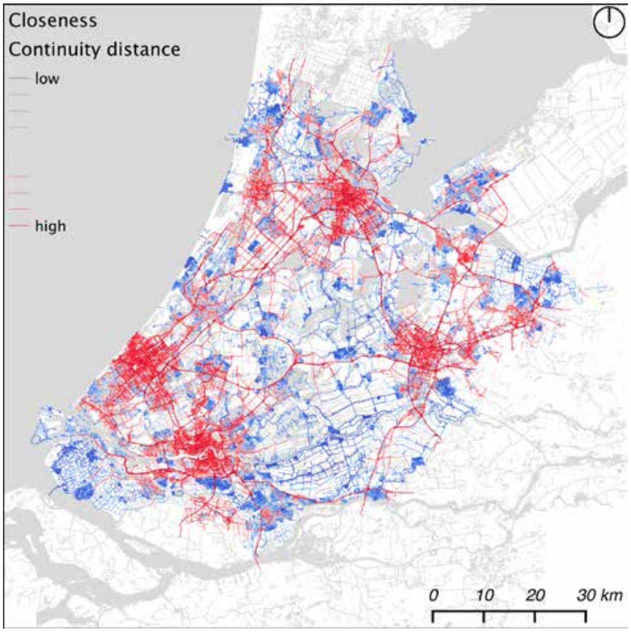


FIGURE APP.D.18 Regional configuration of closeness centrality for continuity distance.

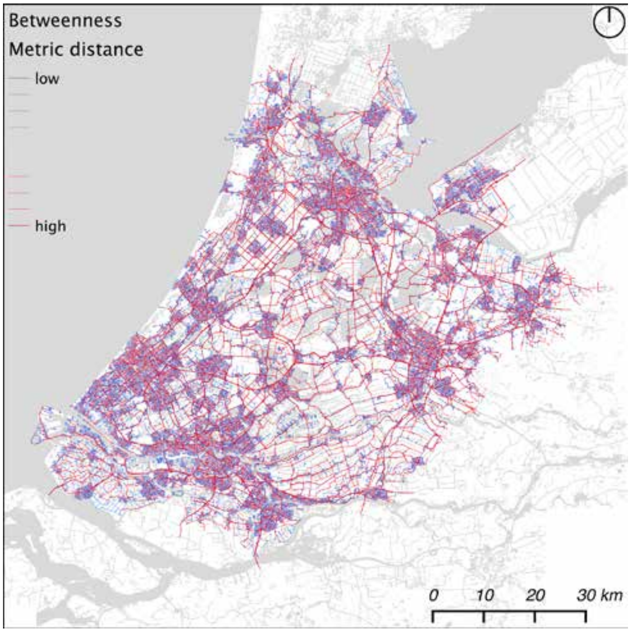


FIGURE APP.D.19 Regional configuration of betweenness centrality for metric distance.

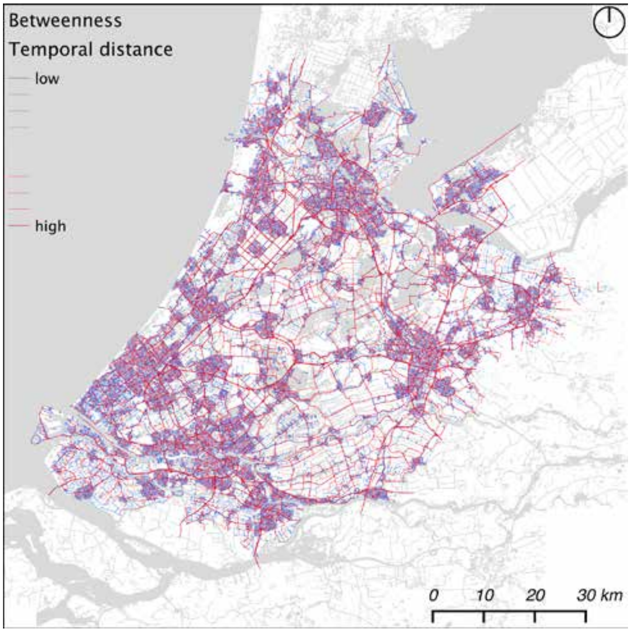


FIGURE APP.D.20 Regional configuration of betweenness centrality for temporal distance.

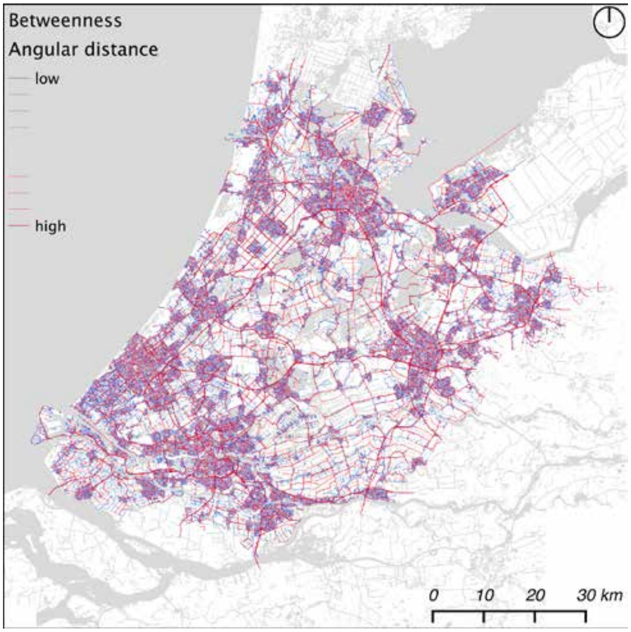


FIGURE APP.D.21 Regional configuration of betweenness centrality for angular distance.

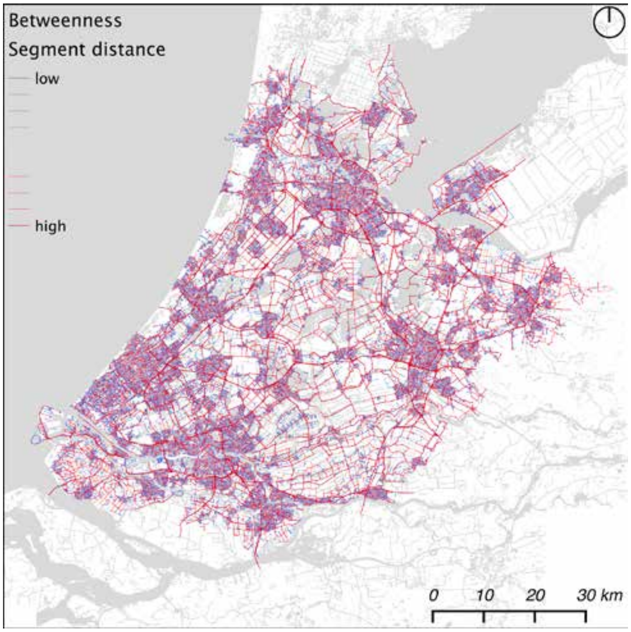


FIGURE APP.D.22 Regional configuration of betweenness centrality for segment distance.

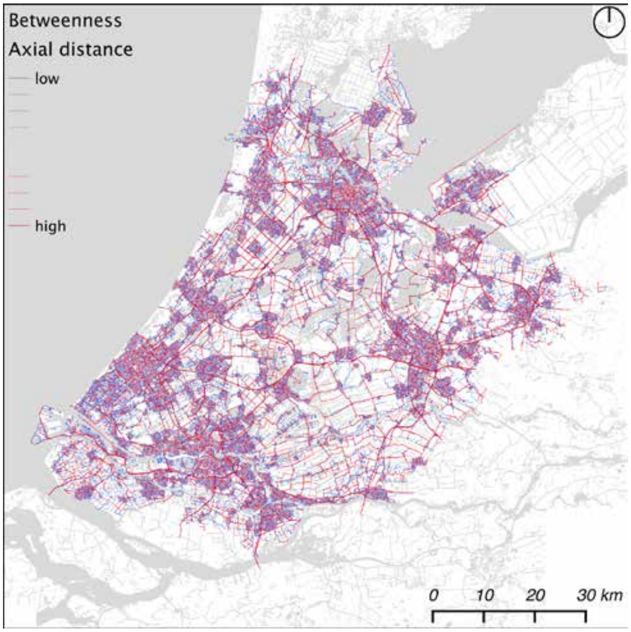


FIGURE APP.D.23 Regional configuration of betweenness centrality for axial distance.

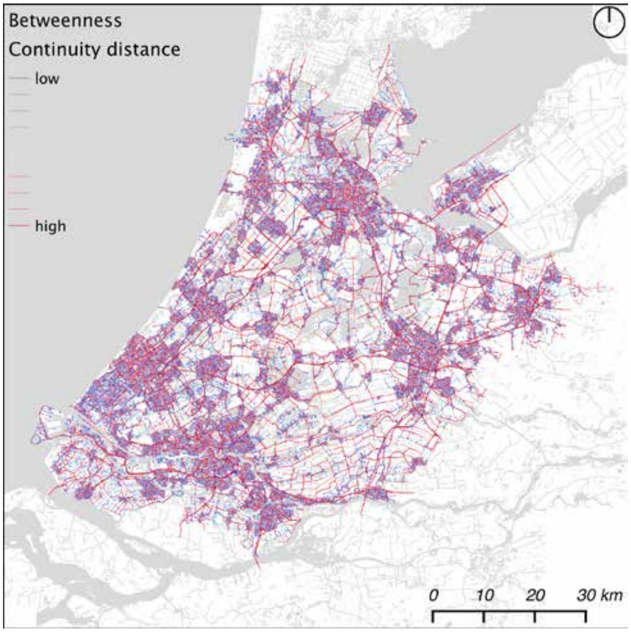


FIGURE APP.D.24 Regional configuration of betweenness centrality for continuity distance.

Appendix E Sustainable mobility profile of the Randstad

This series of maps illustrates the sustainable mobility profile of the Randstad, for each sustainable mobility indicator used in this research. The colour range in the maps reflects the sustainability direction of the indicator, where green represents the most sustainable values, and red the least sustainable. The maps' scale uses quantiles, with the middle values of the scale (yellow) around the median value of the region. The only exception is the short distance transit share map that uses a natural breaks scale, due to its extremely skewed distribution with many 0% values.

Therefore, these maps reflect sustainability in relation to the region's current mobility practice and do not necessarily represent an ideal of sustainability, which would require the creation of specific scales for each mode based on achieving certain sustainability objectives. This distance from an ideal goal is clear for example in Figure E-8 of long distance car share, where 60% share is still considered very good compared to the 80% regional median.

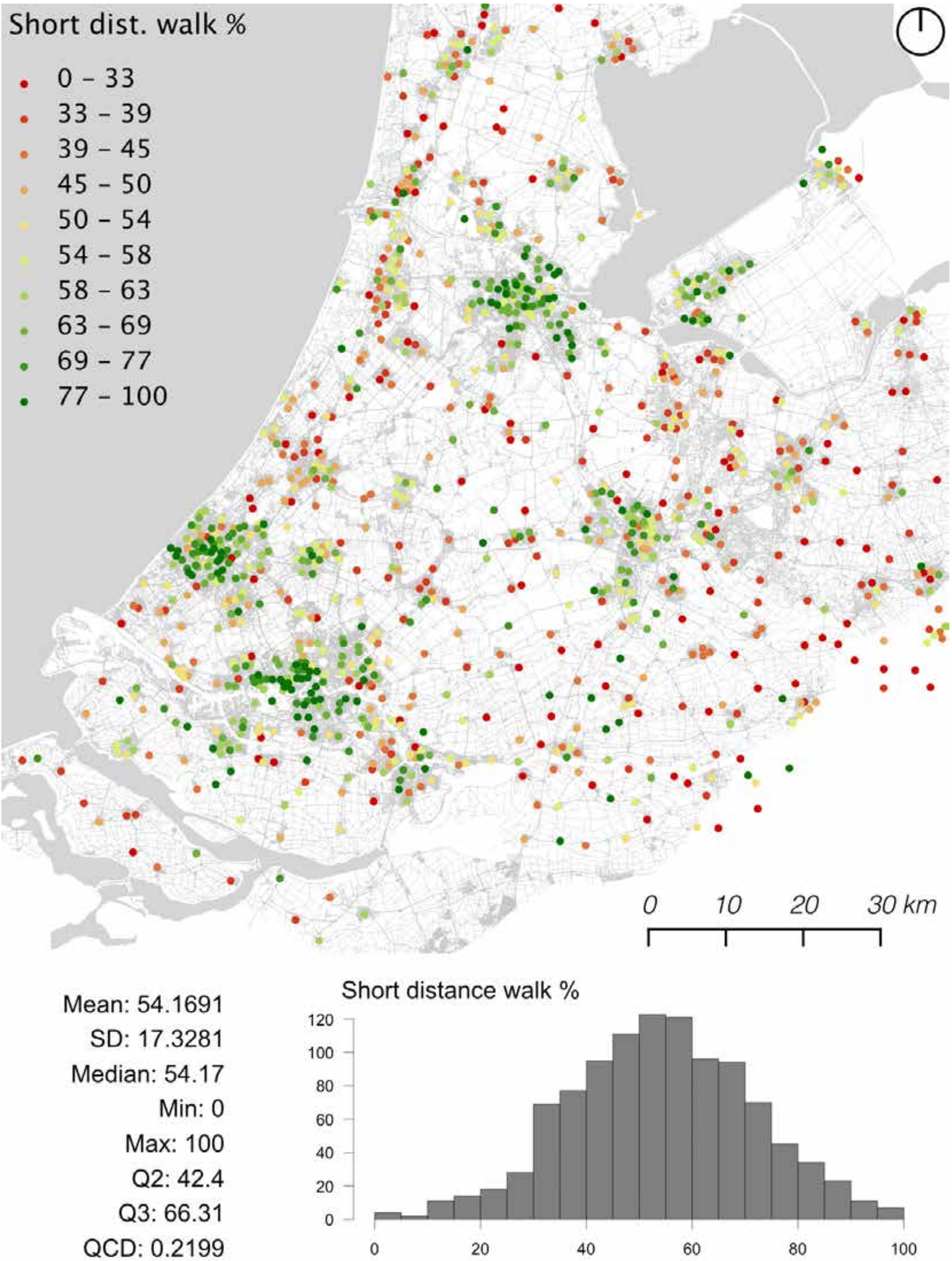


FIGURE APP.E.1 Profile of the short distance walk share in the Randstad.

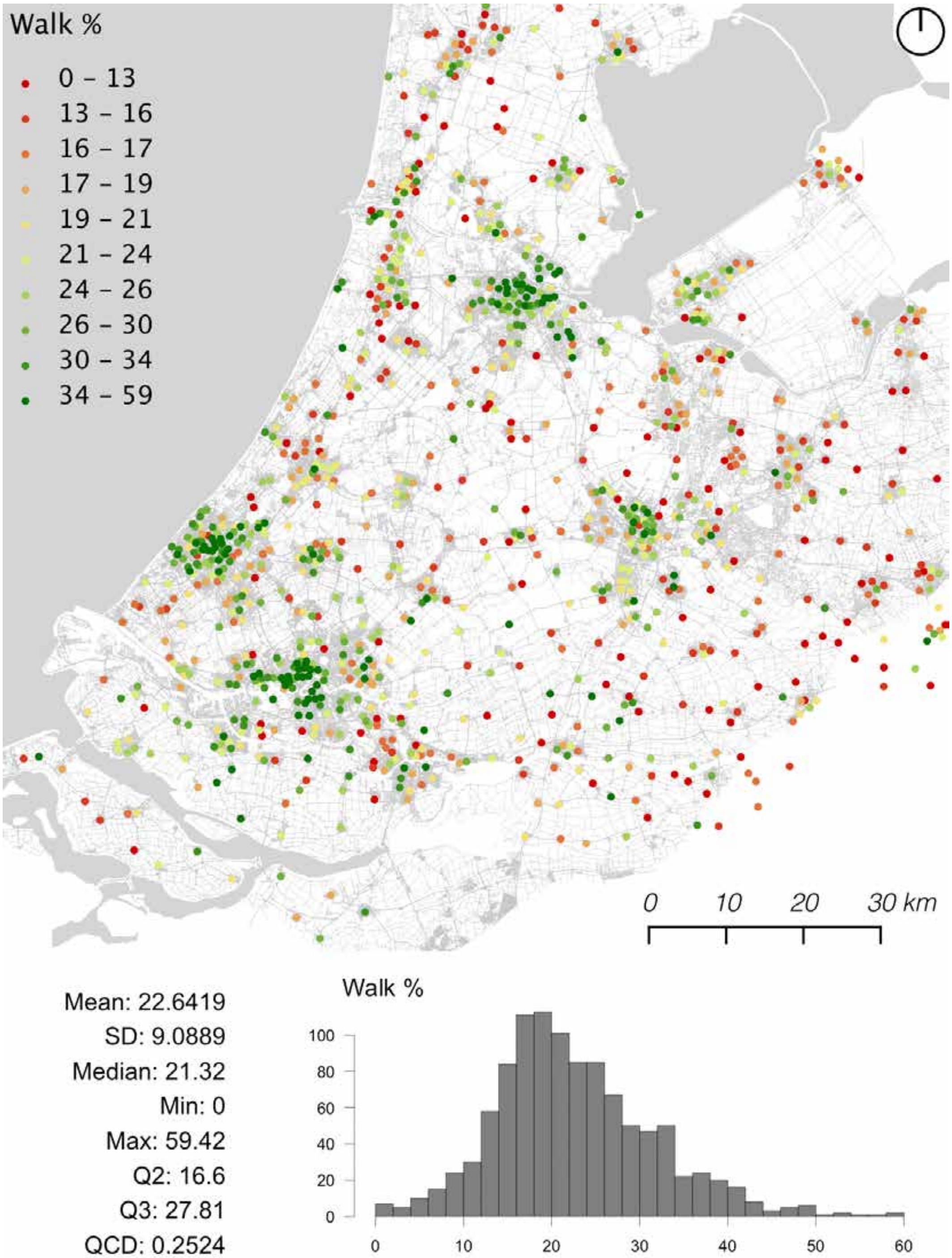


FIGURE APP.E.2 Profile of the walk share in the Randstad.

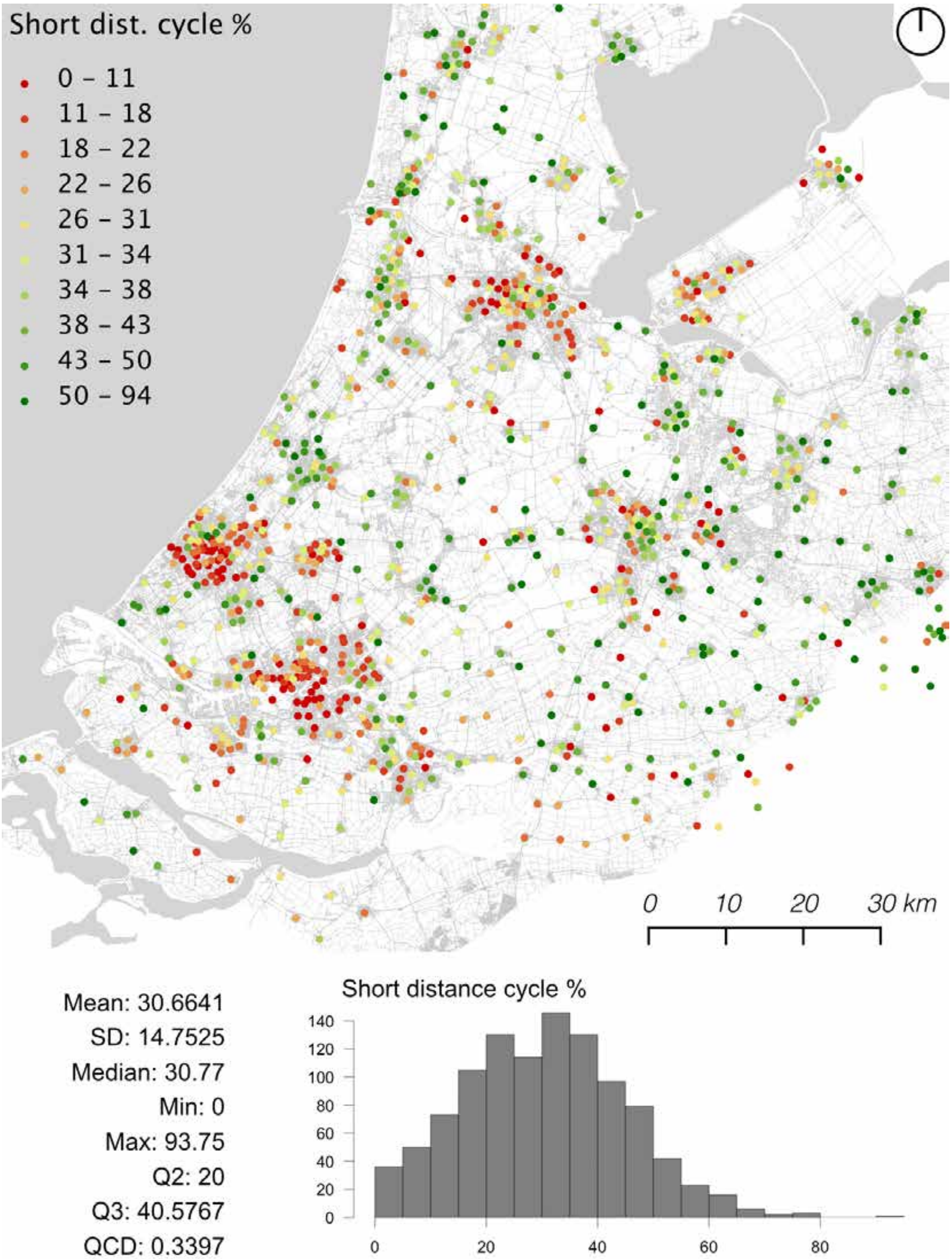


FIGURE APP.E.3 Profile of the short distance cycle share in the Randstad.

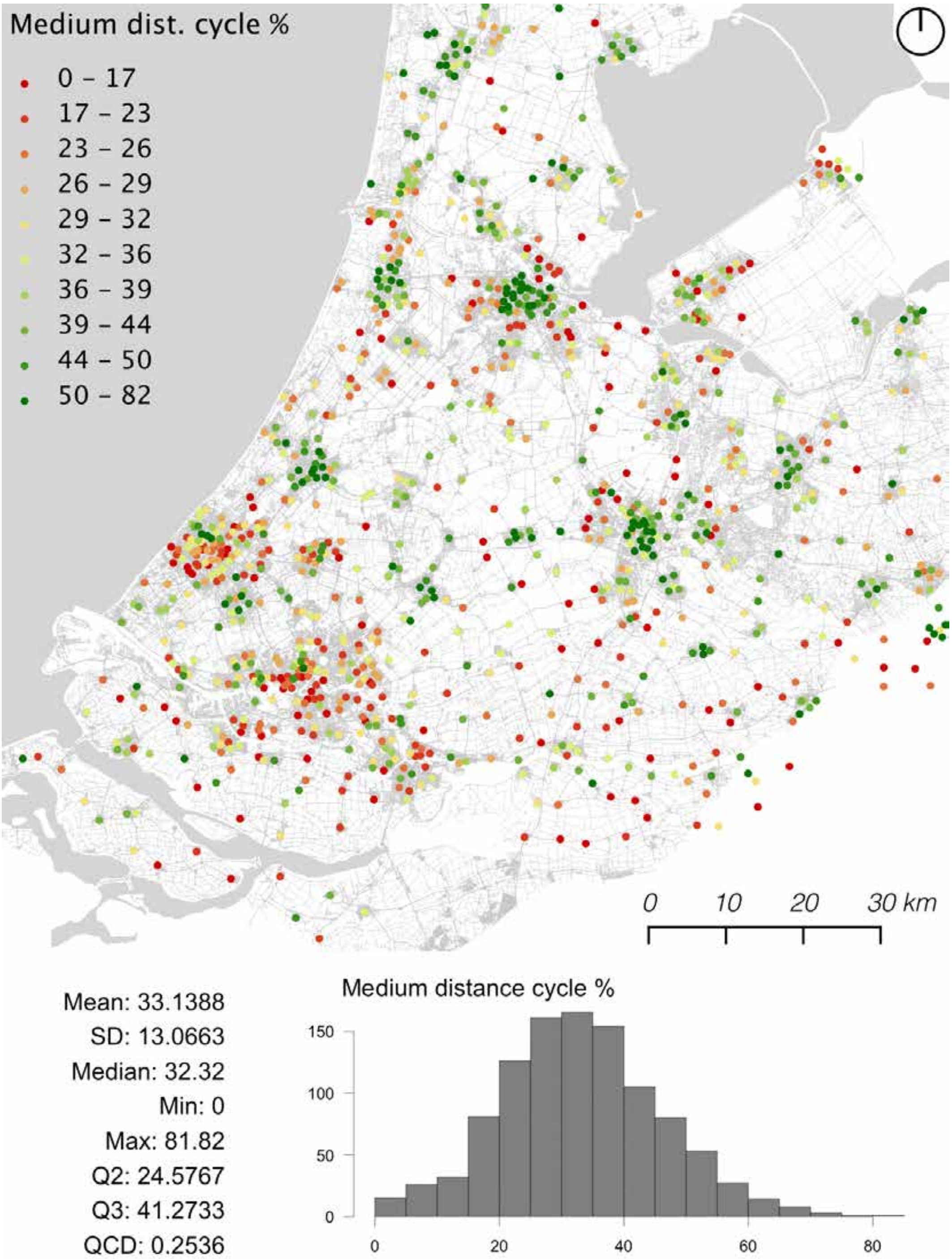


FIGURE APP.E.4 Profile of the medium distance cycle share in the Randstad.

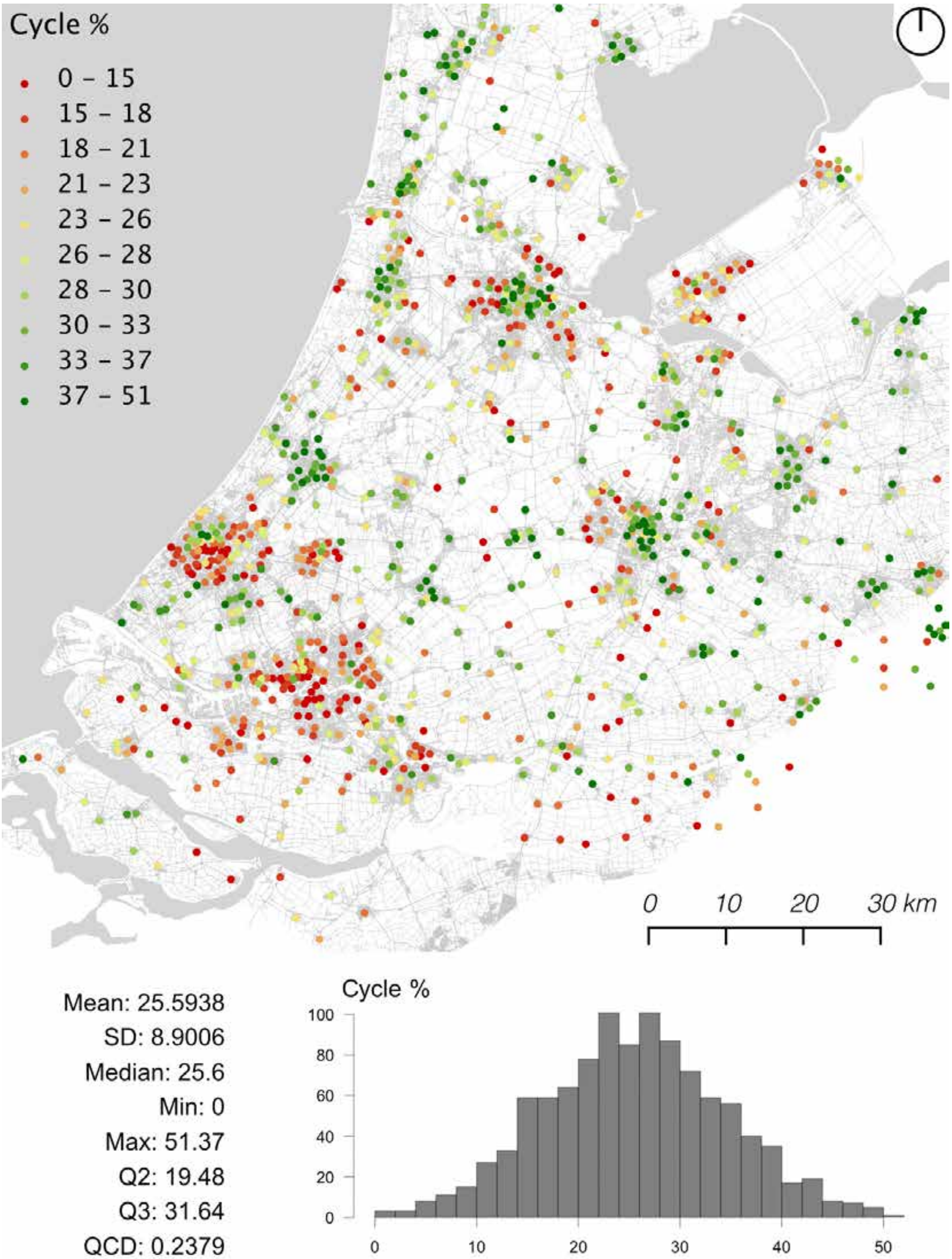


FIGURE APP.E.5 Profile of the cycle share in the Randstad.

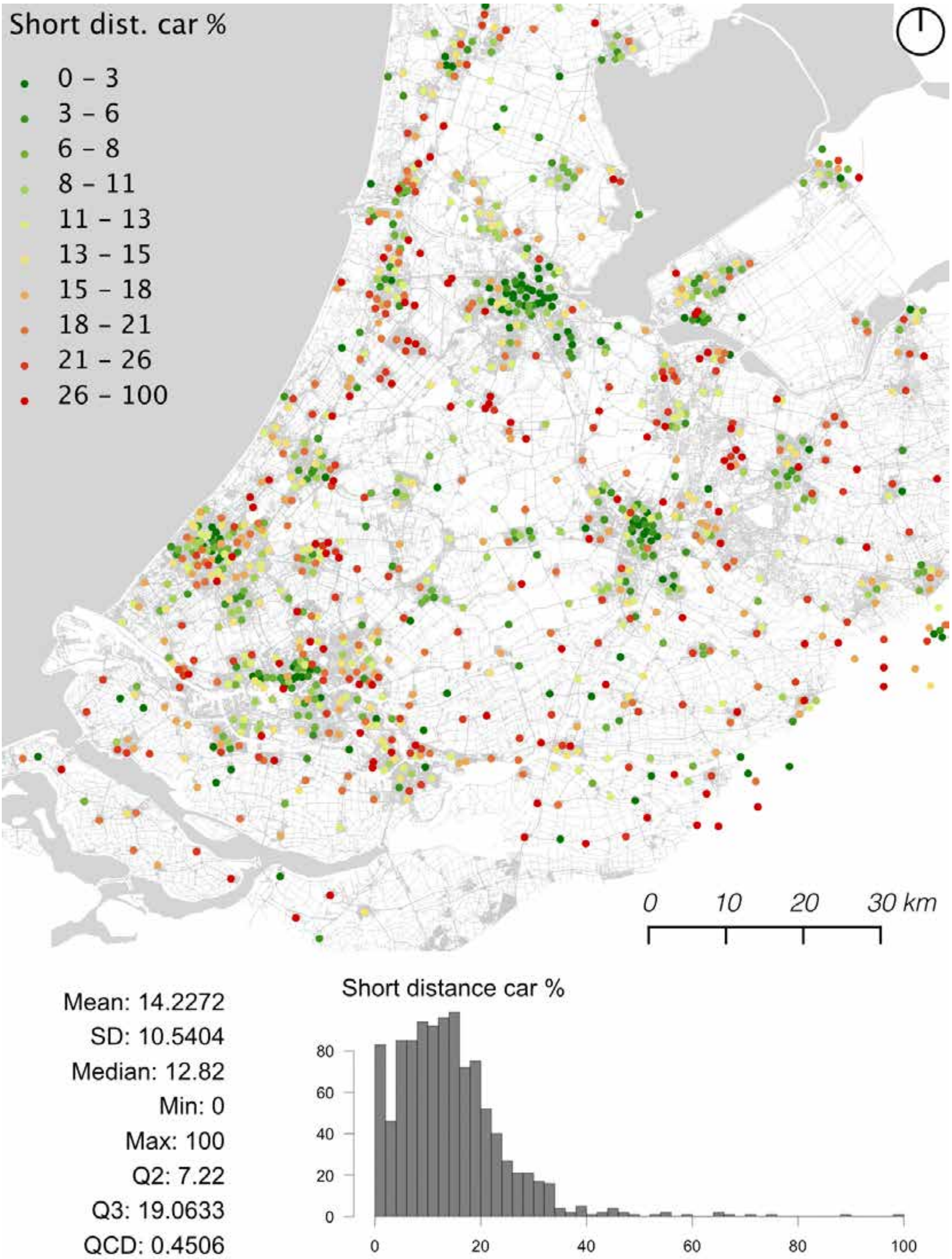


FIGURE APP.E.6 Profile of the short distance car share in the Randstad.

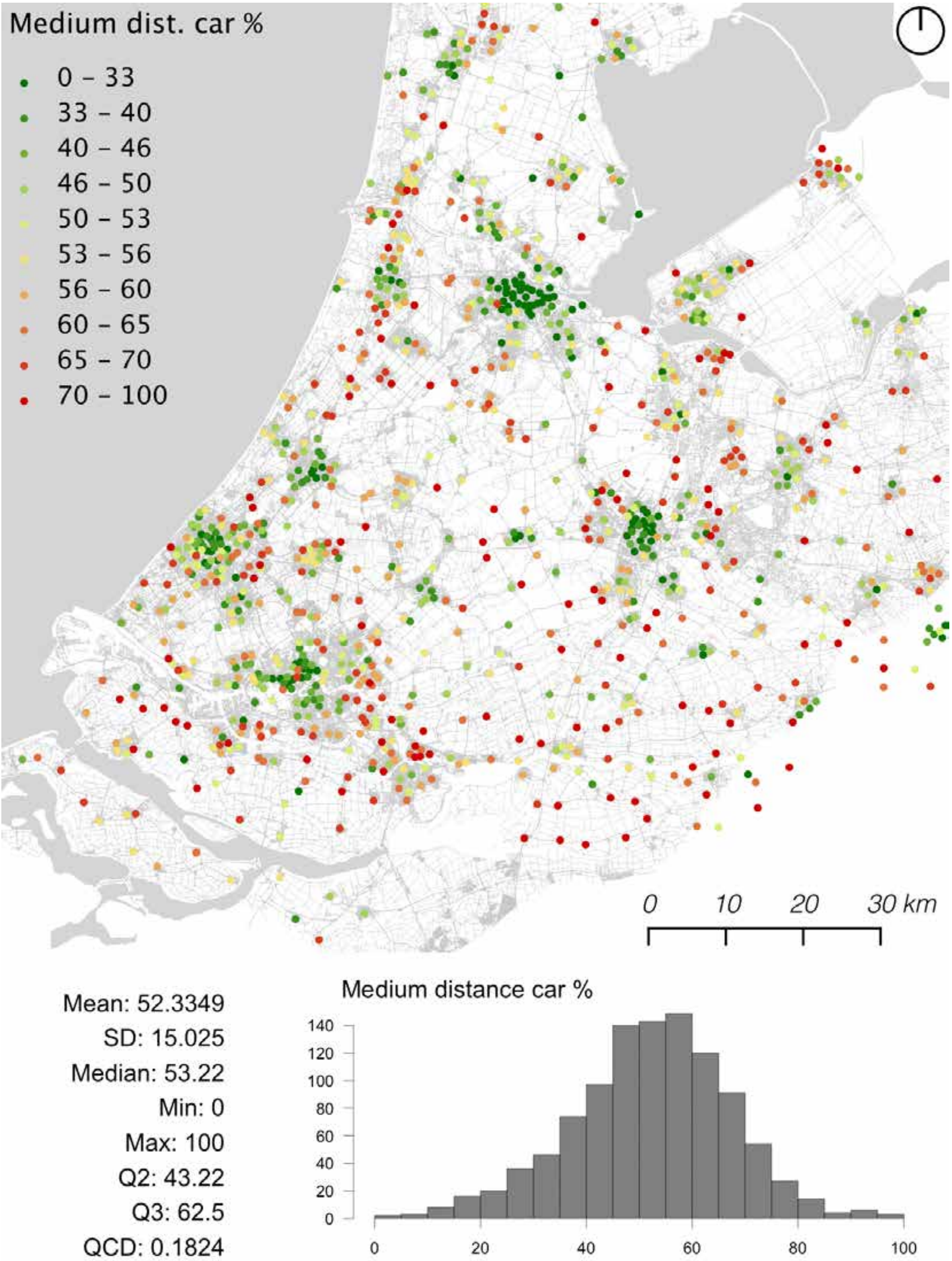


FIGURE APP.E.7 Profile of the medium distance car share in the Randstad.

TOC

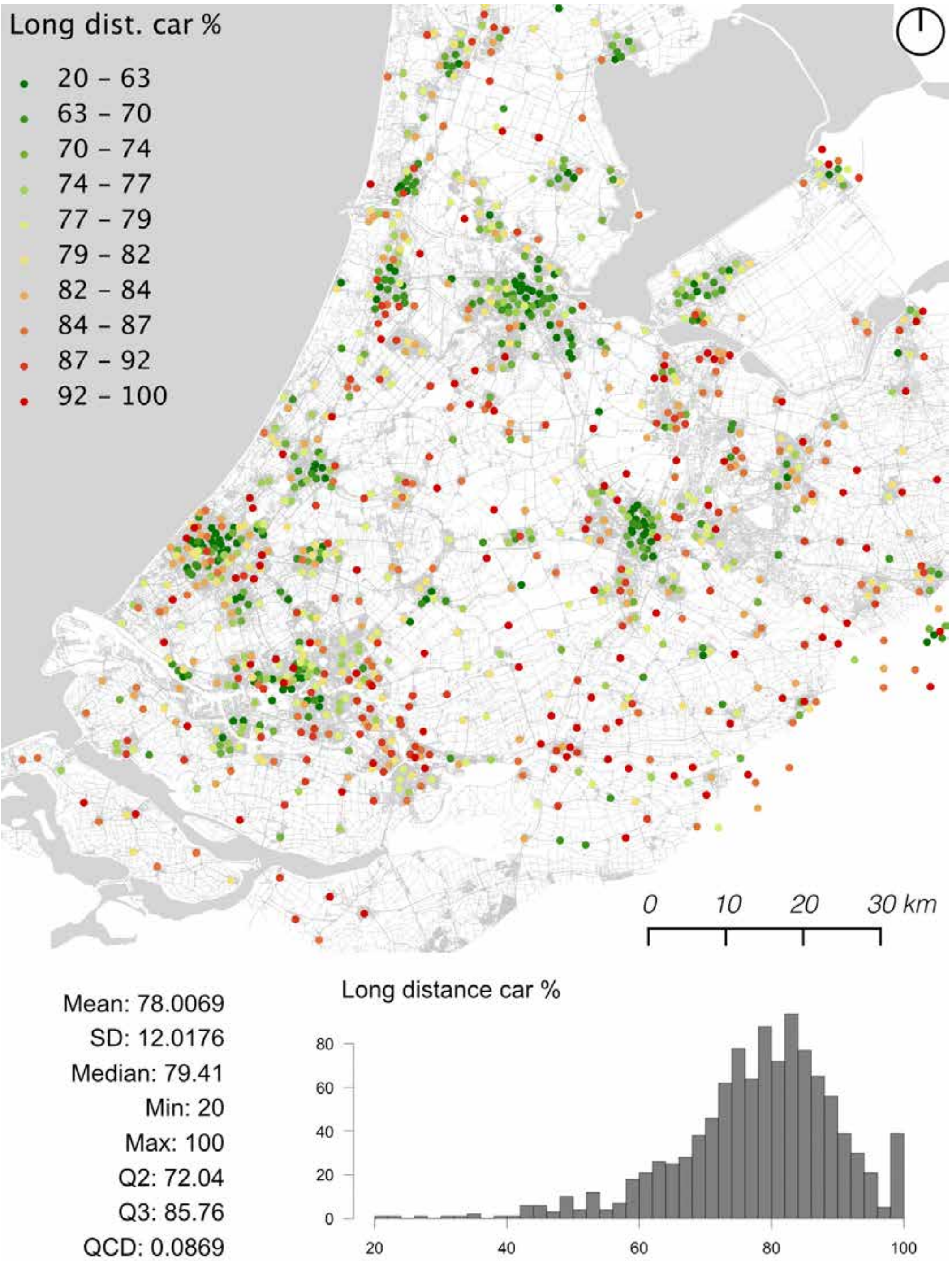


FIGURE APP.E.8 Profile of the long distance car share in the Randstad.

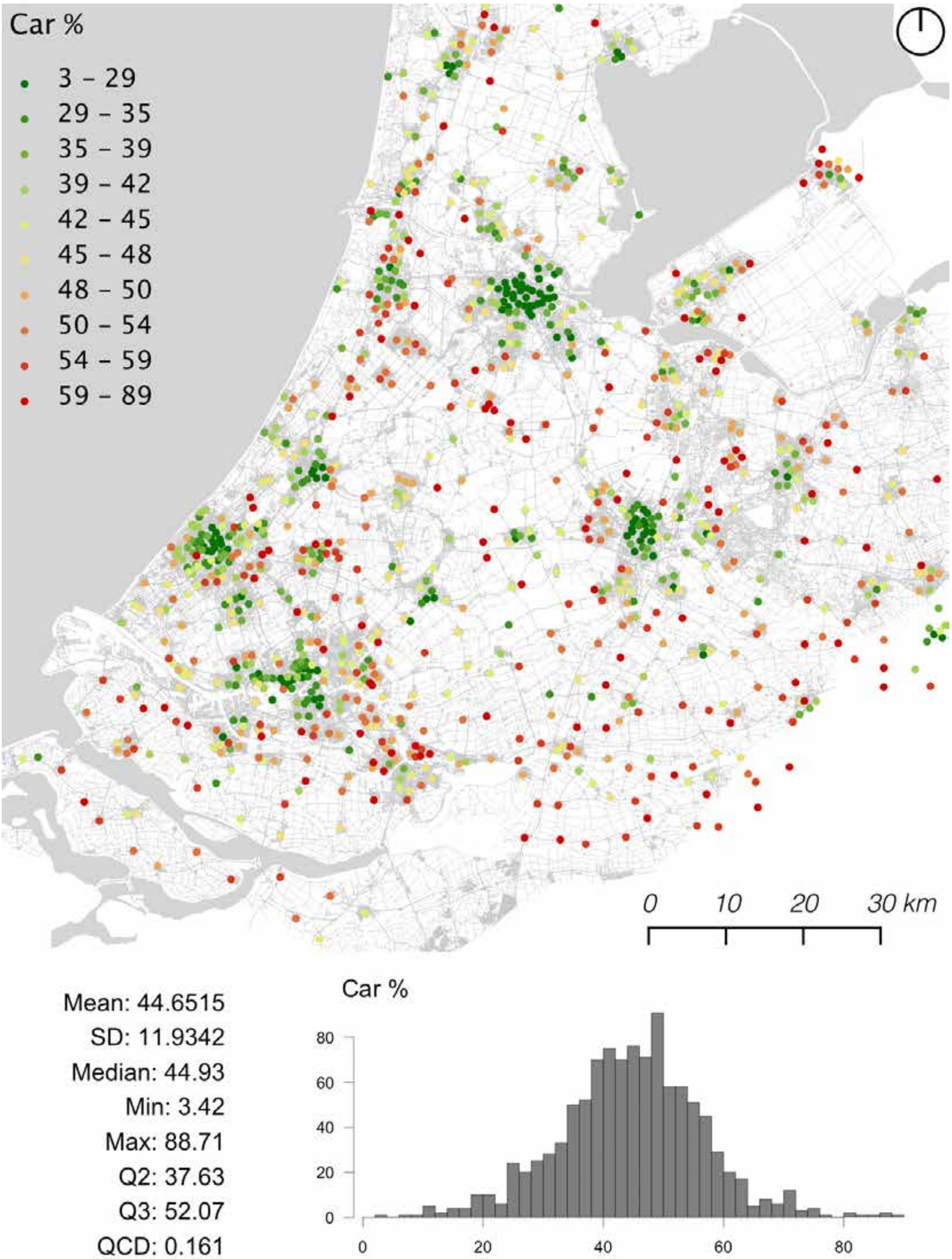


FIGURE APP.E.9 Profile of the car share in the Randstad.

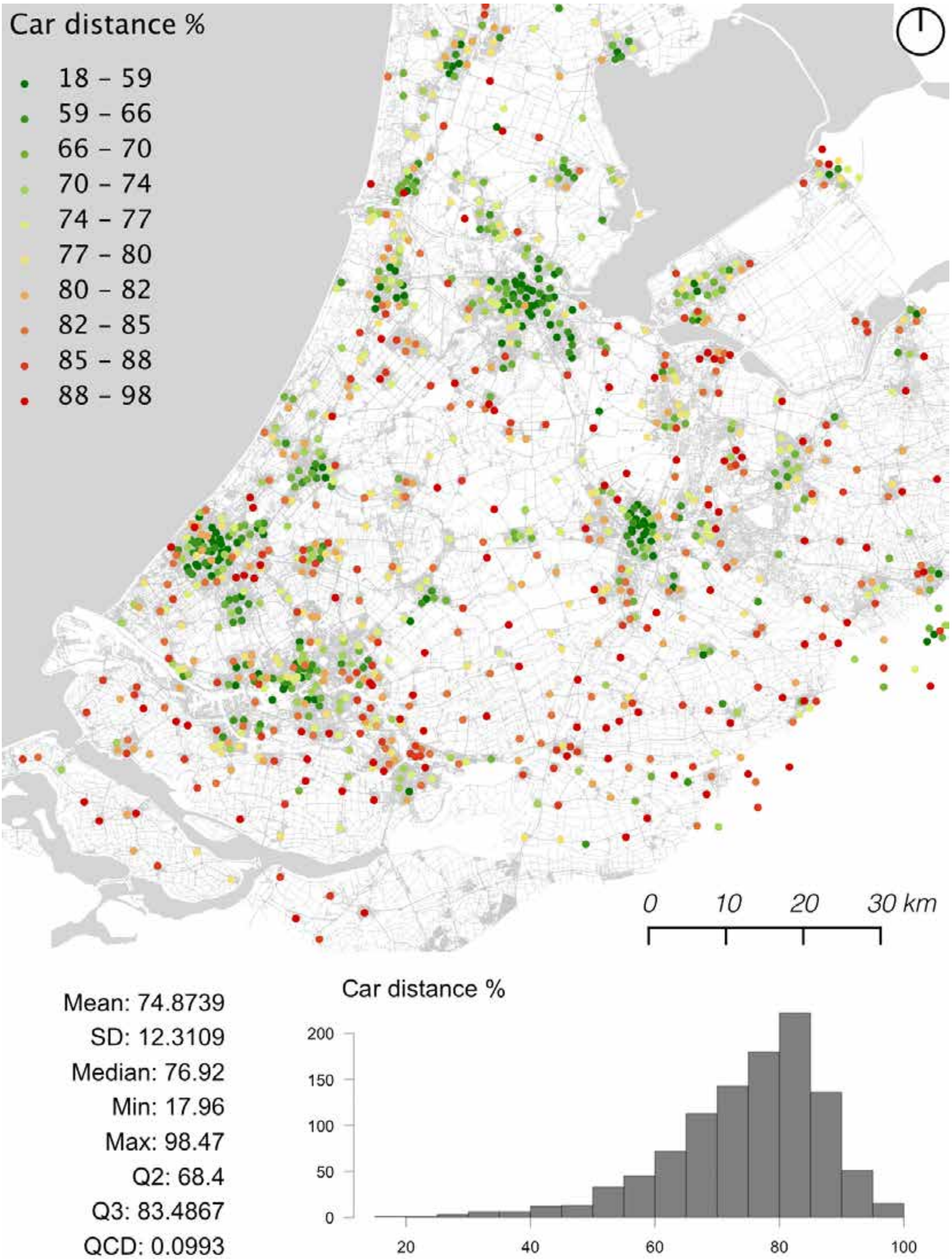


FIGURE APP.E.10 Profile of the travel distance car share in the Randstad.

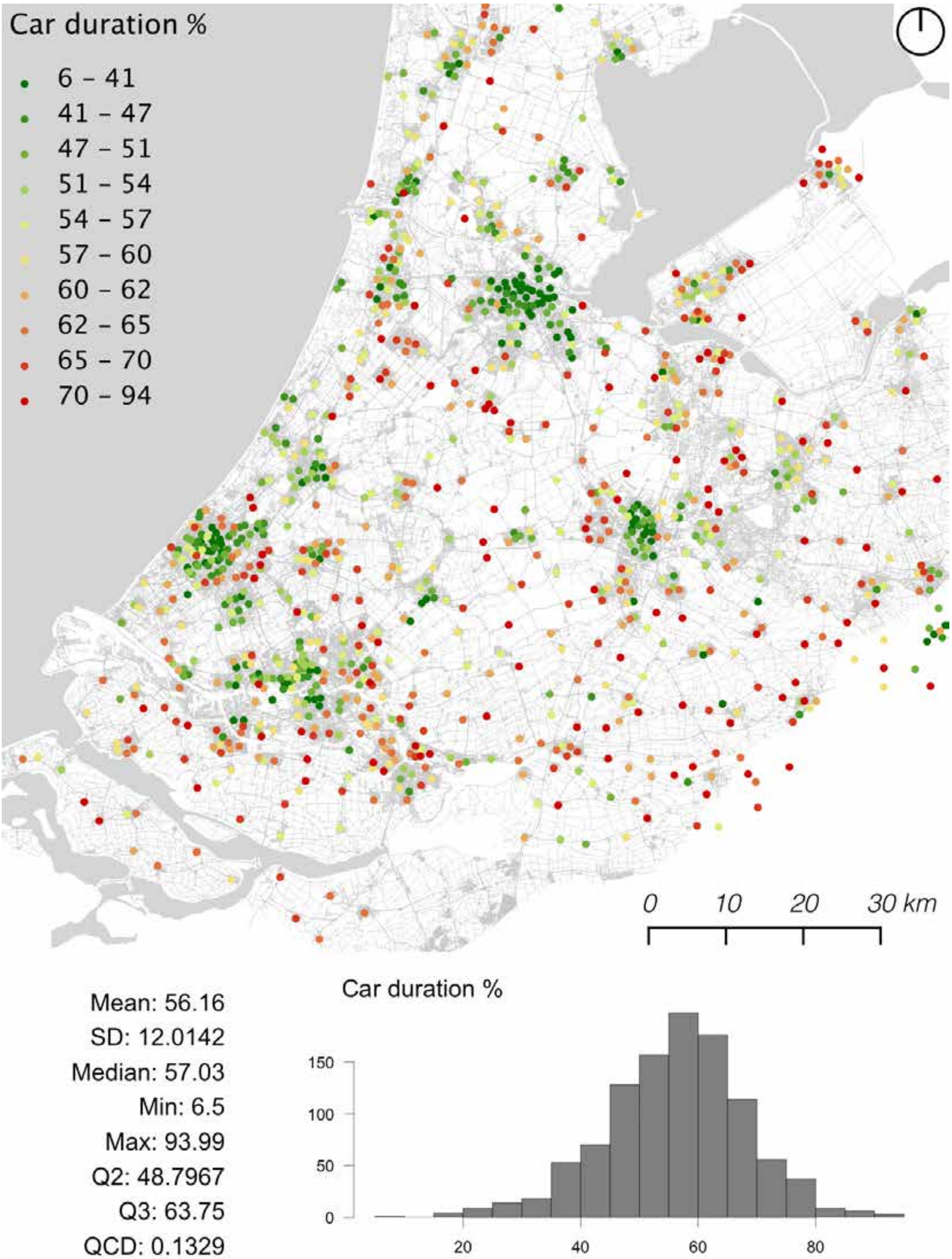


FIGURE APP.E.11 Profile of the travel duration car share in the Randstad.

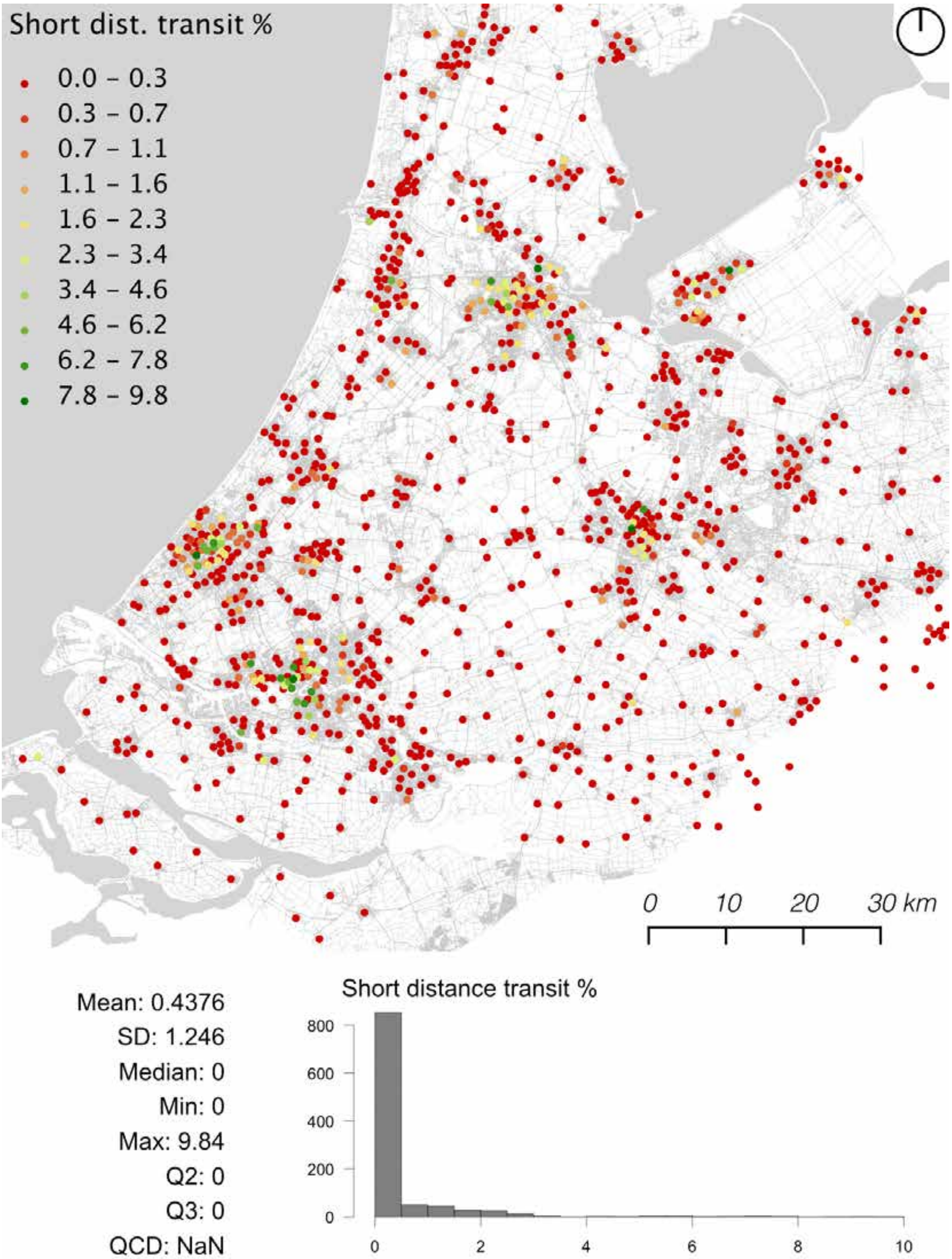


FIGURE APP.E.12 Profile of the short distance transit share in the Randstad.

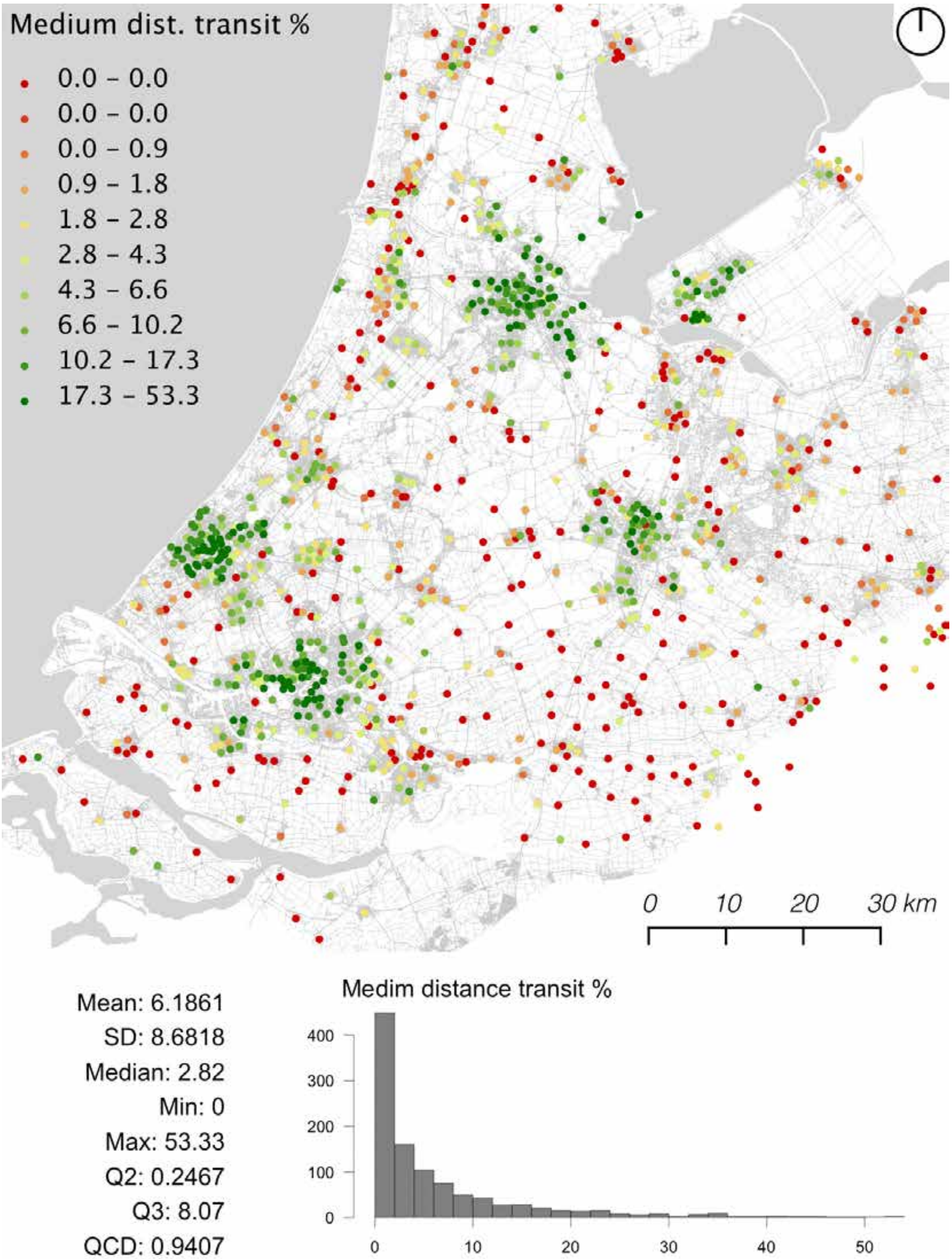


FIGURE APP.E.13 Profile of the medium distance transit share in the Randstad.

TOC

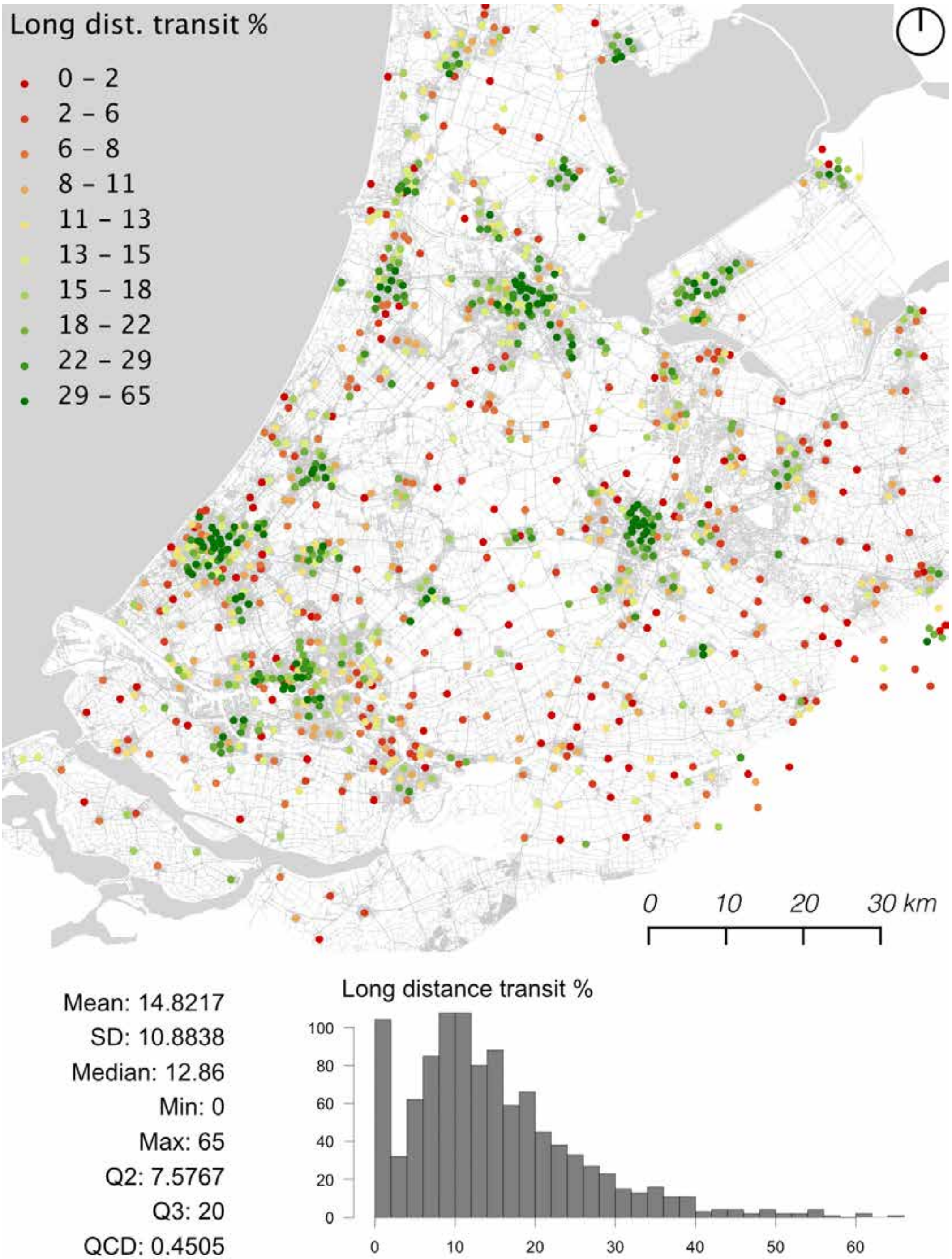


FIGURE APP.E.14 Profile of the long distance transit share in the Randstad.

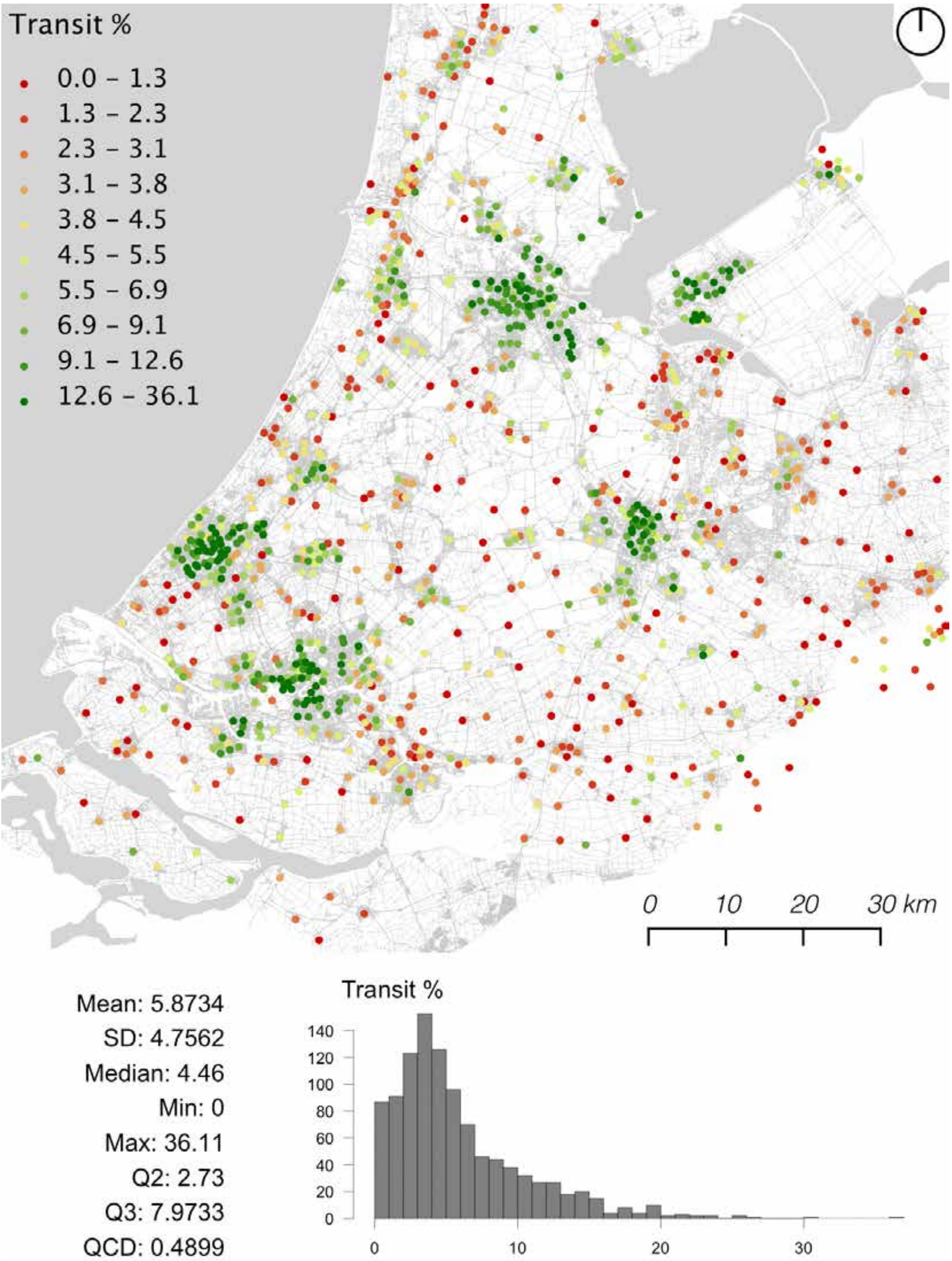


FIGURE APP.E.15 Profile of the transit share in the Randstad.

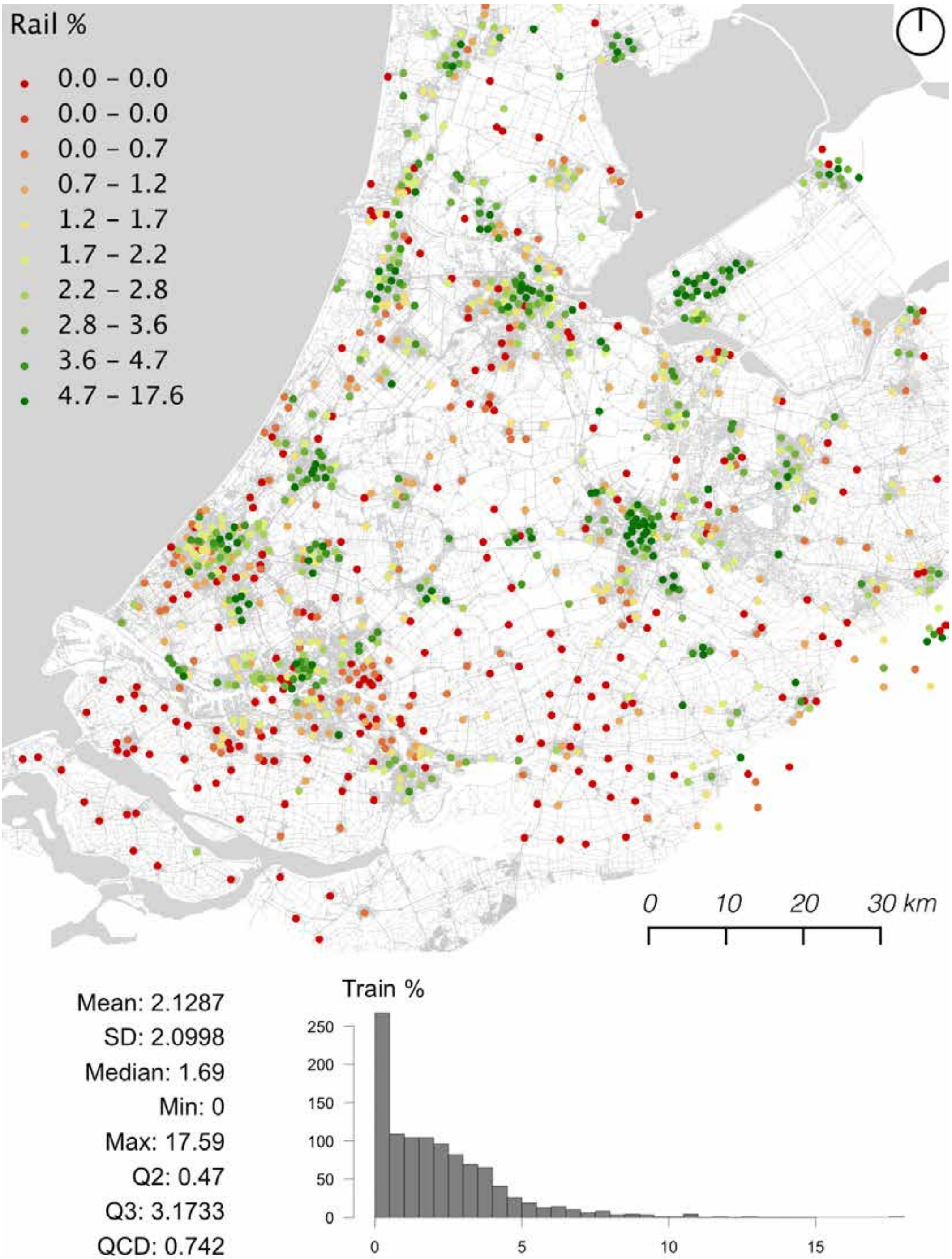


FIGURE APP.E.16 Profile of the rail share in the Randstad.

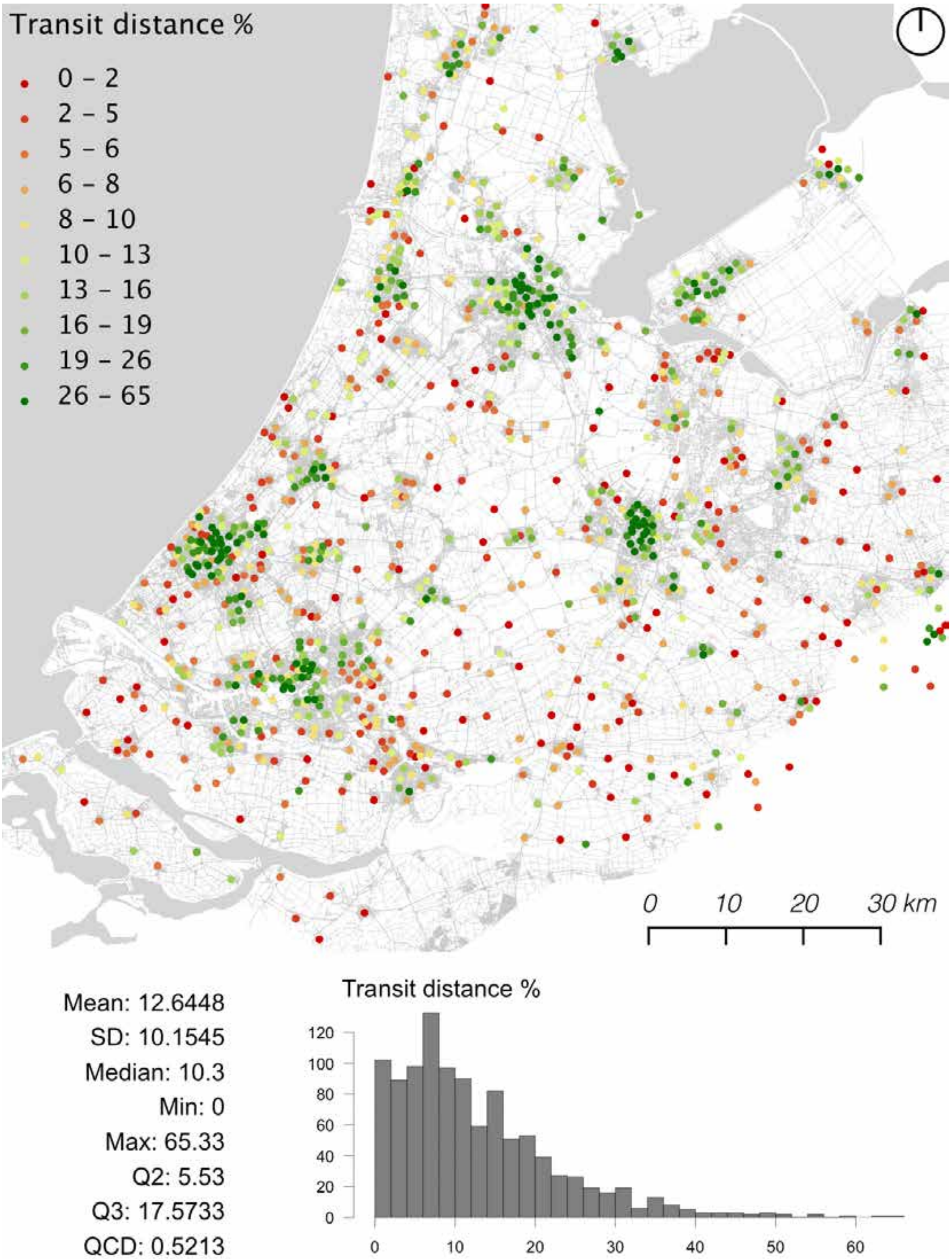


FIGURE APP.E.17 Profile of the travel distance transit share in the Randstad.

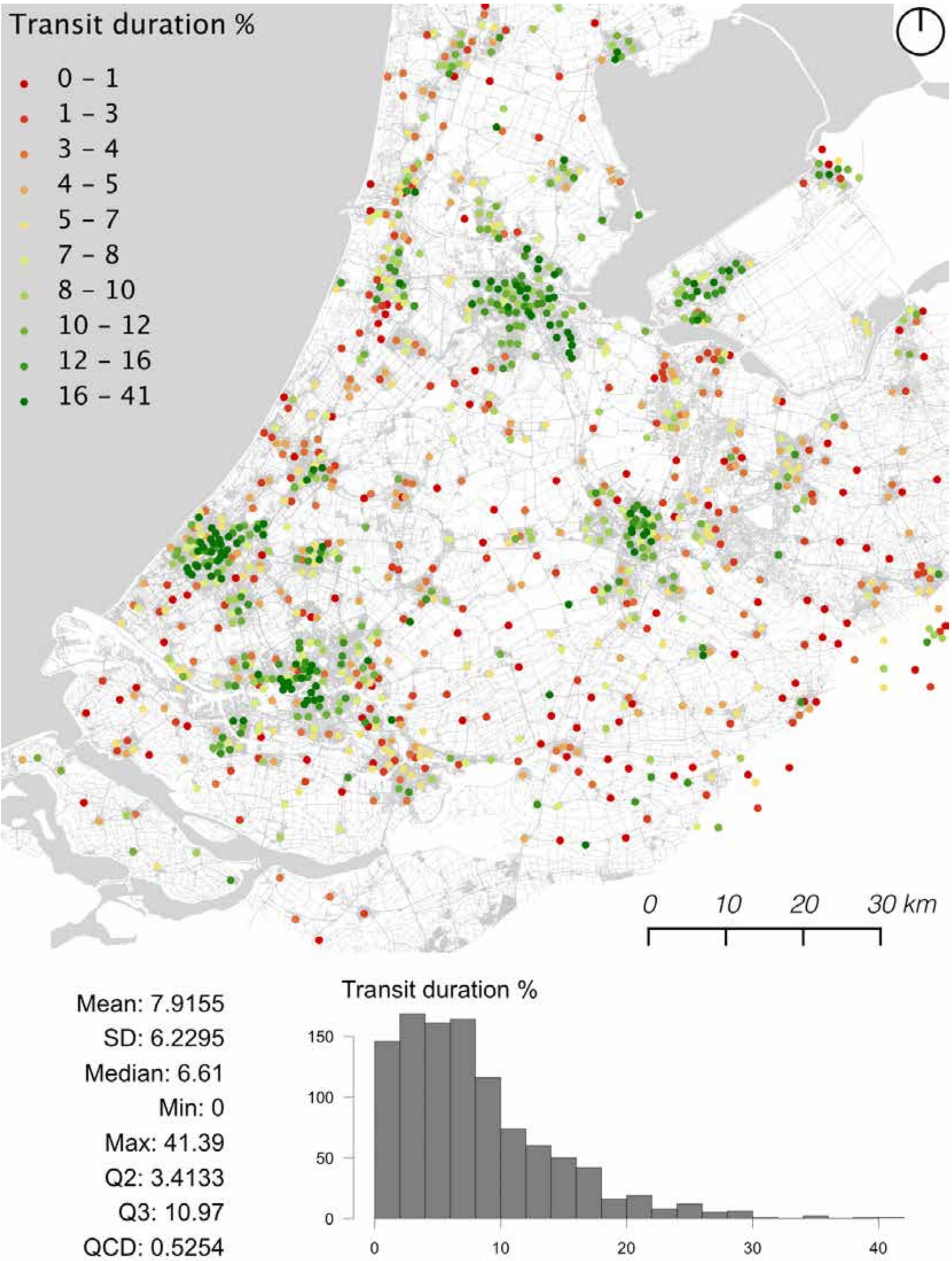


FIGURE APP.E.18 Profile of the travel duration transit share in the Randstad.

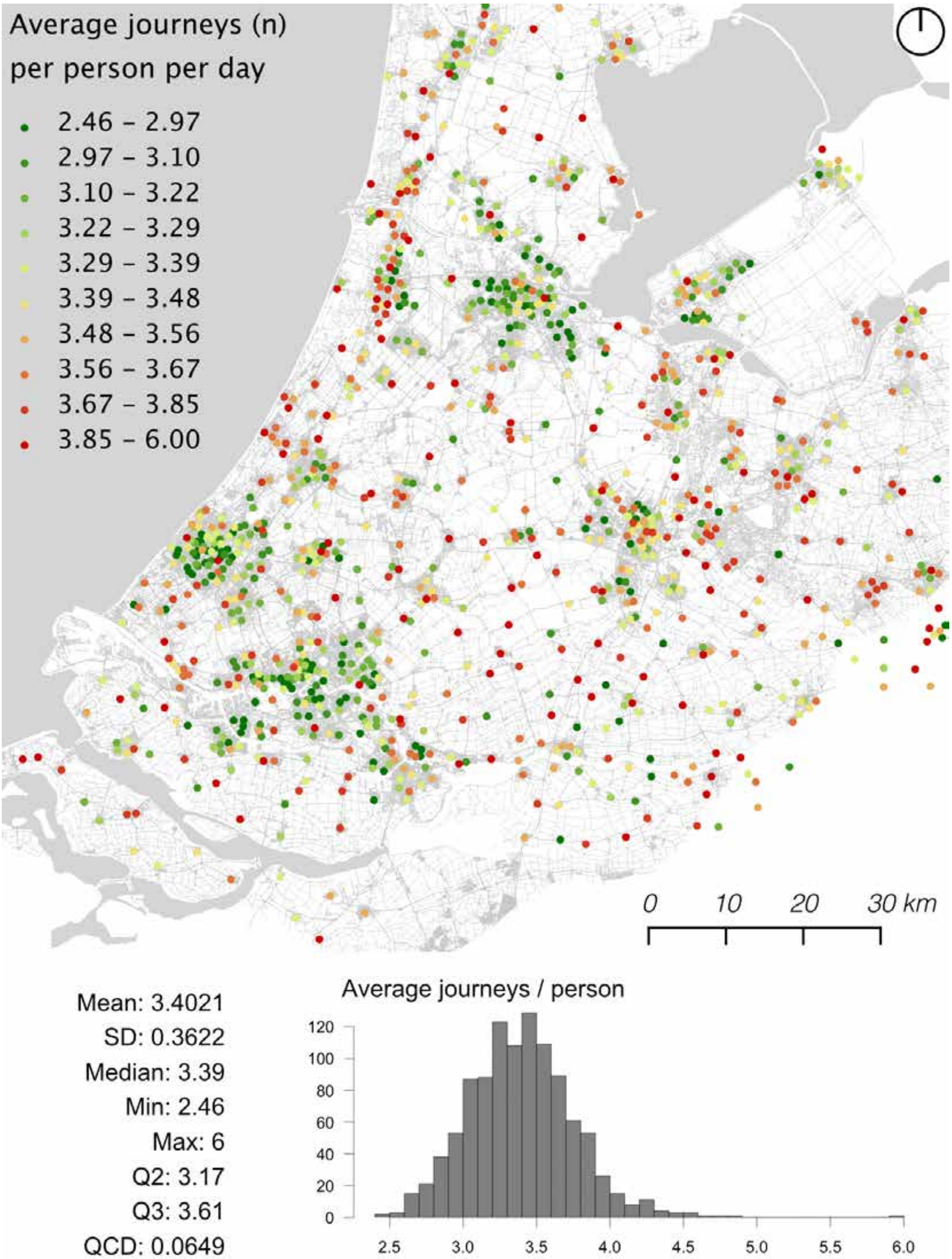


FIGURE APP.E.19 Profile of the average number of journeys per person per day in the Randstad.

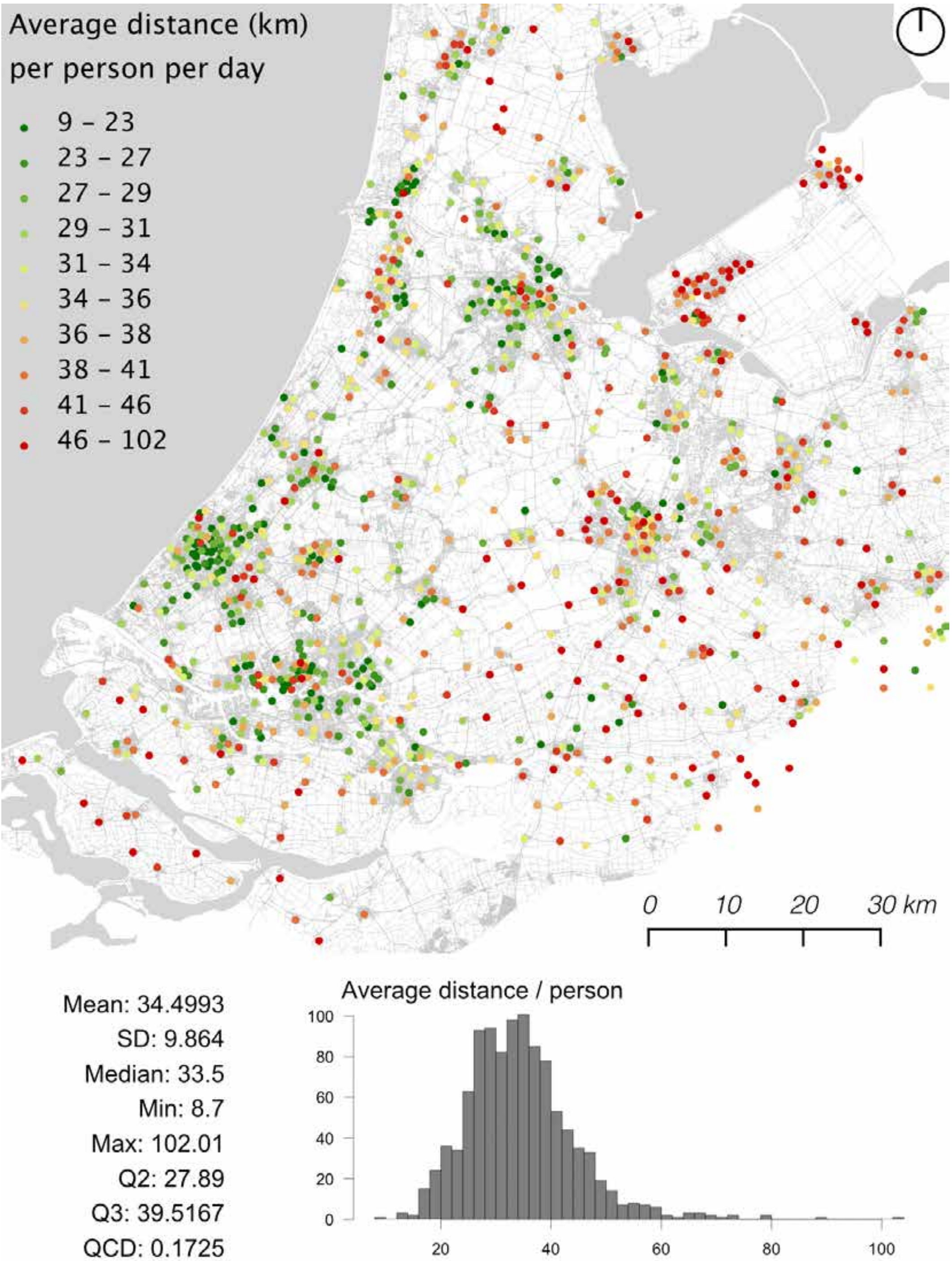


FIGURE APP.E.20 Profile of the average distance travelled per person per day in the Randstad.

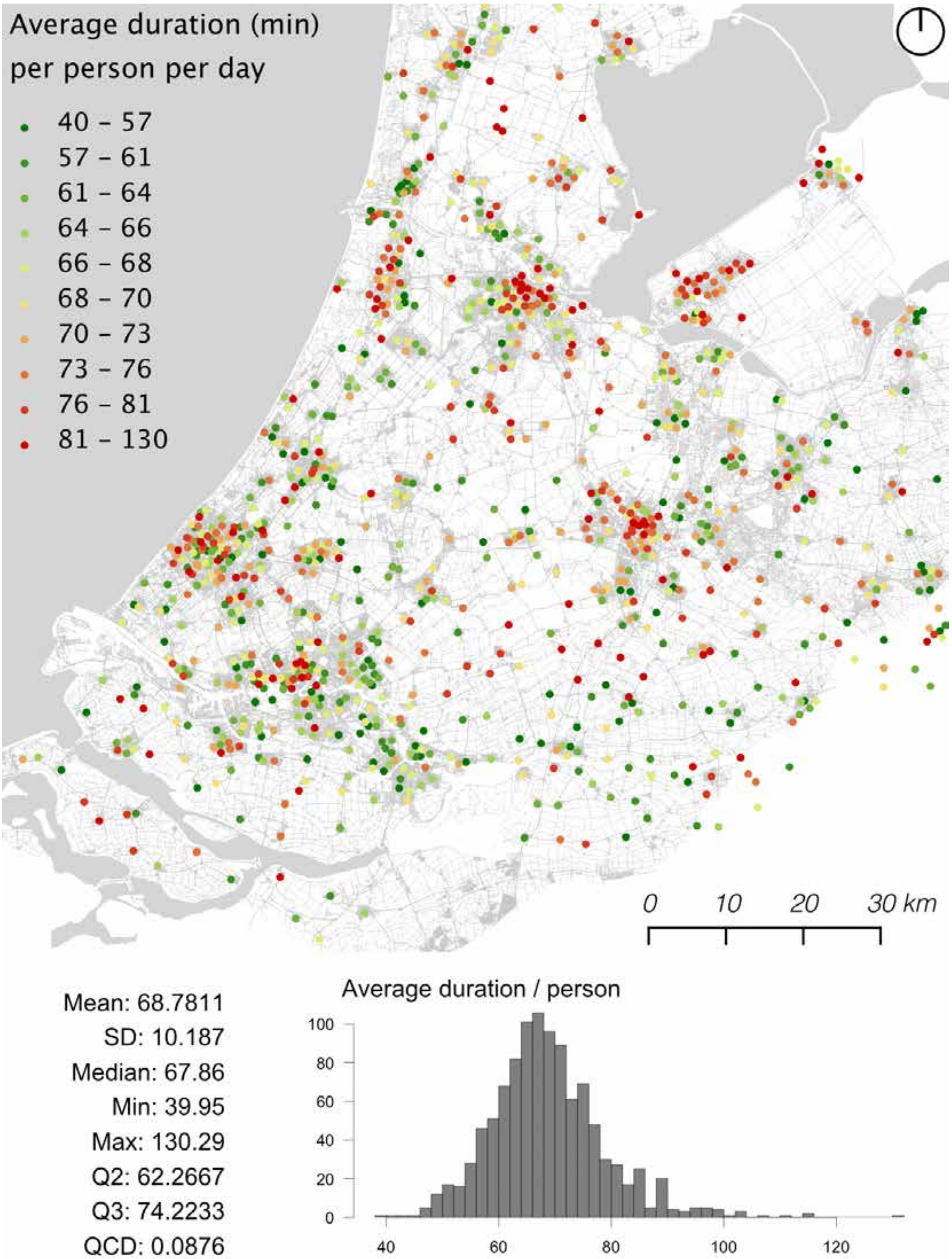


FIGURE APP.E.21 Profile of the average travel duration per person per day in the Randstad.

Appendix F List of urban form and accessibility measures calculated

The analysis of the multimodal network (Table F-1) resulted in more than 550 measures that were correlated within the measure's group for colinearity, and against mobility indicators for relevance. The selection of the best parameters resulted in a reduced set of measures for description and classification of urban areas. The measures have also been calculated for all types of distance (i.e. metric, angular, axial, continuity and topological) but only one type was selected in the end. Temporal distance was only calculated for car and transit, because pedestrians and bicycles have a constant speed and it is equivalent to metric distance.

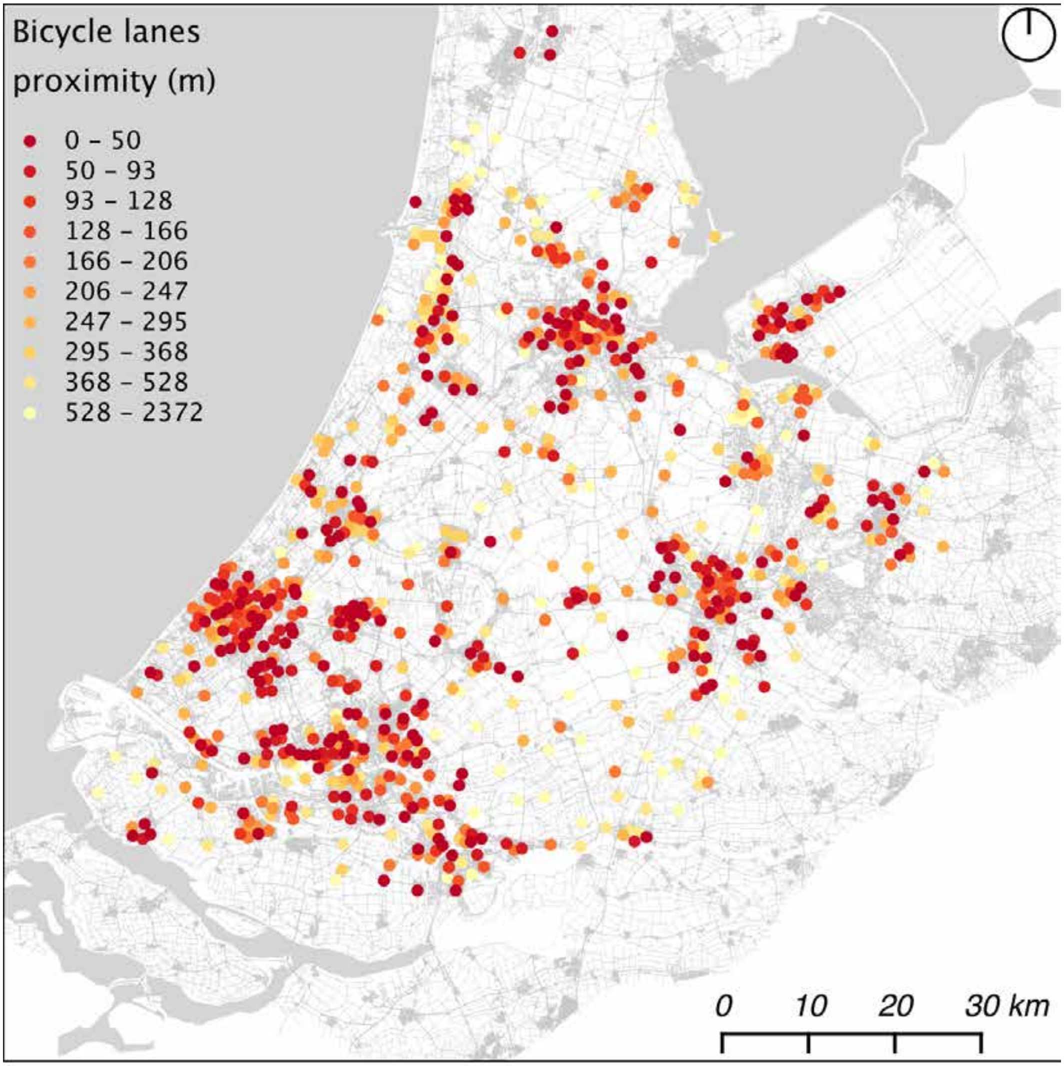
MEASURE	TARGET	DISTANCE TYPE	CUT-OFF	UNIT
Proximity	**Distance to nearest feature**			
Network	Pedestrian areas	Metric	-	m
	Bicycle lanes	Metric	-	m
	Main roads	Metric	-	m
	Motorways	Metric	-	m
	Local transit stops	Metric	-	m
	Rail stations	Metric	-	m
Density	**Size or count of features within catchment**			
Network	Pedestrian areas	Metric	400, 800, 1600m	m, n
	Bicycle lanes	Metric	400, 800, 1600m	m, n
	Motor roads	Metric	400, 800, 1600m	m, n
	Main roads	Metric	400, 800, 1600m	m, n
	Motorways	Metric	400, 800, 1600m	m, n
	Cul-de-sacs	Metric	400, 800, 1600m	n
	Crossings (X and T)	Metric	400, 800, 1600m	n
	Local transit stops	Metric	400, 800, 1600m	n
	Rail stations	Metric	400, 800, 1600m	n
Reach	Streets with non-motorised access	Angular	90, 180 degrees	m, n
	Motor roads	Angular	90, 180 degrees	m, n
Activity	Residential land use	Metric	400, 800, 1600m	m2, n
	Active land use	Metric	400, 800, 1600m	m2, n
	Work land use	Metric	400, 800, 1600m	m2, n
	Education land use	Metric	400, 800, 1600m	m2, n
Accessibility	**Activities within catchment (area; utility)**			
Activity	Active land use by car	Temporal	10, 20, 30 min	m2, -
	Active land use by transit	Temporal	10, 20, 30 min	m2, -
	Work land use by car	Temporal	10, 20, 30 min	m2, -
	Work land use by transit	Temporal	10, 20, 30 min	m2, -
Configuration	**Network centrality of area (mean; top decile share)**			
Closeness	Streets with non-motorised access	Angular	400, 800, 1600m	-
	Motor roads	Angular	400, 800, 1600m	-
	Local transit stops	Topological	400, 800, 1600m	-
	Rail stations	Topological	400, 800, 1600m	-
Betweenness	Bicycle lanes	Angular	400, 800, 1600m	-
	Motor roads	Angular	400, 800, 1600m	-

TABLE APP.F.1 Long list of the urban form and accessibility measures calculated for the individual postcode areas of the Randstad region.

Appendix G Multimodal urban form and accessibility of the Randstad

This series of maps and descriptive statistics shows the selection of urban form and accessibility indicators calculated for the urban areas in the Randstad, representing those used in the classification of 'urban modality'.

The coropleth maps use quantiles scales with 10 ranges, except where indicated in the caption. The maps only show the analysis results for postcodes within the study area, because the results in the buffer zone are potentially affected by edge effect. The buffer zone's network and land use was nevertheless included in the analysis.



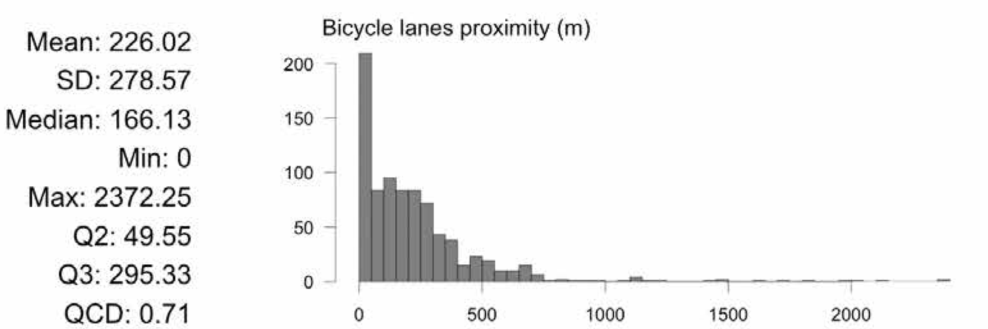


FIGURE APP.G.1 Proximity to bicycle lanes, map and descriptive statistics. (12 initial quantiles, with bottom ranges (value = 0) merged).

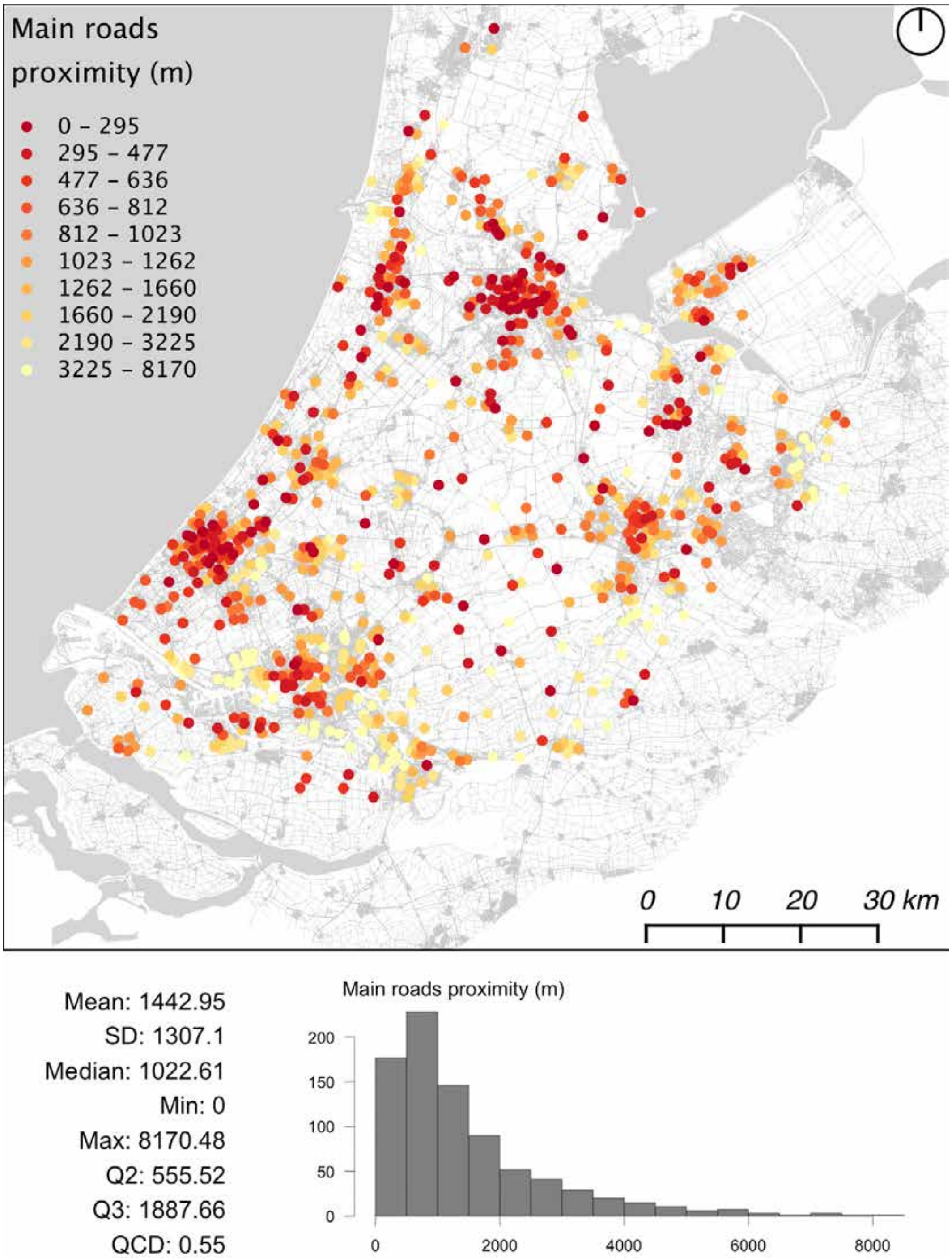


FIGURE APP.G.2 Proximity to main roads, map and descriptive statistics.

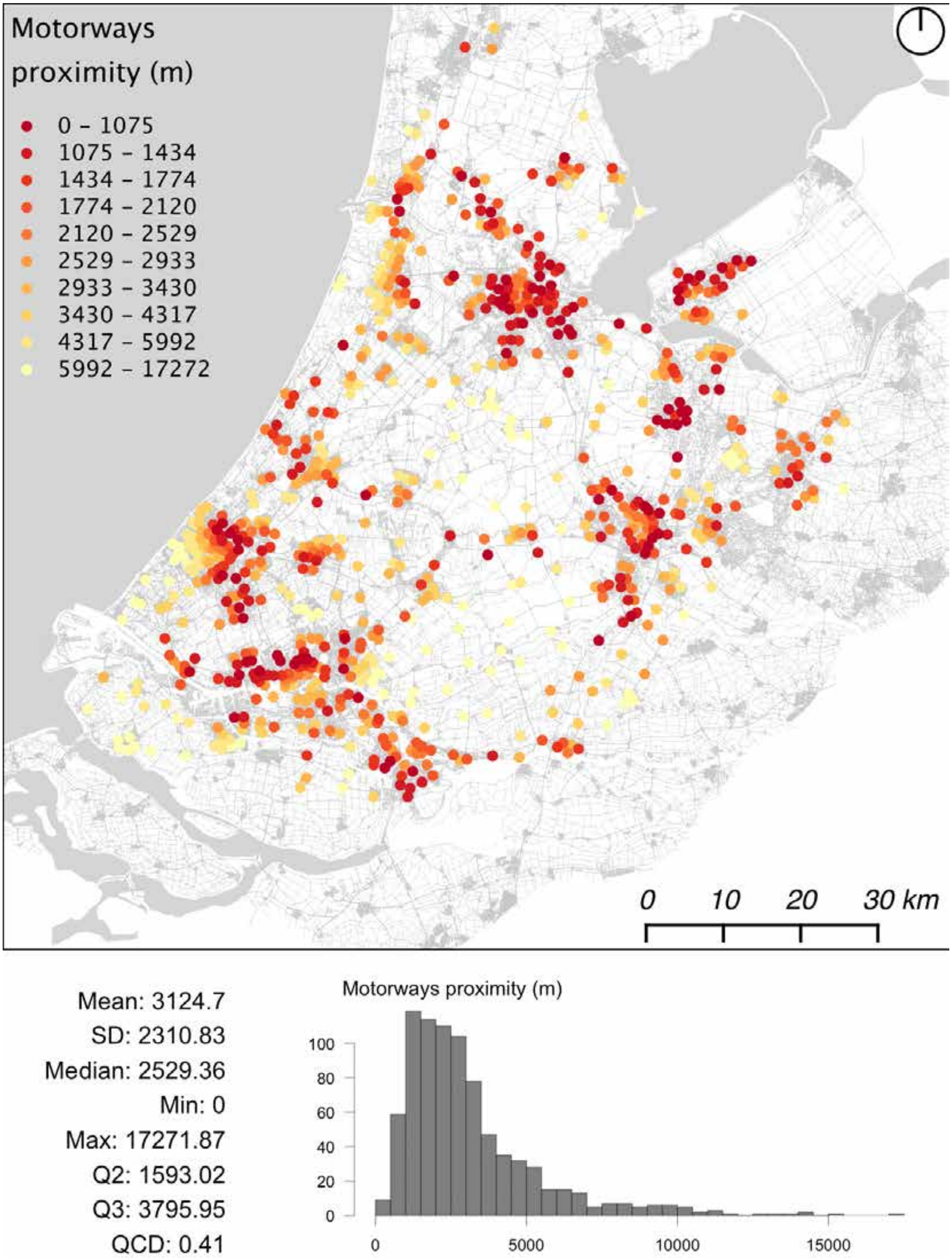


FIGURE APP.G.3 Proximity to motorways, map and descriptive statistics.

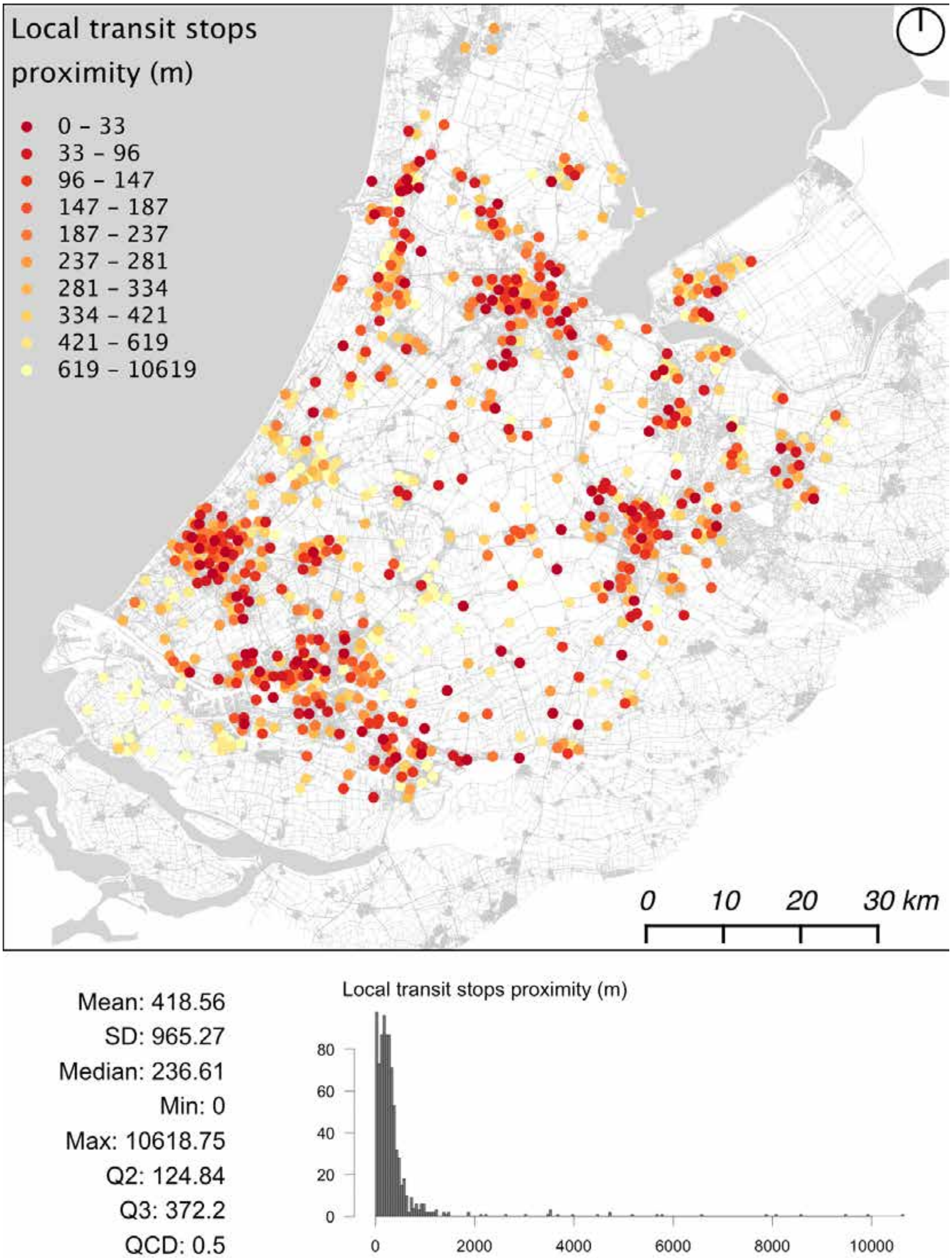


FIGURE APP.G.4 Proximity to local transit stops, map and descriptive statistics.

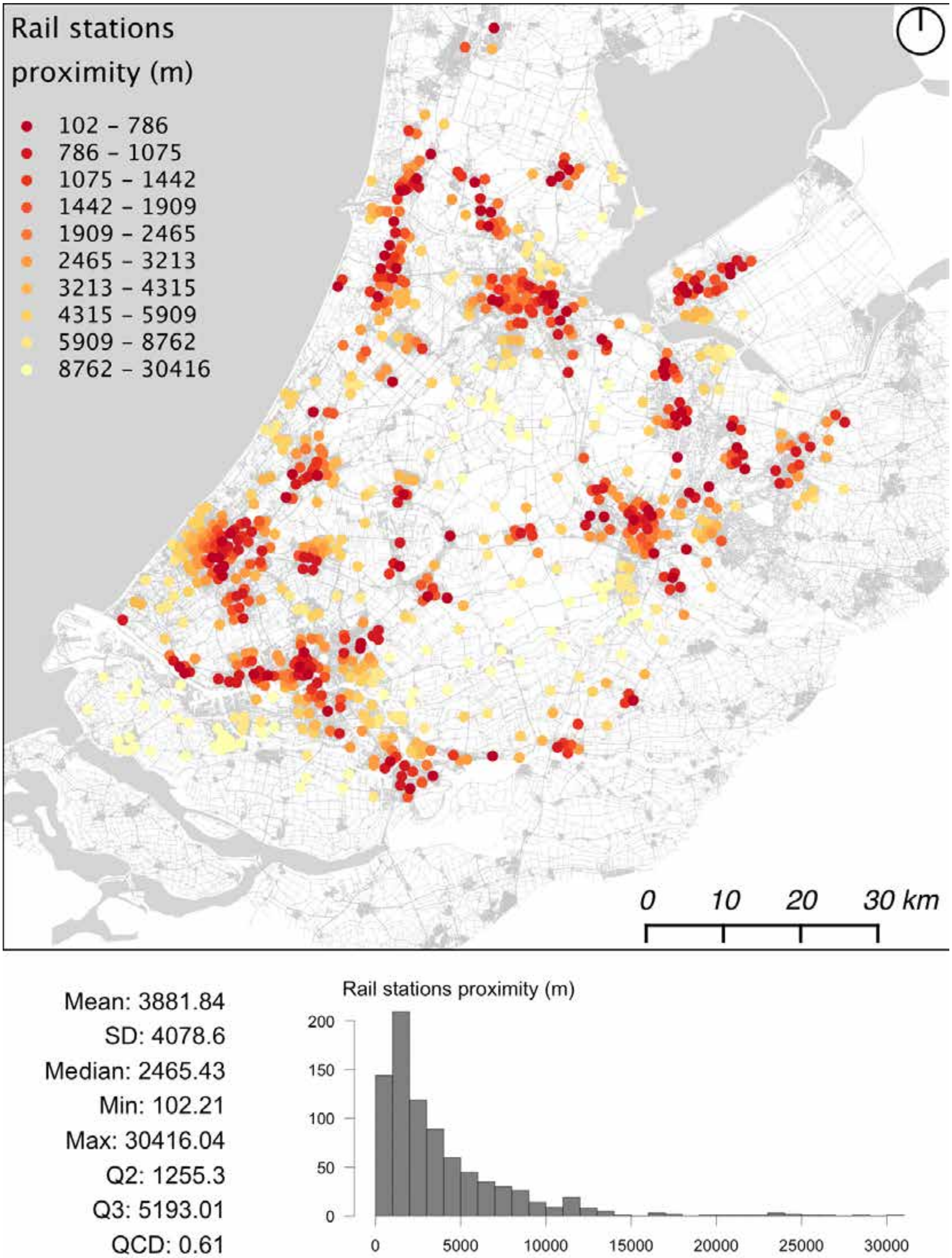


FIGURE APP.G.5 Proximity to rail stations, map and descriptive statistics.

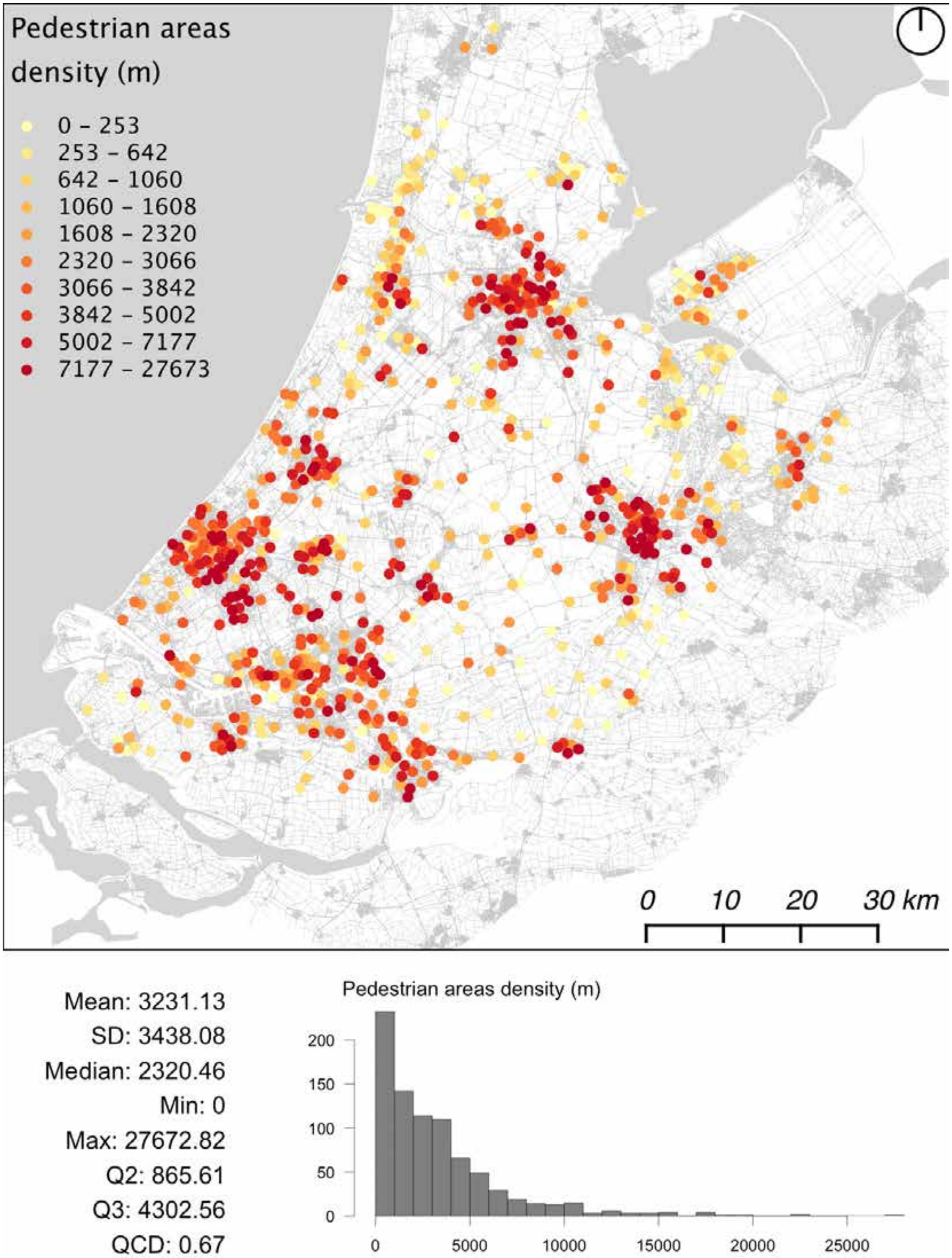


FIGURE APP.G.6 Network density of pedestrian areas (m) within 800m catchment, map and descriptive statistics.

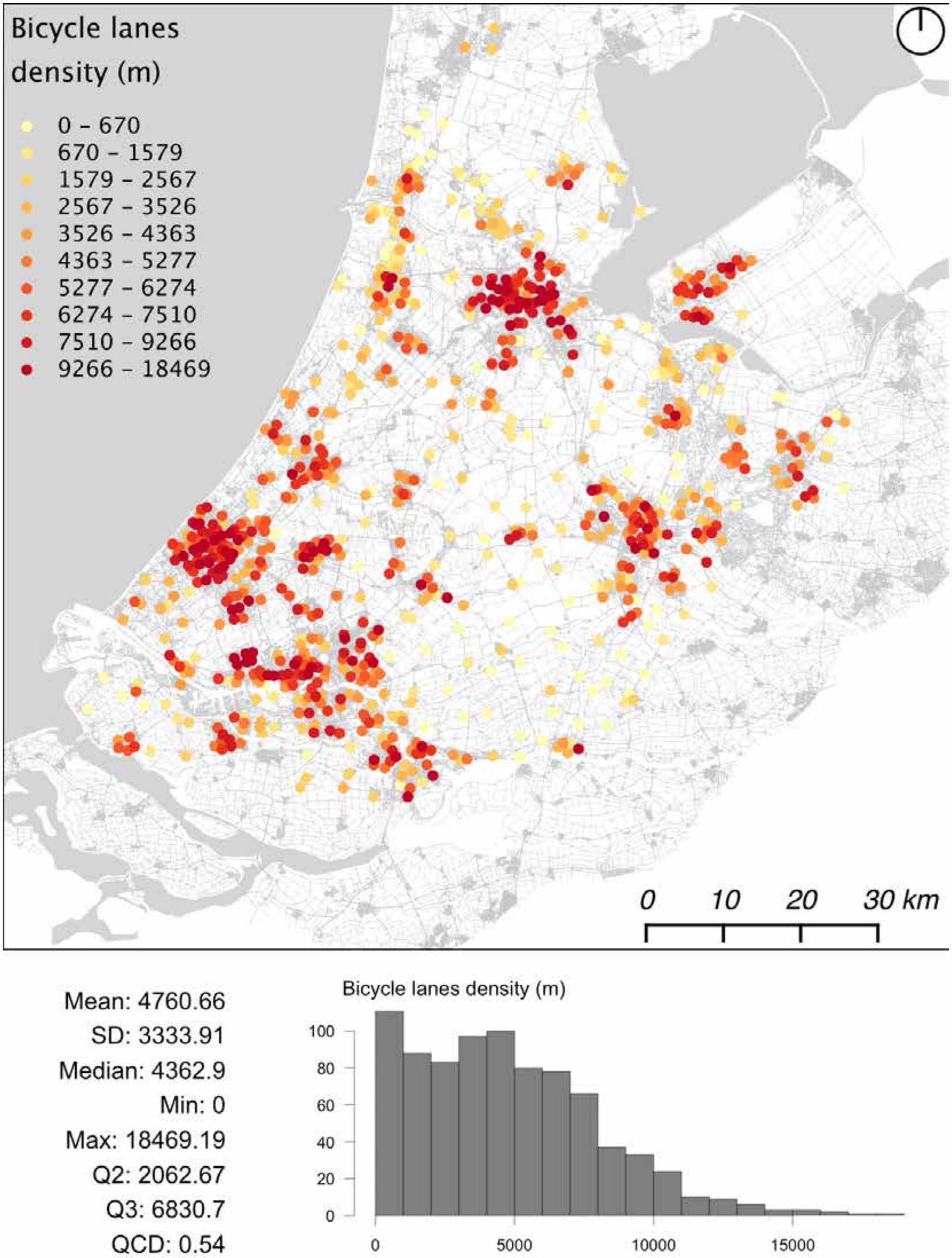


FIGURE APP.G.7 Network density of bicycle lanes (m) within 800m catchment, map and descriptive statistics.

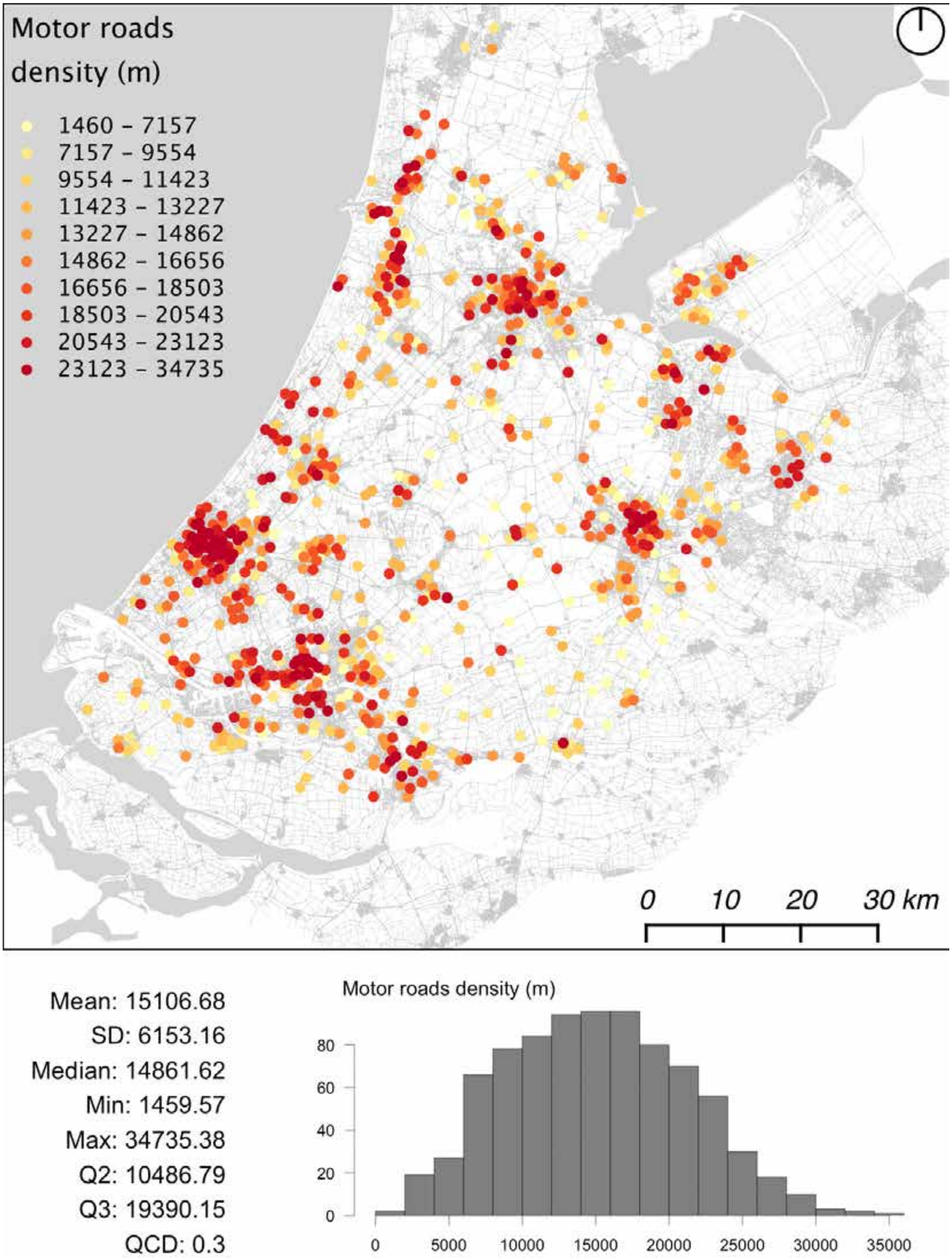


FIGURE APP.G.8 Network density of motor roads (m) within 800m catchment, map and descriptive statistics.

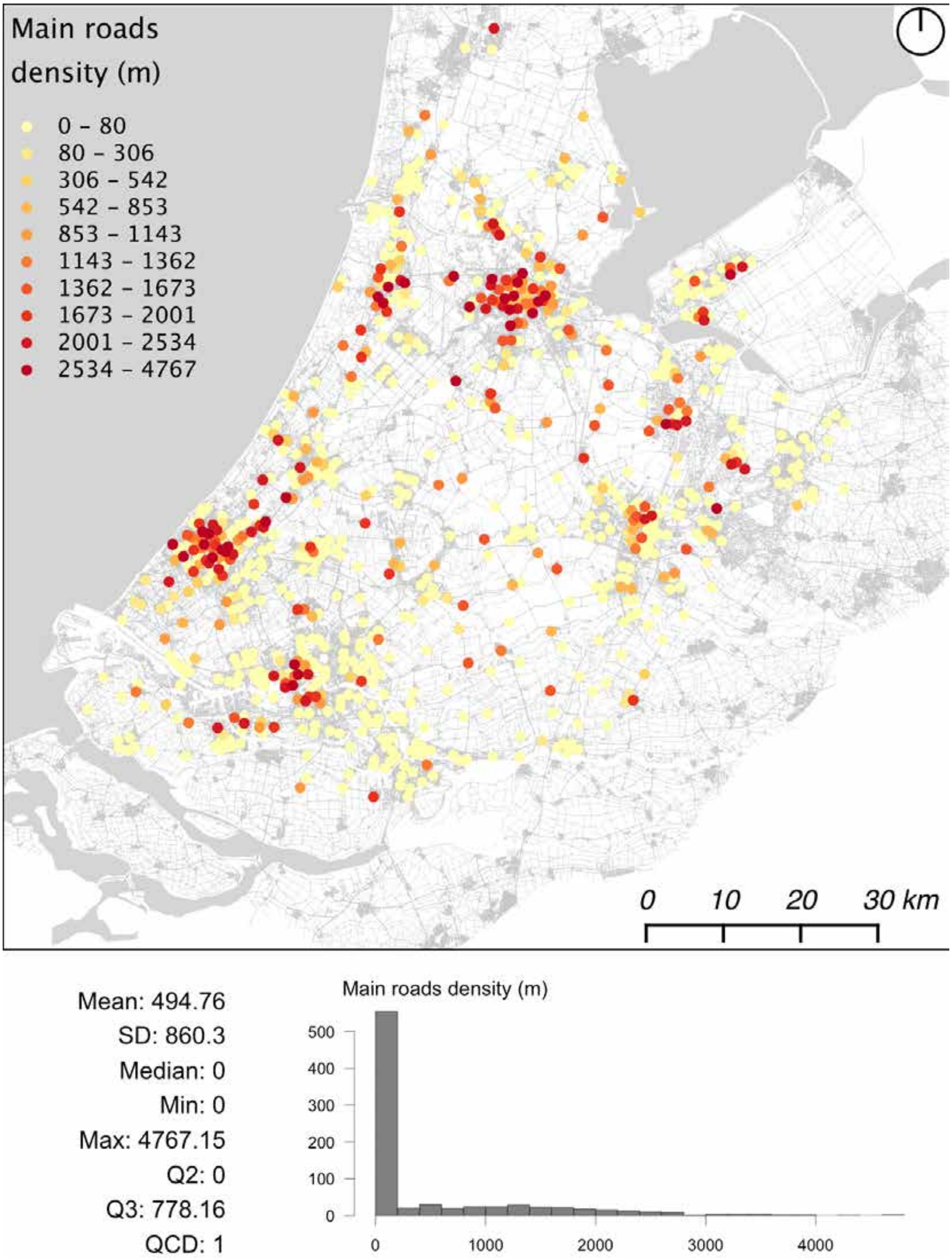


FIGURE APP.G.9 Network density of main roads (m) within 800m catchment, map and descriptive statistics. (25 initial quantiles, with bottom ranges (value = 0) merged)

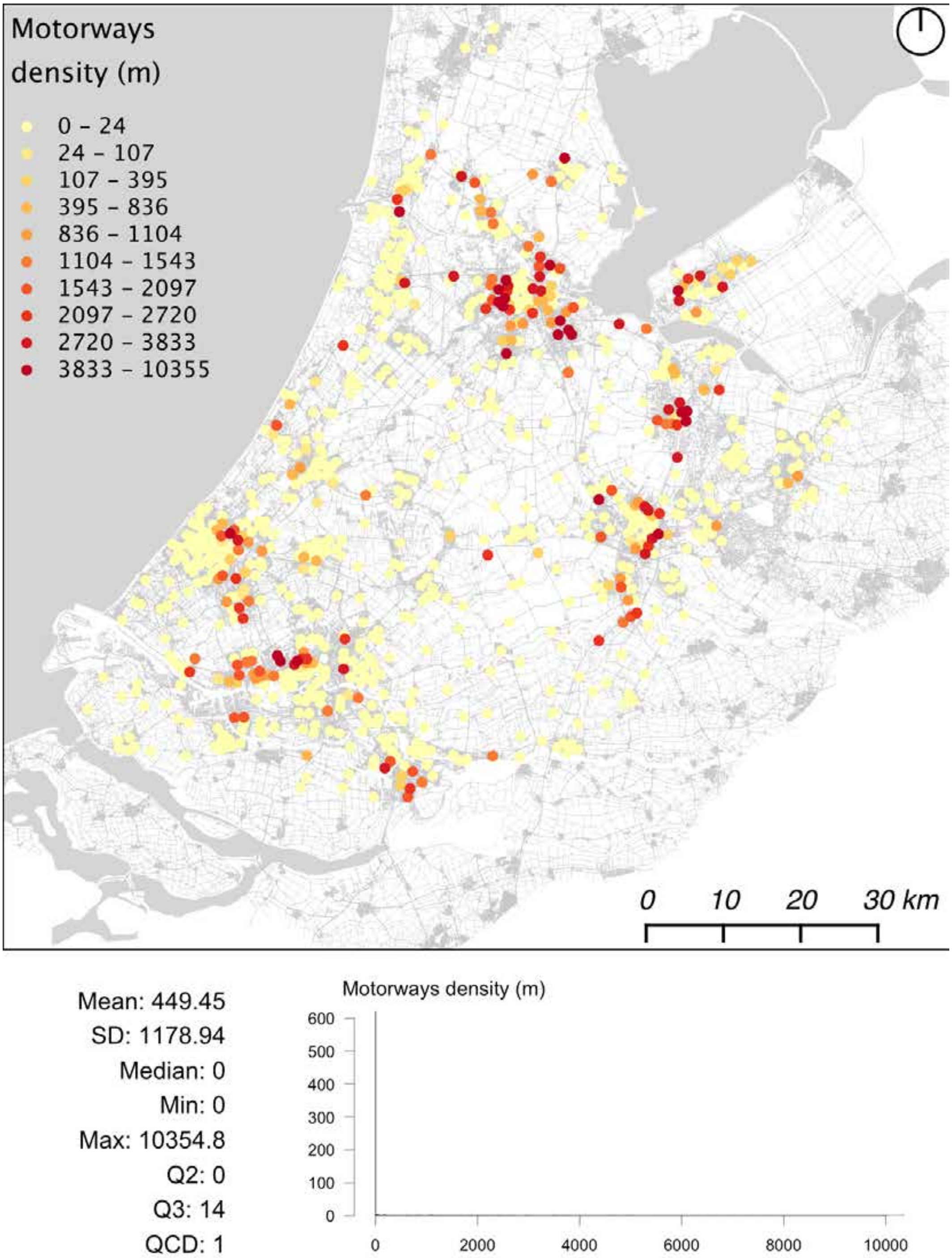


FIGURE APP.G.10 Network density of motorways (m) within 1600m catchment, map and descriptive statistics. (37 initial quantiles, with bottom ranges (value = 0) merged)

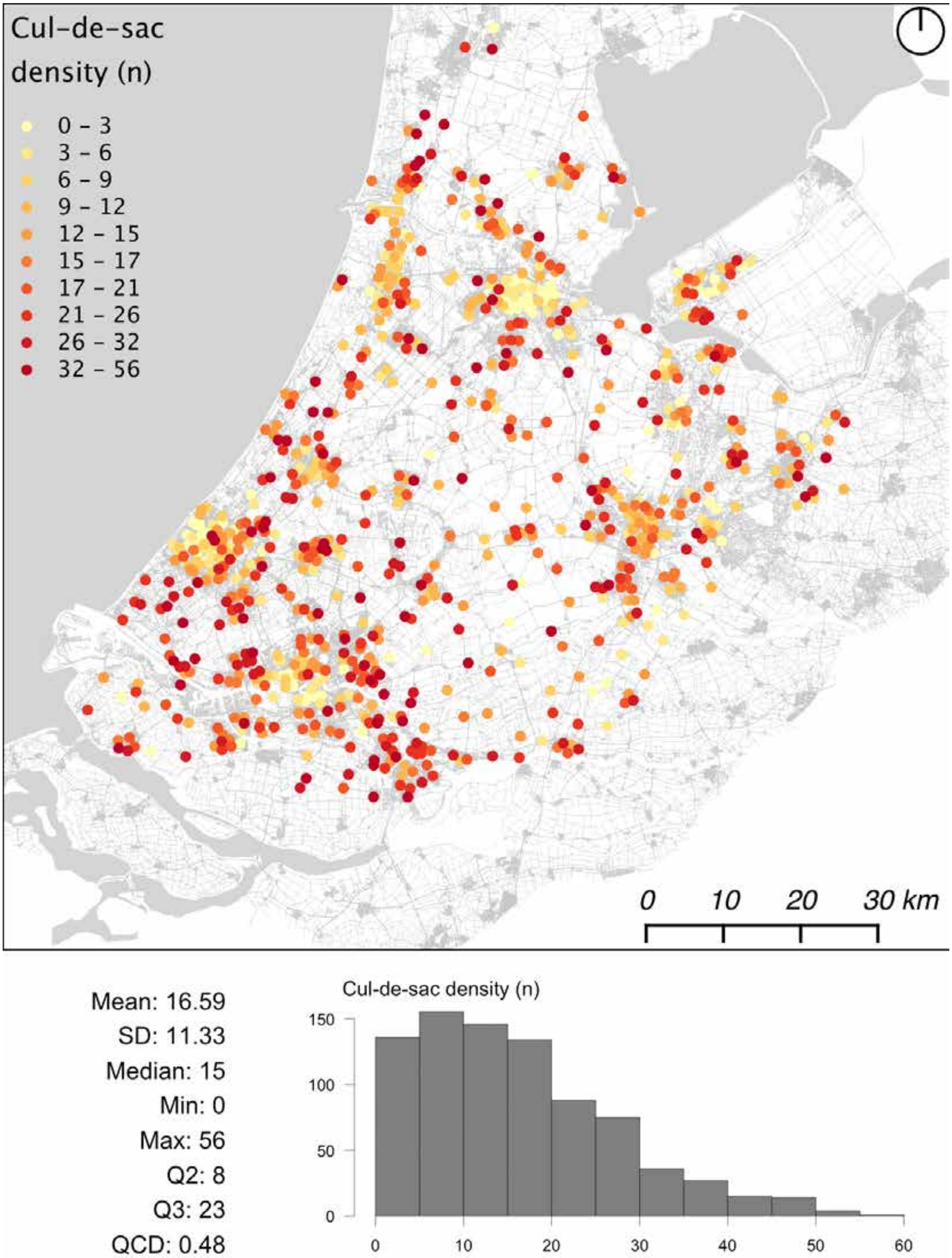
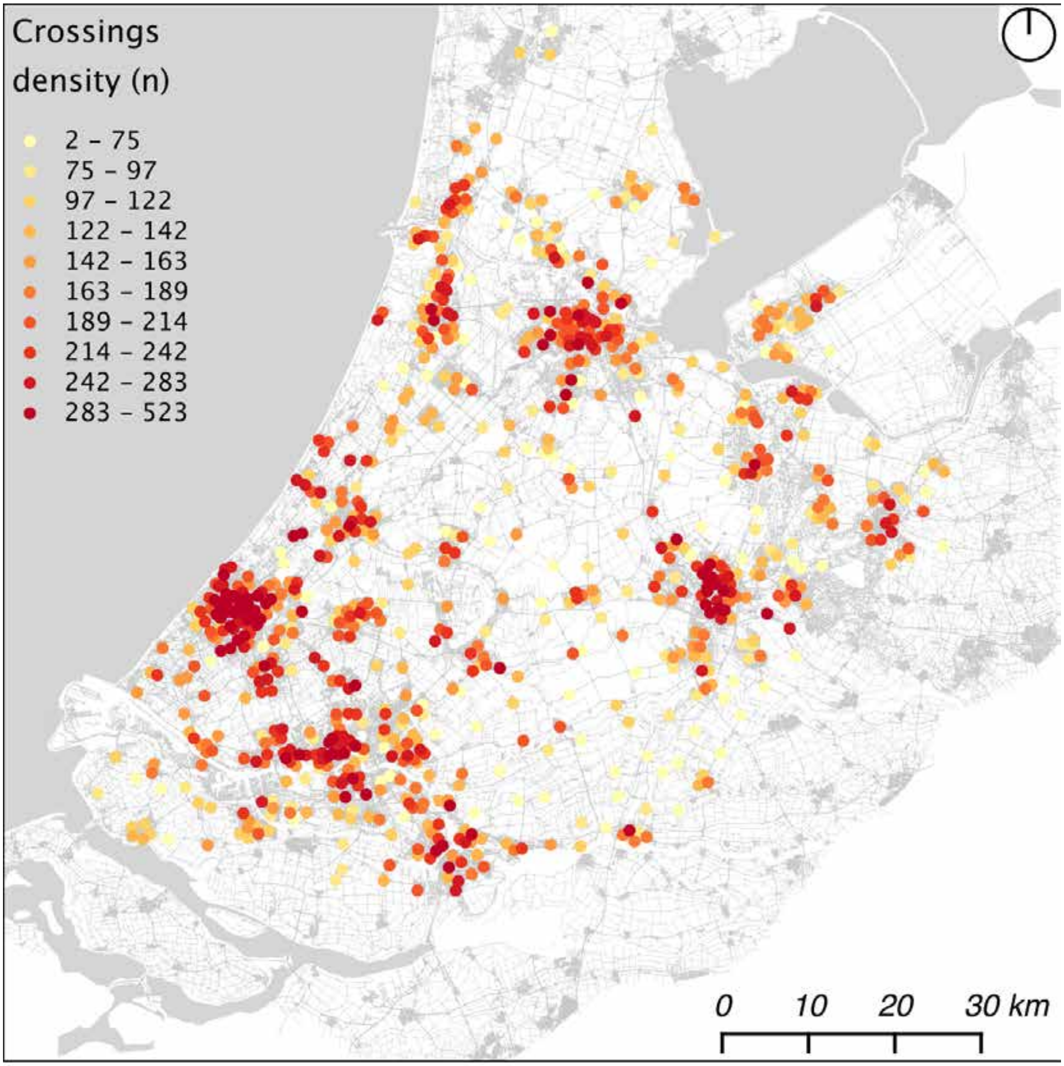


FIGURE APP.G.11 Density of cul-de-sacs (count) within 800m catchment, map and descriptive statistics.



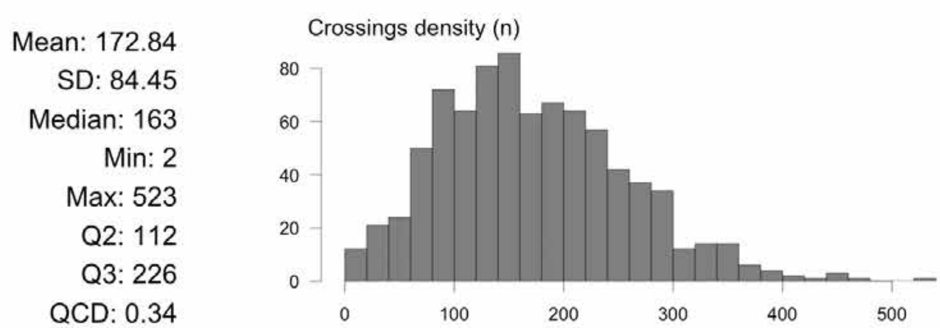


FIGURE APP.G.12 Density of X and T crossings (count) within 800m catchment, map and descriptive statistics.

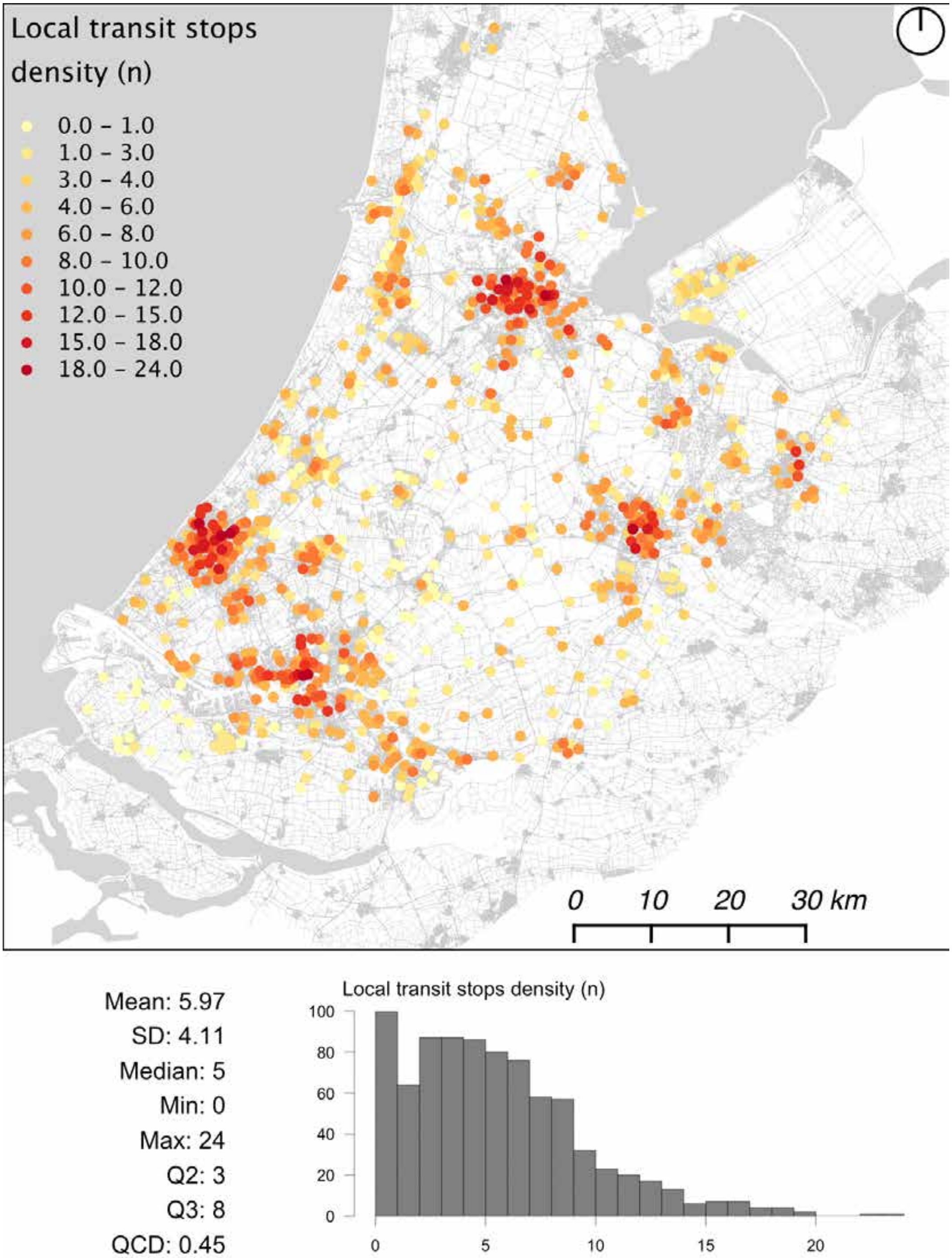
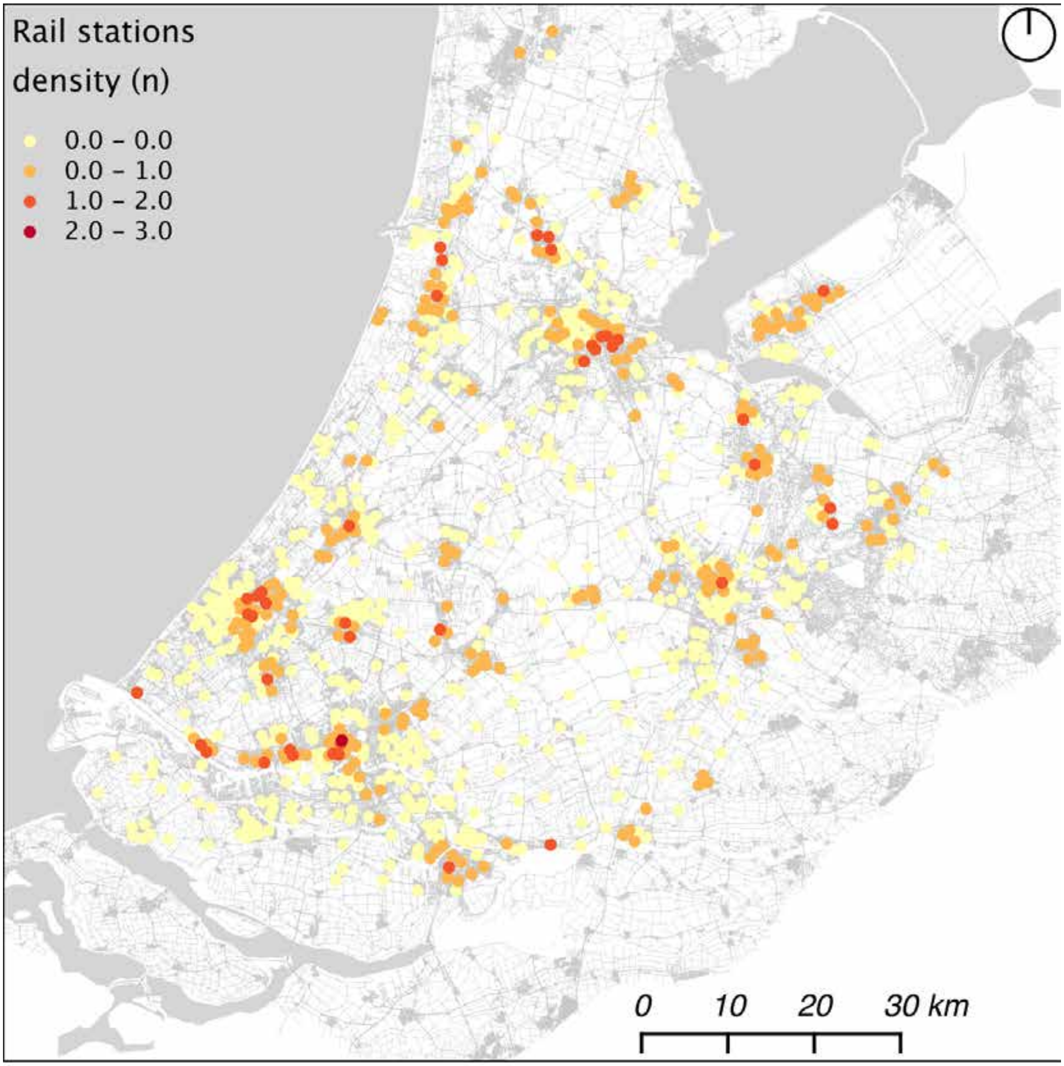


FIGURE APP.G.13 Density of local transit stops (count) within 800m catchment, map and descriptive statistics. (Jenks natural breaks scale)



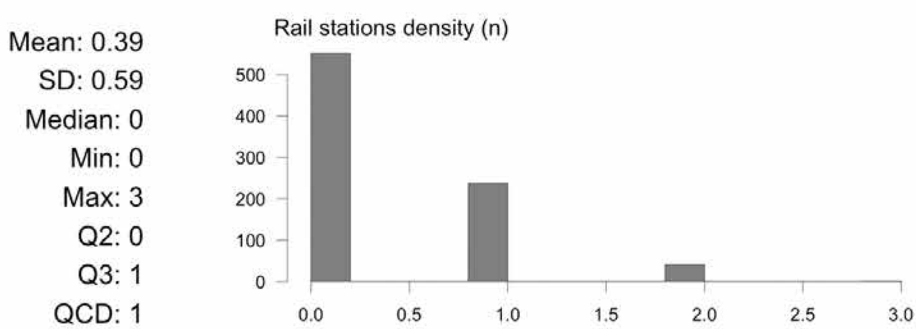
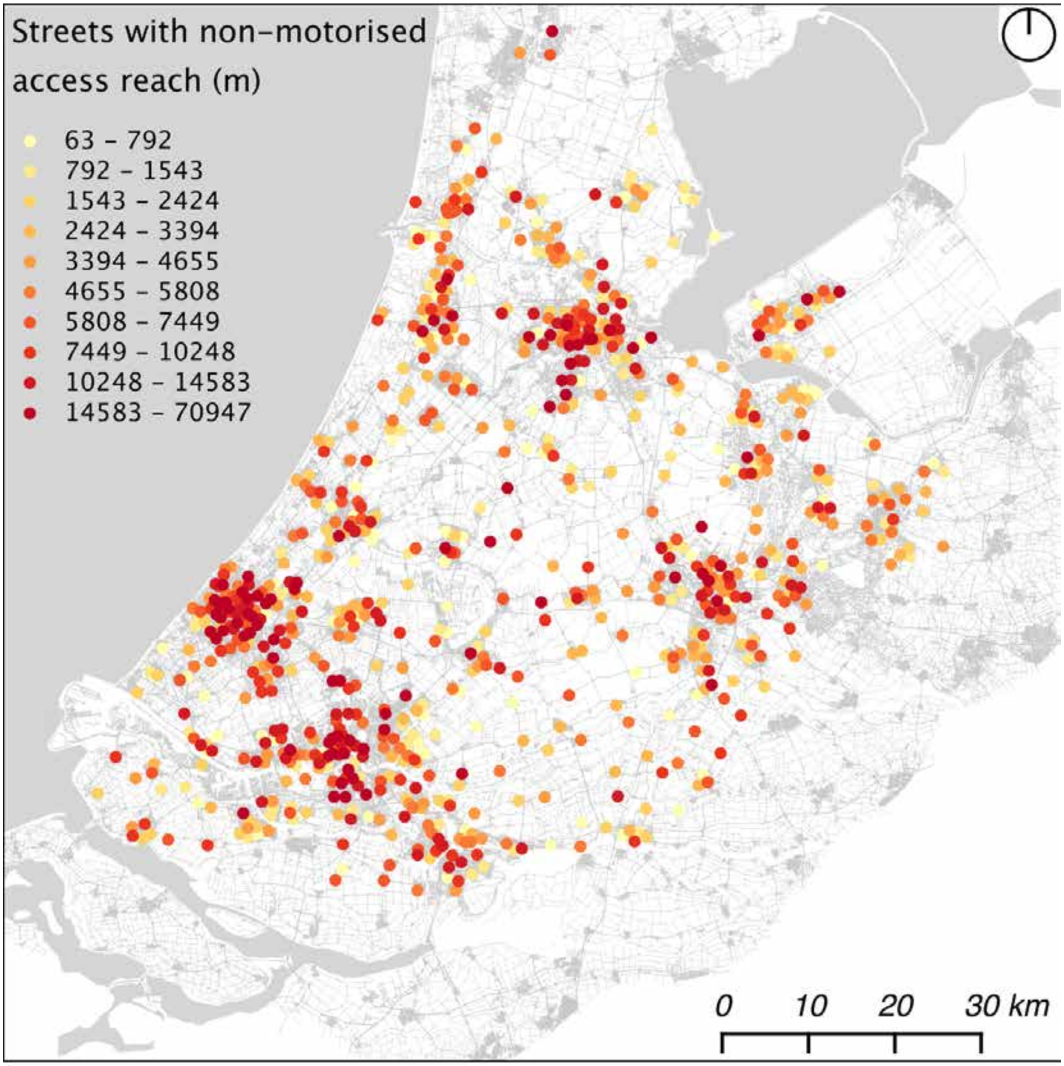


FIGURE APP.G.14 Density of railway stations (count) within 1600m catchment, map and descriptive statistics. (Jenks natural breaks scale)



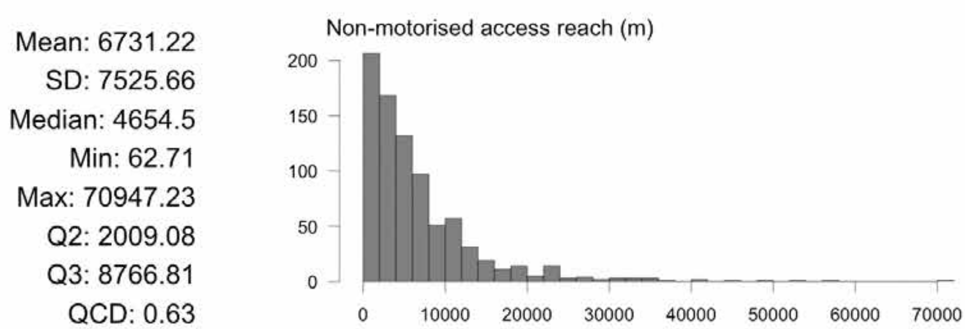


FIGURE APP.G.15 Network reach along non-motorised access streets (m) within 180 degrees angular catchment, map and descriptive statistics.

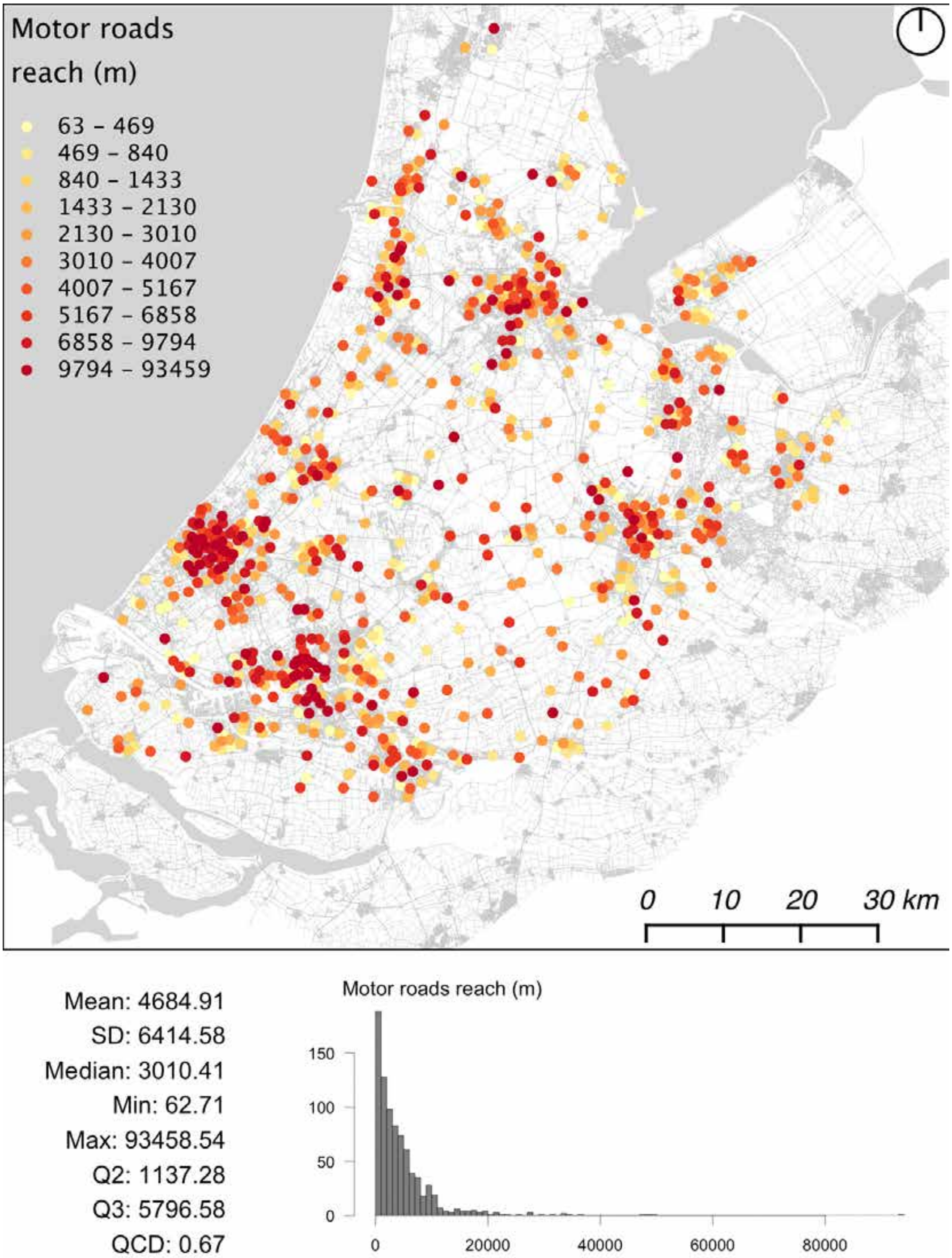


FIGURE APP.G.16 Network reach along motor roads (m) within 180 degrees angular catchment, map and descriptive statistics.

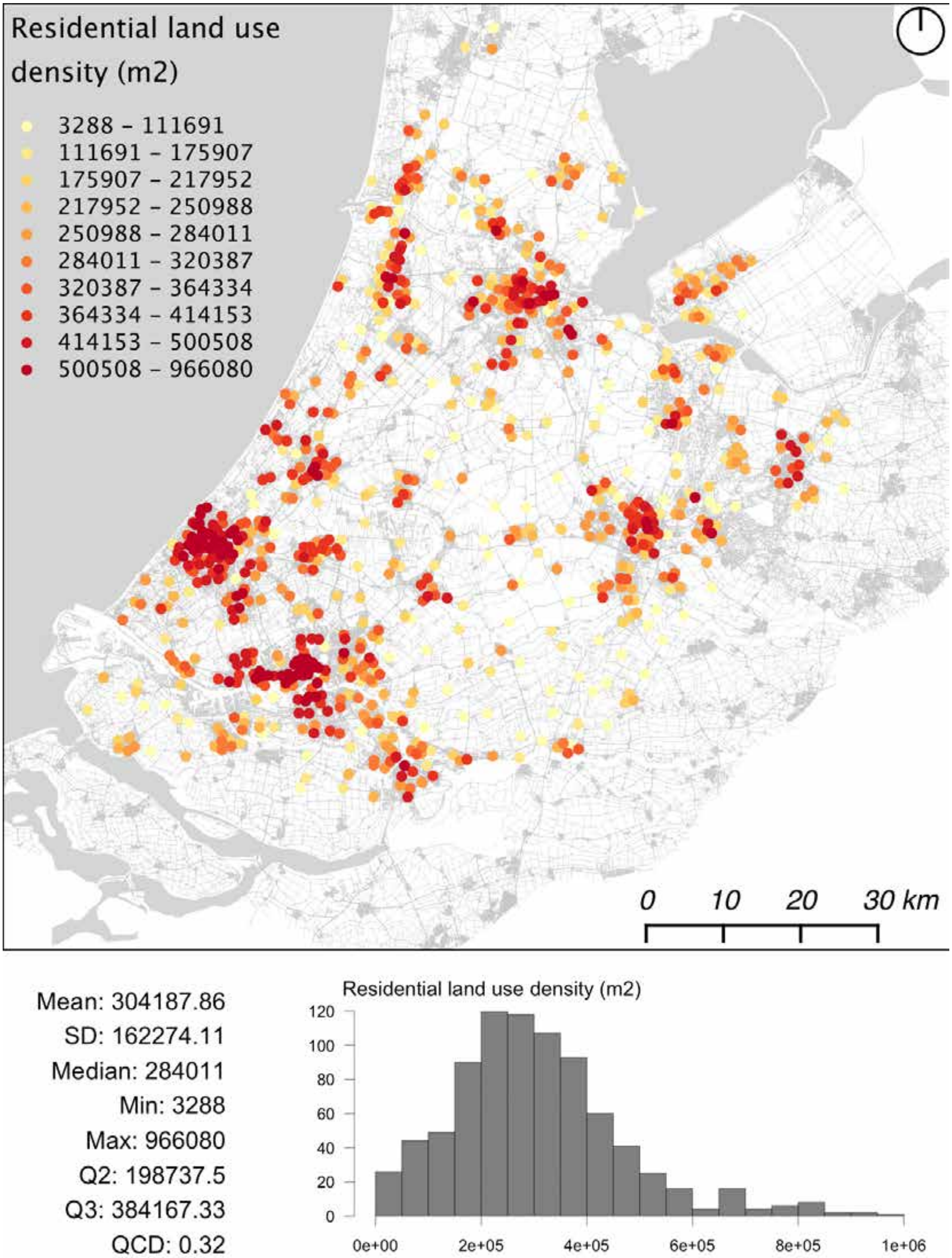


FIGURE APP.G.17 Activity density of residential land use (m2) within 800m walking distance, map and descriptive statistics.

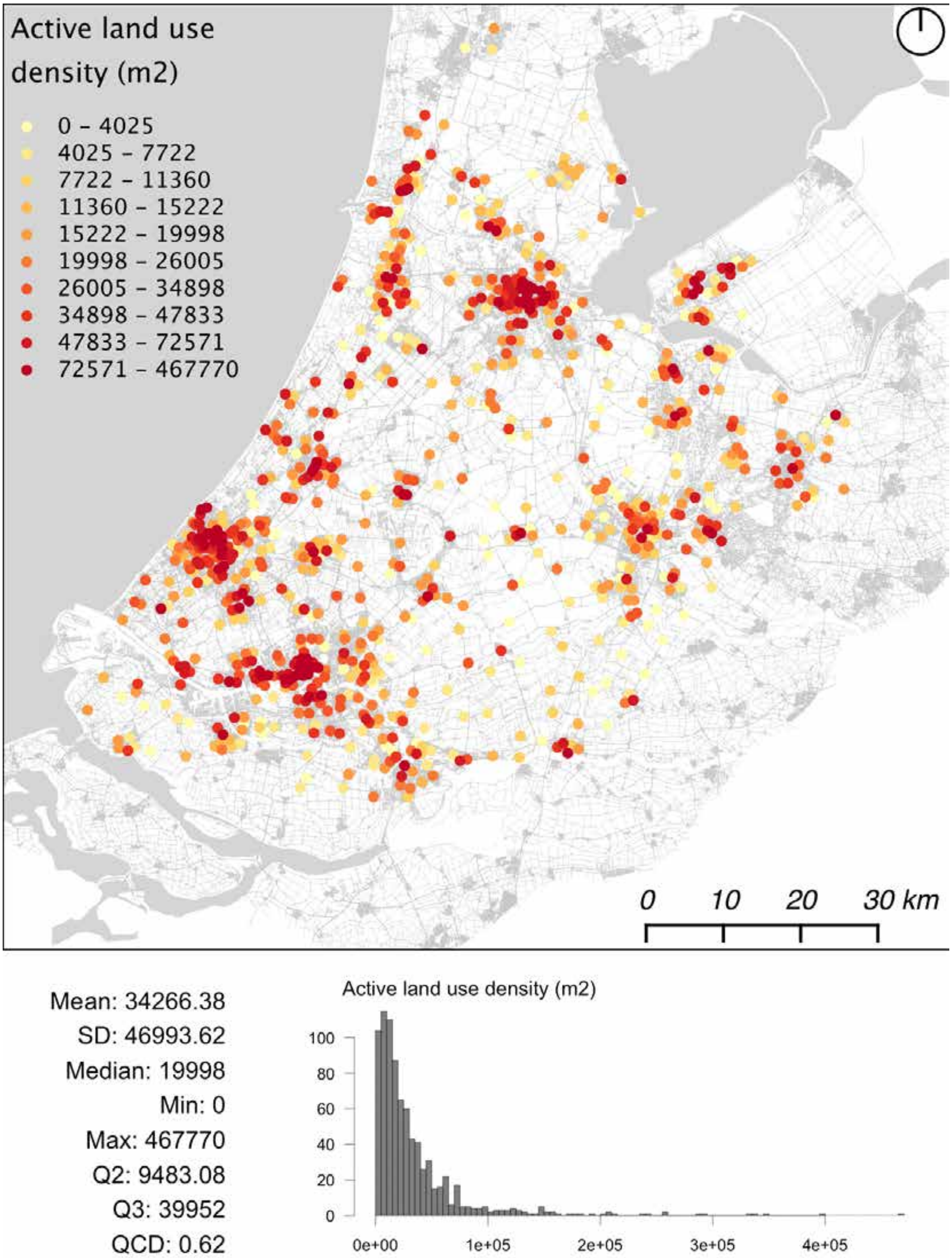
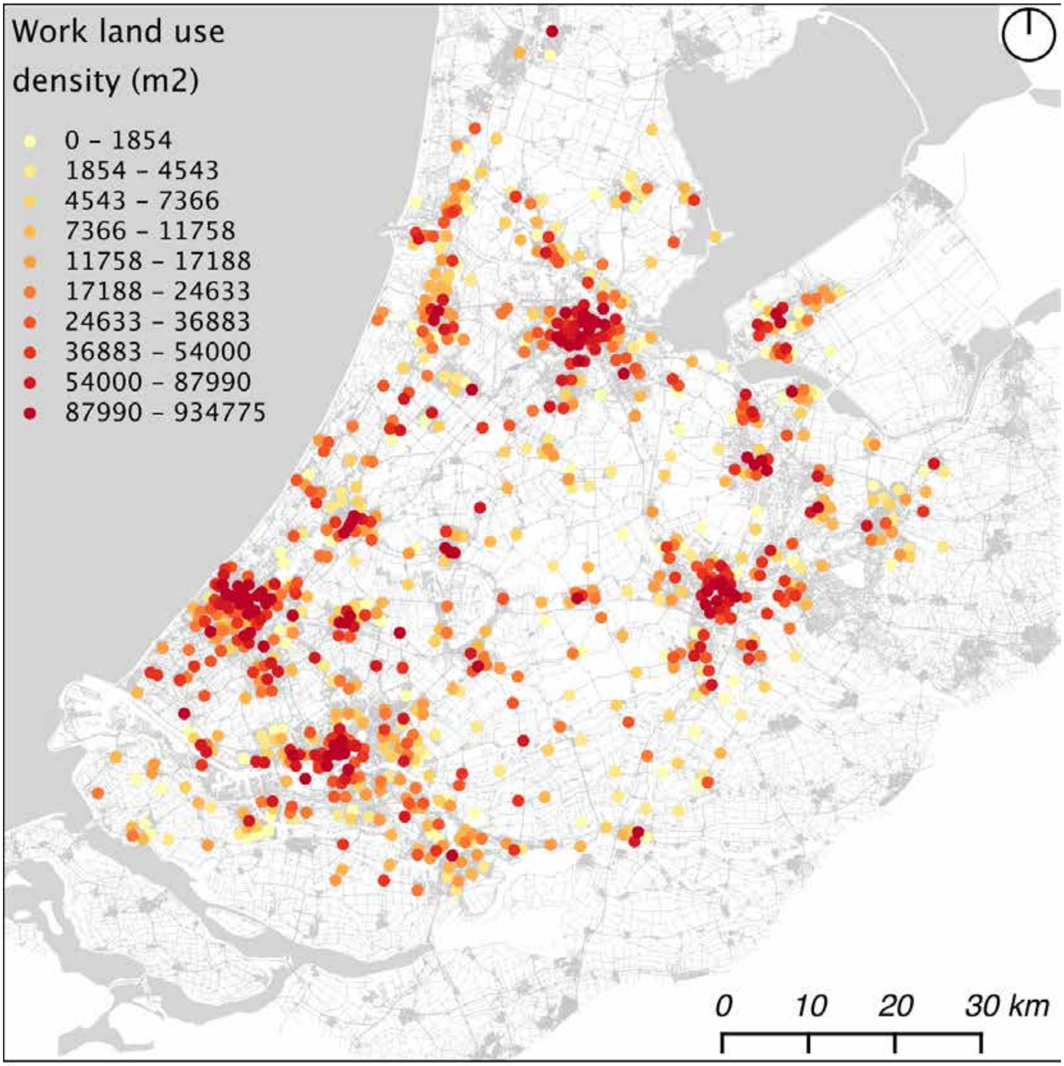


FIGURE APP.G.18 Activity density of active land uses (m2) within 800m walking distance, map and descriptive statistics.



Mean: 39534.89
SD: 76522.15
Median: 17187.5
Min: 0
Max: 934775
Q2: 6065.42
Q3: 45244.17
QCD: 0.76

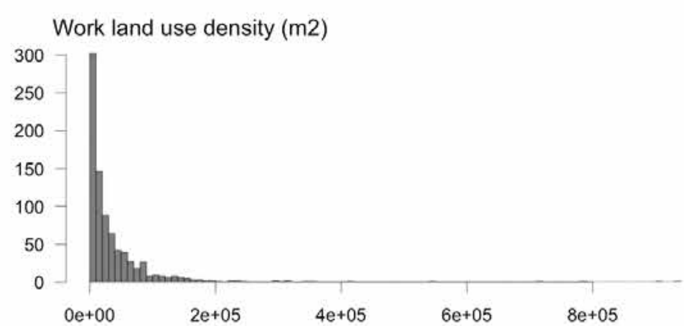


FIGURE APP.G.19 Activity density of work land uses (m2) within 800m walking distance, map and descriptive statistics.

TOC

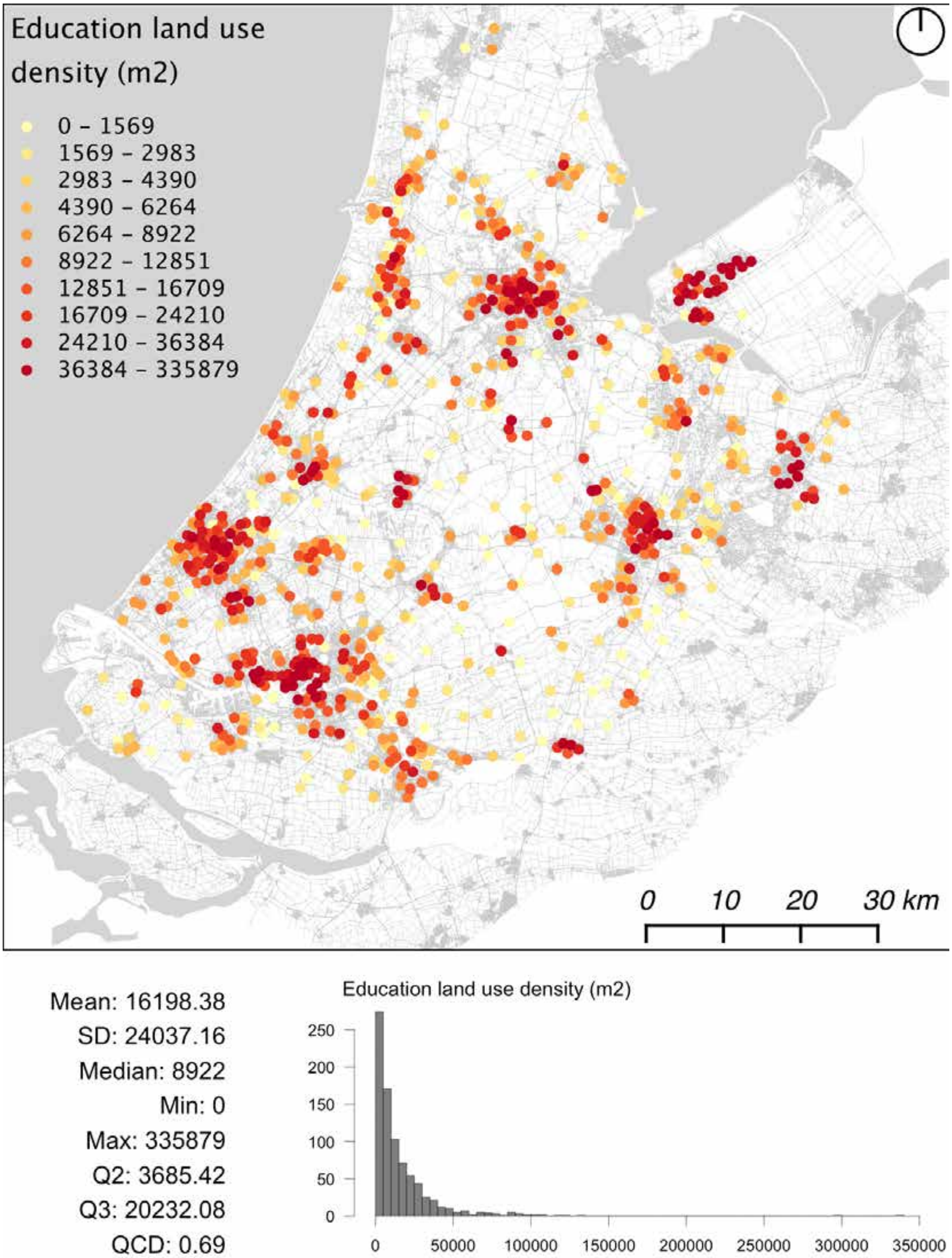


FIGURE APP.G.20 Activity density of educational land uses (m2) within 800m walking distance, map and descriptive statistics.

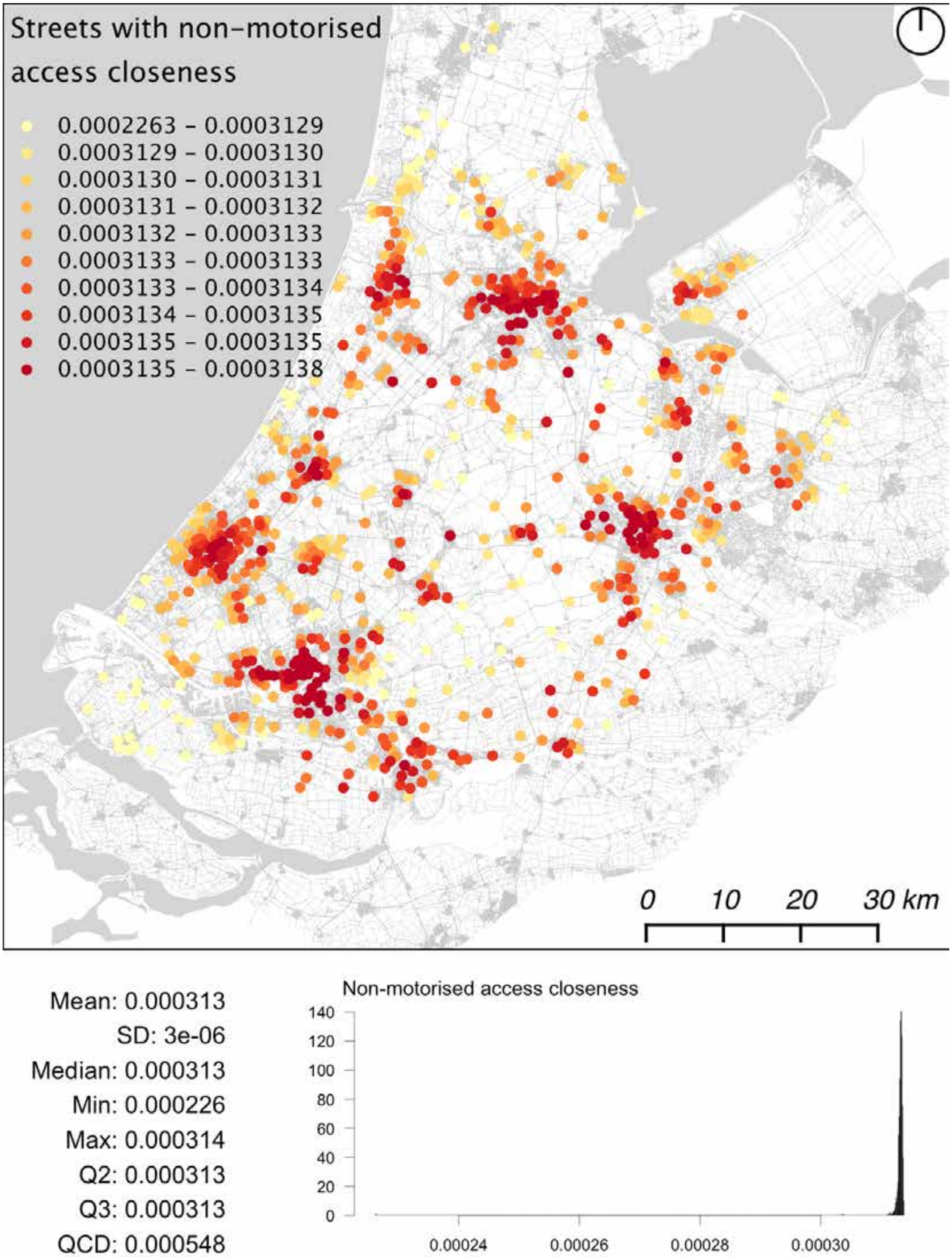


FIGURE APP.G.21 Mean centrality (closeness) of street network with non-motorised access within a 800m catchment, map and descriptive statistics.

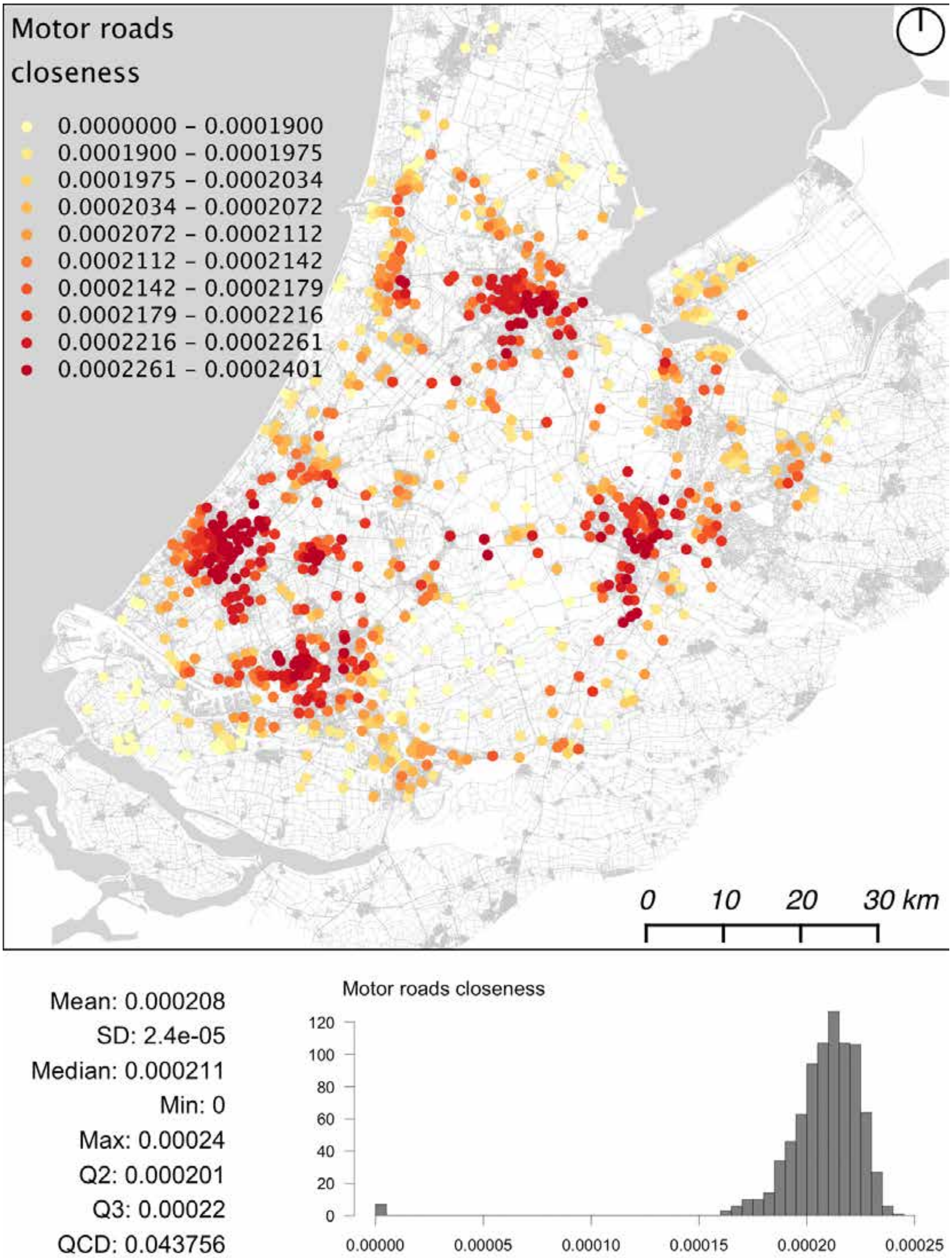
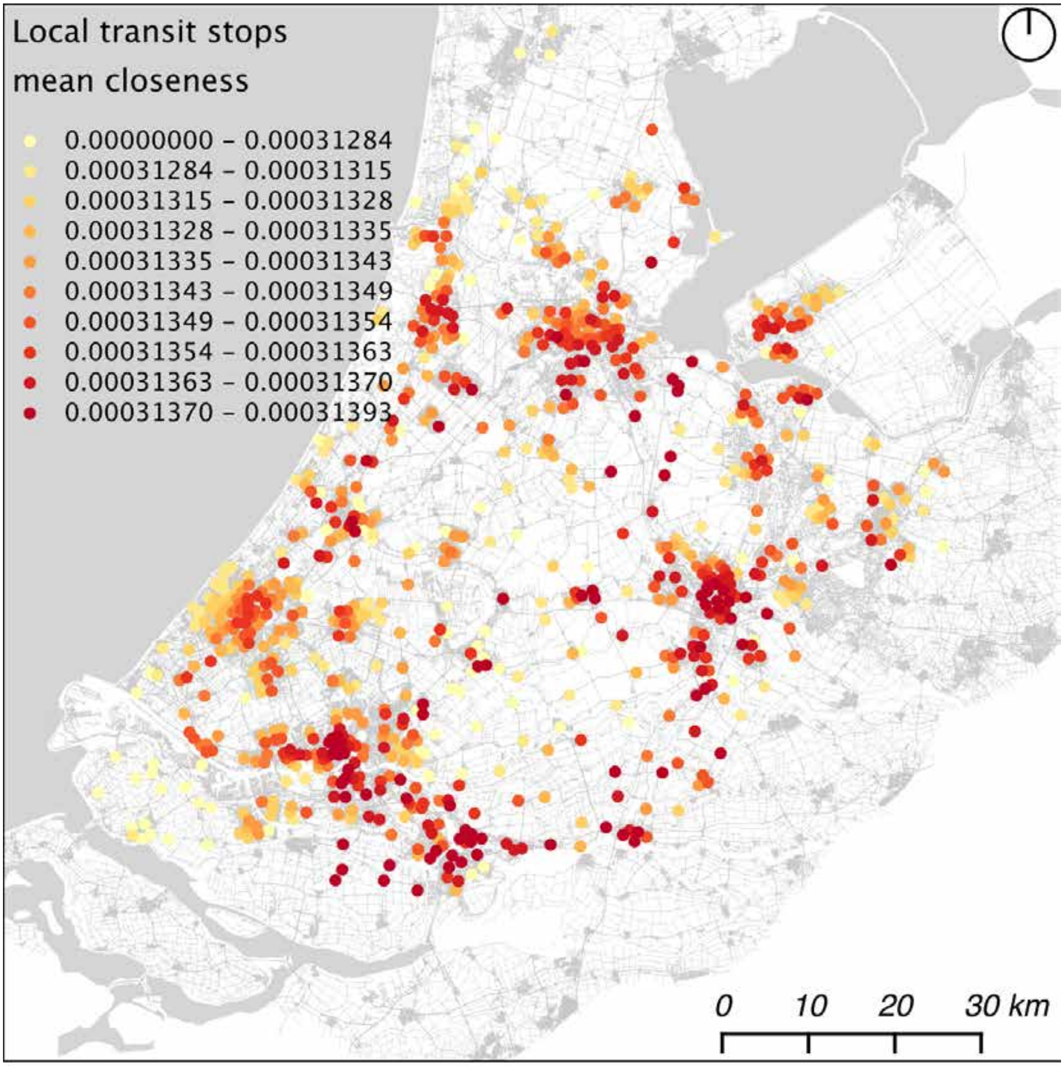


FIGURE APP.G.22 Mean centrality (closeness) of motor road network within a 800m catchment, map and descriptive statistics.



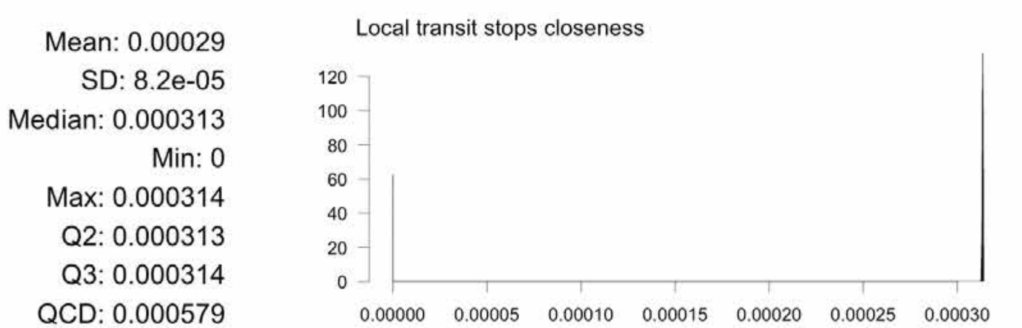


FIGURE APP.G.23 Mean centrality (closeness) of local transit stops within a 800m catchment, map and descriptive statistics.

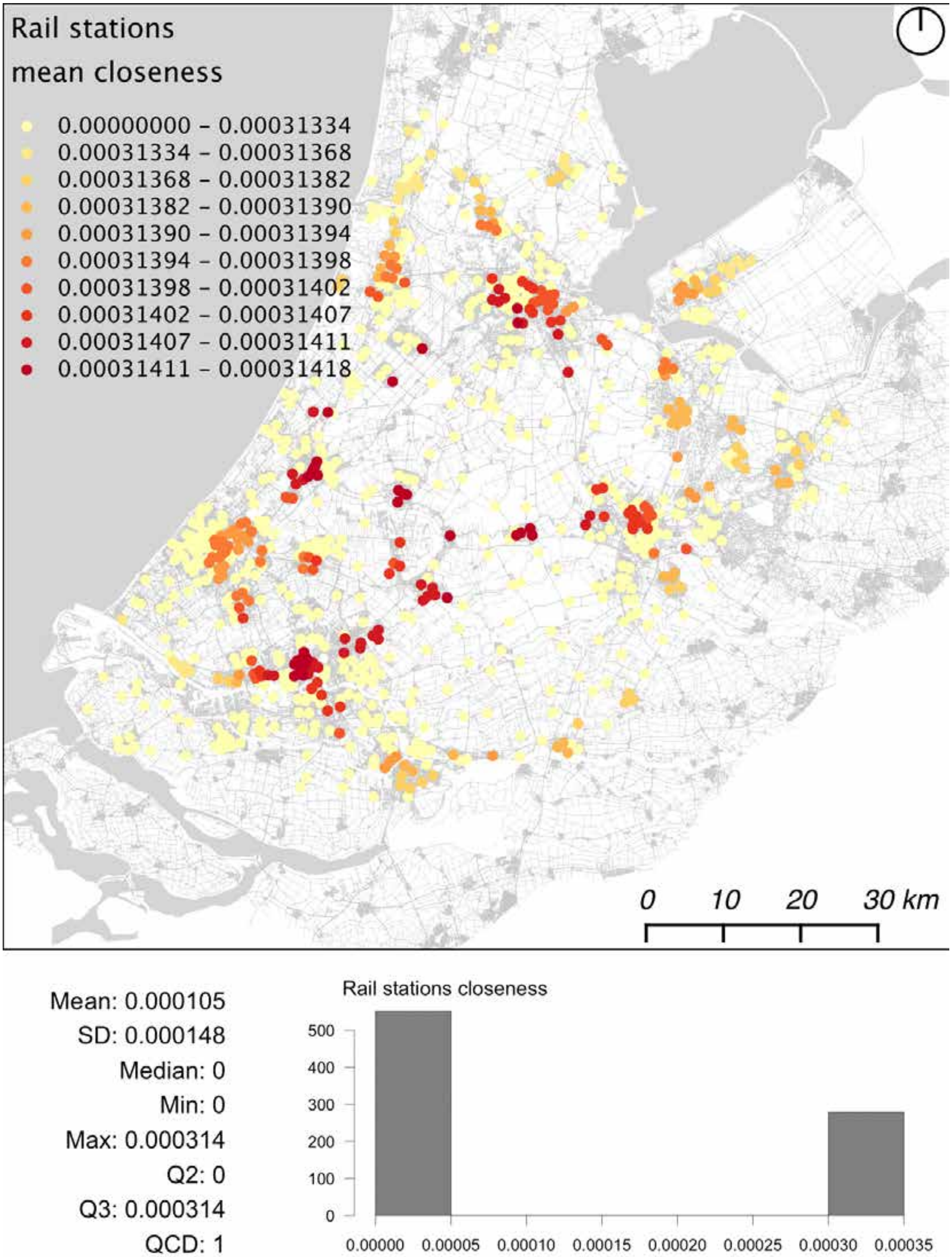


FIGURE APP.G.24 Mean centrality (closeness) of railway stations within a 800m catchment, map and descriptive statistics. (27 initial quantiles, with bottom ranges (value = 0) merged)

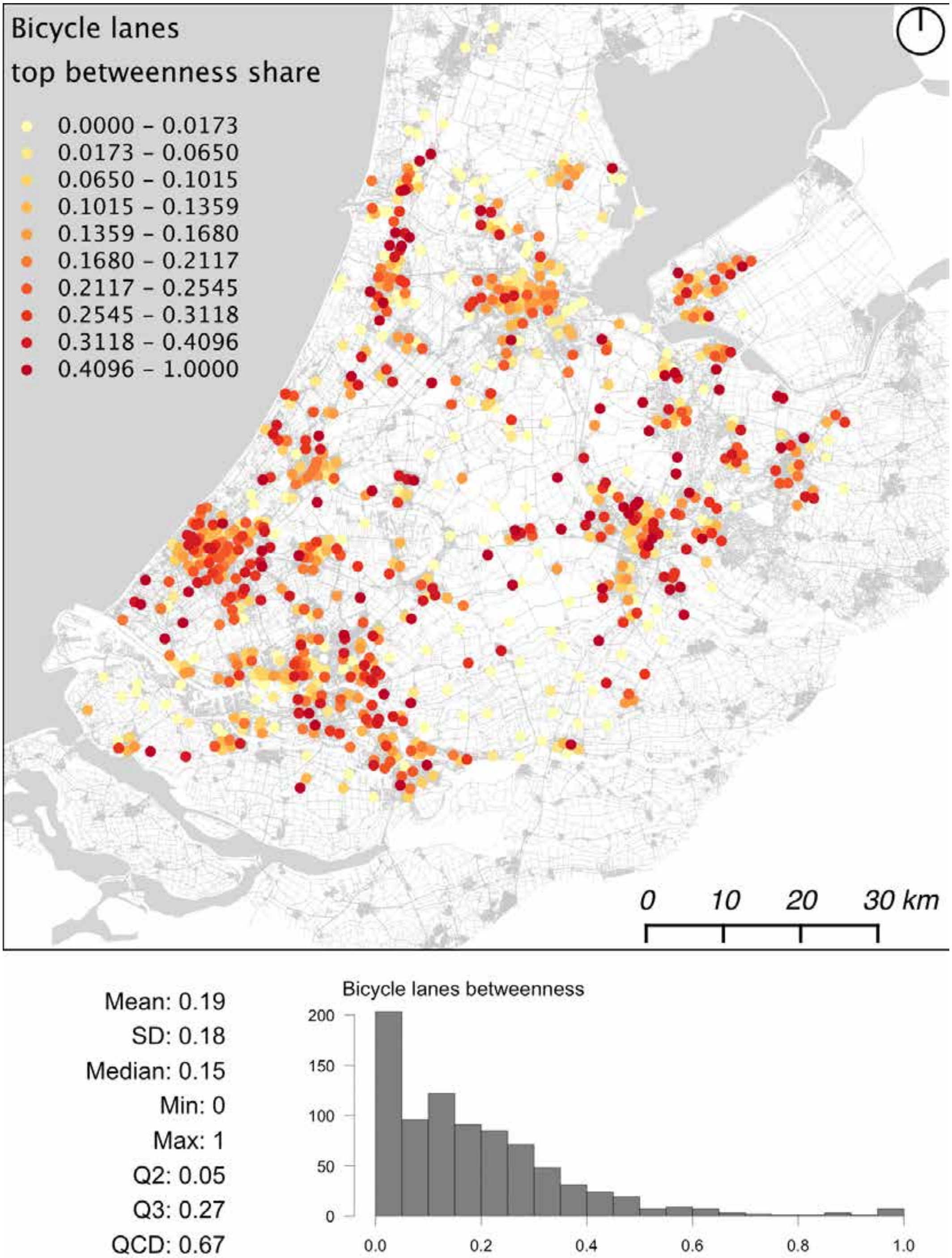


FIGURE APP.G.25 Share of top decile centrality (betweenness) of bicycle lanes network within a 800m catchment, map and descriptive statistics. (11 initial quantiles, with bottom ranges (value = 0) merged)

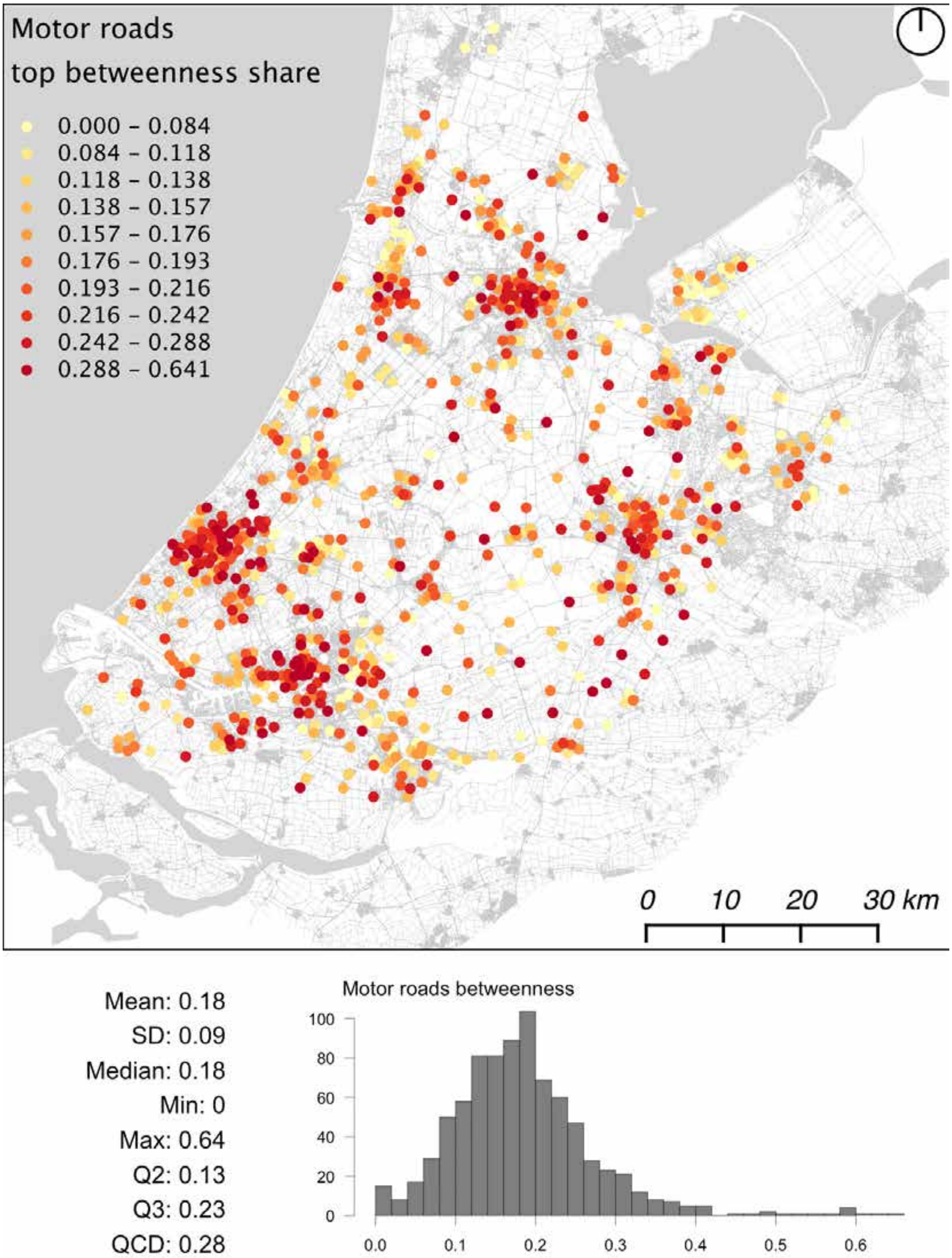


FIGURE APP.G.26 Share of top decile centrality (betweenness) of motor roads network within a 800m catchment, map and descriptive statistics.

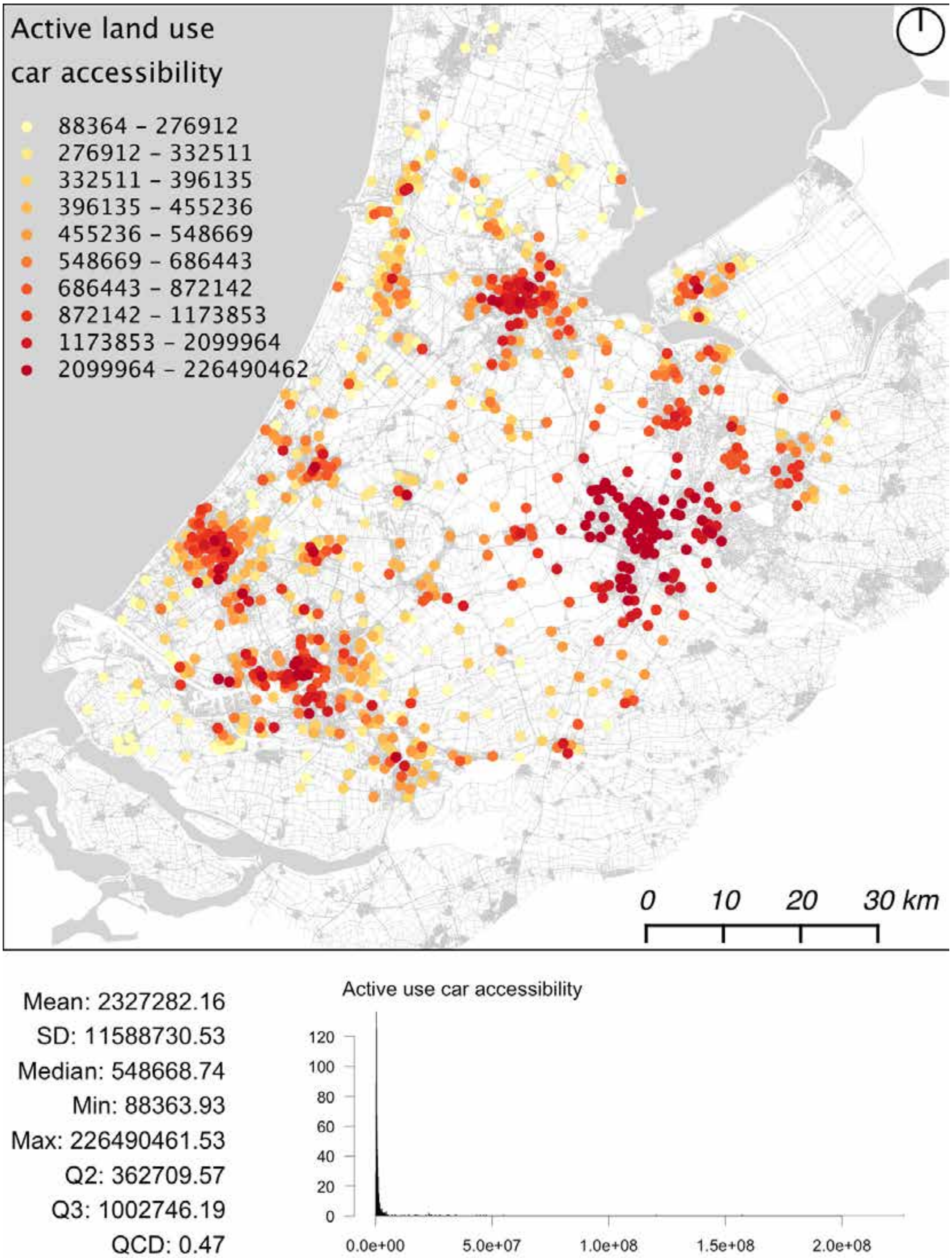


FIGURE APP.G.27 Accessibility to active land uses by car in a 20 min journey, map and descriptive statistics.

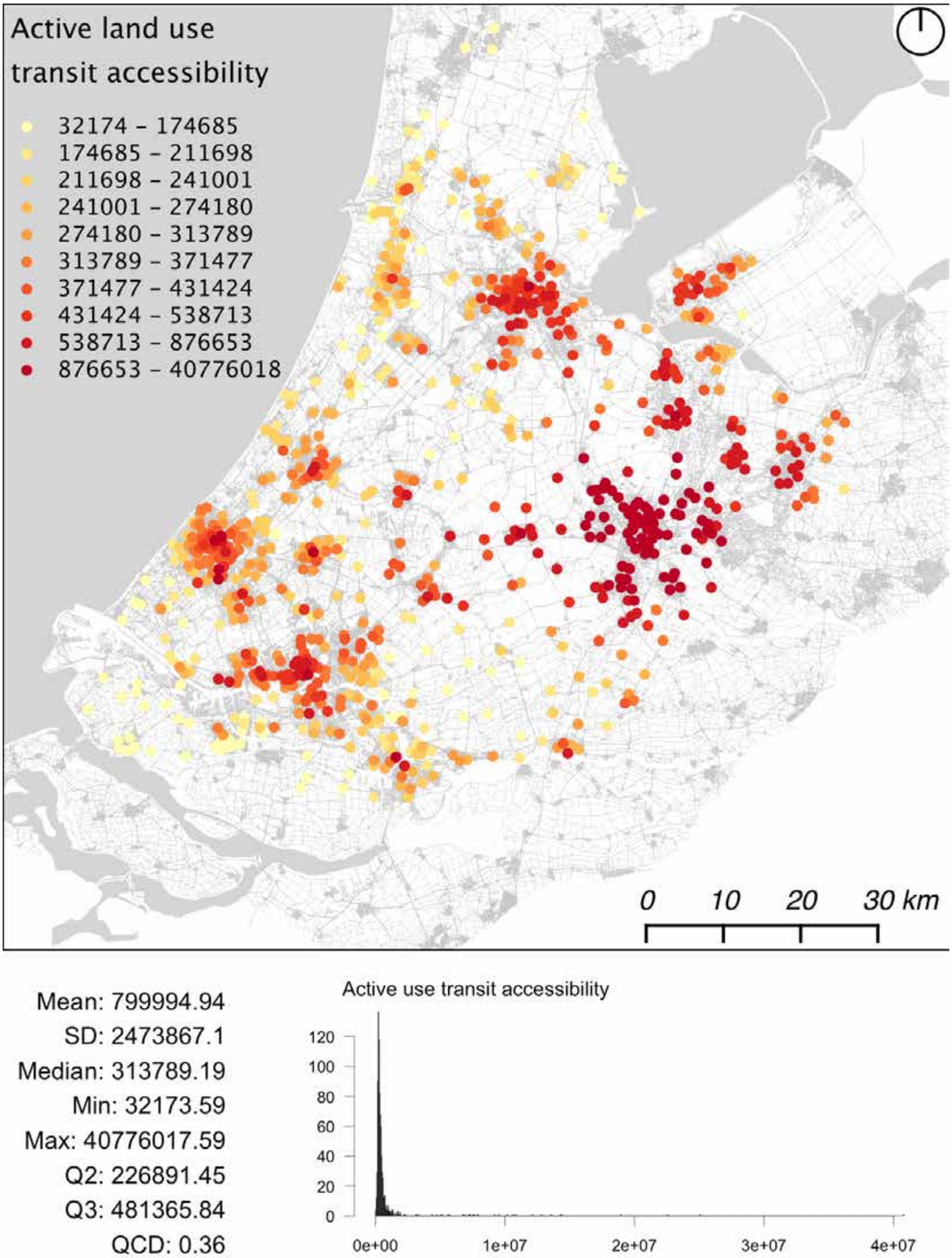


FIGURE APP.G.28 Accessibility to active land uses by public transport in a 20 min journey, map and descriptive statistics.

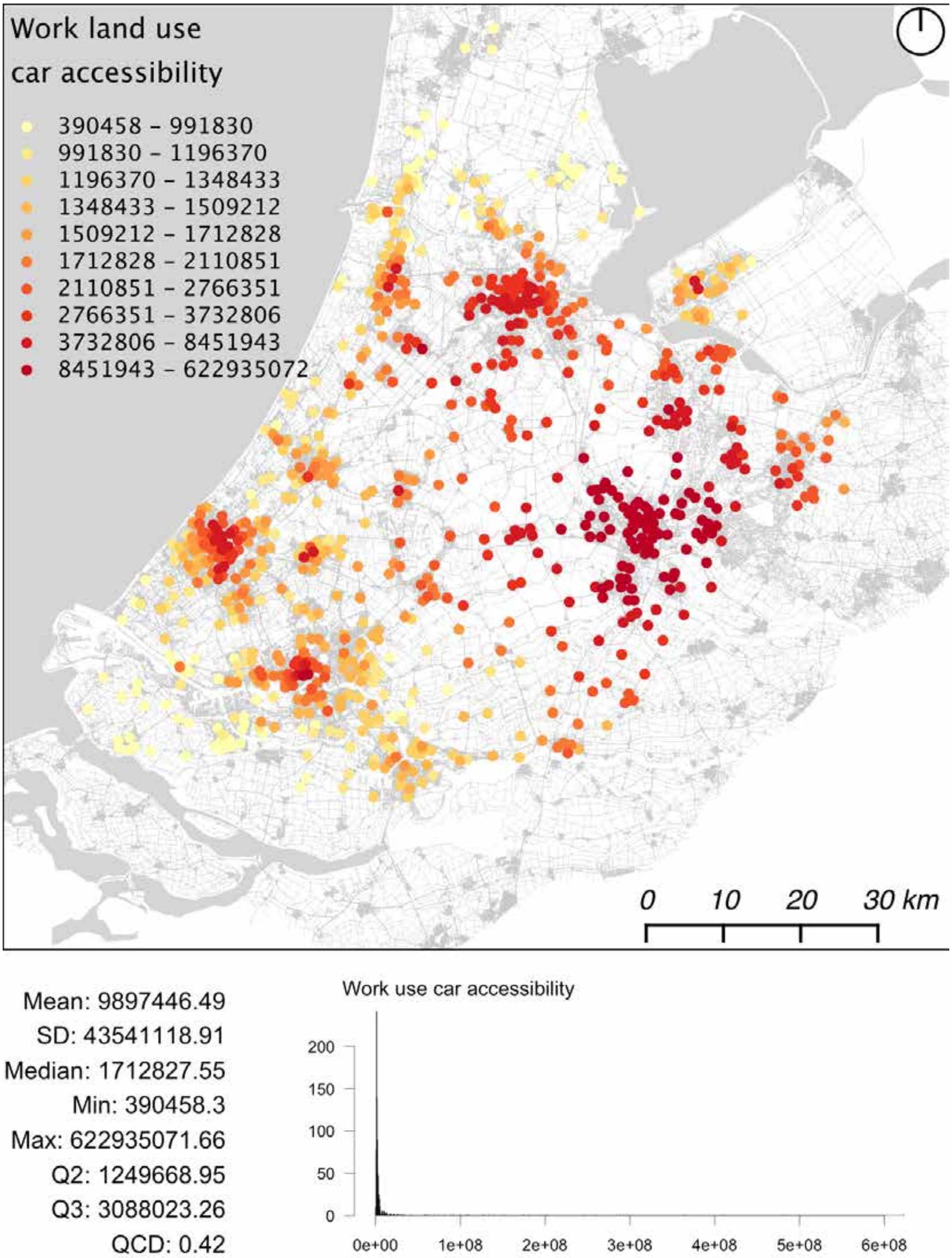


FIGURE APP.G.29 Accessibility to work land uses by car in a 20 min journey, map and descriptive statistics.

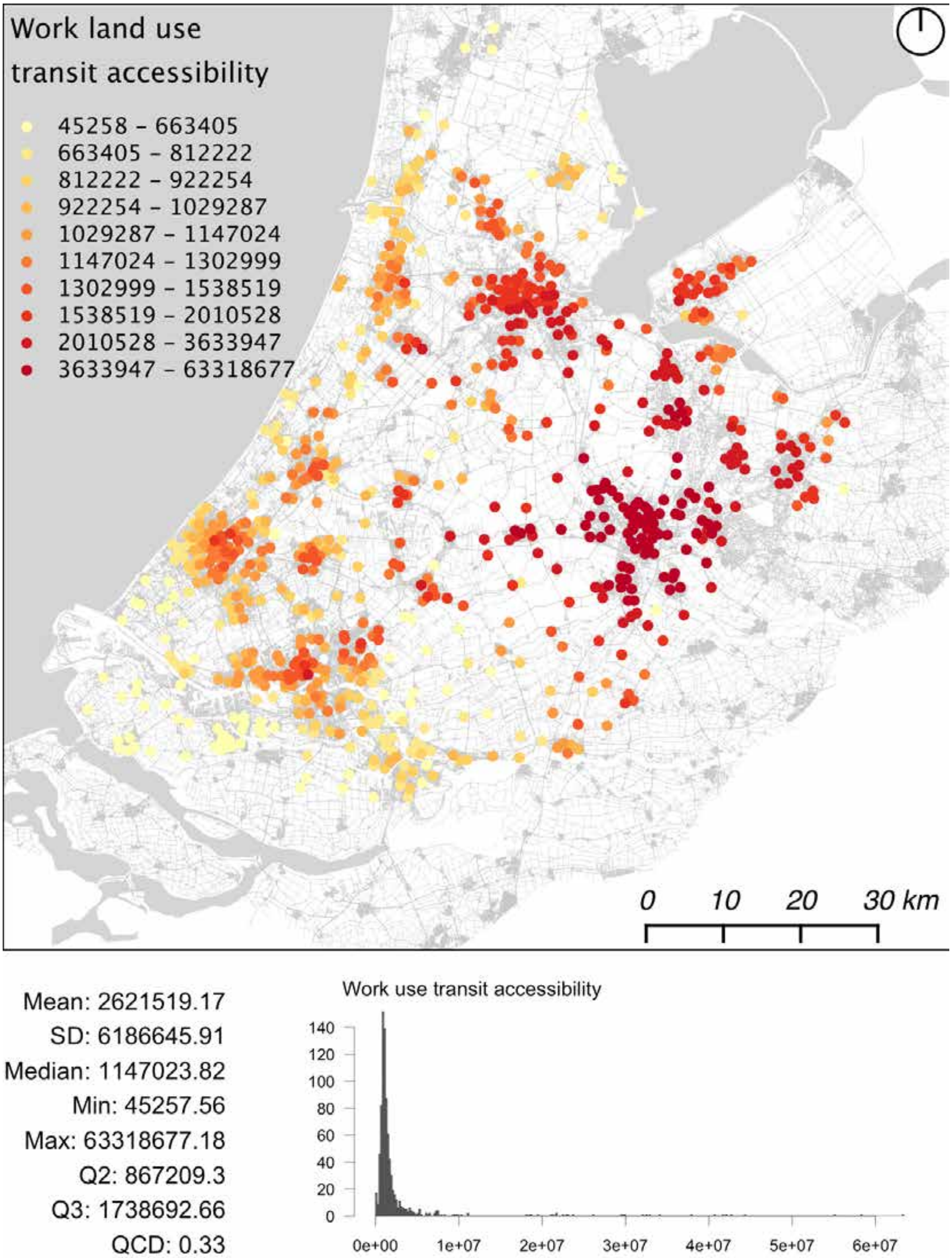


FIGURE APP.G.30 Accessibility to work land uses by public transport in a 20 min journey, map and descriptive statistics.

Appendix H

Correlation of travel patterns, urban form and socio-economic characteristics

Series of correlograms of the three dimensions of the study, i.e. travel patterns, urban form and socio-economic characteristics. They show the correlation (Spearman), p-values and scatterplot between pairs of variables of each dimension, and their correlation with mobility patterns.

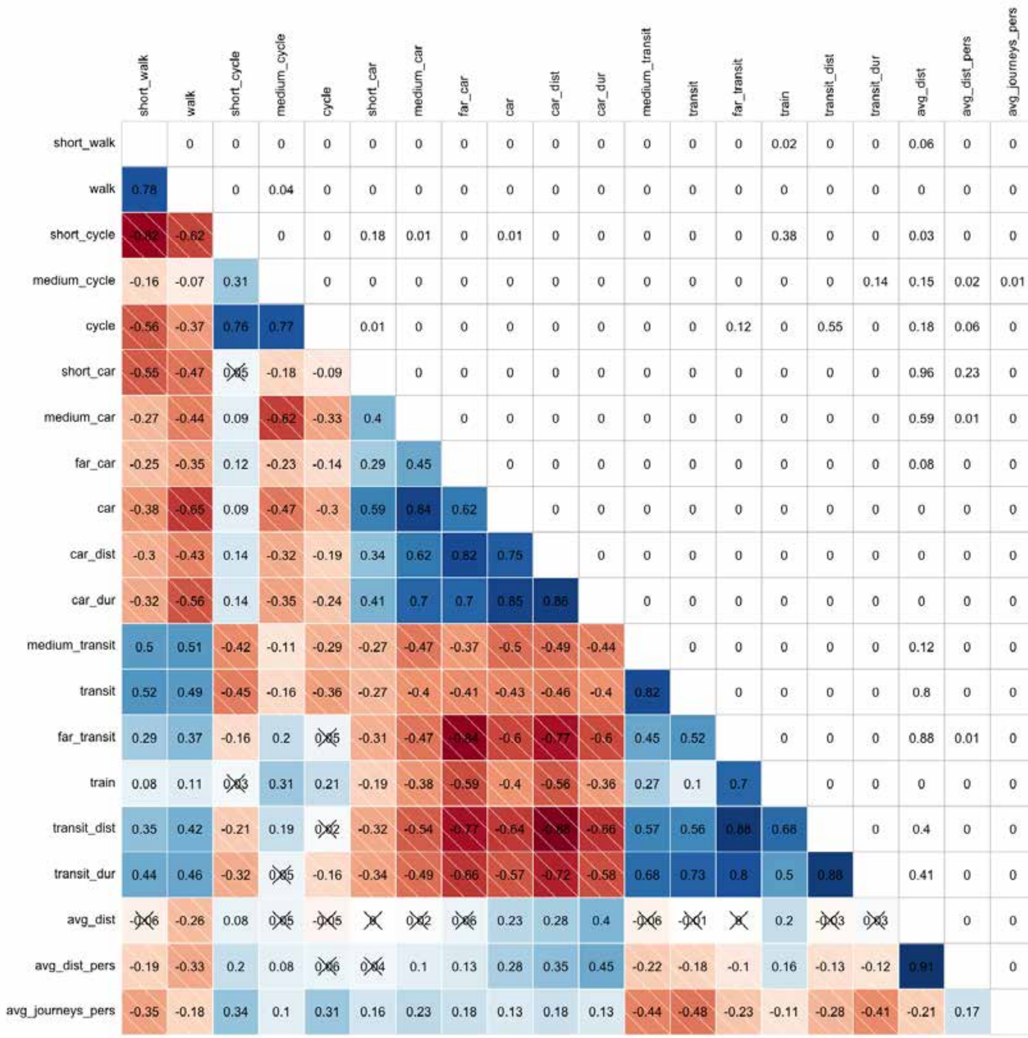


FIGURE APP.H.1 Correlogram of sustainable mobility indicators, showing the correlation coefficient below the diagonal, and the p-value above the diagonal.

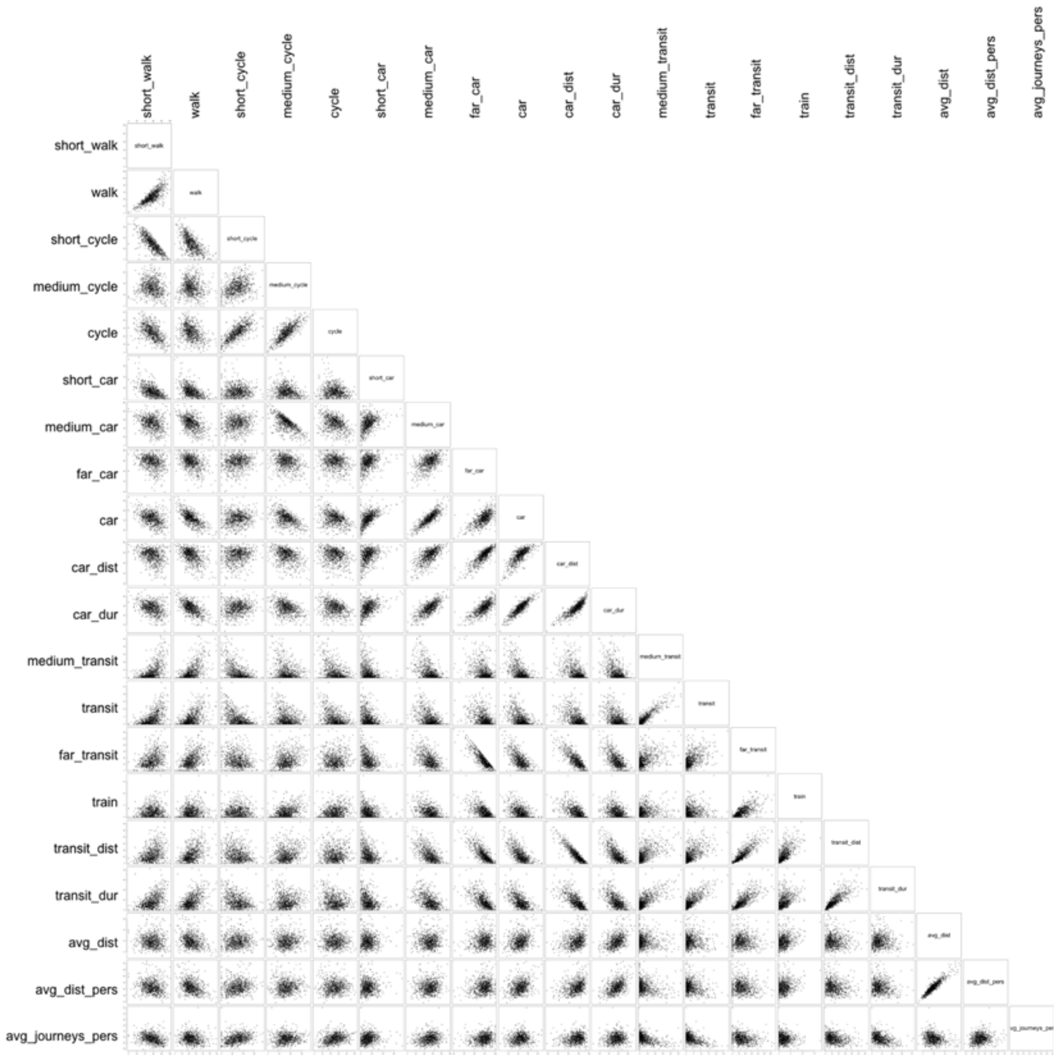


FIGURE APP.H.2 Scatterplot matrix of sustainable mobility indicators.

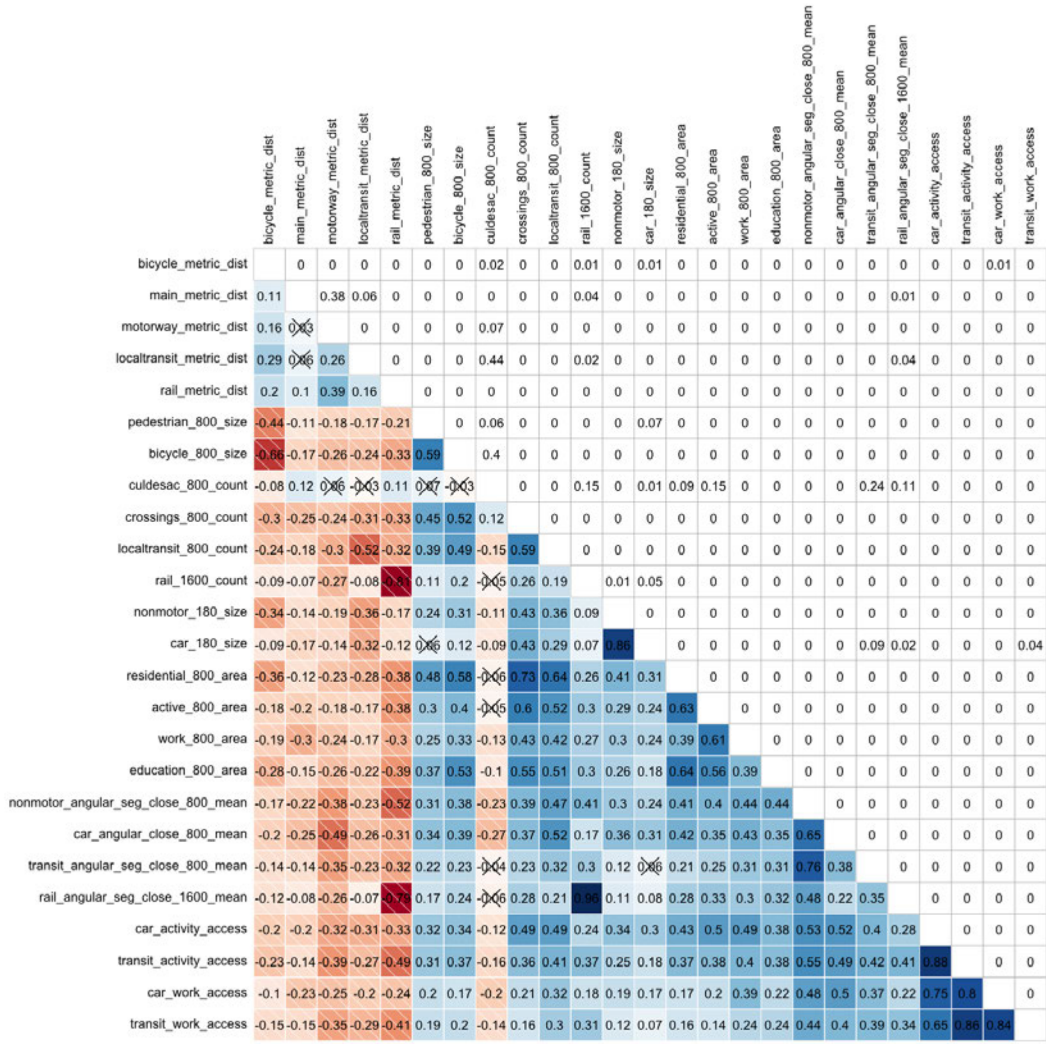


FIGURE APP.H.3 Correlogram of urban form and accessibility variables, showing the correlation coefficient below the diagonal, and the p-value above the diagonal.

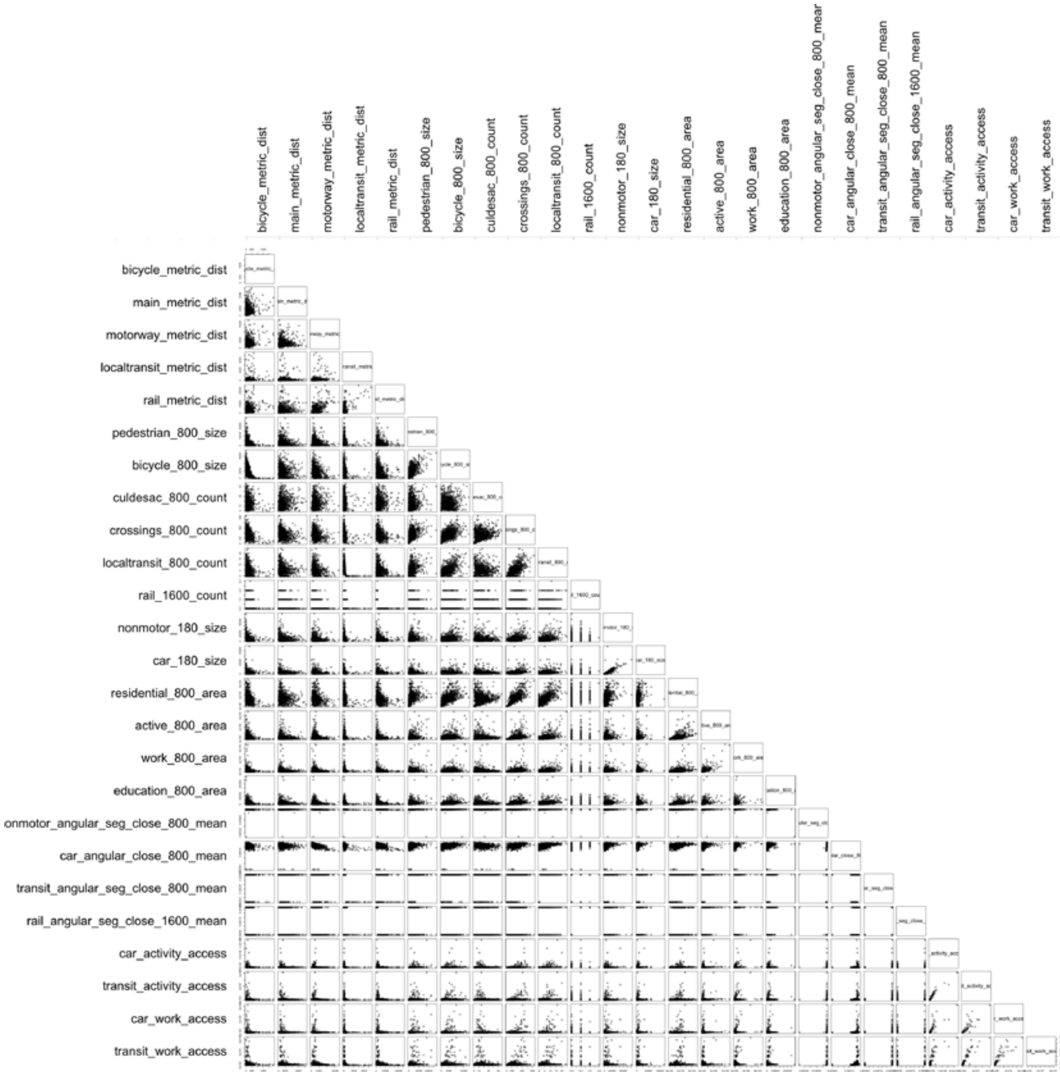


FIGURE APP.H.4 Scatterplot matrix of urban form and accessibility variables.

	short_walk	walk	short_cycle	medium_cycle	cycle	short_car	medium_car	far_car	car	car_dist	car_dur	medium_transit	transit	far_transit	train	transit_dist	transit_dur	avg_dist	avg_dist_pers	avg_journeys_pers
bicycle_metric_dist	-0.15	-0.09	0.11	-0.05	0.05	0.1	0.14	0.08	0.12	0.12	0.09	-0.22	-0.2	-0.16	-0.13	-0.17	-0.22	-0.06	-0.01	0.14
main_metric_dist	-0.1	-0.16	0.04	-0.06	-0.05	0.15	0.22	0.22	0.28	0.26	0.26	-0.21	-0.2	-0.21	-0.13	-0.23	-0.22	0.12	0.13	0.05
motorway_metric_dist	-0.15	-0.12	0.07	-0.1	-0.04	0.18	0.22	0.17	0.23	0.23	0.22	-0.27	-0.19	-0.23	-0.28	-0.27	-0.26	-0.01	0.06	0.14
localtransit_metric_dist	-0.16	-0.16	0.14	0.05	0.09	0.08	0.13	0.07	0.14	0.15	0.13	-0.24	-0.23	-0.13	-0.08	-0.18	-0.22	0.02	0.07	0.1
rail_metric_dist	-0.14	-0.18	0.04	-0.2	-0.11	0.2	0.31	0.3	0.36	0.36	0.32	-0.24	-0.03	-0.39	-0.58	-0.39	-0.3	0.03	0.06	0.1
pedestrian_800_size	0.22	0.24	-0.13	0.13	0.02	-0.19	-0.28	-0.24	-0.31	-0.28	-0.27	0.34	0.3	0.27	0.22	0.32	0.3	-0.01	-0.09	-0.18
bicycle_800_size	0.32	0.3	-0.24	0.1	-0.06	-0.24	-0.34	-0.28	-0.37	-0.34	-0.32	0.46	0.44	0.36	0.27	0.39	0.43	0	-0.12	-0.31
culdesac_800_count	-0.2	-0.16	0.15	0.03	0.08	0.19	0.14	0.16	0.16	0.14	0.15	-0.17	-0.14	-0.14	-0.12	-0.15	-0.16	-0.06	-0.02	0.11
crossings_800_count	0.18	0.34	-0.09	0.2	0.12	-0.17	-0.39	-0.27	-0.47	-0.36	-0.41	0.36	0.3	0.32	0.26	0.35	0.33	-0.15	-0.19	-0.09
localtransit_800_count	0.32	0.41	-0.23	0.05	-0.06	-0.24	-0.38	-0.26	-0.44	-0.37	-0.42	0.5	0.47	0.32	0.18	0.38	0.43	-0.13	-0.23	-0.25
rail_1600_count	0.12	0.19	-0.03	0.16	0.08	-0.18	-0.24	-0.26	-0.3	-0.27	-0.25	0.14	-0.02	0.32	0.46	0.31	0.23	0.01	-0.01	-0.04
nonmotor_180_size	0.21	0.19	-0.15	0	-0.06	-0.15	-0.2	-0.13	-0.23	-0.15	-0.18	0.23	0.21	0.15	0.09	0.17	0.19	-0.03	-0.06	-0.11
car_180_size	0.11	0.15	-0.07	-0.01	-0.02	-0.09	-0.16	-0.08	-0.19	-0.1	-0.16	0.15	0.13	0.09	0.05	0.1	0.11	-0.09	-0.1	-0.03
residential_800_area	0.3	0.42	-0.19	0.14	0.01	-0.24	-0.43	-0.33	-0.51	-0.42	-0.43	0.5	0.43	0.43	0.32	0.46	0.44	-0.13	-0.21	-0.22
active_800_area	0.24	0.46	-0.13	0.21	0.1	-0.26	-0.45	-0.29	-0.55	-0.4	-0.48	0.37	0.27	0.33	0.25	0.35	0.31	-0.2	-0.24	-0.1
work_800_area	0.23	0.37	-0.07	0.19	0.11	-0.3	-0.41	-0.28	-0.5	-0.38	-0.42	0.32	0.23	0.3	0.25	0.33	0.28	-0.14	-0.18	-0.07
education_800_area	0.27	0.37	-0.17	0.19	0.04	-0.26	-0.47	-0.32	-0.49	-0.41	-0.41	0.48	0.42	0.42	0.38	0.46	0.44	-0.03	-0.12	-0.23
nonmotor_angular_seg_close_800_mean	0.29	0.33	-0.2	0.07	-0.05	-0.28	-0.37	-0.23	-0.42	-0.33	-0.34	0.4	0.31	0.34	0.33	0.38	0.36	-0.05	-0.13	-0.22
car_angular_close_800_mean	0.3	0.31	-0.24	0.01	-0.08	-0.22	-0.32	-0.22	-0.37	-0.33	-0.36	0.49	0.42	0.28	0.21	0.35	0.38	-0.12	-0.22	-0.24
transit_angular_seg_close_800_mean	0.17	0.22	-0.1	0.06	-0.02	-0.21	-0.25	-0.13	-0.27	-0.18	-0.19	0.24	0.19	0.23	0.22	0.25	0.24	0.03	-0.01	-0.1
rail_angular_seg_close_1600_mean	0.13	0.21	-0.03	0.16	0.07	-0.2	-0.27	-0.26	-0.32	-0.28	-0.26	0.17	0.02	0.33	0.46	0.32	0.24	0	-0.02	-0.06
car_activity_access	0.2	0.31	-0.08	0.14	0.07	-0.26	-0.36	-0.21	-0.42	-0.3	-0.32	0.35	0.24	0.26	0.26	0.32	0.29	-0.04	-0.07	-0.09
transit_activity_access	0.17	0.23	-0.04	0.17	0.1	-0.28	-0.35	-0.22	-0.38	-0.3	-0.28	0.32	0.18	0.3	0.39	0.35	0.29	0.05	0.01	-0.09
car_work_access	0.07	0.1	0.02	0.14	0.11	-0.18	-0.23	-0.11	-0.24	-0.18	-0.17	0.18	0.1	0.16	0.23	0.22	0.18	0.05	0.04	-0.01
transit_work_access	0.05	0.07	0.04	0.17	0.13	-0.18	-0.24	-0.16	-0.23	-0.2	-0.15	0.2	0.08	0.24	0.36	0.27	0.22	0.12	0.11	-0.02

FIGURE APP.H.5 Correlation of travel patterns against urban form and accessibility variables. The colour indicates a positive (blue) or negative (red) correlation, and the crossed values have an insignificant correlation (p > 0.05).

TOC

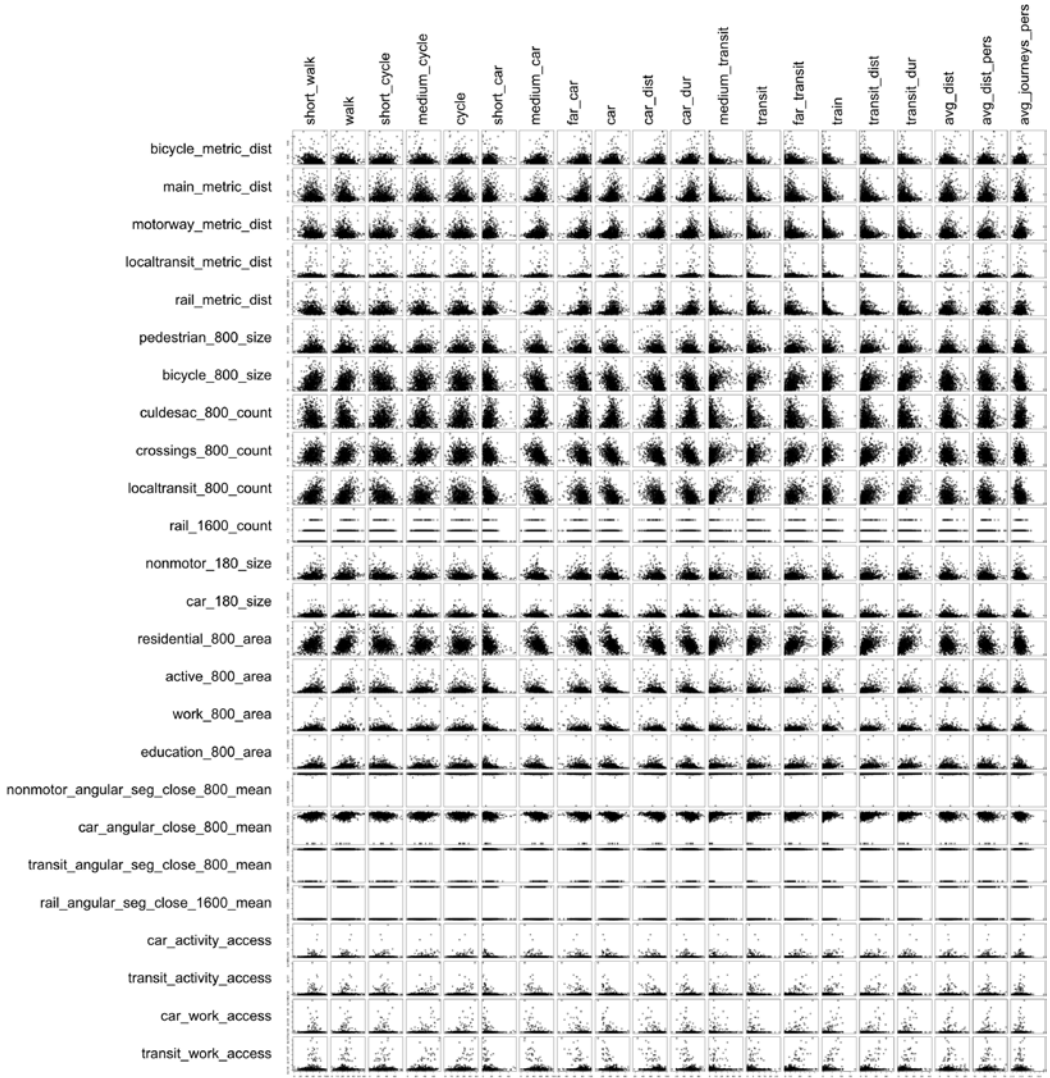


FIGURE APP.H.6 Scatterplots of travel apatterns gainst urban form and accessibility variables.

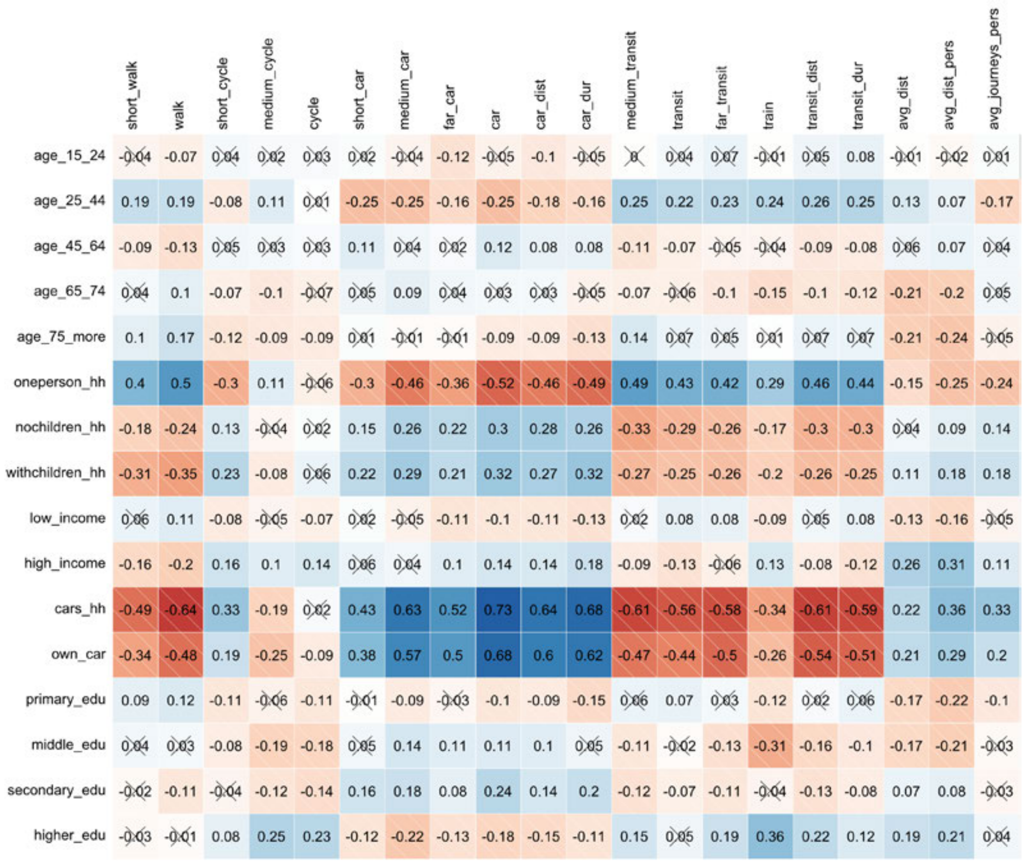


FIGURE APP.H.7 Correlation of travel patterns against socio-economic variables. The colour indicates a positive (blue) or negative (red) correlation, and the crossed values have an insignificant correlation (p > 0.05).

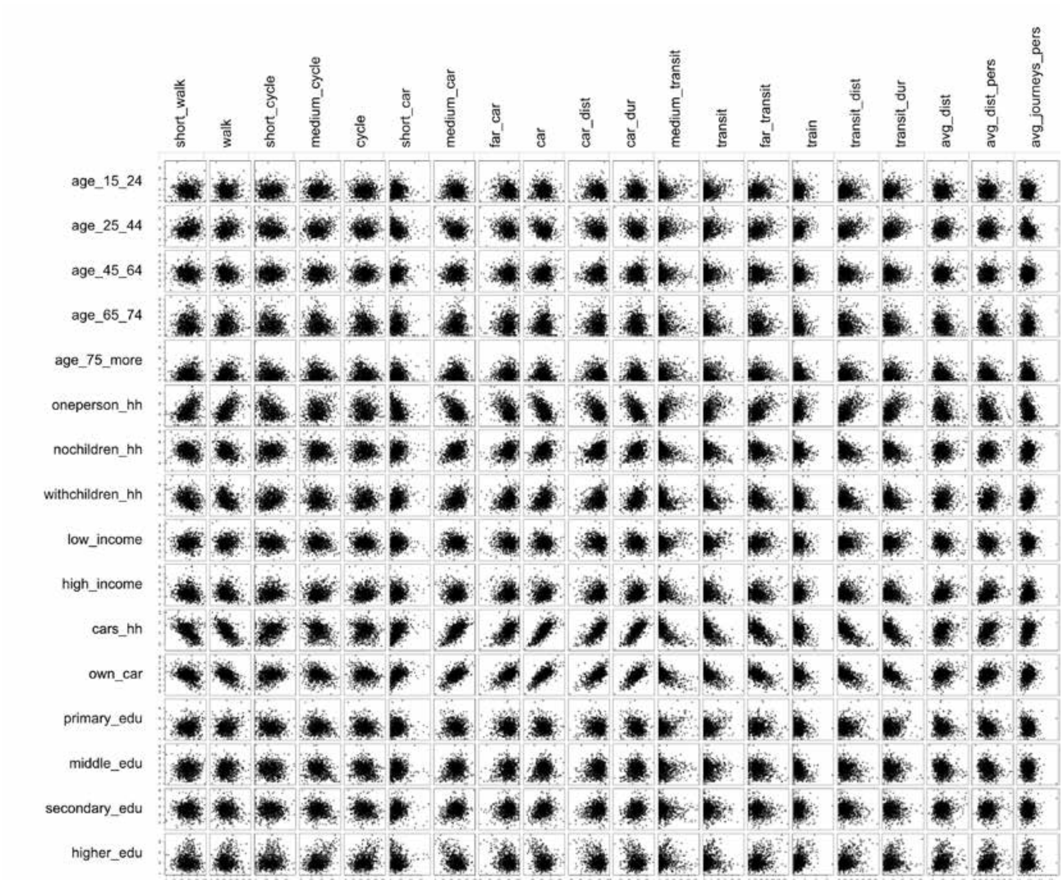


FIGURE APP.H.8 Scatterplots of travel patterns against socio-economic variables.

	bicycle_metric_dist	main_metric_dist	motorway_metric_dist	localtransit_metric_dist	rail_metric_dist	pedestrian_800_size	bicycle_800_size	culdesac_800_count	crossings_800_count	localtransit_800_count	rail_1600_count	nonmotor_180_size	car_180_size	residential_800_area	active_800_area	work_800_area	education_800_area	nonmotor_angular_seg_close_800_mean	car_angular_close_800_mean	transit_angular_seg_close_800_mean	rail_angular_seg_close_1600_mean	car_activity_access	transit_activity_access	car_work_access	transit_work_access
short_walk	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.05	0.14
walk	0.01	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.06
short_cycle	0	0.27	0.05	0	0.2	0	0	0	0.01	0	0.42	0	0.04	0	0	0.03	0	0	0	0	0.33	0.02	0.23	0.57	0.2
medium_cycle	0.12	0.07	0	0.15	0	0	0	0.38	0	0.16	0	0.99	0.72	0	0	0	0	0.03	0.72	0.08	0	0	0	0	0
cycle	0.13	0.18	0.27	0.01	0	0.47	0.06	0.03	0	0.1	0.03	0.09	0.51	0.85	0.01	0	0.3	0.16	0.02	0.52	0.03	0.04	0.01	0	0
short_car	0	0	0	0.02	0	0	0	0	0	0	0	0	0.01	0	0	0	0	0	0	0	0	0	0	0	0
medium_car	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
far_car	0.03	0	0	0.04	0	0	0	0	0	0	0	0	0.01	0	0	0	0	0	0	0	0	0	0	0	0
car	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
car_dist	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
car_dur	0.01	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
medium_transit	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
transit	0	0	0	0	0.42	0	0	0	0	0	0.65	0	0	0	0	0	0	0	0	0	0.53	0	0	0.01	0.01
far_transit	0	0	0	0	0	0	0	0	0	0	0	0	0.01	0	0	0	0	0	0	0	0	0	0	0	0
train	0	0	0	0.02	0	0	0	0	0	0	0	0.01	0.17	0	0	0	0	0	0	0	0	0	0	0	0
transit_dist	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
transit_dur	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
avg_dist	0.07	0	0.78	0.5	0.45	0.68	0.9	0.09	0	0	0.87	0.44	0.01	0	0	0	0.32	0.14	0	0.39	0.97	0.31	0.14	0.14	0
avg_dist_pers	0.77	0	0.08	0.06	0.06	0.01	0	0.54	0	0	0.79	0.06	0.01	0	0	0	0	0	0	0.76	0.58	0.04	0.68	0.2	0
avg_journeys_pers	0	0.13	0	0.01	0.01	0	0	0	0.01	0	0.23	0	0.38	0	0	0.04	0	0	0	0	0.1	0.01	0.01	0.69	0.54

FIGURE APP.H.9 P value of travel against urban form and accessibility variables.

	age_15_24	age_25_44	age_45_64	age_65_74	age_75_more	oneperson_hh	nochildren_hh	withchildren_hh	low_income	high_income	cars_hh	own_car	primary_edu	middle_edu	secondary_edu	higher_edu
short_walk	0.23	0	0.01	0.27	0.01	0	0	0	0.07	0	0	0	0.01	0.2	0.51	0.46
walk	0.05	0	0	0	0	0	0	0	0	0	0	0	0	0.39	0	0.7
short_cycle	0.31	0.02	0.16	0.05	0	0	0	0	0.02	0	0	0	0	0.02	0.2	0.01
medium_cycle	0.51	0	0.37	0	0.01	0	0.24	0.02	0.15	0	0	0	0.11	0	0	0
cycle	0.4	0.81	0.41	0.05	0.01	0.07	0.61	0.06	0.05	0	0.52	0.01	0	0	0	0
short_car	0.61	0	0	0.12	0.74	0	0	0	0.59	0.08	0	0	0.82	0.18	0	0
medium_car	0.22	0	0.22	0.01	0.69	0	0	0	0.12	0.21	0	0	0.01	0	0	0
far_car	0	0	0.46	0.2	0.74	0	0	0	0	0	0	0	0.36	0	0.02	0
car	0.14	0	0	0.39	0.01	0	0	0	0	0	0	0	0	0	0	0
car_dist	0	0	0.03	0.38	0.01	0	0	0	0	0	0	0	0.01	0	0	0
car_dur	0.12	0	0.02	0.14	0	0	0	0	0	0	0	0	0	0.12	0	0
medium_transit	0.95	0	0	0.05	0	0	0	0	0.47	0.01	0	0	0.08	0	0	0
transit	0.28	0	0.04	0.07	0.05	0	0	0	0.02	0	0	0	0.04	0.66	0.05	0.15
far_transit	0.06	0	0.15	0.01	0.14	0	0	0	0.02	0.07	0	0	0.35	0	0	0
train	0.77	0	0.24	0	0.85	0	0	0	0.01	0	0	0	0	0	0.23	0
transit_dist	0.14	0	0.01	0	0.06	0	0	0	0.16	0.03	0	0	0.52	0	0	0
transit_dur	0.02	0	0.01	0	0.06	0	0	0	0.03	0	0	0	0.08	0.01	0.02	0
avg_dist	0.83	0	0.1	0	0	0	0.25	0	0	0	0	0	0	0	0.05	0
avg_dist_pers	0.55	0.03	0.05	0	0	0	0.01	0	0	0	0	0	0	0	0.02	0
avg_journeys_pers	0.77	0	0.2	0.18	0.13	0	0	0	0.18	0	0	0	0	0.42	0.35	0.23

FIGURE APP.H.10 P value of travel against socio-economic variables.

Appendix I Descriptive statistics of the urban form typology

Quantitative description of the urban form types identified in Chapter 6 (excluding type 12 that is an outlier) using descriptive statistics and boxplots.

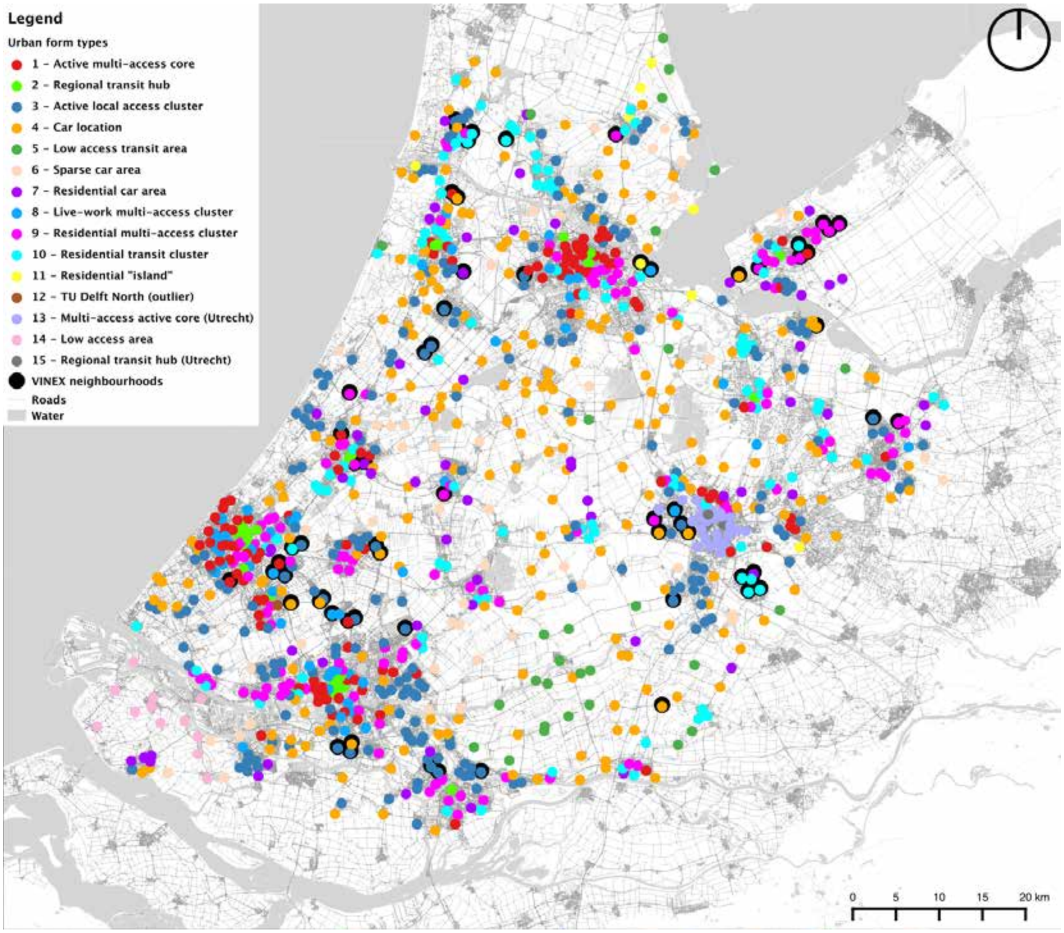


FIGURE APP.I.1 Map of the 'urban modality' types of the Randstad.

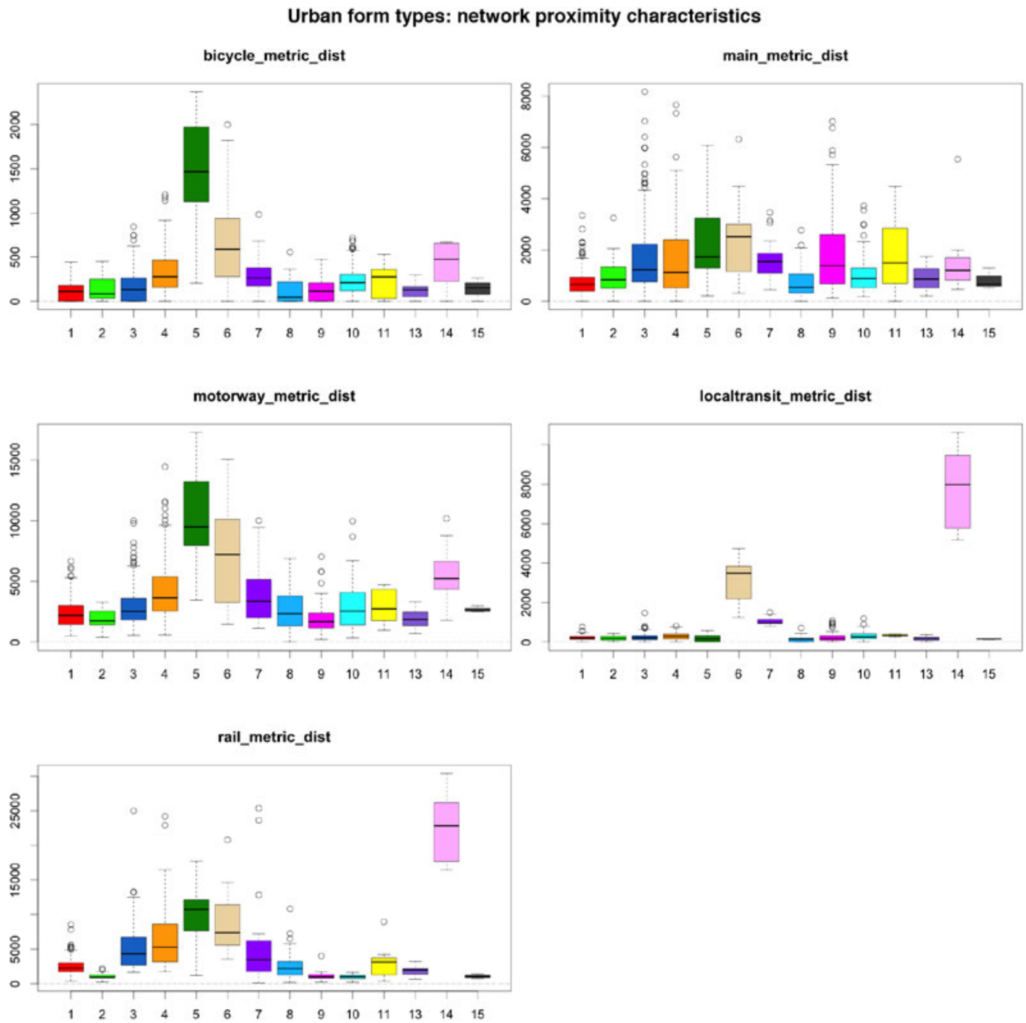


FIGURE APP.I.2 Boxplots of urban form types' network distance characteristics.

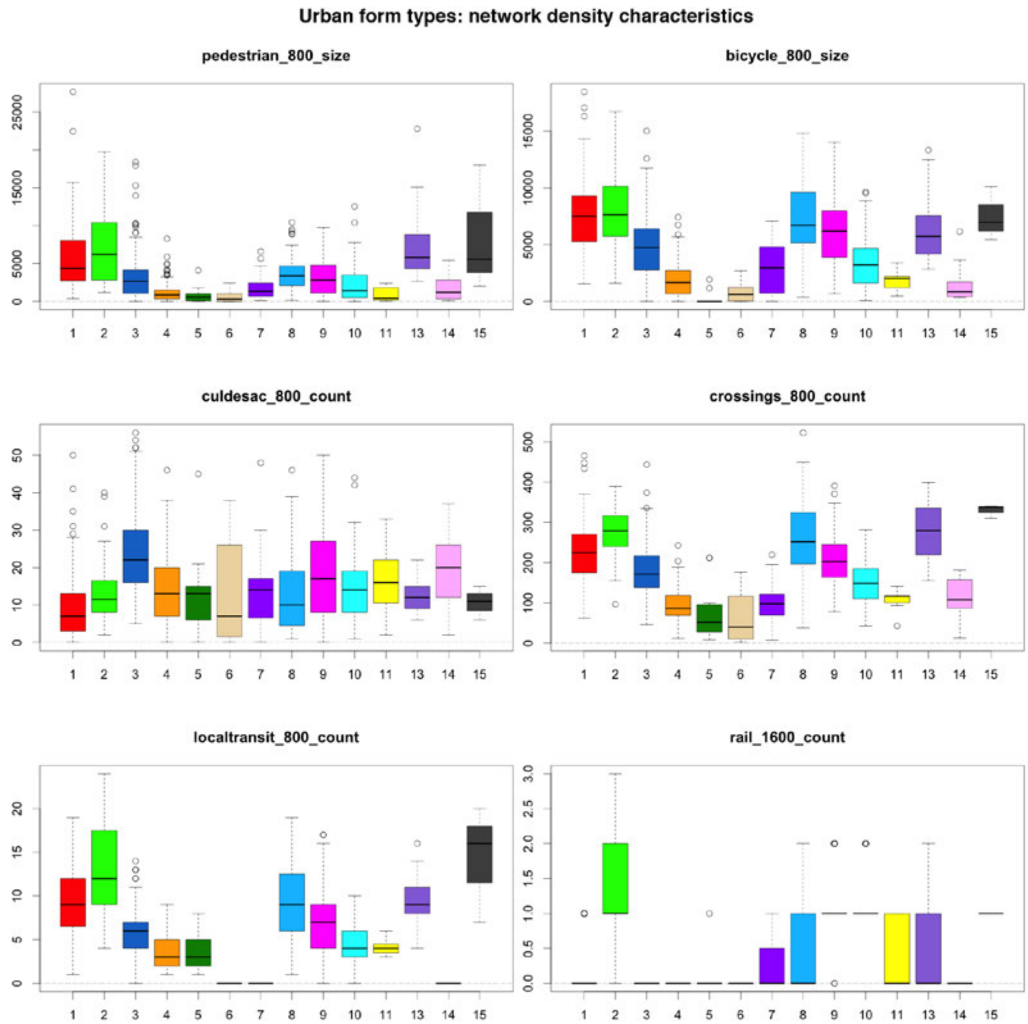


FIGURE APP.I.3 Boxplots of urban form types' network density characteristics.

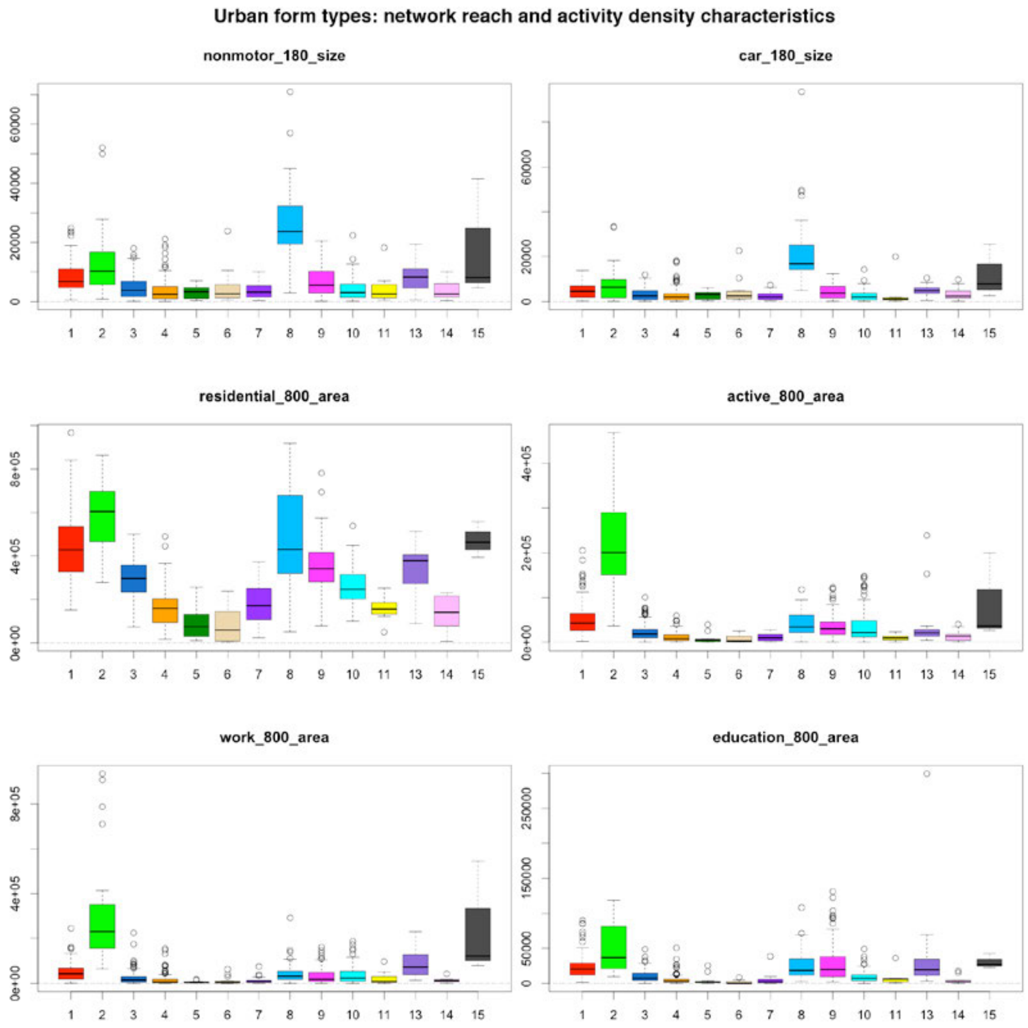
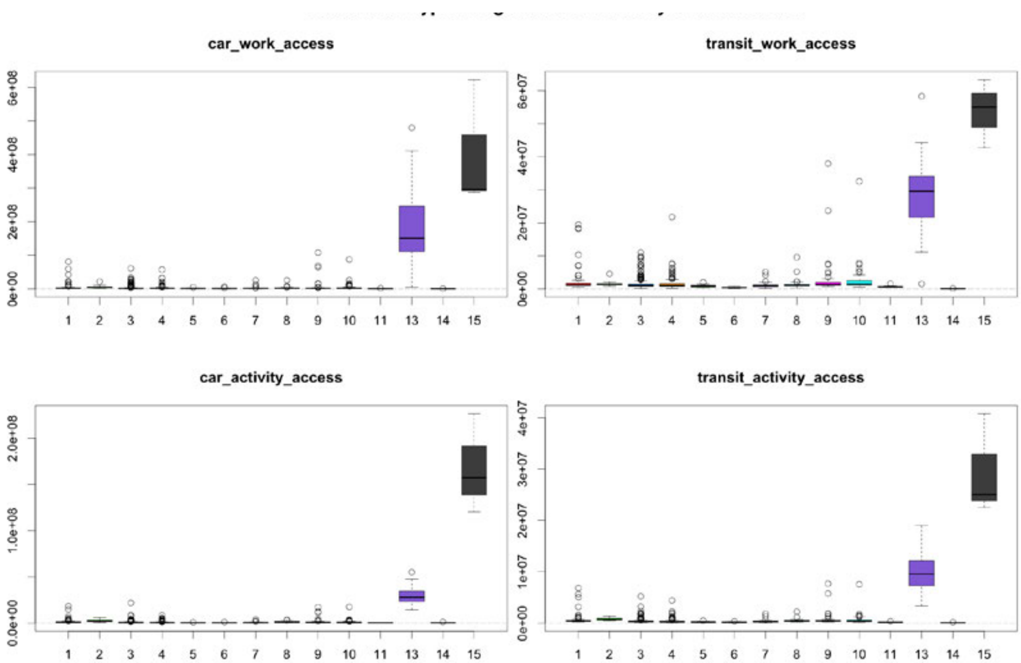
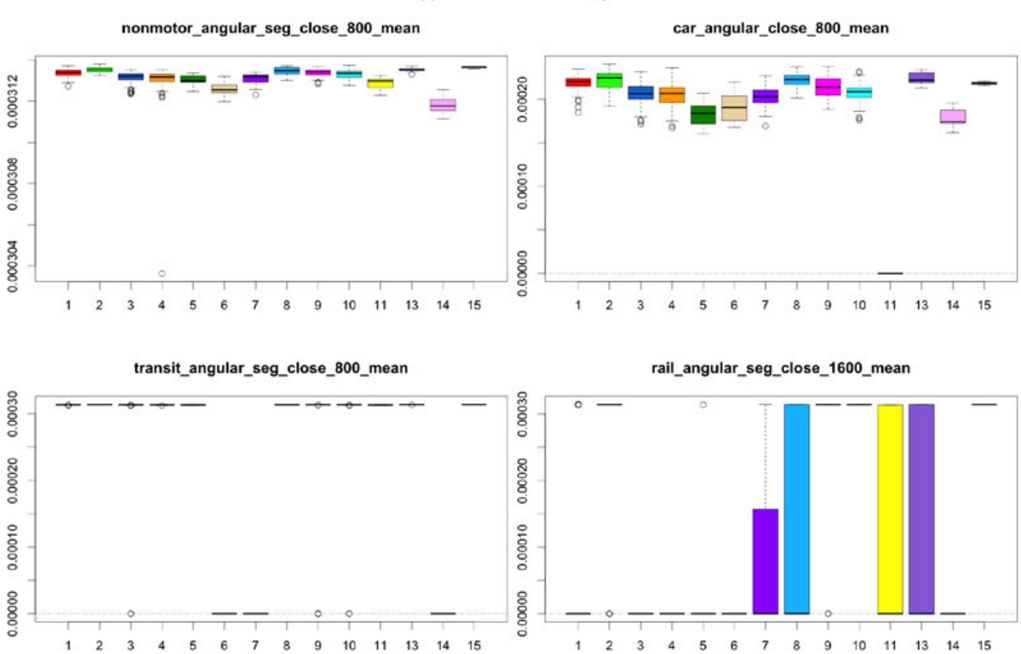


FIGURE APP.I.4 Boxplots of urban form types' network reach and activity density characteristics.



1



2

FIGURE APP.I.5 Boxplots of urban form types' regional accessibility characteristics (1) and network configuration characteristics (2)

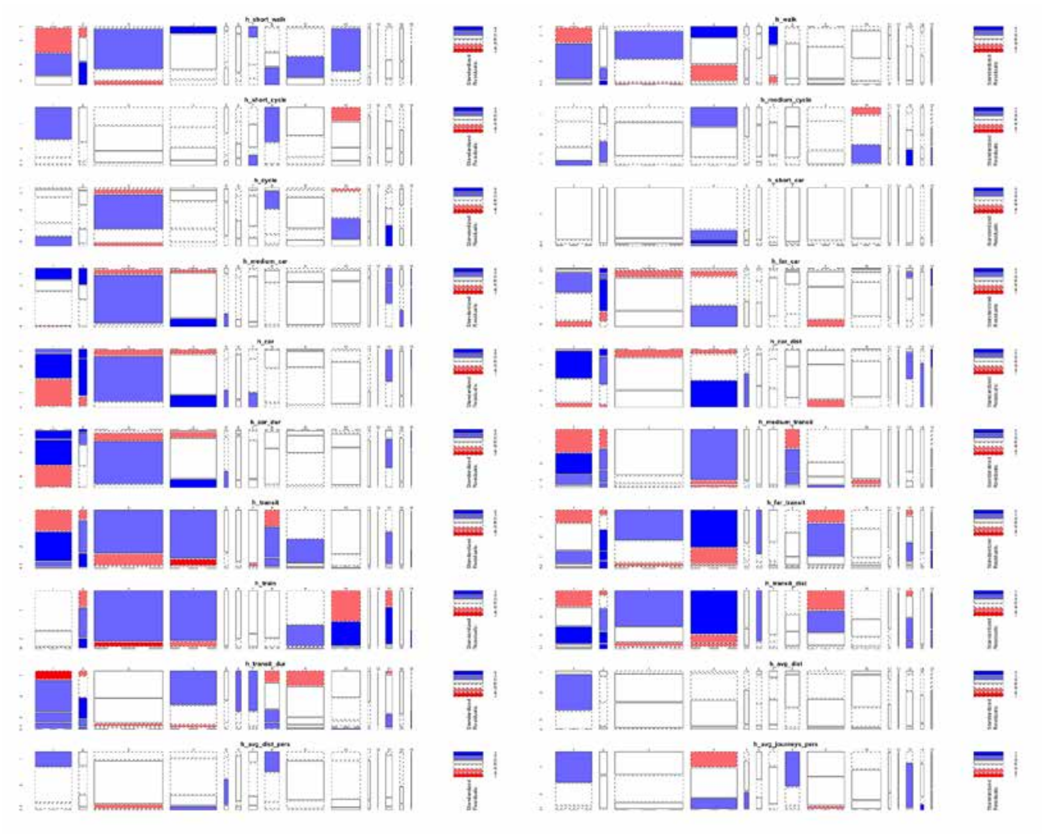


FIGURE APP.I.6 Mosaic plot of the relation between urban form types and sustainable mobility indicators.

MEASURE	TYPE 1	TYPE 2	TYPE 3	TYPE 4	TYPE 5	TYPE 6
Bicycle proximity	116	136	170	325	1441	737
Main road proximity	804	998	1699	1626	2391	2475
Motorway proximity	2415	1944	2912	4283	9896	7081
Transit proximity	214	201	245	292	214	3167
Rail proximity	2508	1027	5050	6009	9984	8732
Pedestrian density	5966	7364	3137	1207	880	543
Bicycle density	7669	8254	4809	1947	238	720
Cul-de-sac density	9	14	24	15	13	13
Crossings density	226	269	177	94	76	62
Transit density	9	13	6	4	4	0
Rail density	0	1	0	0	0	0
Non-motorised reach	8039	14586	4890	3775	3269	4613
Car reach	4737	8641	3213	2944	2812	4237
Residential density	447235	588478	296987	159843	89995	85194
Activity density	52562	218516	22666	11580	8479	7509
Work density	50217	321778	21762	15493	5696	11632
Education density	23791.09	48473.233	10273.355	4894.859	4543.077	1595.125
Car activity accessibility	1334146.7	2431167	867449.1	696670.5	354234.3	322244.2
Transit activity accessib.	590639.96	739721.36	405438.75	362958.3	203404.93	166053.57
Car work accessibility	4698539.4	5294955.9	3520507.1	3546113.9	1816467.5	1664432.3
Transit work accessibility	2010522.34	1521132.62	1629348.49	1619689.95	987283.3	407087.12
Non-motorised closeness	0.000313	0.000314	0.000313	0.000313	0.000313	0.000313
Car closeness	0.000219	0.000222	0.000206	0.000205	0.000183	0.000191
Transit closeness	0.000313	0.000314	0.00031	0.000313	0.000313	0
Rail closeness	0.000051	0.000275	0	0	0.000024	0

TABLE APP.I.1 Mean values of urban form type characteristics.

	TYPE 7	TYPE 8	TYPE 9	TYPE 10	TYPE 11	TYPE 13	TYPE 14	TYPE 15
	303	112	138	248	227	118	409	139
	1599	752	1817	1048	1869	939	1586	828
	3837	2640	1961	2848	2943	1911	5648	2678
	1047	152	242	300	341	159	7777	147
	5105	2575	1022	948	3186	1897	22448	1043
	1851	3798	3014	2398	973	7467	1803	8524
	2950	7043	6306	3416	1825	6308	1634	7509
	14	13	18	15	17	12	20	11
	101	263	205	149	106	273	111	330
	0	9	7	4	4	10	0	14
	0	0	1	1	0	0	0	1
	3689	26527	6666	3899	5051	7912	4025	18120
	2513	21907	4292	2686	3719	4988	3572	12025
	183922	483450	356866	260666	156933	349736	143734	471530
	10934	41087	35711	36842	10412	36946	14674	87873
	12883	48358	32596	38293	24794	87481	13079	249277
	4424.963	26034.773	29148.421	9498.906	8601.429	36386.095	5077.7	30508.333
	613857.8	1153524.3	1102953.2	950438.2	255562.6	31011575.6	308751.1	167995107.1
	363318.61	458155.92	555728.21	557779.62	176879.55	9838152.82	71777.59	29460173.8
	3284328	3037269.1	4362047.9	4223290.5	931042.8	189368648.7	575200.4	402299486.7
	1235251.5	1498171.57	2176956.59	2344139.26	786070.68	28829125.58	84248.09	53696370.54
	0.000313	0.000313	0.000313	0.000313	0.000313	0.000314	0.000312	0.000314
	0.000202	0.000222	0.000214	0.000207	0	0.000223	0.000179	0.000218
	0	0.000313	0.0003	0.000306	0.000313	0.000314	0	0.000314
	0.000081	0.000121	0.000308	0.000314	0.000134	0.000105	0	0.000314

MEASURE	TYPE 1	TYPE 2	TYPE 3	TYPE 4	TYPE 5	TYPE 6
Bicycle proximity	110	83	132	278	1468	590
Main road proximity	658	842	1228	1120	1727	2520
Motorway proximity	2196	1740	2530	3654	9499	7217
Transit proximity	206	192	214	282	157	3491
Rail proximity	2201	932	4295	5263	10737	7364
Pedestrian density	4371	6213	2665	859	551	331
Bicycle density	7513	7637	4748	1660	0	611
Cul-de-sac density	7	12	22	13	13	7
Crossings density	225	280	172	86	52	40
Transit density	9	12	6	3	3	0
Rail density	0	1	0	0	0	0
Non-motorised reach	6804	10292	3821	2466	3312	2623
Car reach	4537	6451	2569	1950	3160	2559
Residential density	428585	604808	296520	159428	75299	60175
Activity density	43088	200713	18574	8243	5485	3056
Work density	42495	231052	14722	6386	4478	3237
Education density	20372	36620.5	7472.5	2833.5	1896	0
Car activity accessibility	825826.9	1938909.1	463304.3	375832.9	287472.6	269609.4
Transit activity accessibility	371593.32	706155.37	260980.1	226360.27	198352.88	164823.59
Car work accessibility	2310626.6	4286800.1	1396167.3	1758784	1276460	1194694.7
Transit work accessib.	1192450.63	1423713.68	1012622.71	1003854.74	929618.74	371351.57
Non-motorised closeness	0.000313	0.000314	0.000313	0.000313	0.000313	0.000313
Car closeness	0.00022	0.000225	0.000207	0.000207	0.000184	0.00019
Transit closeness	0.000313	0.000314	0.000313	0.000313	0.000313	0
Rail closeness	0	0.000314	0	0	0	0

TABLE APP.I.2 Median values of urban form type characteristics

TYPE 7	TYPE 8	TYPE 9	TYPE 10	TYPE 11	TYPE 13	TYPE 14	TYPE 15
264	45	113	211	277	130	475	154
1552	545	1387	886	1499	862	1206	664
3372	2349	1676	2553	2728	1863	5235	2560
967	143	188	260	326	180	7985	154
3451	2171	958	1002	3120	1959	22841	1009
1324	3376	2822	1409	408	5792	1208	5563
2970	6707	6210	3229	2017	5732	846	6969
14	10	17	14	16	12	20	11
98	252	203	149	117	280	108	338
0	9	7	4	4	9	0	16
0	0	1	1	0	0	0	1
3216	23731	5556	3100	2561	8334	2559	8149
2009	16807	3752	1978	1130	4835	2464	7903
171420	430360	341792	246543	155991	378660	140759	463414
10199	34494	30462	22015	10027	21163	13534	36754
8543	31245	17684	23529	8640	72204	11615	121890
2532	18436.5	19619.5	7297	6093	19215	2322	26649
367403.6	1008349.7	670883.3	564842.9	227198.2	27732156.4	222202.1	157164758.5
257332.57	390661.02	400081.56	368788.91	153996.56	9540372.58	58705.07	25052381.45
1639382.3	2059836.5	1749705.5	1946117.5	872951.1	151402101.8	551803.6	296399983.1
968523.16	1098387.19	1338680.84	1469769.14	640630.12	29560331.83	73561.51	55074793.48
0.000313	0.000313	0.000313	0.000313	0.000313	0.000314	0.000312	0.000314
0.000203	0.000223	0.000214	0.000209	0	0.000222	0.000174	0.000218
0	0.000313	0.000314	0.000313	0.000313	0.000314	0	0.000314
0	0	0.000314	0.000314	0	0	0	0.000314

MEASURE	TYPE 1	TYPE 2	TYPE 3	TYPE 4	TYPE 5	TYPE 6	
Bicycle proximity	0	0	0	0	205	0	
Main road proximity	0	0	0	0	216	322	
Motorway proximity	519	398	560	591	3452	1460	
Transit proximity	0	0	0	0	0	1242	
Rail proximity	347	211	1621	1701	1157	3553	
Pedestrian density	381	1187	0	0	0	0	
Bicycle density	1569	1614	0	0	0	0	
Cul-de-sac density	0	2	5	0	0	0	
Crossings density	62	97	46	12	8	2	
Transit density	1	4	0	1	1	0	
Rail density	0	0	0	0	0	0	
Non-motorised reach	532	915	94	63	285	639	
Car reach	227	97	94	63	285	639	
Residential density	151874	279133	73228	16746	11278	3288	
Activity density	2263	37001	811	0	0	0	
Work density	575	62893	32	1	1364	0	
Education density	1137	9402	0	0	0	0	
Car activity accessibility	281418.6	604061.38	168841.03	131307.56	190785.8	129399.48	
Transit activity accessibility	203160.56	405625.1	63632.76	53342.8	105407.5	52995.08	
Car work accessibility	1014575.3	1596612.6	489471.2	429119.7	661364.2	415338.7	
Transit work accessib.	540436.79	811848.6	130636.7	119152.4	430120.34	94247.59	
Non-motorised closeness	0.000313	0.000313	0.000312	0.000304	0.000312	0.000312	
Car closeness	0.000185	0.000192	0.000172	0.000167	0.00016	0.000168	
Transit closeness	0.000313	0.000313	0	0.000312	0.000313	0	
Rail closeness	0	0	0	0	0	0	

TABLE APP.I.3 Minimum values of urban form type characteristics

	TYPE 7	TYPE 8	TYPE 9	TYPE 10	TYPE 11	TYPE 13	TYPE 14	TYPE 15
	0	0	0	0	0	0	0	0
	454	0	124	169	0	207	470	519
	1137	0	203	353	967	691	1775	2507
	807	0	0	0	262	0	5187	123
	102	148	197	187	321	601	16412	712
	93	129	0	0	39	2694	66	2019
	0	361	664	62	486	2854	338	5453
	0	1	0	1	2	6	2	6
	7	38	78	43	43	155	13	311
	0	1	0	0	3	4	0	7
	0	0	0	1	0	0	0	1
	284	2945	155	168	450	552	302	4603
	269	4889	155	101	237	460	125	2652
	24474	51877	79726	99886	50786	90962	8132	394143
	0	1551	1149	176	628	4372	100	26518
	0	182	50	103	141	13761	745	80108
	0	2212	1787	0	519	3174	0	22595
	123701.33	361238.41	197860.77	182284.96	154366.42	14286755.84	88363.93	120330101.4
	53243.26	215367.3	201769.78	154239.92	115513.86	3326901.41	32173.59	22552122.36
	439965.1	979366.3	915844.1	628517.1	481500.9	5129621.8	390458.3	287563405.5
	116517.49	376029.3	768946.36	589302.26	508864.62	1527939.71	45257.56	42695640.98
	0.000312	0.000313	0.000313	0.000313	0.000312	0.000313	0.000311	0.000314
	0.000169	0.000201	0.000189	0.000176	0	0.000213	0.000162	0.000216
	0	0.000313	0	0	0.000313	0.000313	0	0.000314
	0	0	0	0.000313	0	0	0	0.000314

MEASURE	TYPE 1	TYPE 2	TYPE 3	TYPE 4	TYPE 5	TYPE 6
Bicycle proximity	445	451	843	1208	2372	2000
Main road proximity	3352	3253	8170	7661	6083	6319
Motorway proximity	6669	3273	10020	14458	17272	15071
Transit proximity	756	432	1475	800	577	4745
Rail proximity	8531	2195	25000	24203	17687	20792
Pedestrian density	27673	19789	18393	8284	4107	2435
Bicycle density	18469	16709	15023	7427	1930	2704
Cul-de-sac density	50	40	56	46	45	38
Crossings density	466	390	444	243	212	176
Transit density	19	24	14	9	8	0
Rail density	1	3	0	0	1	0
Non-motorised reach	24860	52060	18040	21153	7095	23868
Car reach	13820	33483	11949	18254	6281	22667
Residential density	966080	862591	501272	489710	256179	238421
Activity density	205310	467770	100551	59769	39704	25358
Work density	245271	934775	224709	154997	17928	62701
Education density	89660	118799	48633	50723	25369	8463
Car activity accessibility	18132922.7	5530548.3	21559777.6	8191951.4	743458.2	984486.3
Transit activity accessib.	6797894.2	1358497.9	5181884.4	4392371.1	440508	323676.9
Car work accessibility	81344430	21993350	61082671	57390386	4874732	6628063
Transit work accessibility	19446892.6	4569740.2	11035125.5	21791316.5	1997550.8	812182.5
Non-motorised closeness	0.000314	0.000314	0.000314	0.000314	0.000313	0.000313
Car closeness	0.000235	0.00024	0.000232	0.000236	0.000207	0.000219
Transit closeness	0.000314	0.000314	0.000314	0.000314	0.000314	0
Rail closeness	0.000314	0.000314	0	0	0.000314	0

TABLE APP.I.4 Maximum values of urban form type characteristics

TYPE 7	TYPE 8	TYPE 9	TYPE 10	TYPE 11	TYPE 13	TYPE 14	TYPE 15
983	556	477	719	530	297	670	264
3465	2769	7017	3726	4480	1738	5540	1302
10021	6896	7042	9972	4731	3340	10184	2965
1496	713	1087	1194	397	382	10619	164
25362	10806	3978	1588	8930	3203	30416	1409
6587	10446	9754	12539	2415	22796	5399	17990
7086	14830	14048	9670	3417	13335	6162	10104
48	46	50	44	33	22	37	15
220	523	391	282	142	399	182	341
0	19	17	10	6	16	0	20
1	2	2	2	1	2	0	1
10189	70947	20526	22431	18261	19319	10156	41609
7344	93459	12485	14296	20009	10514	9795	25519
374300	917961	780561	538395	252632	512217	229917	557034
28113	117819	122614	148164	23584	238640	40287	200346
74571	291970	161832	187473	97212	230883	42303	545832
38363	108112	131155.3	49086	36136	299280	17843	42281
3906079.2	3232011.9	16892114.2	17300268.9	388016.1	54875820.5	1135262	226490461.5
1795137.7	2197713.9	7648104.8	7533915.6	326321.2	18972443.8	166853.1	40776017.6
25958749	25719224	108212561	88041408	1888294	480007539	1022355	622935072
5123741.3	9586336.7	37938128.4	32570803.4	1611301	58336727	159980.2	63318677.2
0.000313	0.000314	0.000314	0.000314	0.000313	0.000314	0.000313	0.000314
0.000227	0.000237	0.000238	0.000232	0	0.000234	0.000196	0.000221
0	0.000314	0.000314	0.000314	0.000314	0.000314	0	0.000314
0.000314	0.000314	0.000314	0.000314	0.000314	0.000314	0	0.000314

MEASURE	TYPE 1	TYPE 2	TYPE 3	TYPE 4	TYPE 5	TYPE 6
Bicycle proximity	0	40	0	162	1126	283
Main road proximity	391	521	754	520	1301	1296
Motorway proximity	1453	1447	1835	2550	7972	3656
Transit proximity	131	96	118	150	0	2215
Rail proximity	1699	773	2682	3164	7645	5918
Pedestrian density	2748	2899	1067	348	64	0
Bicycle density	5258	5919	2759	664	0	37
Cul-de-sac density	3	8	16	7	6	2
Crossings density	175	243	138	69	28	12
Transit density	6	9	4	2	2	0
Rail density	0	1	0	0	0	0
Non-motorised reach	4775	5823	1739	997	1055	1368
Car reach	1826	1655	907	767	1055	1368
Residential density	326882	465923	235856	96042	29788	10052
Activity density	26401	153092	10258	4034	1918	185
Work density	18368	159728	4935	2315	2548	2840
Education density	12262	20967.75	4339.5	1481.5	982	0
Car activity accessibility	574561.8	1429133.5	350840.8	293989.2	244488.1	199174.1
Transit activity accessibility	300206	539887.17	214366.34	178072.99	135763.69	133763.54
Car work acces-sibility	1524961.3	2997801	1171831.6	1216678.2	1128172.5	1025329.6
Transit work accessib.	989561.82	1189803.45	788770.87	784066.18	594238.74	327445.76
Non-motorised closeness	0.000313	0.000313	0.000313	0.000313	0.000313	0.000312
Car closeness	0.000215	0.000214	0.0002	0.000196	0.000172	0.000176
Transit closeness	0.000313	0.000314	0.000313	0.000313	0.000313	0
Rail closeness	0	0.000314	0	0	0	0

TABLE APP.I.5 First quartile values of urban form type characteristics.

	TYPE 7	TYPE 8	TYPE 9	TYPE 10	TYPE 11	TYPE 13	TYPE 14	TYPE 15
	174	0	11	117	32	52	240	77
	1097	333	692	536	698	521	906	591
	1998	1352	1167	1408	1756	1364	4424	2534
	930	17	95	157	311	90	5970	139
	1764	1278	744	686	1259	1365	18032	860
	698	2104	1142	487	147	4350	417	3791
	737	5276	3872	1621	1230	4173	470	6211
	6	5	8	8	10	9	13	8
	70	198	164	111	100	220	88	324
	0	6	4	3	4	8	0	12
	0	0	1	1	0	0	0	1
	1515	19579	2961	1372	1257	4571	1693	6376
	969	14304	1629	740	659	3624	1663	5278
	108392	323094	281802	203431	133909	273640	89641	428778
	3662	22587	17690	11998	4892	13641	4571	31636
	3602	17754	9064	9650	3540	39336	6760	100999
	765	12864.75	9412	3901	1820	11189	1636.25	24622
	266094.4	588972.1	459183.8	349512.1	198695.7	23095871.2	145878.1	138747429.9
	192725.2	292532.92	322587.84	266762.28	132850.59	7282540.78	45875.64	23802251.9
	1223967.4	1599264.5	1388178.1	1297710.6	583140.6	110654782.2	455512.1	291981694.3
	689301.03	956373.75	1061074.74	1118095.92	586281.54	21639210.1	59690.38	48885217.23
	0.000313	0.000313	0.000313	0.000313	0.000313	0.000313	0.000312	0.000314
	0.000196	0.000217	0.000205	0.000202	0	0.000219	0.000173	0.000217
	0	0.000313	0.000313	0.000313	0.000313	0.000314	0	0.000314
	0	0	0.000314	0.000314	0	0	0	0.000314

MEASURE	TYPE 1	TYPE 2	TYPE 3	TYPE 4	TYPE 5	TYPE 6
Bicycle proximity	179	250	262	463	1975	854
Main road proximity	938	1298	2217	2378	3246	2972
Motorway proximity	2999	2510	3608	5397	13241	9852
Transit proximity	280	287	334	405	336	3769
Rail proximity	2968	1225	6702	8553	12140	11026
Pedestrian density	8051	10346	4144	1509	1025	968
Bicycle density	9290	9760	6402	2719	0	1252
Cul-de-sac density	13	16	30	20	15	24
Crossings density	271	313	217	119	96	115
Transit density	12	17	7	5	5	0
Rail density	0	2	0	0	0	0
Non-motorised reach	11127	16357	6905	5085	4808	5539
Car reach	6943	9587	4810	3467	4069	4411
Residential density	535364	694619	359180	204111	132894	139187
Activity density	64594	287985	29144	16954	6925	13280
Work density	67974	348924	29512	17456	5722	9901
Education density	28737.05	79851	14291.75	5596	2741	2379.25
Car activity accessibility	1164216	3118953.4	747087.6	576434.2	432568.1	367262.2
Transit activity accessibility	482712.05	878705.72	369638.43	348550.63	221148.59	189605.5
Car work accessibility	3356836.9	5974900.2	2450268.8	2979010.8	2030158.3	1643095.6
Transit work accessib.	1705826.4	1610375.4	1487208.6	1603057.9	1054737.8	501319.6
Non-motorised closeness	0.000314	0.000314	0.000313	0.000313	0.000313	0.000313
Car closeness	0.000224	0.000229	0.000215	0.000214	0.000193	0.000203
Transit closeness	0.000314	0.000314	0.000314	0.000314	0.000313	0
Rail closeness	0	0.000314	0	0	0	0

TABLE APP.I.6 Third quartile values of urban form type characteristics.

	TYPE 7	TYPE 8	TYPE 9	TYPE 10	TYPE 11	TYPE 13	TYPE 14	TYPE 15
	379	218	208	306	359	167	623	209
	1875	1062	2598	1303	2854	1280	1595	983
	5177	3728	2392	4087	4330	2473	6609	2763
	1146	203	332	413	390	239	9238	159
	6186	3168	1301	1200	3705	2193	25549	1209
	2440	4608	4775	3473	1827	8859	2738	11776
	4812	9569	7971	4669	2196	7572	1621	8536
	17	19	27	19	22	15	26	13
	122	324	244	185	118	336	156	340
	0	12	9	6	4	11	0	18
	0	1	1	1	1	1	0	1
	5392	32142	10247	5972	5787	11153	5520	24879
	3391	24132	6691	3810	1671	6193	4425	16711
	250936	671648	416812	314434	185652	406450	214733	510224
	17856	60341	45300	48129	14432	28925	16900	118550
	13690	53316	47619	54095	30242	127282	16286	333861
	5469.5	34812.75	37528	12327	6911	34627	4309.5	34465
	593822.4	1463150.8	937389.2	852452.2	310983	34510473.5	309261.9	191827610
	362156.52	524719.21	489986.63	608535.71	188312.03	12143692.36	85878.58	32914199.52
	2102852	2938729	2516296.1	3582481.3	1054136.3	246372542.8	588140.2	459667527.4
	1219893.6	1417471.6	1940295.2	2556048.1	784568	34105098.7	92301	59196735.3
	0.000313	0.000314	0.000314	0.000313	0.000313	0.000314	0.000312	0.000314
	0.000211	0.000228	0.000223	0.000213	0	0.00023	0.000187	0.000219
	0	0.000314	0.000314	0.000314	0.000313	0.000314	0	0.000314
	0.000157	0.000314	0.000314	0.000314	0.000313	0.000314	0	0.000314

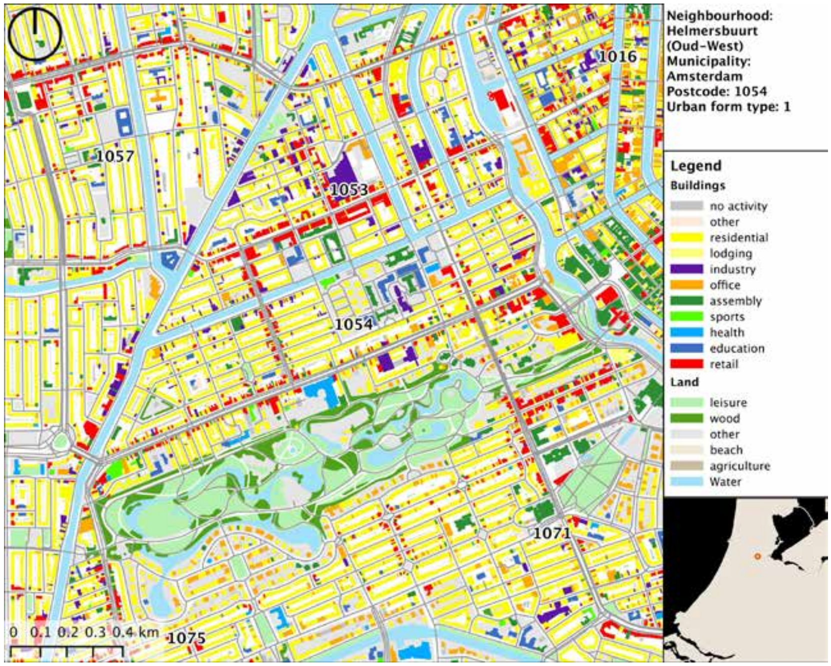
MEASURE	TYPE 1	TYPE 2	TYPE 3	TYPE 4	TYPE 5	TYPE 6
Bicycle proximity	1	0.726	1	0.482	0.274	0.503
Main road proximity	0.412	0.427	0.493	0.641	0.428	0.393
Motorway proximity	0.347	0.269	0.326	0.358	0.248	0.459
Transit proximity	0.364	0.5	0.477	0.459	1	0.26
Rail proximity	0.272	0.226	0.428	0.46	0.227	0.301
Pedestrian density	0.491	0.562	0.59	0.625	0.882	1
Bicycle density	0.277	0.245	0.398	0.607	NaN	0.943
Cul-de-sac density	0.625	0.34	0.293	0.481	0.429	0.864
Crossings density	0.215	0.126	0.222	0.265	0.548	0.819
Transit density	0.297	0.314	0.273	0.429	0.429	NaN
Rail density	NaN	0.333	NaN	NaN	NaN	NaN
Non-motorised reach	0.399	0.475	0.598	0.672	0.64	0.604
Car reach	0.583	0.706	0.683	0.638	0.588	0.526
Residential density	0.242	0.197	0.207	0.36	0.634	0.865
Activity density	0.42	0.306	0.479	0.616	0.566	0.973
Work density	0.575	0.372	0.713	0.766	0.384	0.554
Education density	0.402	0.584	0.534	0.581	0.472	1
Car activity accessibility	0.339	0.372	0.361	0.324	0.278	0.297
Transit activity accessibility	0.233	0.239	0.266	0.324	0.239	0.173
Car work accessibility	0.375	0.332	0.353	0.42	0.286	0.232
Transit work accessib.	0.266	0.15	0.307	0.343	0.279	0.21
Non-motorised closeness	0	0	0	0.001	0.001	0
Car closeness	0.021	0.035	0.035	0.042	0.057	0.07
Transit closeness	0	0	0.001	0.001	0.001	NaN
Rail closeness	NaN	0	NaN	NaN	NaN	NaN

TABLE APP.I.7 Quartile coefficient of dispersion (QCD) values of urban form type characteristics.

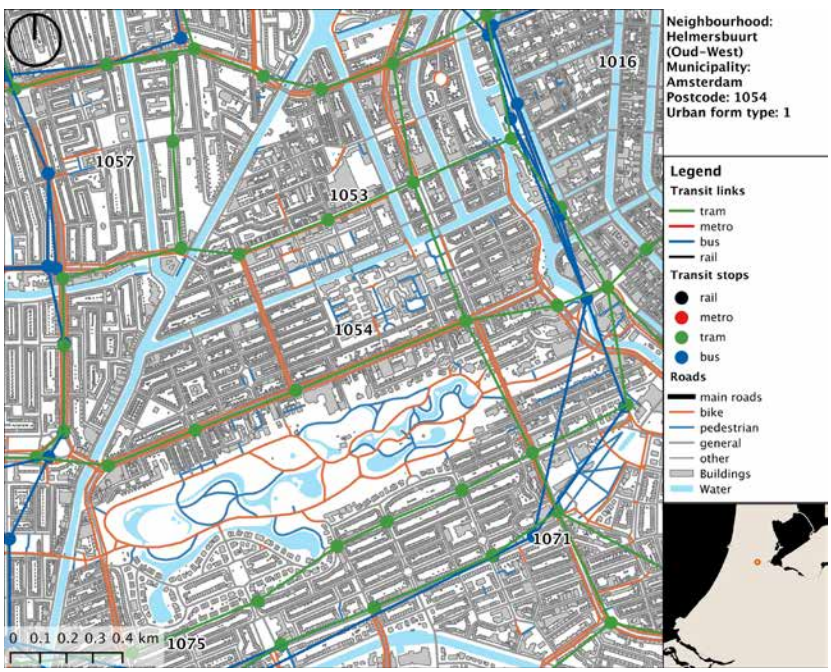
	TYPE 7	TYPE 8	TYPE 9	TYPE 10	TYPE 11	TYPE 13	TYPE 14	TYPE 15
	0.371	1	0.9	0.446	0.838	0.525	0.445	0.461
	0.262	0.523	0.579	0.417	0.607	0.421	0.275	0.249
	0.443	0.468	0.344	0.487	0.423	0.289	0.198	0.043
	0.104	0.848	0.557	0.449	0.113	0.452	0.215	0.069
	0.556	0.425	0.273	0.272	0.493	0.233	0.172	0.168
	0.555	0.373	0.614	0.754	0.851	0.341	0.736	0.513
	0.735	0.289	0.346	0.484	0.282	0.289	0.55	0.158
	0.447	0.6	0.543	0.407	0.354	0.25	0.342	0.209
	0.272	0.239	0.196	0.25	0.082	0.209	0.276	0.023
	NaN	0.342	0.385	0.333	0.125	0.158	NaN	0.22
	1	1	0	0	1	1	NaN	0
	0.561	0.243	0.552	0.626	0.643	0.419	0.531	0.592
	0.555	0.256	0.608	0.675	0.435	0.262	0.454	0.52
	0.397	0.35	0.193	0.214	0.162	0.195	0.411	0.087
	0.66	0.455	0.438	0.601	0.494	0.359	0.574	0.579
	0.583	0.5	0.68	0.697	0.79	0.528	0.413	0.535
	0.755	0.46	0.599	0.519	0.583	0.512	0.45	0.167
	0.381	0.426	0.342	0.418	0.22	0.198	0.359	0.161
	0.305	0.284	0.206	0.39	0.173	0.25	0.304	0.161
	0.264	0.295	0.289	0.468	0.288	0.38	0.127	0.223
	0.278	0.194	0.293	0.391	0.145	0.224	0.215	0.095
	0.001	0	0	0	0.001	0	0.001	0
	0.036	0.024	0.043	0.027	NaN	0.025	0.039	0.006
	NaN	0.001	0	0	0.001	0	NaN	0
	1	1	0	0	1	1	NaN	0

Appendix J The ‘urban modality’ archetypes

The following maps show the archetype postcode for each of the urban form types. This archetype is a statistically representative case in the cluster, the medoid, the case at the centre of the cluster.

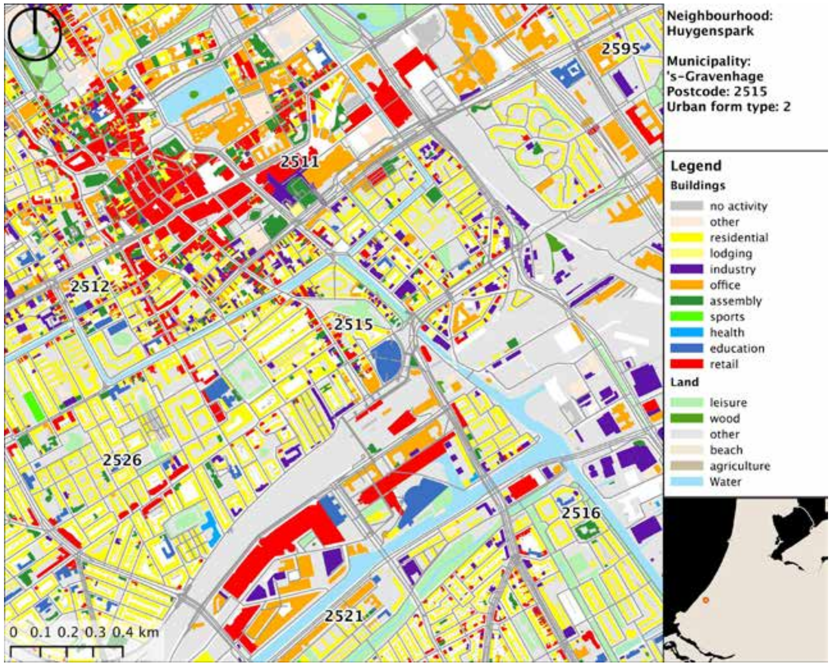


1

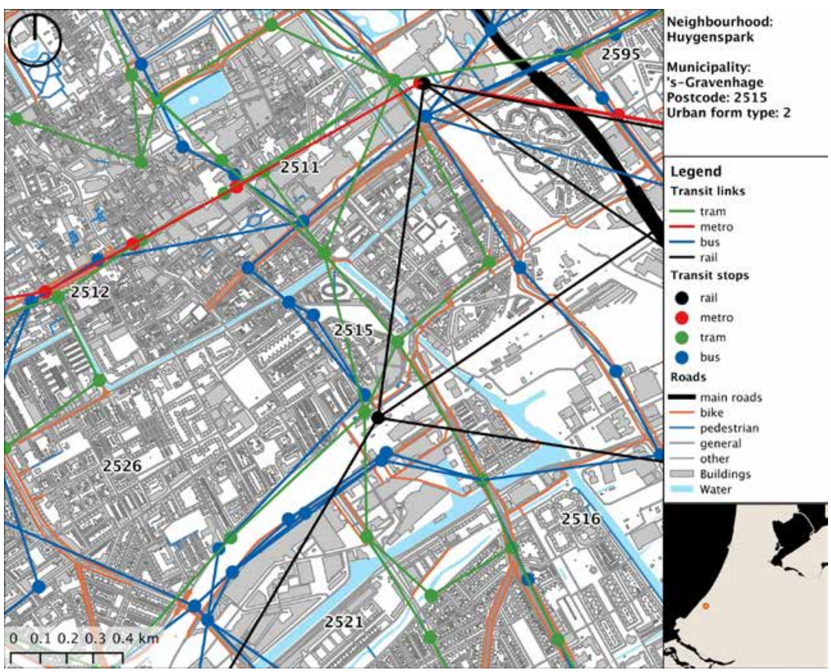


2

FIGURE APP.J.1 Land use and transport maps of Type 1 (Active multi-access core) archetype neighbourhood: Helmersbuurt, Amsterdam.

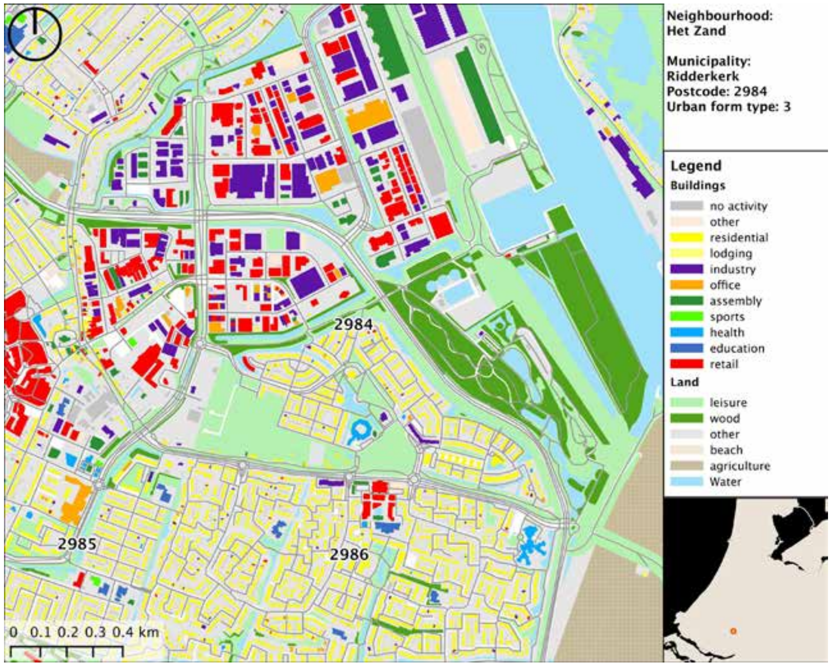


1

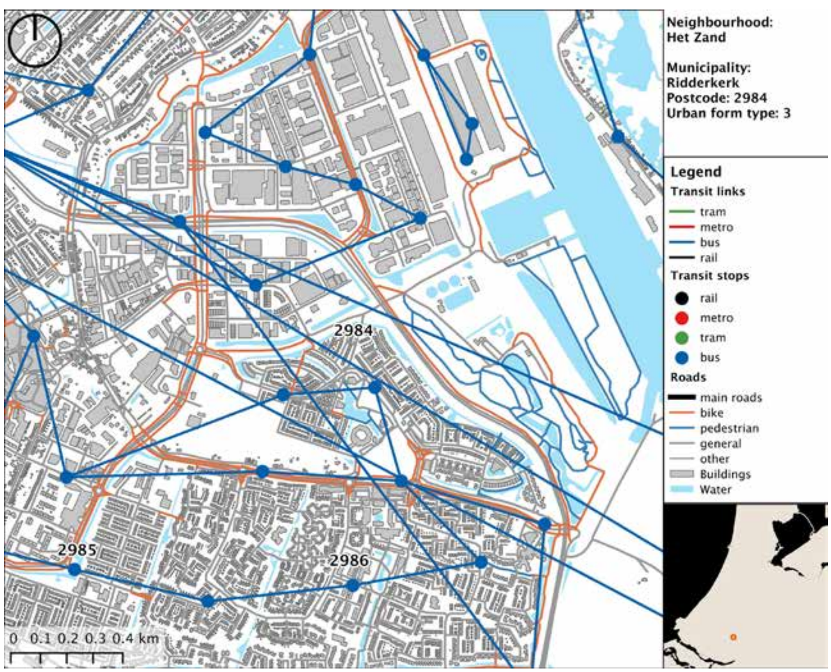


2

FIGURE APP.J.2 Land use and transport maps of Type 2 (Regional transit hub) archetype neighbourhood: Huygenspark, s'Gravenhage.



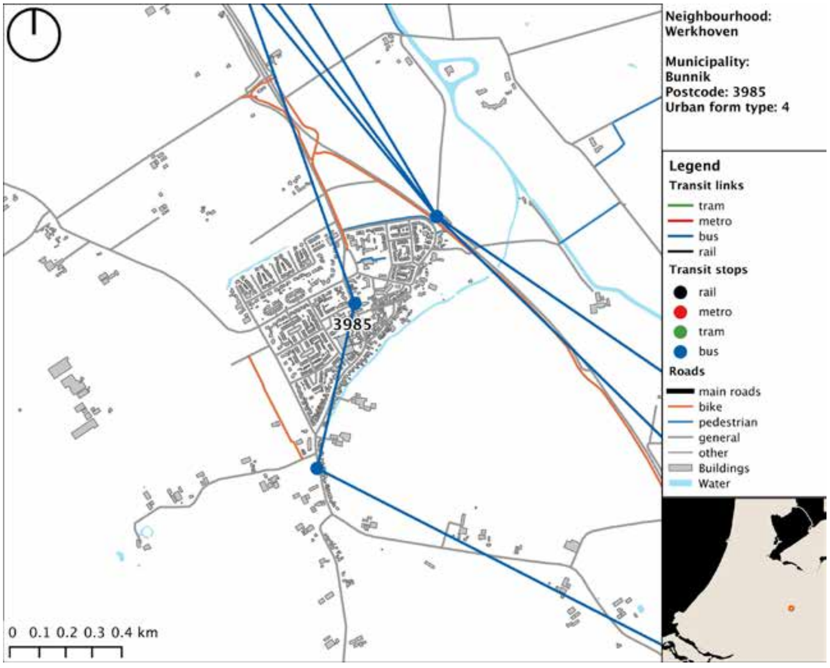
1



2

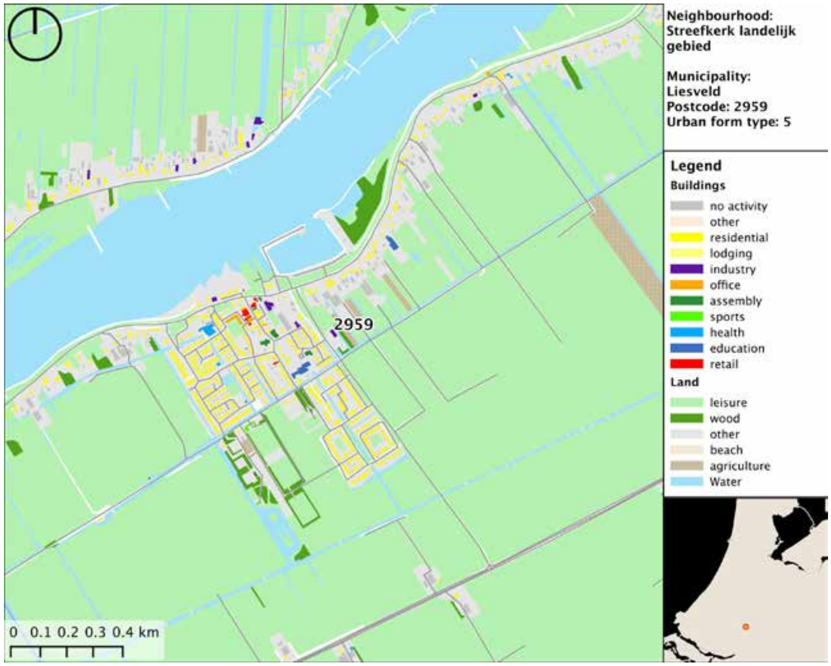
FIGURE APP.J.3 Land use and transport maps of Type 3 (Active local access cluster) archetype neighbourhood: Het Zand, Ridderkerk

1

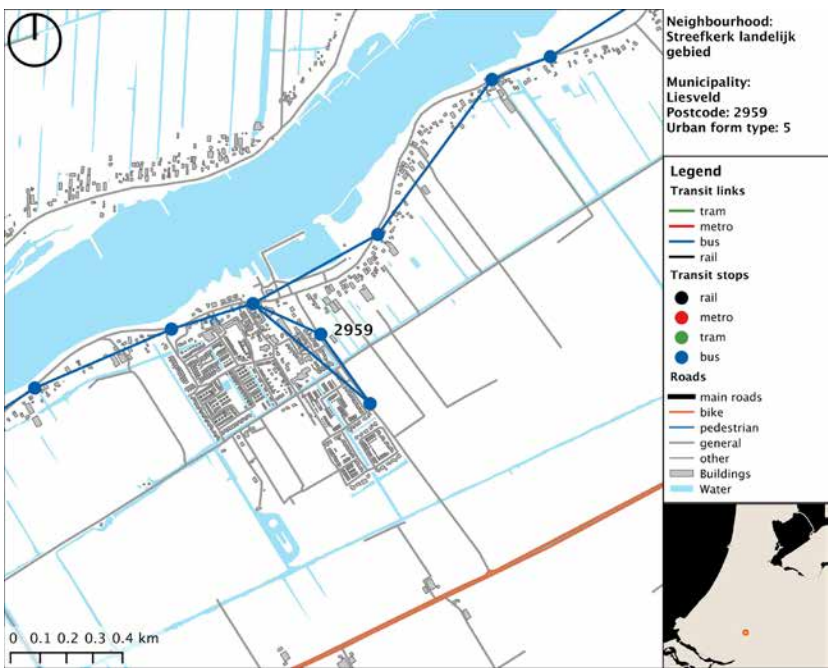


2

FIGURE APP.J.4 Land use and transport maps of Type 4 (Car location) archetype neighbourhood: Werkhoven, Bunnik.



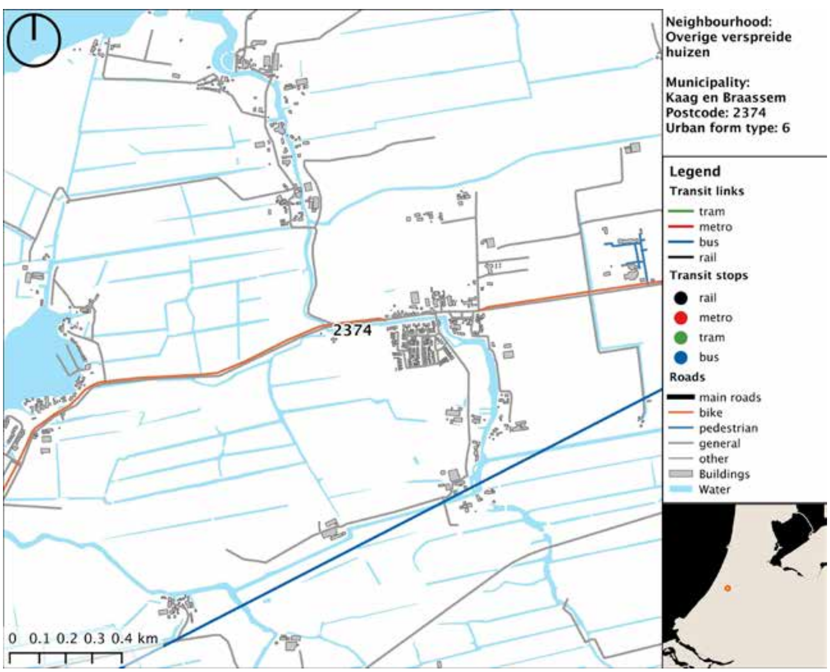
1



2

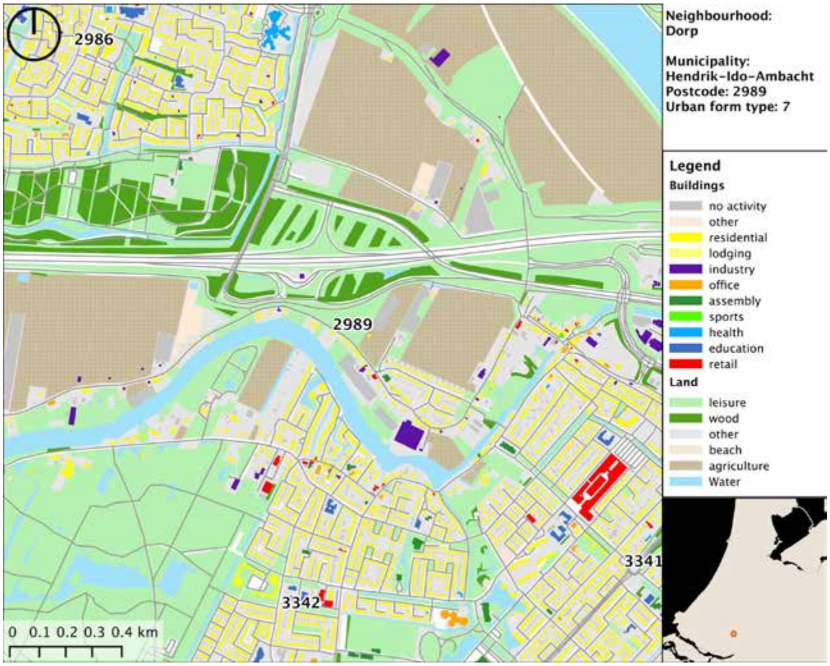
FIGURE APP.J.5 Land use and transport maps of Type 5 (Low access transit area) archetype neighbourhood: Streefkerk landelijk gebied (rural area), Liesveld.

1

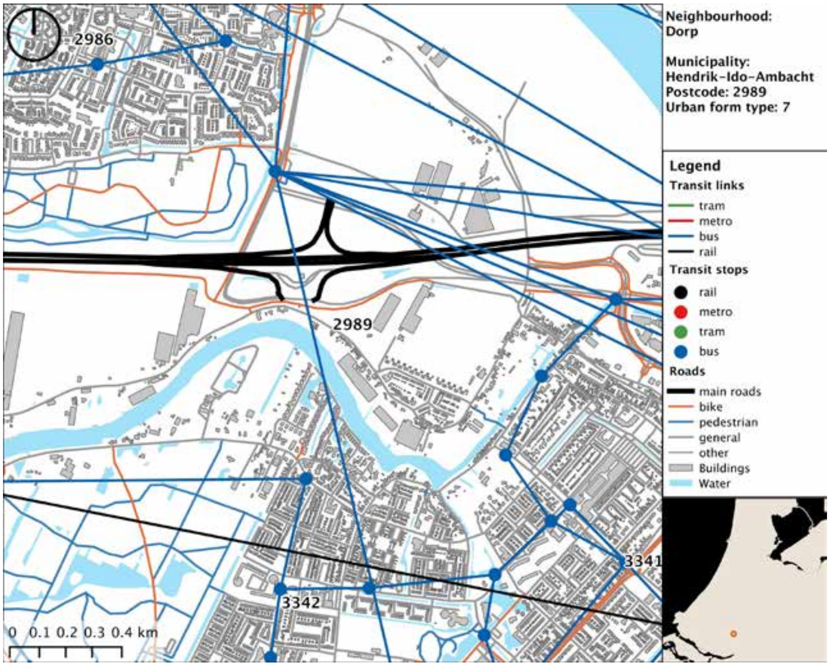


2

FIGURE APP.J.6 Land use and transport maps of Type 6 (Sparse car area) archetype neighbourhood: Postcode 2374 Overige verspreide huizen (Other scattered houses), Kaag en Braassem.

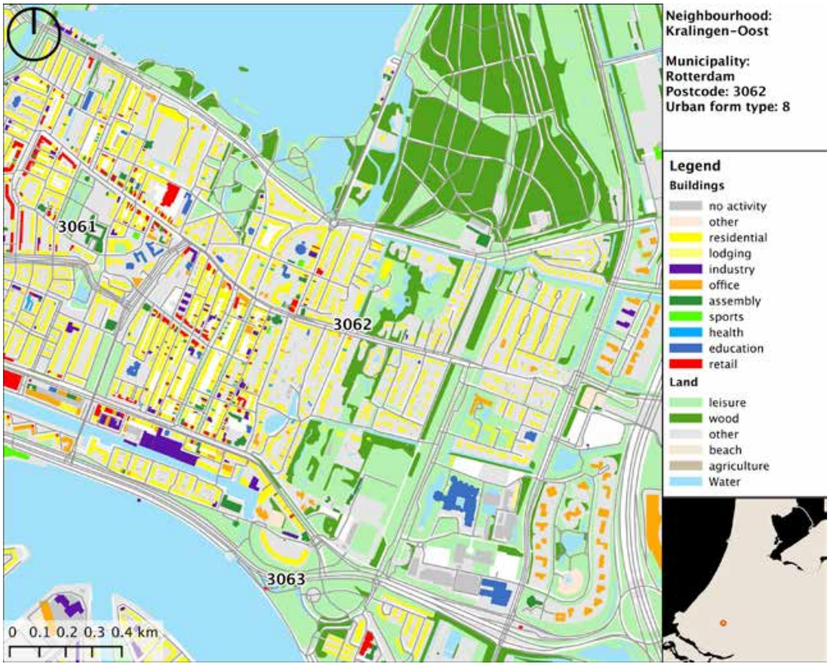


1

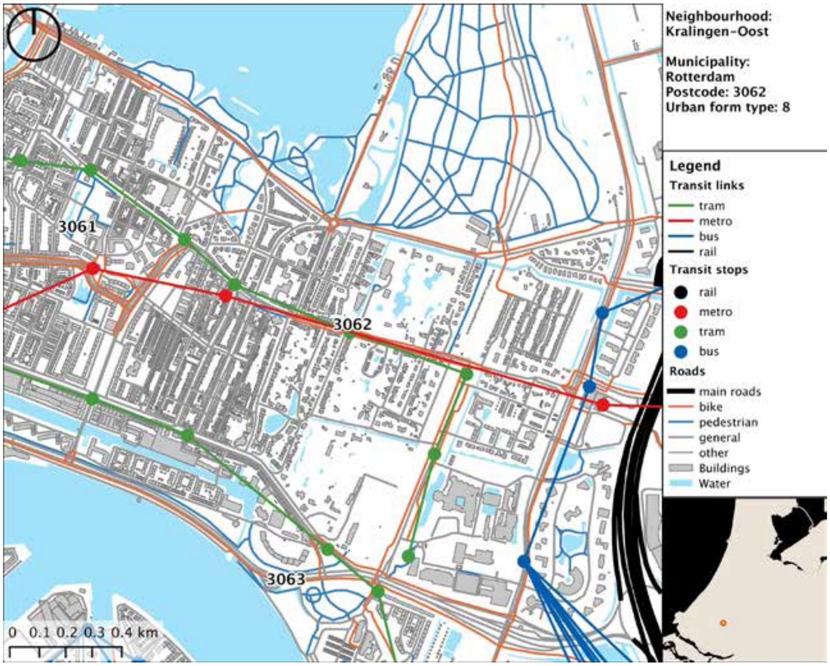


2

FIGURE APP.J.7 Land use and transport maps of Type 7 (Residential car area) archetype neighbourhood: Postcode 2989 Dorp (Village), Hendrik-Ido-Ambacht.

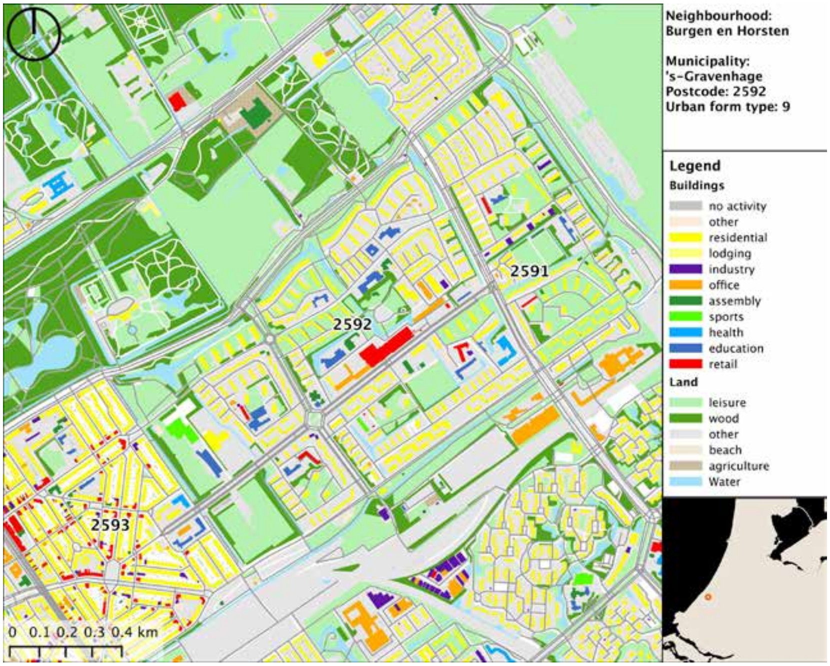


1

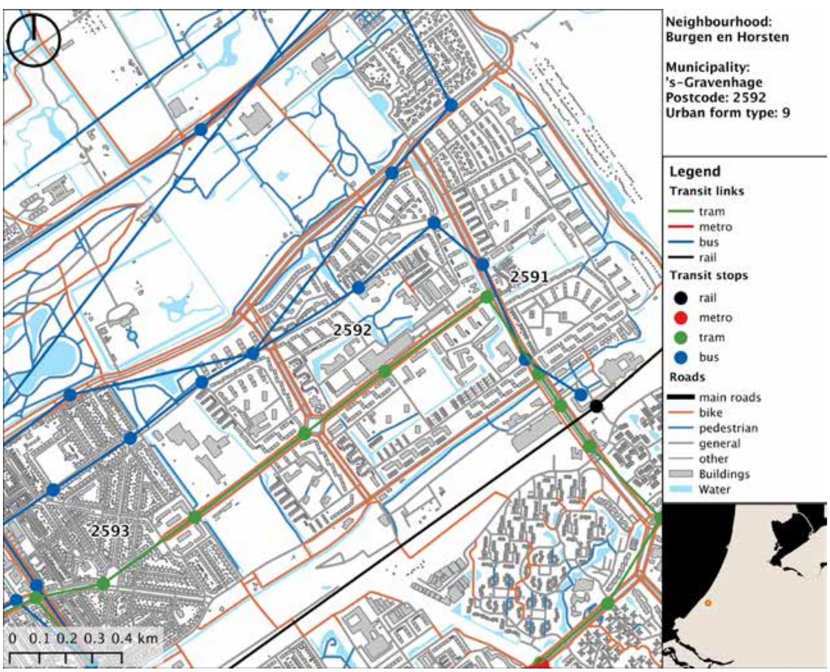


2

FIGURE APP.J.8 Land use and transport maps of Type 8 (Live-work multi-access cluster) archetype neighbourhood: Kralingen-Oost, Rotterdam.

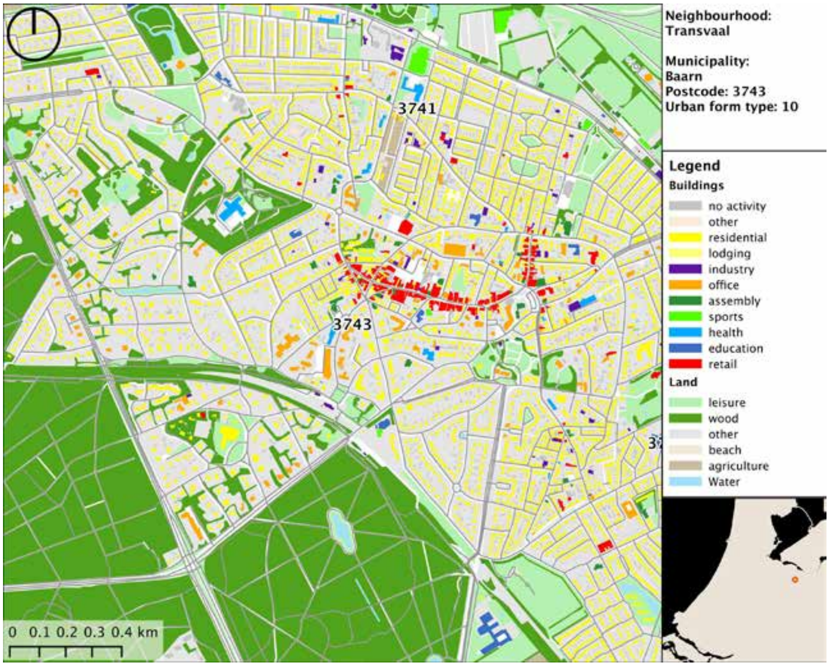


1

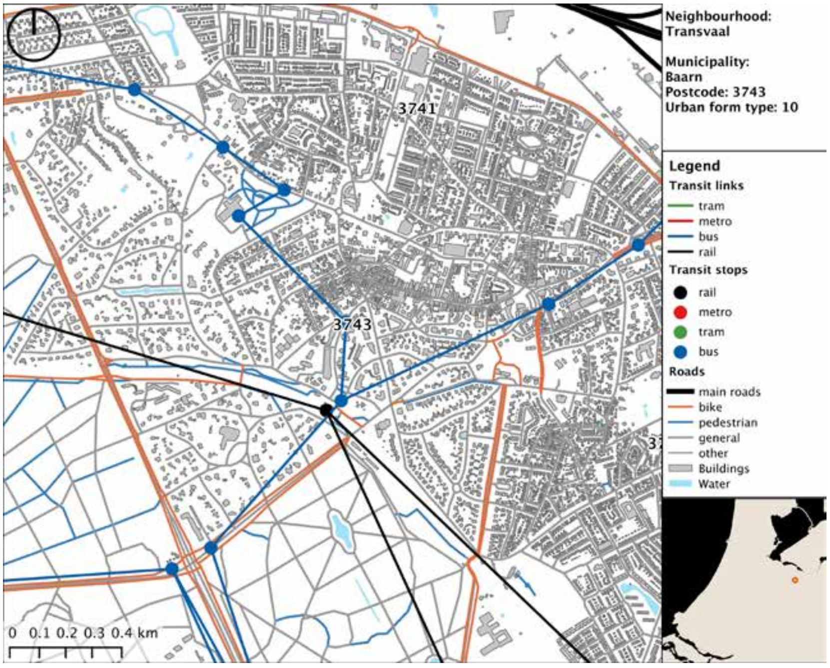


2

FIGURE APP.J.9 Land use and transport maps of Type 9 (Residential multi-access cluster) archetype neighbourhood: Burgen en Horsten, 's-Gravenhage.

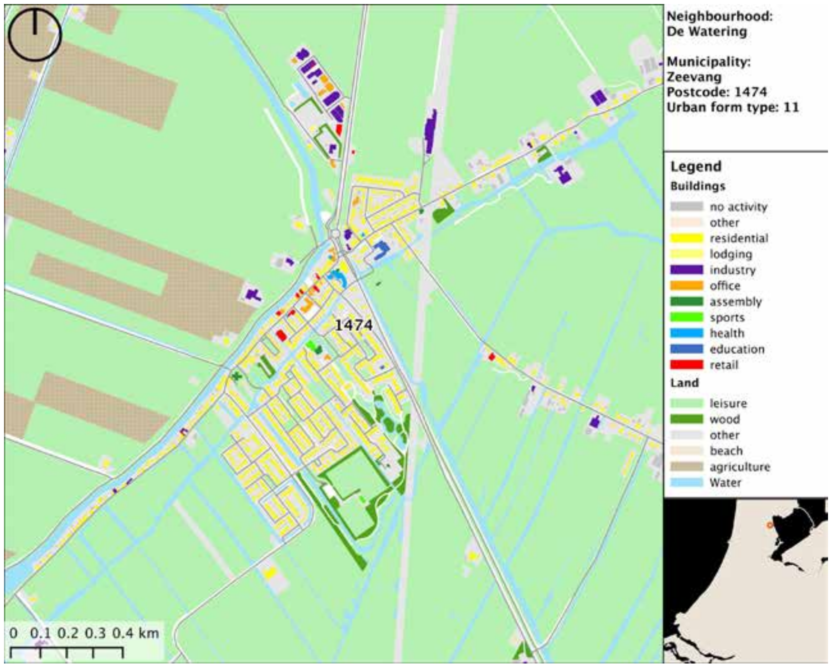


1

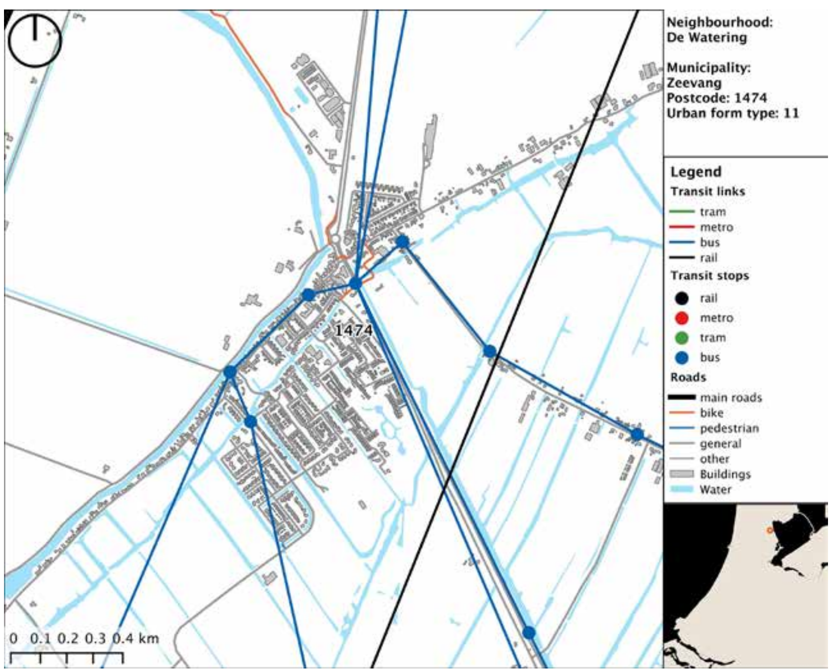


2

FIGURE APP.J.10 Land use and transport maps of Type 10 (Residential transit cluster) archetype neighbourhood: Transvaal, Baarn.

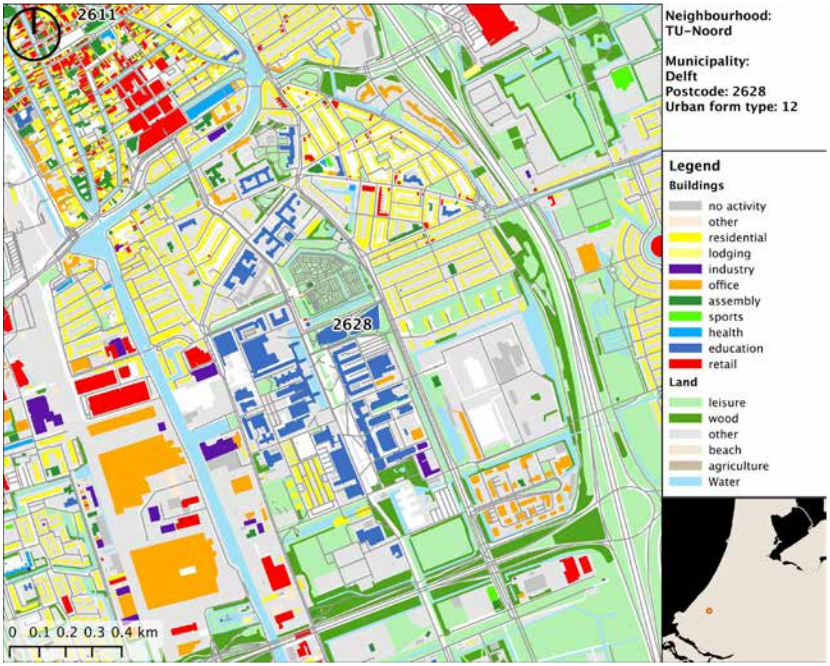


1



2

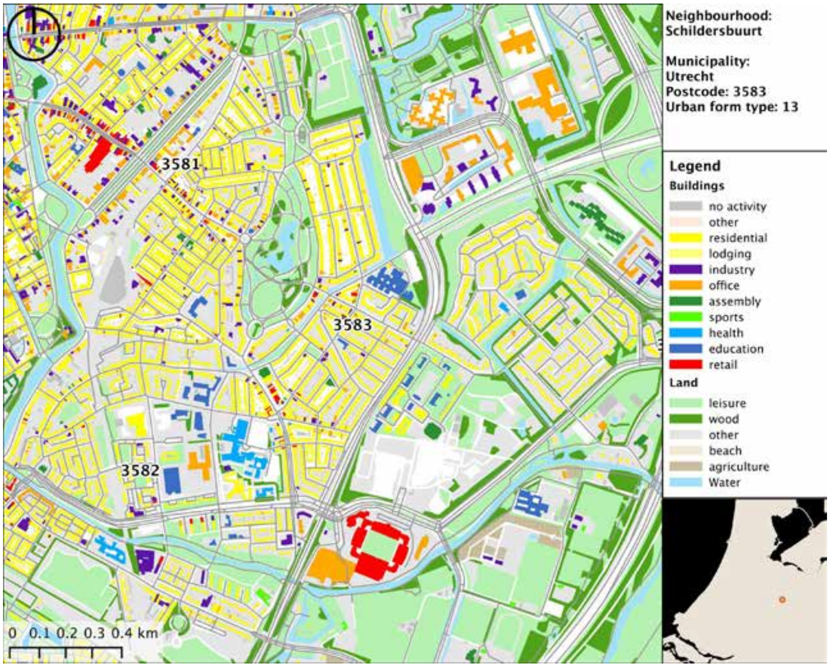
FIGURE APP.J.11 Land use and transport maps of Type 11 (Residential island) archetype neighbourhood: De Watering, Zeevang.



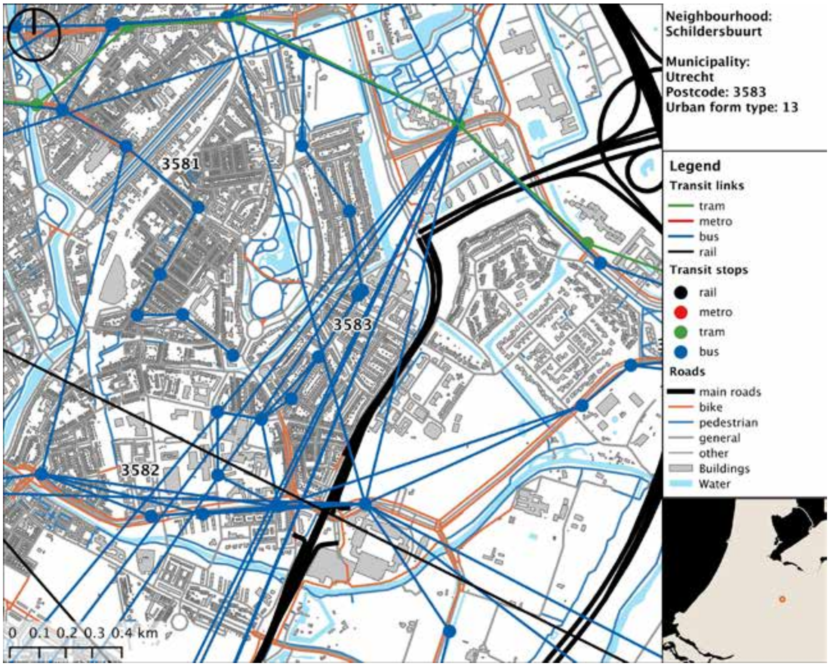
1

2

FIGURE APP.J.12 Land use and transport maps of Type 12 (TU Delft North) outlier neighbourhood: TU-Noord, Delft.

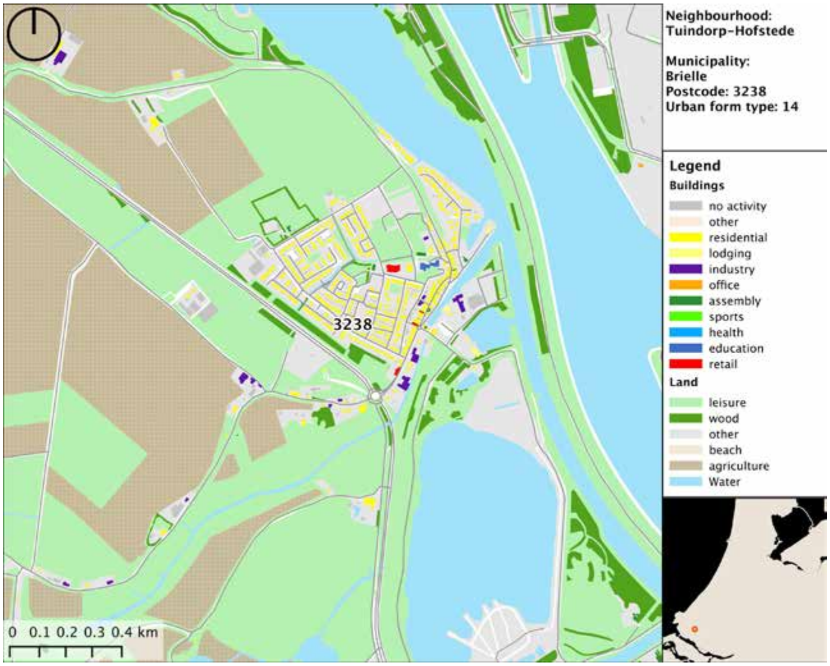


1

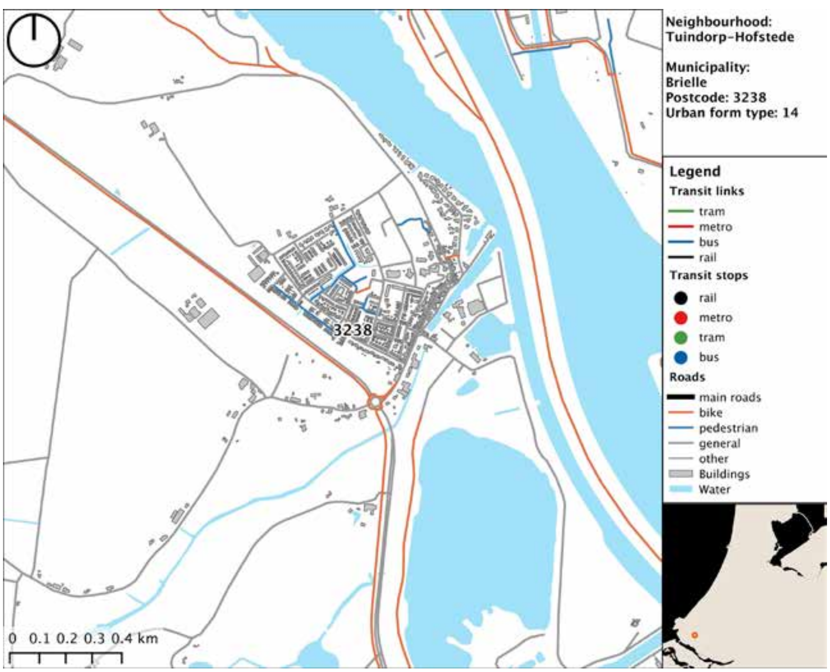


2

FIGURE APP.J.13 Land use and transport maps of Type 13 (Multi-access active core - Utrecht) archetype neighbourhood: Schildersbuurt, Utrecht.

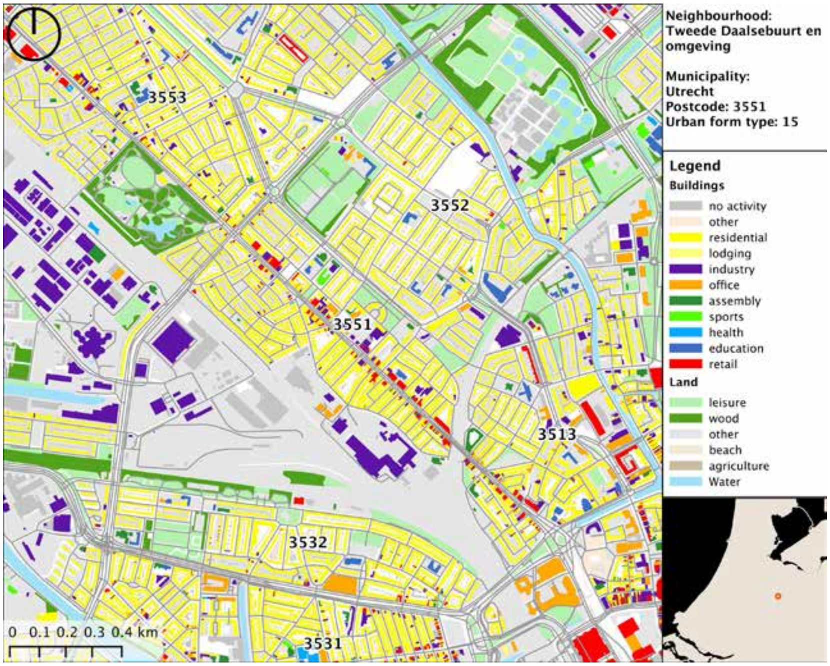


1

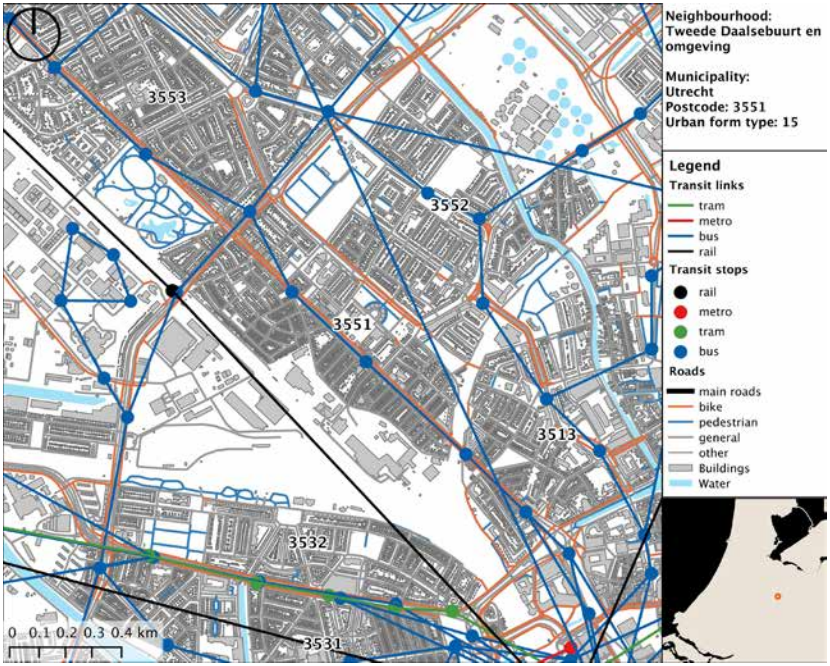


2

FIGURE APP.J.14 Land use and transport maps of Type 14 (Low access area) archetype neighbourhood: Tuindorp-Hofstede, Brielle.



1



2

FIGURE APP.J.15 Land use and transport maps of Type 15 (Regional transit hub (Utrecht)) archetype neighbourhood: Tweede Daalsebuurt en omgeving, Utrecht.

Appendix K

Results of the sustainable mobility performance evaluation of VINEX SET2 neighbourhoods

The following tables and charts provide details on the VINEX SET2 neighbourhoods evaluated in Chapter 7, their travel data and performance assessment.

POSTCODE	URBAN TYPE	NEIGHBOURHOOD NAME	VINEX NAME	MUNICIPALITY
1328	1	Tussen de Vaarten Zuid	Almere-Stad	Almere
1991	1	Buurt 85	Velserbroek	Velsen
2496	1	Morgenweide	Ypenburg	's-Gravenhage
2548	1	Parkbuurt Oosteinde	Wateringse Veld	's-Gravenhage
2662	1	Bergschenhoek buitengebied	Bergschenhoek	Lansingerland
1060	3	Middelveldsche Akerpolder en Sloten	De Aker	Amsterdam
2134	3	Hoofddorp-Overbos-Zuid	Floriande	Haarlemmermeer
2151	3	Nieuw-Vennep-Getsewoud-Zuid	Getsewoud	Haarlemmermeer
2152	3	Nieuw-Vennep-Getsewoud-Noord	Getsewoud	Haarlemmermeer
2492	3	De Vissen	Leidschenveen	's-Gravenhage
2498	3	De Bras	Ypenburg	's-Gravenhage
2642	3	Klapwijk	Pijnacker-Zuid	Pijnacker-Nootdorp
2729	3	Oosterheem-Noordoost	Oosterheem	Zoetermeer
2993	3	Meerwede Zuidwest	Carnisselande	Barendrecht
3059	3	Nesselande	Nesselande	Rotterdam

>>>

TOC

3162	3	Verspreide huizen	Portland	Albrandswaard
3344	3	Volgerlanden-West	De Volgerlanden	Hendrik-Ido-Ambacht
3356	3	Oosteind en De Kooy	Oostpolder	Papendrecht
3404	3	Het Hart	Zenderpark	IJsselstein
3544	3	Parkwijk, 't Zand en omgeving	Langerak	Utrecht
3824	3	Waterkwartier	Nieuwland	Amersfoort
2645	4	Emerald	Emerald-Delfgauw	Pijnacker-Nootdorp
2721	4	Oosterheem-Noordoost	Oosterheem	Zoetermeer
2994	4	Vrijenburg	Carnisselande	Barendrecht
3453	4	Veldhuizen	Veldhuizen	Utrecht
1087	8	IJburg West	IJburg	Amsterdam
2497	8	Singels	Ypenburg	's-Gravenhage
2652	8	Havenwijk (Meerpolder)	Berkel en Rodenrijs	Lansingerland
3543	8	Terwijde	Terwijde	Utrecht
1321	9	Literatuurwijk	Almere-Poort	Almere
1326	9	Parkwijk	Almere-Stad	Almere
1335	9	Seizoenenbuurt	Almere-Buiten	Almere
1336	9	Stripheldenbuurt	Almere-Buiten	Almere
1339	9	Eilandenbuurt	Almere-Buiten	Almere
1448	9	Afrika	Weidevenne	Purmerend
2215	9	Hoogh Teylingen	Hoogh Teylingen	Teylingen
3452	9	Vleuterweide	Vleuterweide	Utrecht
3825	9	Velden-Zuid	Vathorst	Amersfoort
1318	10	Tussen de Vaarten Noord	Almere-Stad	Almere
1948	10	Wijkerbroek	Broekpolder	Beverwijk
2493	10	De Lanen	Leidschenveen	's-Gravenhage
3991	10	Leebrug	Houten-Zuid	Houten
3994	10	Loerik	Houten-Zuid	Houten

TABLE APP.K.1 List of VINEX SET2 neighbourhoods. The urban form type is used to infer the mobility potential of the neighbourhood (Table 7-7), against which performance is calculated.

POSTCODE	SHORT DIST. WALK %	WALK %	SHORT DIST. CYCLE %	MEDIUM DIST. CYCLE %	CYCLE %	SHORT DIST. CAR %	MEDIUM DIST. CAR %	LONG DIST. CAR %	CAR %
1328	79.6	20.8	16.1	25.3	15.7	4.3	55.1	68.8	48.3
1991	51.7	23.9	37.7	37.2	30.1	9.6	52.3	83.6	41.1
2496	55.2	18.1	30.3	32.3	23.3	14.5	61.1	81.1	53.1
2548	68.7	18.1	12.9	28.9	18.7	18.4	62.5	82.7	57.2
2662	50	28.9	25	32.7	28.9	20	46.9	75	38.1
1060	54	18.7	25	29	21	20.2	56.6	84.6	52.9
2134	55.5	19.5	25.5	35.4	22.6	19	53.2	88.4	52.6
2151	30.3	12.7	43	26.6	26.1	25.2	66.3	91.2	57.5
2152	34	14	44.8	29.1	27.8	21.2	67	82.2	52.7
2492	64	17.9	20.1	18	12.3	14.4	63.5	82.7	59
2498	31.8	6.1	59.1	13	17.4	9.1	82.6	93.6	73
2642	34.6	12.7	57.4	49.1	46.3	8	48.6	62	37.7
2729	66.7	24.5	12.7	17.5	12.5	20.7	69.6	80.8	56
2993	70.3	22.8	22.2	22	15.7	5.7	68.7	87.6	55.6
3059	89.2	23.4	5.4	0	1.4	5.4	92.2	82.5	66.7
3162	42.9	11.5	42.9	21.4	20	14.3	70.1	90	62.7
3344	39.1	12.6	32.6	36.1	26.7	28.3	63.9	91.6	59.3
3356	65.3	17.1	16.7	20.2	14.9	18.1	79.9	88.4	65.8
3404	35.7	13.9	34.3	23.3	21.2	25.9	71.7	81.5	57.6
3544	55	18.6	27.7	34.8	22.8	16.5	52.8	83	49.8
3824	51.1	17	41.7	35.2	28.5	7.2	55.6	80.5	48.6
2645	71.3	29.2	14.6	27.4	17.7	14	57.3	78.8	47.1
2721	57.1	27.8	0	15.4	5.6	42.9	38.5	75	55.6
2994	84.6	20.2	7.7	31.4	20.2	7.7	57.1	91.3	52.9
3453	62.9	26	9.9	28.2	14	27.3	65.1	81.3	55.6
1087	77.9	33.7	5.9	7.6	4.6	14.7	28.3	88.9	41.7
2497	67.4	24	15.1	19.1	12.4	17.4	66.7	87.6	56.3
2652	57.1	17.7	14.3	28.6	14.7	28.6	63.3	88.9	61
3543	61.4	19.1	35.1	25.5	20.1	3.5	47.3	84.4	49.2
1321	51.3	24.3	33.8	31.1	24.3	14.2	57.4	72.9	41.1
1326	61.6	26.2	28.5	26.9	22.2	7.7	53.4	72.3	38.4
1335	54.2	17.4	31.7	32	21	13.5	54.8	75.3	49.8
1336	70.6	15.6	11.8	15.5	8.8	17.7	72.2	82.2	67.1
1339	68.1	19.4	22.3	20.8	14.8	7.1	60.7	79.3	53.4
1448	63.4	23	25.1	23.8	16.3	11.5	69.9	72.5	49.7
2215	29.5	13.5	48	38.3	35.8	21.4	51.1	73.9	44.4
3452	82.4	16.7	17.7	8.7	6	0	73.9	95.5	70.2
3825	42.9	15.4	49.6	25.6	26.5	7.5	65	93.2	54.9
1318	63	19	22.5	28	19.4	14.1	56.3	67.7	47.5
1948	15.8	3.9	63.2	25.6	28.6	21.1	66.7	73.7	57.1
2493	60	15.8	30	26.1	15.8	10	65.2	93.9	63.2
3991	40.1	14.5	50.4	46.1	34.1	9.6	49.2	82.8	46.9
3994	48.3	16.4	42.5	43.5	33.1	9.2	51.2	75.1	45.2

TABLE APP.K.2 Travel patterns of VINEX SET2 neighbourhoods. These are absolute values.

	CAR DISTANCE %	CAR DURATION %	MEDIUM DIST. TRANSIT %	TRANSIT %	LONG DIST. TRANSIT %	TRAIN %	TRANSIT DISTANCE %	TRANSIT DURATION %	AVERAGE DISTANCE/ PERSON	AVERAGE JOURNEYS/ PERSON
	69.3	61.8	10.5	5.9	24.5	6.4	22	13.6	46.1	3
	75.3	54.2	2.5	1.8	8.5	0.2	5.5	4.9	31.8	3.75
	82.1	64.2	2.5	3.9	12.6	0.8	8	7.2	42	3.14
	82.9	66.7	6.3	4.3	8.7	0.9	6.7	6.8	33.2	3.08
	80.4	50.4	0	0	0	0	0	0	24.2	3.59
	84	64.6	7.9	4.7	8.2	0.3	5.7	6.6	31.3	3.25
	85.3	67.9	3.2	2	7.5	1.2	5.3	3.8	34.3	3.2
	89.9	73.1	2.3	1.2	7.1	1	3.8	2.7	36.9	3.26
	86.6	69.7	1.7	1.5	11.7	2.5	5.8	4.6	39.2	3.41
	82.3	69.5	10.1	6.7	13.7	2.4	10.9	8.5	36.7	3.04
	95.2	88.5	4.4	3.5	4.3	0	2.4	1.8	47.7	3.05
	75.3	51.5	0	0.9	10.7	2	7.2	3.2	37.4	3.23
	80.3	63.2	7	3.4	14.2	2.5	11.7	7.1	32.2	3.2
	82.7	66.5	3	3.2	10.1	1.4	9.3	6.5	32	3.14
	79.9	76.6	7.8	7.1	17.5	1.4	17.9	10.1	31.1	3.02
	89.8	76.6	4.3	3.5	7.5	0.8	3.6	3.9	36.6	3.23
	79.5	64.9	0	0	5.6	1.4	10.6	5.7	31.9	3.65
	83.2	72.9	0	0	8.7	2.2	9.6	6.5	33.5	3.57
	87.7	69.8	1.7	5.5	15.1	0.3	6.5	8.1	36	3.13
	75.6	63	8.4	3.8	12.8	3.1	15.9	9.3	39.6	3.17
	74.4	57.5	1.1	1.3	13.8	2.9	13.6	7.7	32.7	3.08
	71.8	56	5.5	1.4	6.8	0.9	11.3	4.7	29.2	3.2
	79.7	58.4	0	7	25	4.2	15.1	11.9	55.6	2.67
	74.5	60.8	8.6	6.7	8.7	0	9.2	7.9	33.9	4.83
	84.8	69.8	2.9	2.3	11.2	2.1	7.9	6.9	41.8	3.45
	84.8	70.9	52.8	20	11.1	0	12.2	12.8	39.1	3.02
	88.8	69.7	8.7	3.7	8.5	1.4	4.8	6.2	43	3.28
	85	74.7	0	2.9	11.1	0.7	7.9	5.8	34.4	3.54
	82	68.6	25.5	7.4	7.8	3.2	9.6	8.6	50.2	2.89
	70.9	57.8	9.3	4.2	22.7	4.1	20.4	14.4	35.8	3.56
	70.9	58.8	16.9	7.7	25.2	4.3	21.7	13.4	38.4	3.58
	74.9	64.5	8.3	4.4	23	6.2	19.4	13.7	50.2	3.21
	86.9	79	4.1	2.8	10.4	3.5	7.2	5.9	59.6	2.86
	81.7	68.3	10.6	5.1	18.1	6	13.7	13	51.3	3.07
	78.5	64.1	1.4	7.6	23.8	1.3	14.8	11.7	42.4	3.25
	72.3	54.4	4.3	1.1	14.1	3.5	11.8	6.5	33.8	3.51
	96	84.5	17.4	6	2.3	0	2.3	6.8	52.2	2.67
	88.3	70.2	3.3	0	5.1	1.4	5.4	5	46	3.59
	68.3	57.8	11.9	5.6	30.7	7.9	25.5	17.6	45.8	3.25
	66.8	49.7	7.7	3.9	26.3	6.5	24.1	35.8	32.9	3.61
	86.1	76	0	0	0	0	0	0	27.5	3.04
	83.2	64.3	2.4	0.8	10.5	3.3	8	6.6	41.2	3.3
	80.2	63.5	2	0.3	12.7	4.3	9.3	4.5	43.9	3.42

POSTCODE	SHORT DIST. WALK %	WALK %	SHORT DIST. CYCLE %	MEDIUM DIST. CYCLE %	CYCLE %	SHORT DIST. CAR %	MEDIUM DIST. CAR %	LONG DIST. CAR %	CAR %
1328	**1**	**0.3**	**0.14**	**-0.05**	**0**	**0.04**	**0.67**	**0.05**	**0.65**
1991	0.2	0.57	0.71	0.88	0.76	0.24	0.55	0.8	0.37
2496	0.3	0.07	0.52	0.5	0.4	0.41	0.94	0.68	0.84
2548	**0.69**	**0.07**	**0.05**	**0.24**	**0.16**	**0.56**	**1**	**0.75**	**1**
2662	0.15	1	0.37	0.53	0.69	0.61	0.31	0.36	0.25
1060	0.5	0.55	0.36	0.46	0.4	0.57	0.41	0.51	0.52
2134	0.52	0.59	0.37	0.6	0.44	0.53	0.33	0.64	0.51
2151	0.16	0.24	0.69	0.41	0.53	0.75	0.63	0.73	0.64
2152	0.21	0.31	0.73	0.46	0.57	0.61	0.65	0.44	0.52
2492	0.64	0.51	0.27	0.23	0.19	0.37	0.57	0.45	0.68
2498	**0.18**	**-0.1**	**0.99**	**0.12**	**0.32**	**0.18**	**1.01**	**0.82**	**1.05**
2642	**0.22**	**0.24**	**0.96**	**0.88**	**1.01**	**0.14**	**0.22**	**-0.24**	**0.13**
2729	0.68	0.85	0.13	0.22	0.2	0.59	0.71	0.39	0.6
2993	0.73	0.76	0.31	0.31	0.27	0.06	0.69	0.61	0.59
3059	**1**	**0.8**	**0**	**-0.15**	**-0.07**	**0.05**	**1.23**	**0.44**	**0.88**
3162	0.34	0.18	0.69	0.3	0.38	0.37	0.72	0.69	0.78
3344	0.28	0.24	0.5	0.61	0.54	0.86	0.58	0.75	0.69
3356	0.66	0.47	0.21	0.27	0.26	0.5	0.95	0.64	0.86
3404	0.23	0.3	0.53	0.34	0.41	0.78	0.76	0.41	0.64
3544	0.51	0.54	0.41	0.58	0.45	0.45	0.32	0.46	0.44
3824	0.45	0.46	0.67	0.59	0.58	0.11	0.39	0.38	0.41
2645	0.82	0.94	0.23	0.46	0.33	0.24	0.36	0.37	0.25
2721	**0.63**	**0.89**	**0**	**0.22**	**0**	**1**	**0**	**0.26**	**0.44**
2994	**1**	**0.58**	**0.12**	**0.54**	**0.4**	**0.07**	**0.36**	**0.74**	**0.38**
3453	0.7	0.82	0.16	0.48	0.23	0.59	0.51	0.45	0.44
1087	**0.69**	**1**	**0.15**	**0**	**0**	**0.45**	**0**	**0.34**	**0.04**
2497	0.47	0.51	0.38	0.46	0.5	0.56	0.61	0.25	0.53
2652	**0.26**	**0.18**	**0.36**	**0.83**	**0.65**	**1**	**0.55**	**0.34**	**0.69**
3543	**0.35**	**0.25**	**0.89**	**0.7**	**1**	**0**	**0.3**	**0.02**	**0.29**
1321	0.41	0.57	0.54	0.67	0.6	0.66	0.4	0.19	0.1
1326	0.61	0.66	0.41	0.55	0.53	0.36	0.25	0.17	0.01
1335	0.47	0.2	0.49	0.7	0.49	0.63	0.3	0.27	0.4
1336	**0.78**	**0.11**	**0**	**0.2**	**0.09**	**0.83**	**0.93**	**0.52**	**1.01**
1339	0.73	0.31	0.26	0.36	0.29	0.33	0.51	0.42	0.53
1448	0.64	0.5	0.33	0.45	0.34	0.54	0.85	0.17	0.4
2215	**0**	**0**	**0.89**	**0.89**	**0.98**	**1**	**0.17**	**0.22**	**0.22**
3452	**1**	**0.17**	**0.14**	**0**	**0**	**0**	**0.99**	**1**	**1.12**
3825	0.25	0.1	0.93	0.51	0.68	0.35	0.67	0.92	0.58
1318	**1**	**0.61**	**0**	**0.07**	**0.12**	**0.64**	**0.7**	**0**	**0.5**
1948	**0**	**-0.2**	**1**	**0**	**0.42**	**1**	**0.99**	**0.23**	**0.81**
2493	**0.94**	**0.44**	**0.18**	**0.01**	**0**	**0.43**	**0.95**	**1**	**1**
3991	0.51	0.37	0.69	0.6	0.59	0.4	0.51	0.57	0.48
3994	0.69	0.47	0.49	0.52	0.56	0.38	0.56	0.28	0.42

TABLE APP.K.3 Mobility performance score of VINEX SET2 neighbourhoods. Performance is a relative score based on the urban form and socio-economic typology of the neighbourhood, calculated according to the evaluation framework in Chapter 7.

	CAR DISTANCE %	CAR DURATION %	MEDIUM DIST. TRANSIT %	TRANSIT %	LONG DIST. TRANSIT %	TRAIN %	TRANSIT DISTANCE %	TRANSIT DURATION %	AVERAGE DISTANCE/ PERSON	AVERAGE JOURNEYS/ PERSON
	0.2	**0.68**	**0.55**	**0.61**	**0.77**	**1**	**1**	**0.98**	**0.88**	**0.32**
	0.49	0.34	0.13	0.18	0.27	0.03	0.25	0.35	0.37	1
	0.82	0.78	0.13	0.4	0.4	0.13	0.37	0.52	0.74	0.45
	0.86	**0.89**	**0.33**	**0.44**	**0.27**	**0.14**	**0.31**	**0.49**	**0.42**	**0.39**
	0.74	0.16	0	0	0	0	0	0	0.1	0.85
	0.62	0.51	0.67	0.59	0.37	0.06	0.29	0.51	0.4	0.41
	0.66	0.6	0.27	0.25	0.34	0.3	0.26	0.29	0.51	0.38
	0.82	0.75	0.19	0.15	0.32	0.24	0.19	0.21	0.61	0.42
	0.71	0.65	0.14	0.19	0.53	0.6	0.29	0.35	0.69	0.51
	0.56	0.65	0.85	0.84	0.62	0.58	0.54	0.65	0.6	0.28
	1	**1.17**	**0.37**	**0.44**	**0.19**	**0**	**0.12**	**0.14**	**1**	**0.29**
	0.32	**0.15**	**0**	**0.11**	**0.49**	**0.48**	**0.36**	**0.24**	**0.63**	**0.4**
	0.49	0.47	0.59	0.43	0.64	0.61	0.58	0.54	0.44	0.38
	0.57	0.57	0.25	0.4	0.45	0.34	0.46	0.5	0.43	0.34
	0.48	**0.84**	**0.66**	**0.9**	**0.79**	**0.35**	**0.89**	**0.78**	**0.4**	**0.27**
	0.81	0.84	0.36	0.44	0.34	0.19	0.18	0.3	0.6	0.4
	0.46	0.52	0	0	0.25	0.34	0.53	0.44	0.43	0.66
	0.59	0.74	0	0	0.39	0.53	0.48	0.5	0.48	0.61
	0.74	0.65	0.14	0.69	0.68	0.06	0.32	0.62	0.58	0.34
	0.33	0.47	0.71	0.48	0.58	0.77	0.79	0.71	0.7	0.36
	0.29	0.32	0.09	0.16	0.62	0.71	0.67	0.59	0.46	0.31
	0.22	0.29	0.44	0.22	0.27	0.18	0.52	0.29	0.26	0.32
	0.47	**0.37**	**0**	**1.11**	**1**	**0.85**	**0.7**	**0.73**	**1**	**0**
	0.3	**0.44**	**0.69**	**1.08**	**0.35**	**0**	**0.43**	**0.49**	**0.39**	**1.3**
	0.64	0.71	0.23	0.37	0.45	0.42	0.37	0.43	0.61	0.47
	0.54	**0.6**	**1**	**1**	**1**	**0**	**1**	**1**	**0.64**	**0.2**
	0.7	0.55	0.17	0.19	0.77	0.44	0.39	0.49	0.76	0.6
	0.55	**0.73**	**0**	**0.15**	**1**	**0.23**	**0.65**	**0.45**	**0.48**	**1**
	0.43	**0.51**	**0.48**	**0.37**	**0.7**	**1**	**0.79**	**0.67**	**1**	**0**
	0.16	0.18	0.52	0.55	0.79	0.66	0.94	0.94	0.27	0.64
	0.16	0.21	0.97	1	0.88	0.68	1	0.85	0.35	0.65
	0.3	0.39	0.45	0.57	0.8	1	0.88	0.88	0.71	0.38
	0.7	**0.84**	**0.21**	**0.37**	**0.31**	**0.57**	**0.25**	**0.17**	**1**	**0.11**
	0.52	0.51	0.6	0.67	0.61	0.96	0.59	0.82	0.75	0.27
	0.41	0.38	0.04	0.99	0.83	0.21	0.65	0.7	0.47	0.41
	0.21	**0.08**	**0.22**	**0.14**	**0.46**	**0.57**	**0.49**	**0.23**	**0.21**	**0.6**
	1	**1.01**	**1**	**0.77**	**0**	**0**	**0**	**0.26**	**0.77**	**-0.03**
	0.74	0.57	0.16	0	0.11	0.22	0.16	0.09	0.58	0.66
	0.3	**0.35**	**1**	**1.1**	**1**	**1**	**1**	**0.8**	**0.65**	**0.24**
	0.25	**0.06**	**0.65**	**0.77**	**0.86**	**0.82**	**0.95**	**1.63**	**0.26**	**0.66**
	0.95	**1**	**0**	**0**	**0**	**0**	**0**	**0**	**0.1**	**0**
	0.84	0.58	0.2	0.15	0.34	0.41	0.31	0.3	0.51	0.3
	0.74	0.56	0.17	0.05	0.41	0.54	0.36	0.2	0.59	0.44

Postcodes with outlier and extreme performances, especially regarding car use, are highlighted in bold with relevant values signalled as positive (green) or negative (red).

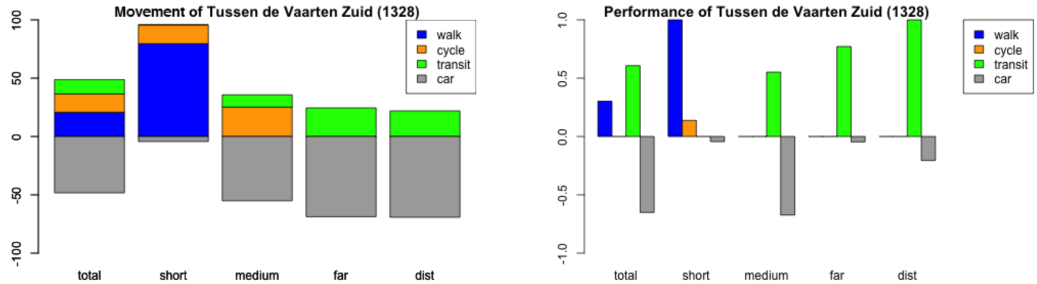


FIGURE APP.K.1 Absolute travel pattern and contextual performance values of postcode 1328, modality type 1.

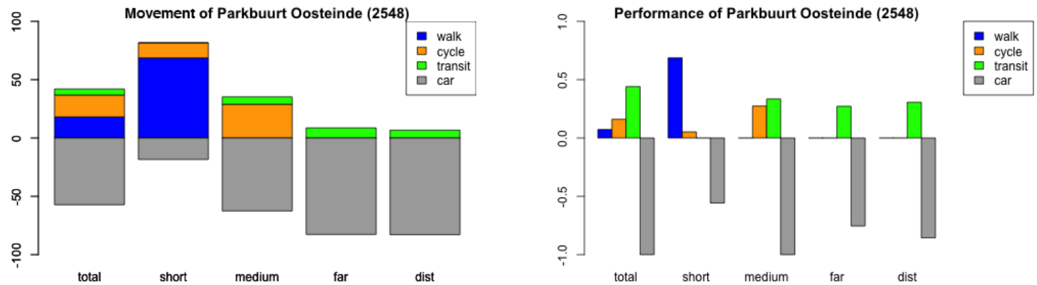


FIGURE APP.K.2 Absolute travel pattern and contextual performance values of postcode 2548, modality type 1.

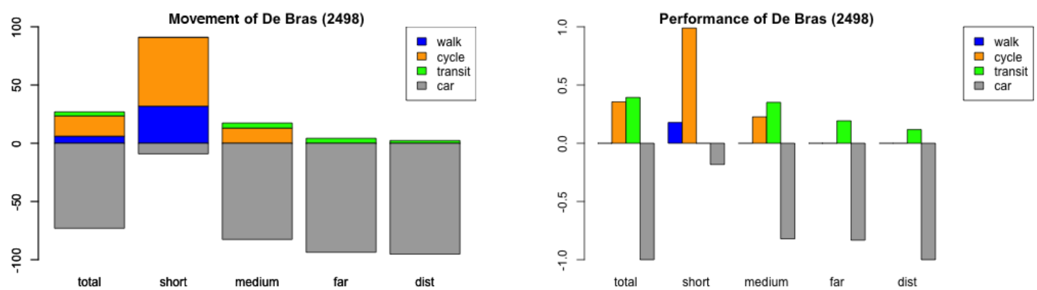


FIGURE APP.K.3 Absolute travel pattern and contextual performance values of postcode 2498, modality type 3.

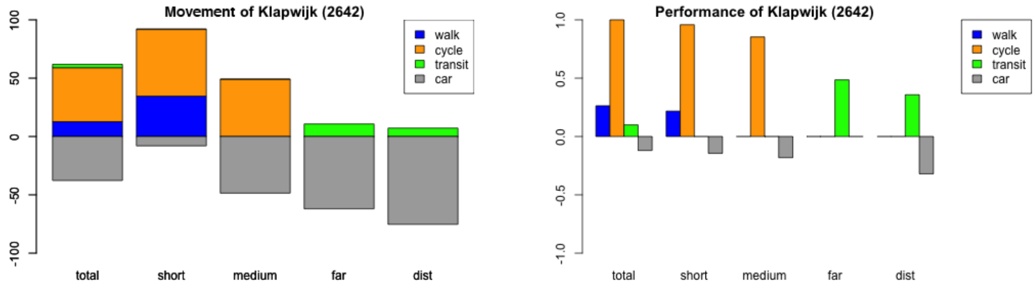


FIGURE APP.K.4 Absolute travel pattern and contextual performance values of postcode 2642, , modality type 3.

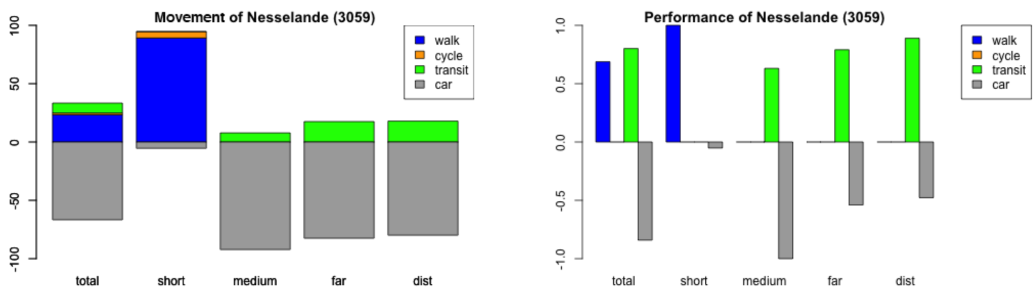


FIGURE APP.K.5 Absolute travel pattern and contextual performance values of postcode 3059, modality type 3.

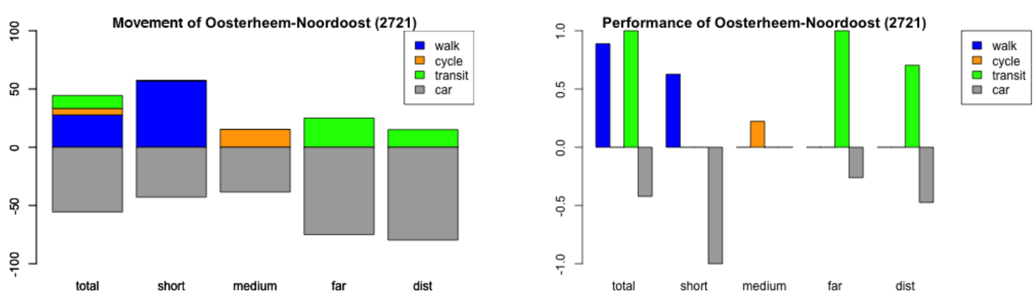


FIGURE APP.K.6 Absolute travel pattern and contextual performance values of postcode 2721, modality type 4.

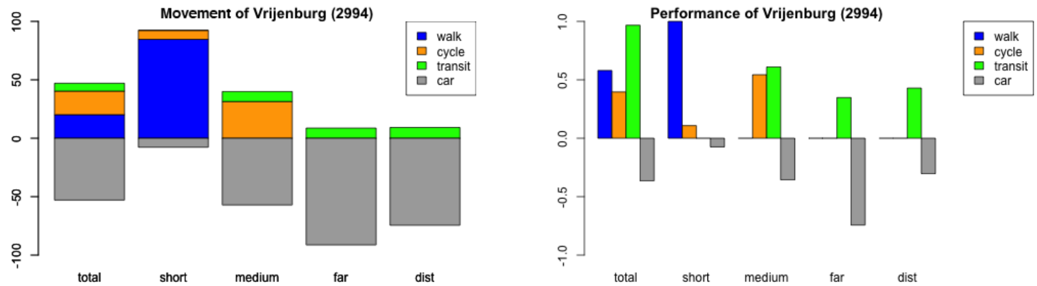


FIGURE APP.K.7 Absolute travel pattern and contextual performance values of postcode 2994, modality type 4.

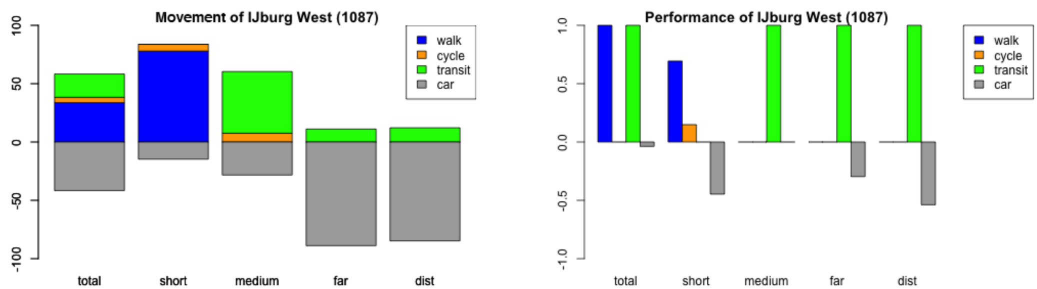


FIGURE APP.K.8 Absolute travel pattern and contextual performance values of postcode 1087, modality type 8.

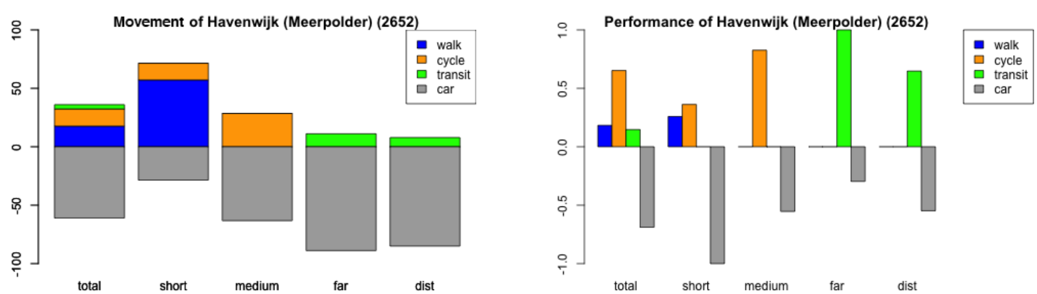


FIGURE APP.K.9 Absolute travel pattern and contextual performance values of postcode 2652, modality type 8.

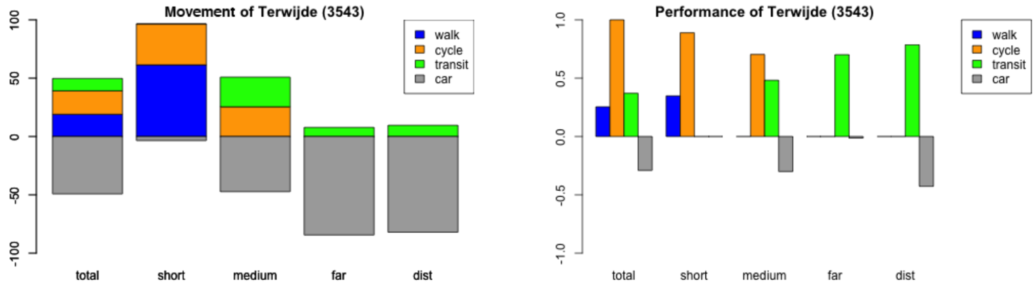


FIGURE APP.K.10 Absolute travel pattern and contextual performance values of postcode 3543, modality type 8.

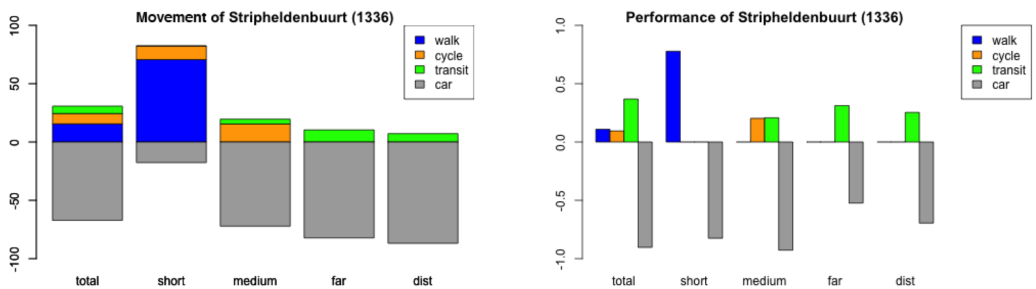


FIGURE APP.K.11 Absolute travel pattern and contextual performance values of postcode 1336, modality type 9.

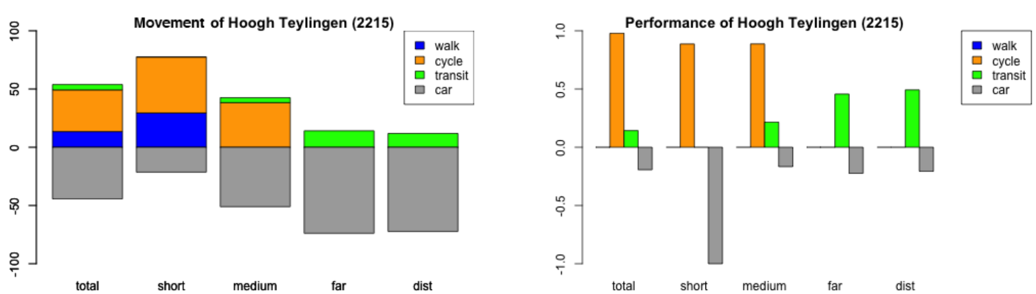


FIGURE APP.K.12 Absolute travel pattern and contextual performance values of postcode 2215, modality type 9.

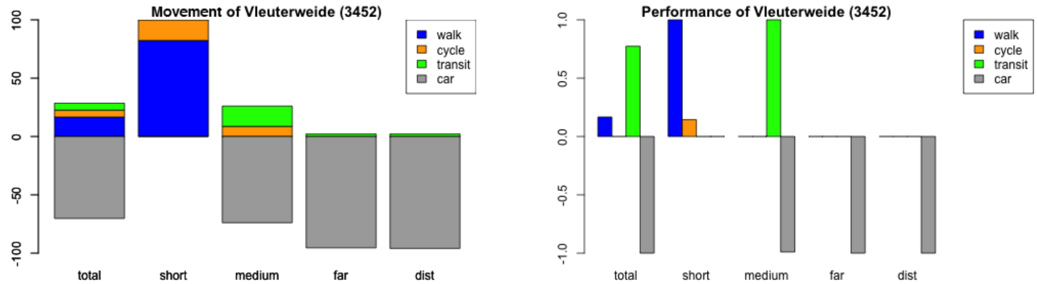


FIGURE APP.K.13 Absolute travel pattern and contextual performance values of postcode 3452, modality type 9.

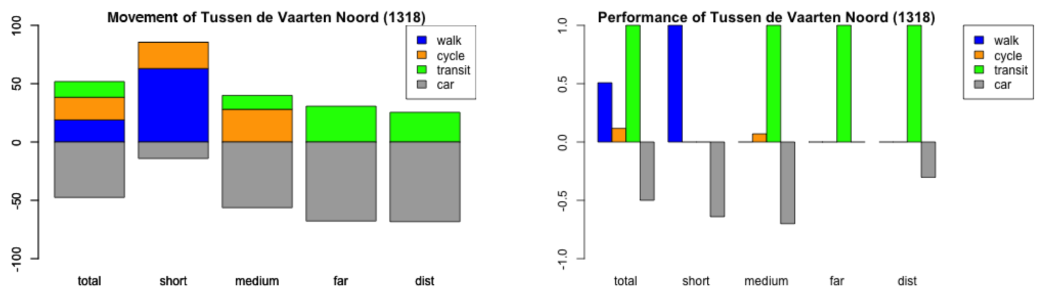


FIGURE APP.K.14 Absolute travel pattern and contextual performance values of postcode 1318, modality type 10.

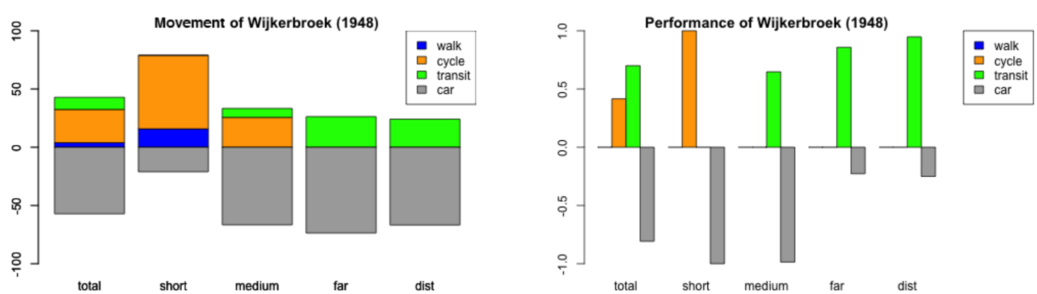


FIGURE APP.K.15 Absolute travel pattern and contextual performance values of postcode 1948, modality type 10.

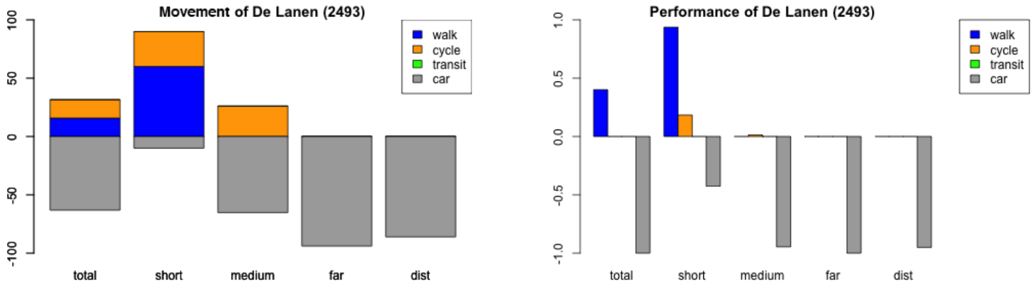
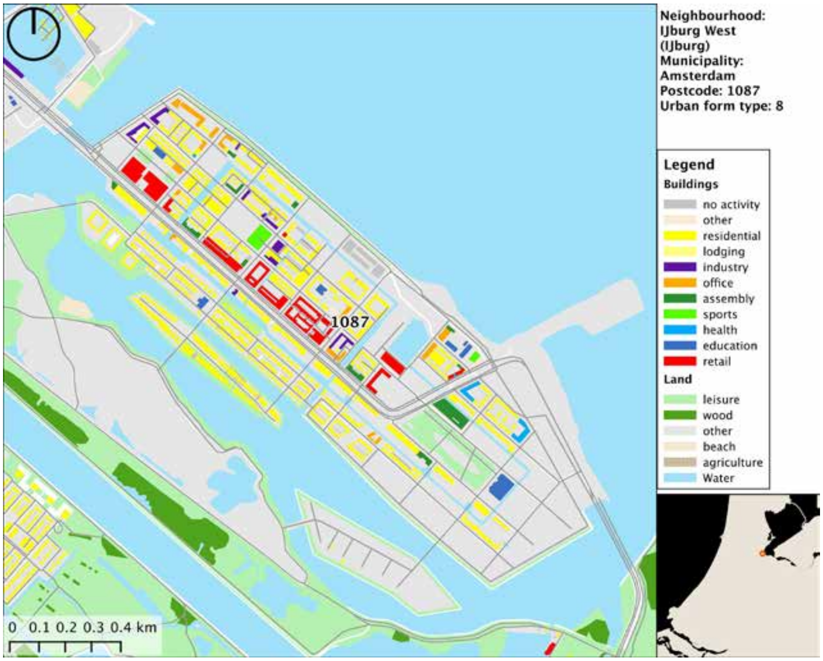


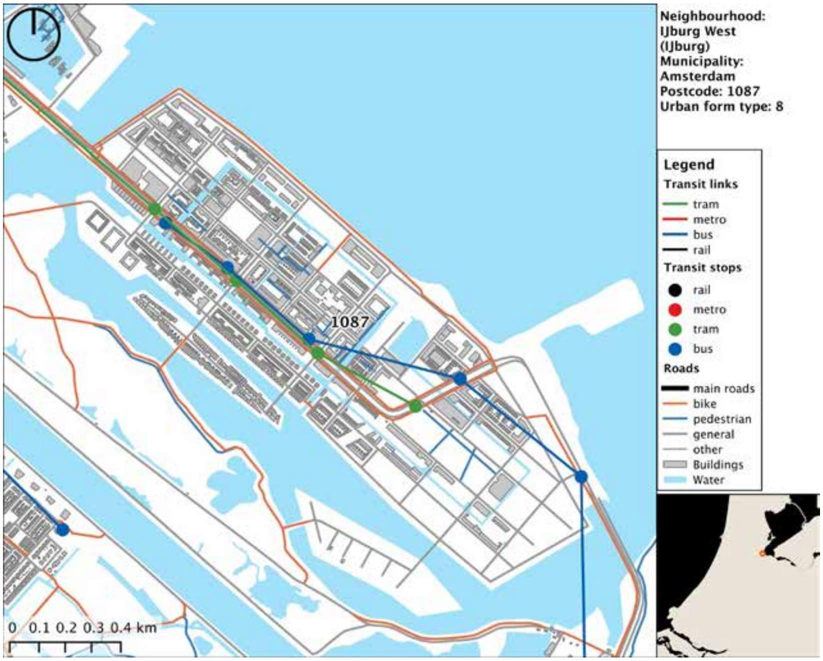
FIGURE APP.K.16 Absolute travel pattern and contextual performance values of postcode 2493, modality type 10.

Appendix L VINEX SET2 neighbourhoods with outlier mobility performance

The following maps present the land use and transport infrastructure of the VINEX SET2 neighbourhoods that have outlier performance (positive or negative), which was the focus of Appendix K.



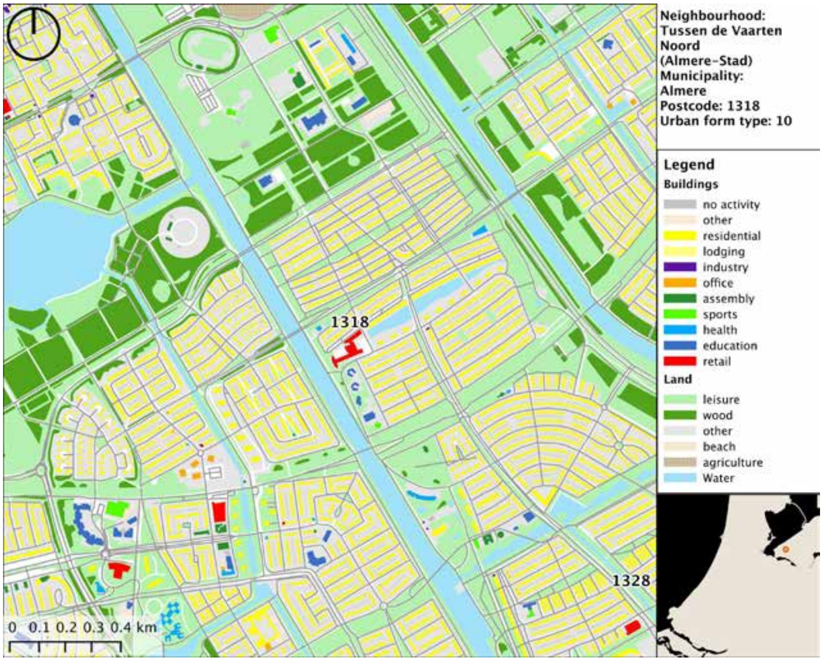
1



2

FIGURE APP.L.1 Land use and transport maps of postcode 1087: Ijburg West (Ijburg), Amsterdam.

1



2

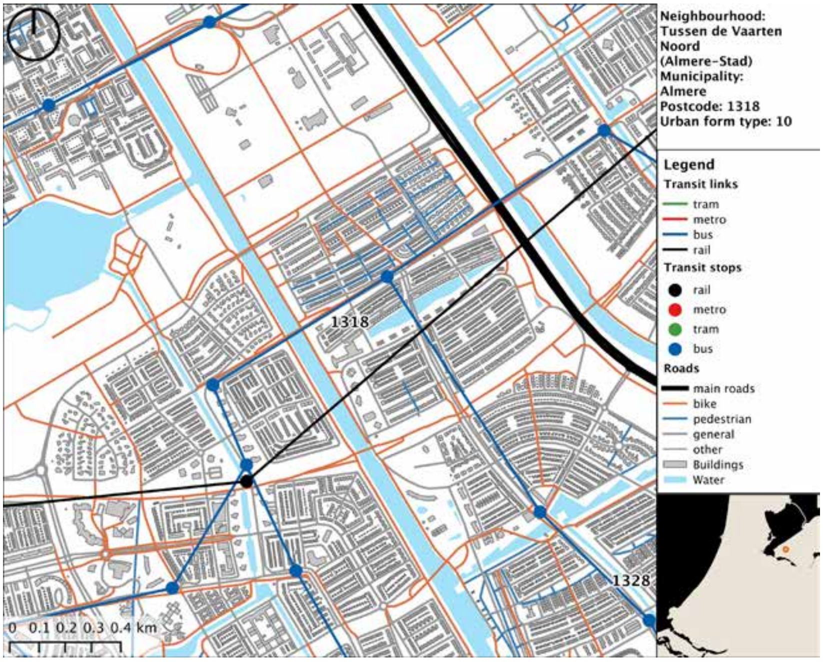
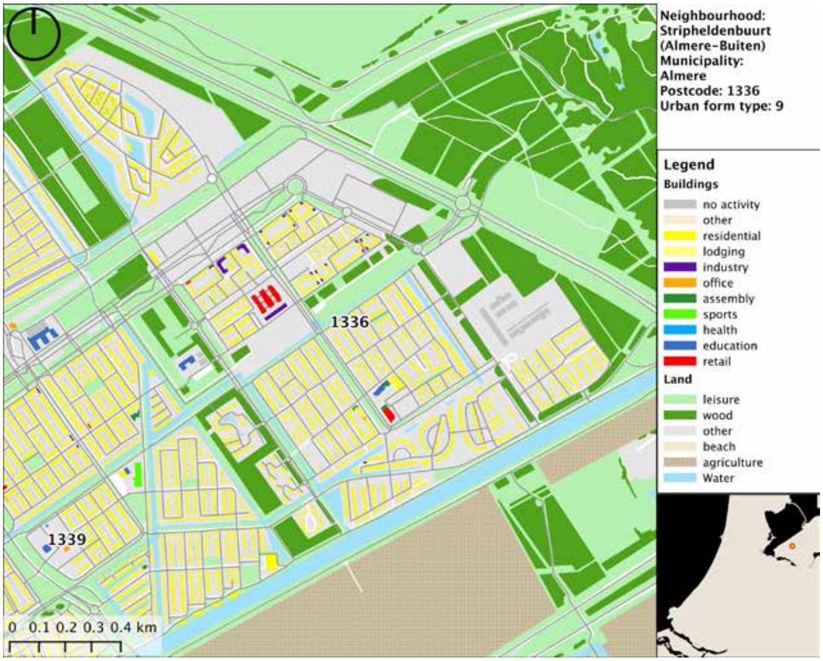


FIGURE APP.L.2 Land use and transport maps of postcode 1318: Tussen de Vaarten Nooerd (Almere-Stad), Almere.

1

2

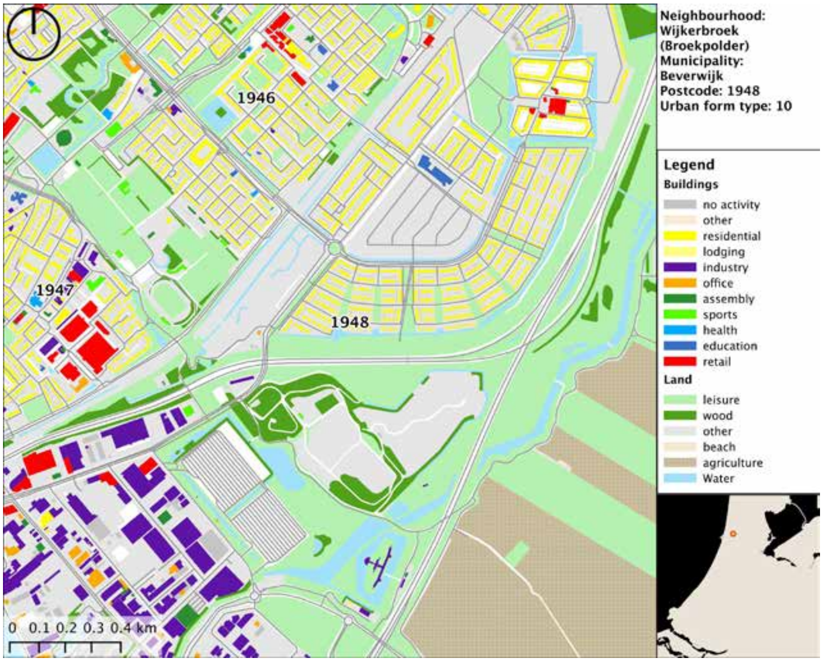
FIGURE APP.L.3 Land use and transport maps of postcode 1328: Tussen de Vaarten Zuid (Almere-Stad), Almere.



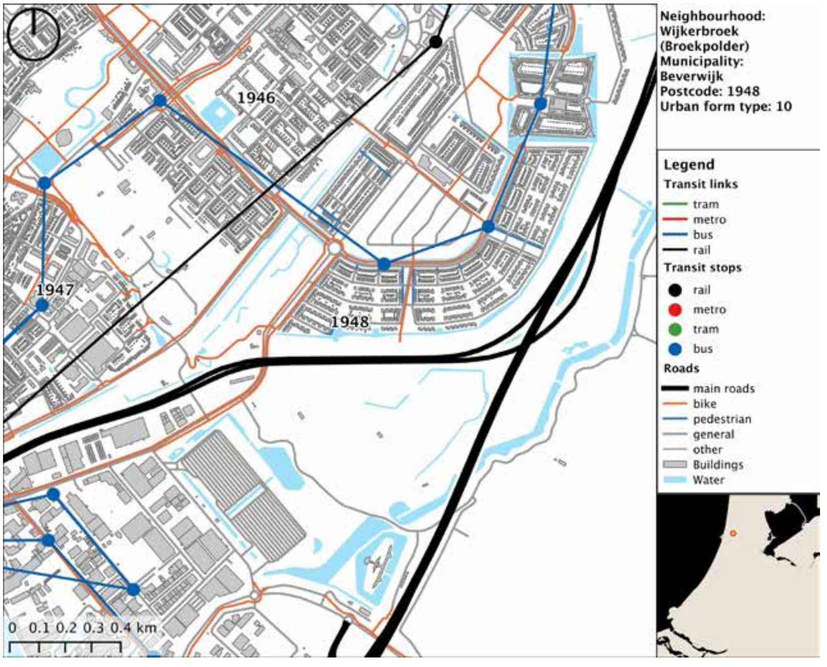
1

2

FIGURE APP.L.4 Land use and transport maps of postcode 1336: Stripheldenbuurt (Almere-Buiten), Almere.

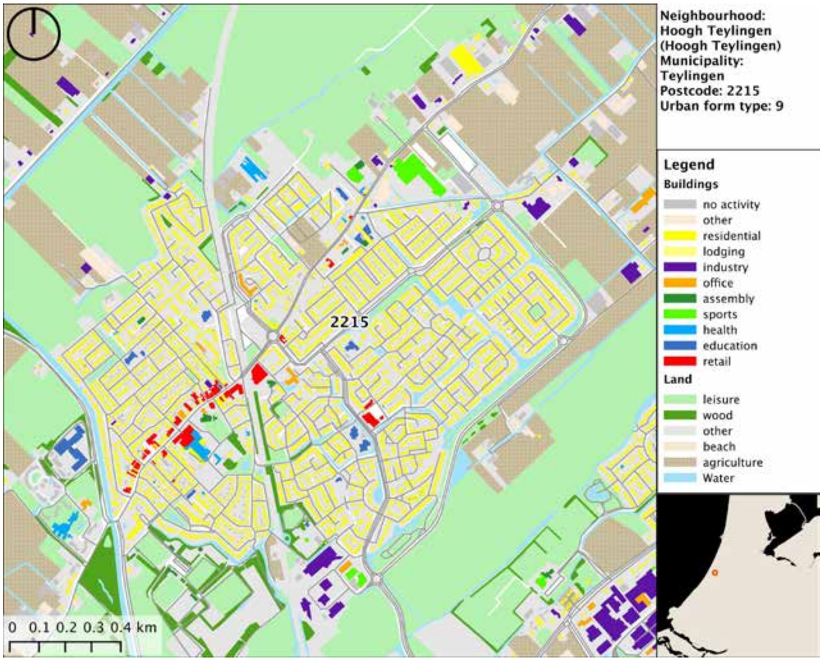


1

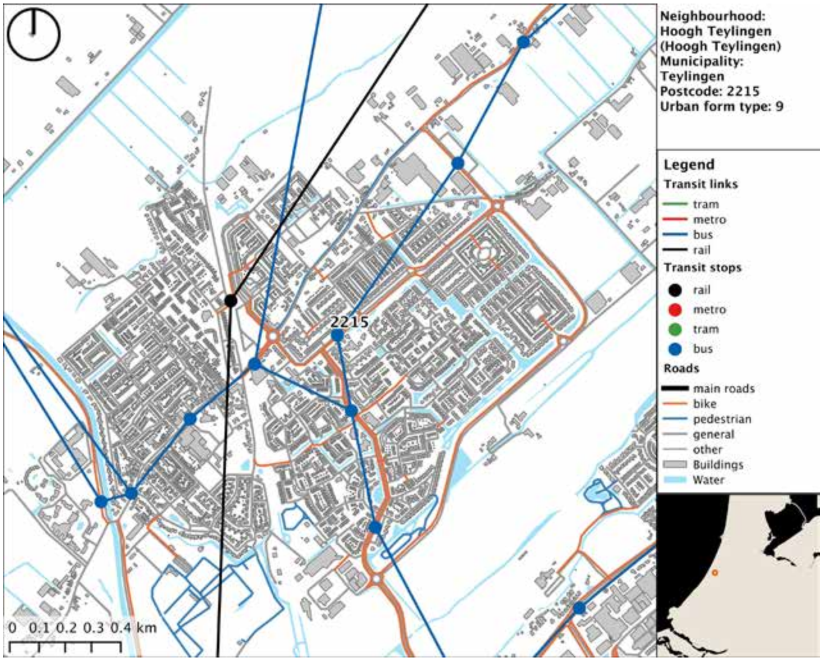


2

FIGURE APP.L.5 Land use and transport maps of postcode 1948: Wijkerbroek (Broekpolder), Beverwijk.

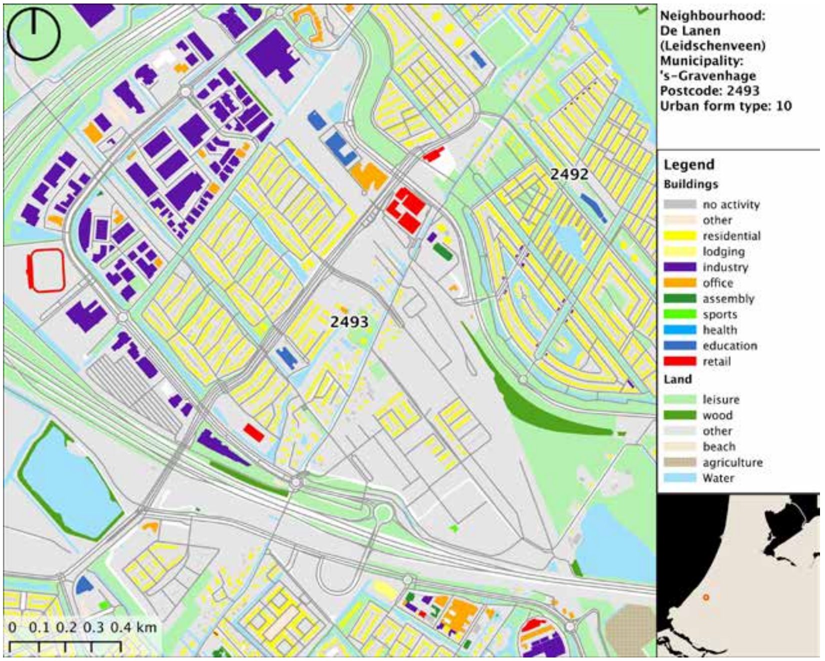


1

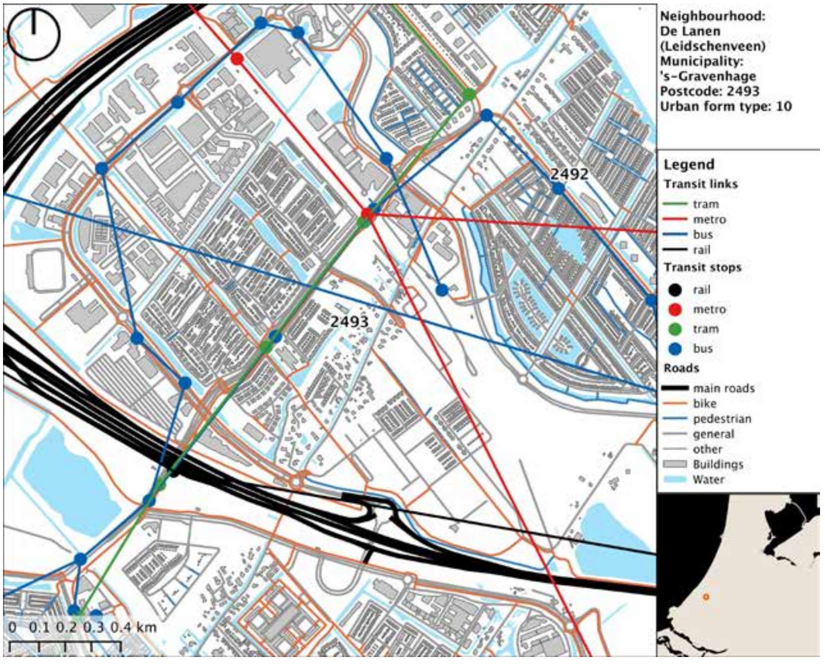


2

FIGURE APP.L.6 Land use and transport maps of postcode 2215: Hoogh Teylingen, Teylingen.

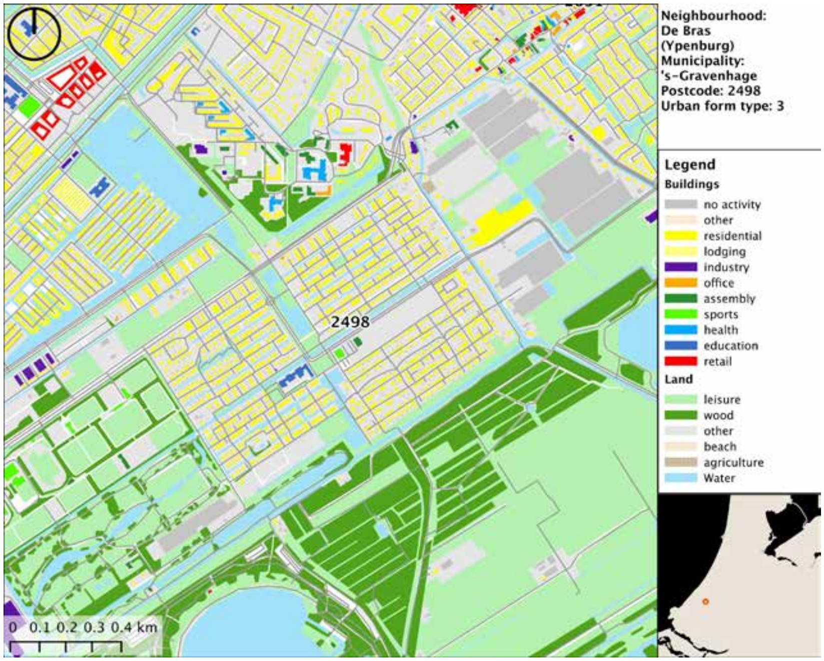


1



2

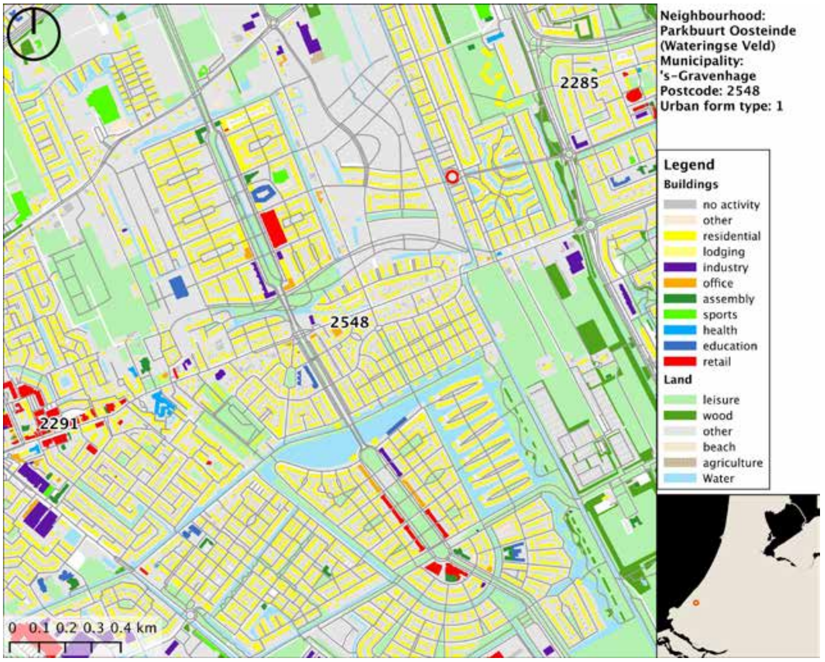
FIGURE APP.L.7 Land use and transport maps of postcode 2493: De Lanen (Leidschenveen), s'-Gravenhage.



1

2

FIGURE APP.L.8 Land use and transport maps of postcode 2498: De Bras (Ypenburg), s'-Gravenhage.

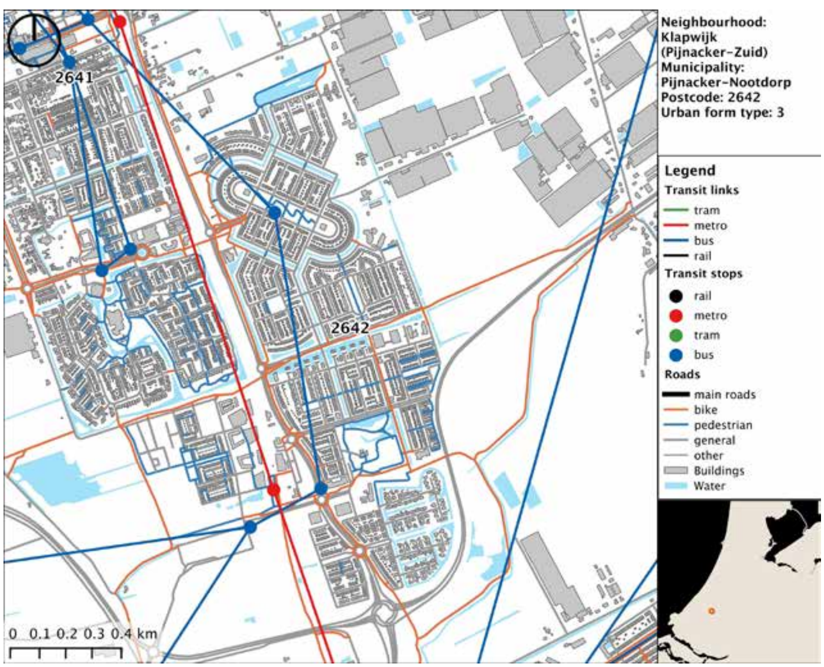


1

2

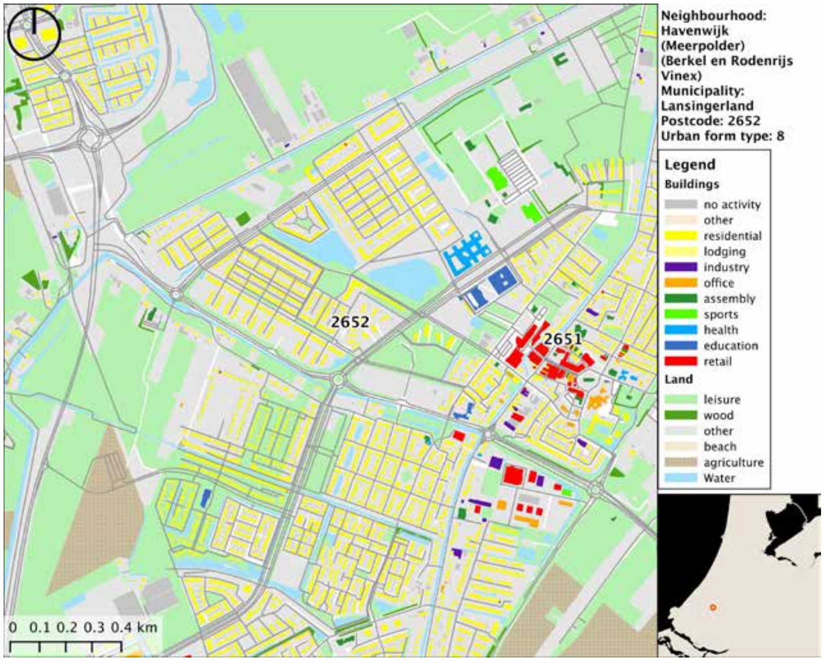
FIGURE APP.L.9 Land use and transport maps of postcode 2548: Parkbuurt Oosteinde (Wateringse Veld), 's-Gravenhage.

1

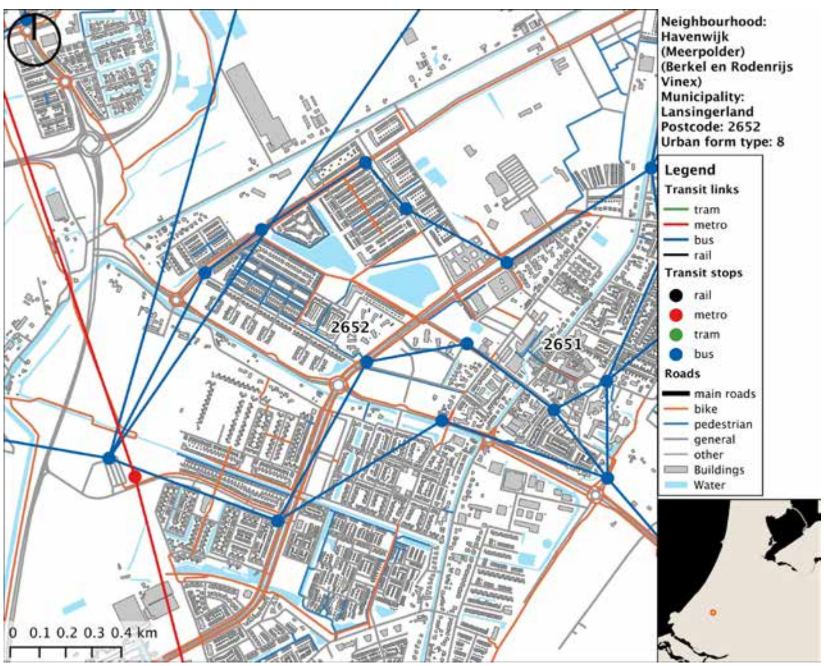


2

FIGURE APP.L.10 Land use and transport maps of postcode 2642: Klapwijk (Pijnacker-Zuid), Pijnacker-Nootdorp.

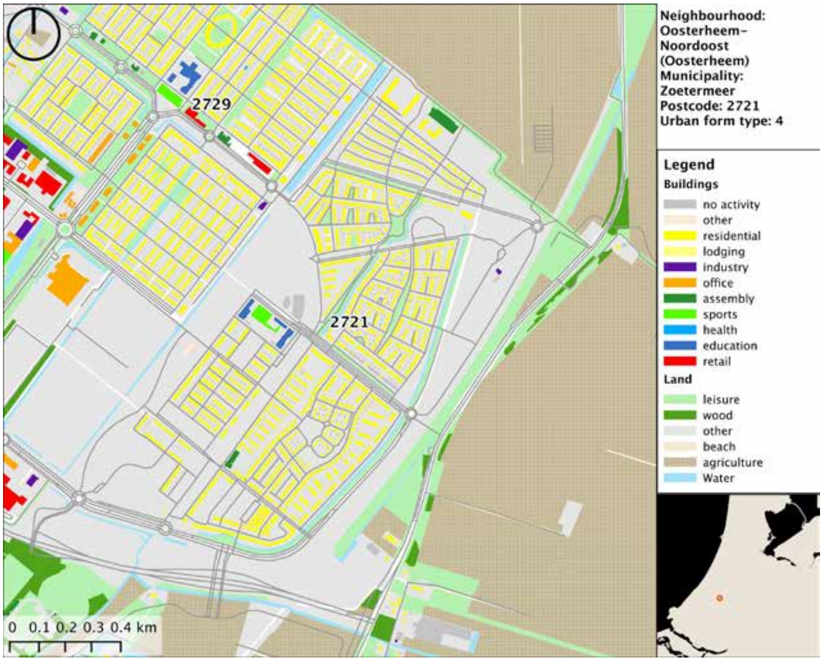


1

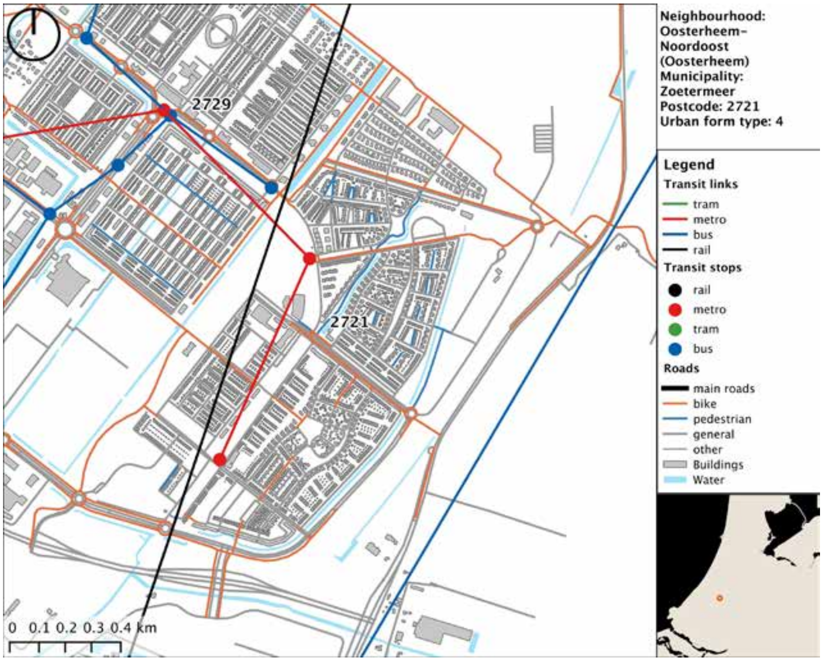


2

FIGURE APP.L.11 Land use and transport maps of postcode 2652: Havenwijk (Berkel en Rodenrijs), Lansingerland.

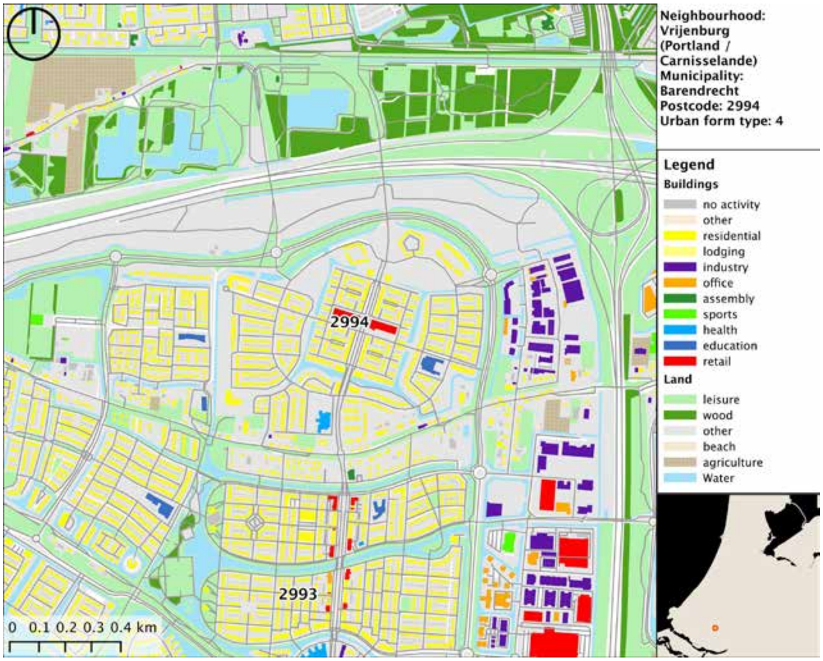


1

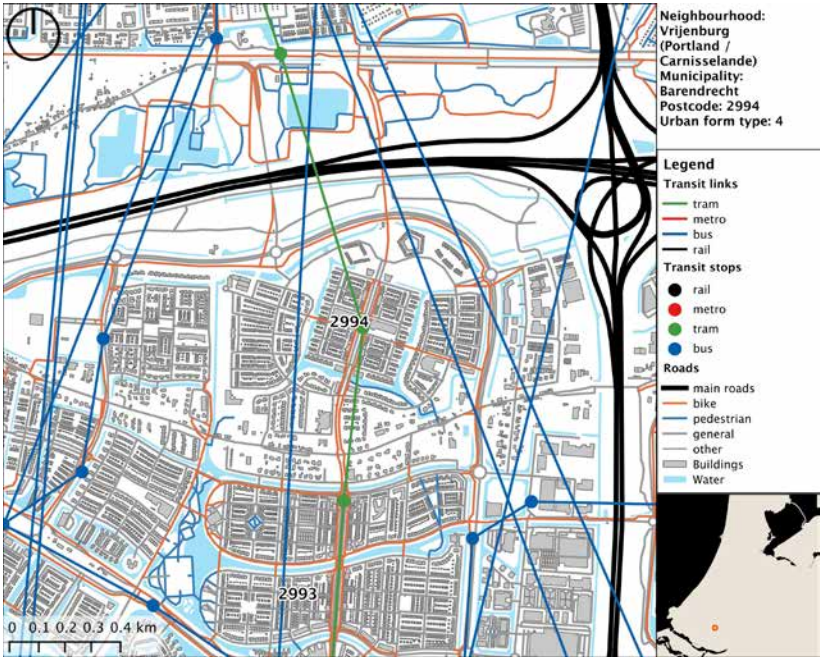


2

FIGURE APP.L.12 Land use and transport maps of postcode 2721: Oosterhem-Noordoost (Oosterheem), Zoetermeer.



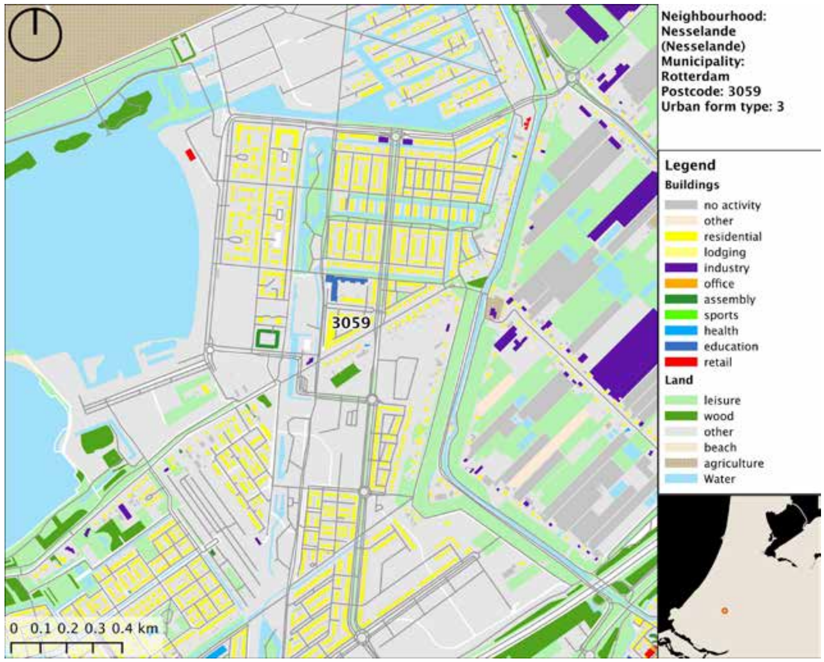
1



2

FIGURE APP.L.13 Land use and transport maps of postcode 2994: Vrijenburg (Portland / Carnisselande), Barendrecht.

1



2

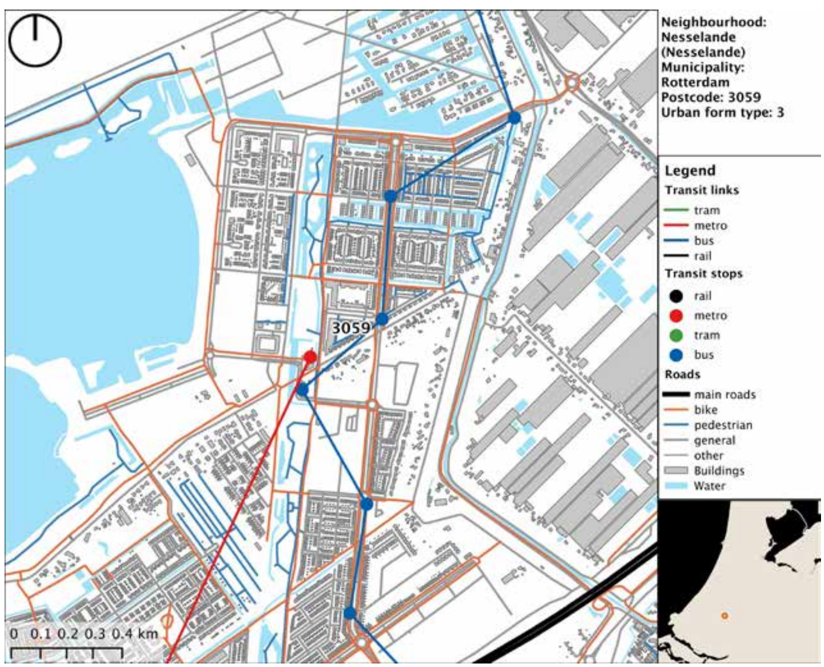
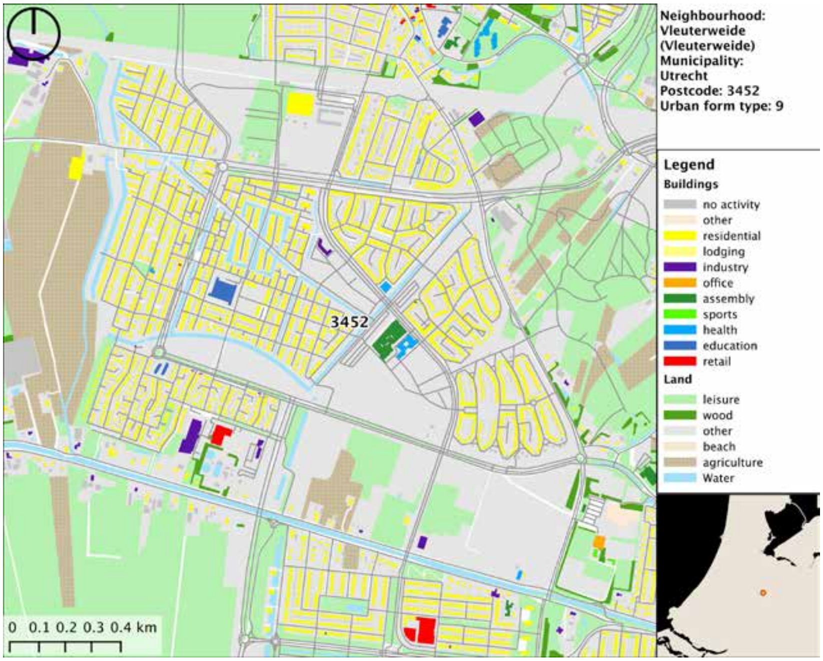
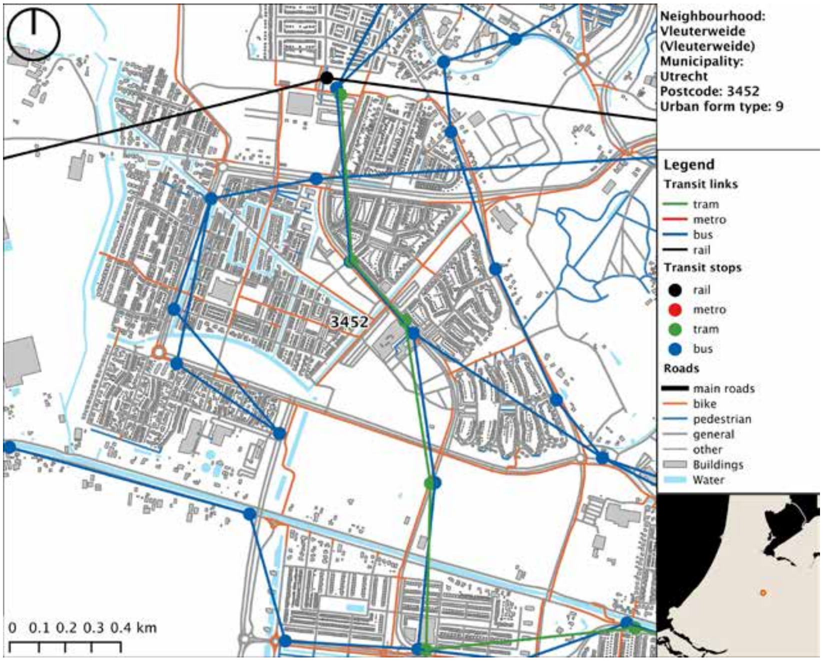


FIGURE APP.L.14 Land use and transport maps of postcode 3059: Nesselande, Rotterdam.



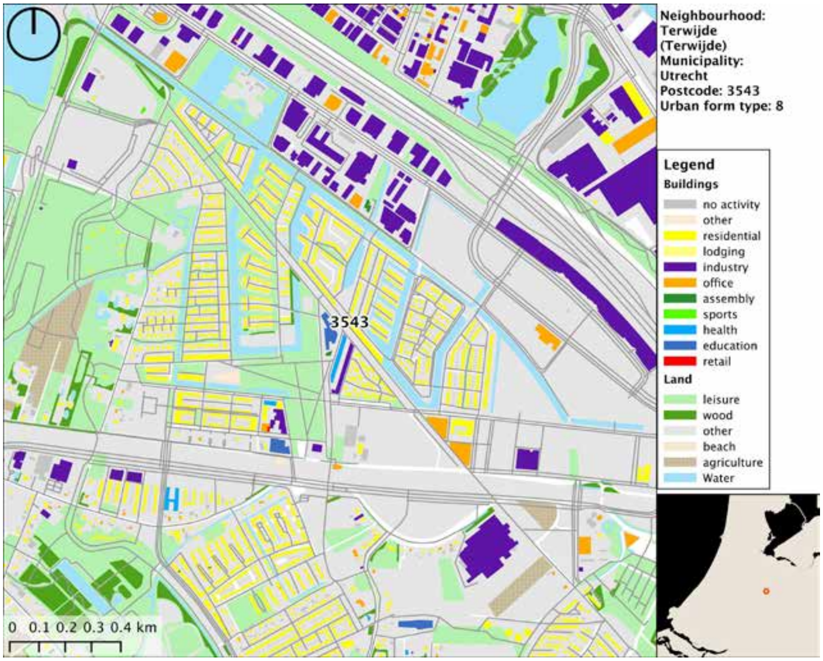
1



2

FIGURE APP.L.15 Land use and transport maps of postcode 3452: Vleuterweide, Utrecht.

1



2

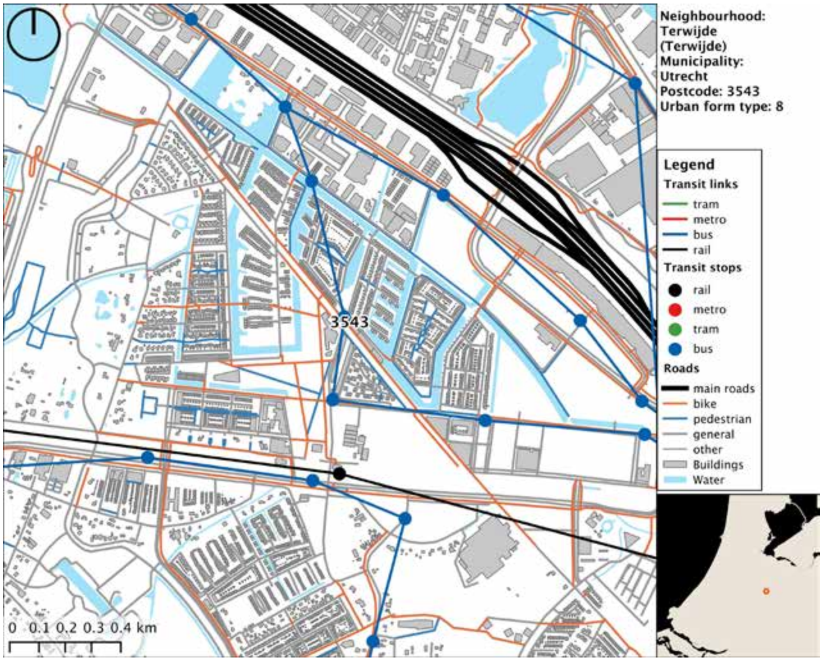


FIGURE APP.L.16 Land use and transport maps of postcode 3543: Terwijde, Utrecht.

Appendix M Source code repository

Throughout the PhD work I had to write pieces of code to carry out various tasks, from building the network model, to analysing the empirical data, or producing the regional typologies. The snippets of code and some longer scripts have been uploaded to a source code repository in Github: https://github.com/jorgegil/phdThesisCode.

The material is organised by thesis chapter, where it is first used, and the name of the files refers to specific sections, figures and tables of the chapters. These files are of various kinds: SQL commands and pl/SQL functions for PostGIS, scripts for R, or command line operations for Mac OSX. The repository also contains small data sets with postcode level analysis results that can be used to reproduce the later stages of the work.

This source code is released under a GNU GPL2 license, open for anyone to use and to reproduce or validate the steps of the thesis work. The code is not optimised or necessarily structured for general use, as it was intended for personal use in a set of very specific tasks. For this reason, this release will not be fixed or improved. Nevertheless, some of this code will eventually evolve into new projects, as plugins for QGIS or scripts for R, so suggestions and contributions from others are greatly welcome.