Climate, Weather and Daily Mobility

Transport Mode Choices and Travel Experiences in the Randstad Holland

The research reported on in this book was conducted at the Urban and Regional research centre Utrecht (URU), Faculty of Geosciences, Utrecht University, which is part of the Netherlands Graduate School of Housing and Urban Research (NETHUR). The research was conducted within the programme Climate and Environmental change and Sustainable Accessibility of the Randstad (CESAR), which is part of the Sustainable Accessibility of the Randstad (SAR) research programme funded by the Netherlands Organisation for Scientific Research (NWO).

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Climate, Weather and Daily Mobility

Transport Mode Choices and Travel Experiences in the Randstad Holland

Klimaat, weer en dagelijkse mobiliteit: Vervoermiddelkeuze en reisbeleving in de Randstad

(met een samenvatting in het Nederlands)

Proefschrift

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door

Lars Böcker

geboren op 15 mei 1985 te Arnhem

Promotor: Prof.dr. M.J.Dijst
Copromotor: Dr. J. Prillwitz

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Preface

If weather conditions were to describe the trajectory of writing this dissertation they would have been typically Dutch. Changeable. Wind from the back. Wind from the front. At times, there were periods in which dark clouds packed above my head, wind was building up, thunder was rumbling in the background, and lightning was just about to strike. The ink of my phrases being rinsed away by rain, before I even fully got it on paper. Yes, at times I felt like a steerless ship, amidst large waves in the middle of a vast ocean, with no idea how I got there and no idea how to get out, wondering what the hell I was thinking when I started this whole thing in the first place. But then, as quickly as these clouds could emerge they disappeared, making space for the sun to light up the skies, brighten the horizon, colouring the surroundings and boosting me with morale and energy to move forward. It were these moments that I realised how beautiful and rewarding a PhD trajectory can be. However, my exposures to weather were not just faith, I learned. Over the past four and a half years, I have managed to develop tools to navigate the periods of darkness and look beyond the clouds towards the clear skies ahead of me. This was something, however, I did not accomplished alone. I have been very lucky with the support of people around me: supervisors, colleagues, friends, family and my girlfriend.

First of all I would like to thank Prof.dr. Martin Dijst, who guided my Bachelor thesis, lured me into a research master, supervised my master thesis and invited me to present this at a conference in Washington, triggered enthusiasm and passion in me to do scientific writing, got me into this challenging but incredibly rewarding PhD trajectory, and guided me with patience, passion and devotion every step of the way through. Martin, I greatly appreciate the way you kept me on track when I was wandering off, and learned me to be critical, to be precise, to focus, and to have confidence in myself. I would also like to thank my copromotor Dr. Jan Prillwitz. Jan, it came as a shock to me, halfway my PhD, to hear you were leaving the department. However, your contributions during the first two years, not just methodologically and conceptually but also mentally, in writing my first two scientific publications have been very helpful and laid a solid foundation to this dissertation.

I would also like to thank Dr. Sofia Thorsson and Dr. Fredrik Lindberg from Gothenburg University, Sweden. It was a great pleasure to meet both of you on various locations in Utrecht and Gothenborg. You gave me a speed-course in urban climatology, which contributed a great deal to my interdisciplinary understanding of the relationships between weather, urban form and mobility behaviours and experiences studied in this dissertation. Sofia I enjoyed very much our collaboration, which resulted in our joint publication, an important chapter in this book. I admire very much the way you always manage to explain and write complex matter in a clear and simple way. Fredrik, I would like to thank you for the assistance you gave us by calculating the thermal indices to link to my fieldwork data.

I would also like to thank Dr. Jan Faber and Dr. Marco Helbich, my colleagues from Utrecht and co-authors during the last phases of my PhD. Jan, I value very much the, at times intense, discussions we had on statistical issues related to the structural equation models used in our articles. It is incredible how much you know about statistics. Marco, it was very pleasant to work with you. I have never had such a smooth and quick collaboration on writing and publishing a scientific article as we did together with Martin. I also enjoyed the coffee breaks and beers we had during and after work and at conferences and meetings, and I am looking forward to keep doing so in the future.

Many thanks also to all my other present and former colleagues, with whom I had great discussions on work related issues as well as lots of other stuff. I would like to thank Mervin van Veen and Peter van der Vijver at questionnaire agency GFK Intomart for their excellent assistance with the fieldwork and Julia McQuoid for her native speaker assistance in one of the chapters. I would also like to thank my former colleagues Annelien Meerts, Dr. Martin Zebracki, Dr. Hanneke Posthumus, Dr. Barabara Heebels, Dr. Jelle Brandts and Dr. Bart Sleutjens (yes, I realise most of you have already made it) for the wonderful weekends that we had to blow off some steam at some of the most vibrant and inspiring European locations, such as Essen, Frankfurt and Texel. I would also like to thank Dr. Wouter Jacobs, Niels van der Vaart, Dr. Linda Nijland and Qianfan Zhang for the wonderful company you have provided while sharing the office with me. I hope I have not distracted you too much from your work. Many thanks also to Marijke, Ineke, Nico and Joost for our inspiring and refreshing lunch walks and to all the other Dutch and international colleagues at the department of Human Geography and Planning, who I have met at lunch, in the hallways and at the coffee machine.

This PhD project was embedded within the research consortium Climate and Environmental change and Sustainable Accessibility of the Randstad (CESAR), as part of the larger Sustainable Accessibility of the Randstad (SAR) research programme, funded by the Netherlands Organisation for Scientific Research (NWO). I would like to thank all the funding agencies. I would also like to thank all the CESAR members. I think we had a great research community and I enjoyed very much the interdisciplinary plenary meetings we had once or twice a year. Specifically, I would like to thank Natalie Theeuwes, Niels van der Vaart, Peter Pelzer and Dr. Marco te Brömmelstroet, the individual researchers over the years on the other CESAR projects, with whom I shared pleasant and interesting discussions at universities, bars and restaurants in Utrecht, Wageningen and Amsterdam. Natalie and Peter, a special thanks goes out to you as my paranymphs. With the two of you by my side, I know that "every little thing is gonna be all right" at the 19th of December.

But it was not only supervisors and colleagues who have kept me on track. A first very special thanks goes out to my girlfriend Benedikte and my parents Urban and Désirée who have always been there for me during the pleasant as well as during the difficult moments, and who have given me the confidence that I could complete this thing. Urban, special thanks also for your assistance with the layout of this book. Finally I would like to thank my family, my brother Kaj, Raymond, and all my other friends for supporting me over the past four and a half years.

The experience of a hot, summer sun is not limited to the look of a round yellow disk against the cloudless sky; it includes the oppressive heat and humidity, a momentary relief from occasional wind felt on our skin, and the feeling of parched lips and dry mouth.

Our experience of a fierce autumn wind is not simply the feeling of wind against our body; the way in which fallen leaves swirl around, the dynamic swaying of tree branches, the rustling sound they make, the slightly musty smell coming from half-decaying leaves accumulated on the ground, and the rapid movement of clouds all contribute toward our experience of this windy weather.

Yuriko Saito (2005:160)

1 Introduction

1.1 Climate, society and mobility: background and research gaps

July 28th, 2014: "Torrential rain and flash floading cause travel chaos" (BBC, 2014); "Floading in West- and East-Flanders" (Het Laatste Nieuws, 2014); and "Disturbance in the Netherlands due to very heavy rain (De Volkskrant, 2014). National newspaper headlines report on extreme rain and hail showers throughout Western Europe. A local Dutch weather station recorded 76 mm of rain in the timespan of one hour, equal to the national average over an entire month (KNMI, 2014a). Images, accompanying the articles illustrate the scope of the adverse weather (Figure 1.1), and bring closer the topic of climate change as well as the idea that we may be witnessing its effects in our own countries already today. Moreover, they demonstrate the clear impact that weather can have on society in general, and its disruptive effects on transport in particular.

But it is not only the extremes in weather that matter. Also normal, subtle everyday weather fluctuations play important roles in our everyday choices to travel, where to go, how far, for how long, with which transport mode, as well as in our experiences of weather and emotions before we get out, on the way, and after we arrive. For instance when deciding to take the bus instead of the bicycle to work on a rainy morning; when warmly dressing up your four-year-old for a backseat bicycle ride to the kindergarten through a cold winter morning; when heading for the beach or barbequing in a nearby park on a warm summer day; when unfolding an umbrella while walking through an autumn shower; when frustratingly gazing through a window on a rainy afternoon knowing that you have to go outside soon to do the groceries; or when taking notice of the weather forecast (Figure 1.2). Subsequently, small gradual changes in these everyday weather conditions due to climate change, such as an overall increase in temperatures, may have profound impacts on everyday travel patterns.

Figure 1.1 Extreme precipitation events throughout Europe on July 28th, 2014. Source: Shutterstock

Figure 1.2 Weather forecast: a roller coaster of emotions. Source: translated from Peter de Wit in *De Volkskrant*, 3-3-2012

Changes in weather conditions are related to changes in climates. Although climate scepticism remains (e.g. Curry and Webster 2011; Idso et al., 2013), today most scientists agree on the notion of anthropogenic climate change. The latest report from the Intergovernmental Panel on Climate Change (IPCC, 2013) states with more certainty than in earlier editions that: (1) climate change is on its way since the mid 20th century, with especially each of the last three decades being successively warmer than any preceding decade since 1850; and (2) human influence on the system, via anthropogenic green house gas emissions, is clear (ICCP, 2013). Climate projections indicate that global temperatures will continue to raise, ranging from +1°C degree by 2100 in an emission reduction scenario (which requires substantial CO2 emission reductions), to +4°C in a high emission increase scenario (Figure 1.3). Some regions in the world, especially the temperate climates in the northern hemisphere, are projected to warm more quickly than others. In terms of precipitation, existing differences between cold and wet climates are expected to increase: most dry regions are likely to get dryer, most wet regions are likely to get wetter. More specifically, Mediterranean and subtropical climates in Southern Europe, Central America and southern Africa are expected to become much dryer, while especially the Polar Regions and some regions around the equator in East Africa and the Pacific Ocean will become wetter. The degree of change is larger in higher compared to lower emission scenarios (Figure 1.4). Not only between, but also within regions, differences between wet and dry weather are likely to become larger. For most regions, increases are expected in the frequency, intensity and amounts of heavy precipitation events. Simultaneously, the intensity and duration of drought are likely to increase (IPCC, 2013).

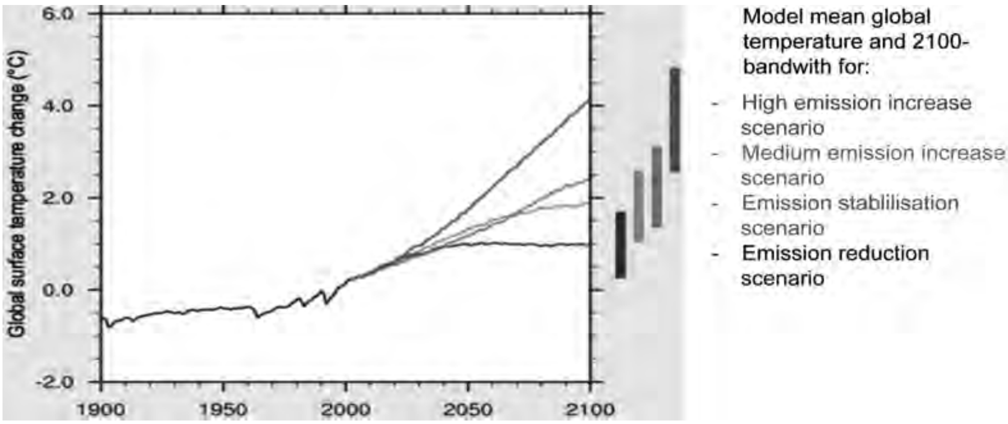

Figure 1.3 Projected global temperature rise. Source: IPCC, 2013

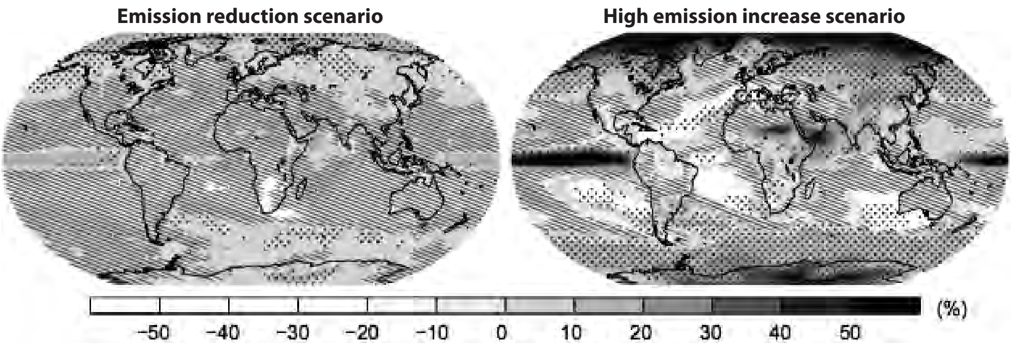

Figure 1.4 Regional changes in average precipitation (1986–2005 to 2081–2100). Source: IPCC, 2013

Although differences between lower and higher emission scenarios clearly illustrate the importance and necessity of climate change mitigation (Figure 1.3 and Figure 1.4), recently scholars and policy makers have increasingly realised that we need, in addition, measures to adapt our societies to climate change (IPCC, 2014). Hereto, it is first of all important to develop a comprehensive understanding of how current and projected climate conditions affect our society. Climate change effects on society have been reported for various domains. Some studies point out potential positive effects of climate change for some regions related to reductions in cold weather, snow and ice. Examples include reduced heating costs (Issac and Van Vuren, 2009), reduced cold stress (e.g. Matzarakis and Mayer 1996), fewer transport disturbances (e.g. Jaroszweski, et al., 2010; Chung et al., 2005) and lower traffic accident rates (e.g. Transportation Research Board, 2008). However, the majority of climate impact assessments investigate societal threats. For instance increases in hot weather may lead to problems with thermal discomfort (e.g. Matzarakis and Mayer 1996), heat stress (e.g. McMichael et al., 2006), heat-related mortality (e.g. Huang et al., 2011), water supply and irrigation, infectious diseases (IPCC, 2014), higher energy consumption through air conditioning (Issac and Van Vuren, 2009) and lower labour productivity (Kjellstrom et al., 2009) amongst others. The increasing frequency and intensity of heavy precipitation may lead to increased risks of flooding as well as disruptions of utility and transport networks (Transportation Research Board, 2008).

Climate change impact assessments and adaptation strategies require an interdisciplinary approach, in which not only natural sciences, but especially also social sciences and humanities play an important role (Driessen et al., 2013). The research presented in this thesis is part of such interdisciplinary approach. Together with three other projects, this research is part of an overarching research programme on Climate and Environmental change and Sustainable Accessibility of the Randstad (CESAR, [http://climateplanning.tk]). The programme has the aim to develop systematic knowledge on the relationships between climate conditions, urban form and daily mobility choices, and to integrate this knowledge into improved interactive planning support systems. The programme is part of a series of programmes on Sustainable Accessibility of the Randstad (SAR), financed by the Dutch Ministry of Infrastructure and Environment through the Netherlands Organisation for Scientific Research (NWO). In line with the other programmes, this research is situated in the Randstad Holland: the densely populated and economically viable conurbation of cities (e.g. Amsterdam, Rotterdam, The Hague and Utrecht) located in the west of the Netherlands.

Climate change projections for this region are as follows. As with most of Western Europe, since 1951 temperatures in the Randstad Holland (+1.4°C between 1950 and 2013) have increased approximately twice as much as the global average. Based on the IPCC-2013 knowledge, the Royal Dutch Meteorological Institute (KNMI, 2014b) developed 2050- and 2085-climate change scenarios for the Netherlands, which also apply on the Randstad Holland. Temperatures are expected to rise with 1.0 to 2.3°C by 2050 and 1.3 to 3.7°C by 2085, depending on different emission and prevailing wind pattern scenarios. Temperatures are expected to rise less on relatively warm winter and relatively cold summer days, but are expected to rise more on relatively cold winter days and relatively warm summer days. This implicates a reduced likelihood of very cold weather, snow and ice, and an increased likelihood of very hot weather. Precipitation in the Netherlands has increased with 14% since 1951, although summers actually got dryer. A further increase of about 2.5 to 5% by 2050 and 5.0 to 7.0% by 2085, depending on different emission and prevailing wind pattern scenarios, is projected. Precipitation changes are season-specific. Overall precipitation and large amounts of precipitation in limited timespans are expected to increase in winter. In summer the intensity of on the one hand periods of drought and on the other hand heavy rain showers, including hail and thunder, are likely to increase.

Similar to many other urban regions around the world, the Randstad Holland faces several distinct climate challenges: First, its strategic location in a coastal area and along major rivers, makes the Randstad Holland more vulnerable to sea level rise and inland or coastal flooding. Second, in comparison to less urbanised areas, urban areas like the Randstad are more severely impacted by the interaction effects of warmer climate conditions and air pollution, not only due to the concentration of domestic, industrial and transport-related polluting sources in cities, but also due to reduced ventilation capacities resulting from dense urban design. Third, in metropolitan regions, such as the Randstad Holland, climate change effects may be enhanced or altered due to the existence and formation of local microclimates. Over the last few decades it has increasingly become clear that due to differences in land use designs, built densities, built materials and vegetation cover, amongst others, considerable differences exist between cities and their surrounding countryside, as well as within cities, with regard to temperature (Hidalgo et al., 2008; Mills, 2009; Oke, 1973, 1982; Steeneveld, et al., 2011), wind environments around buildings (e.g. Blocken and Carmeliet, 2004), and potentially also with regard to cloud coverage (Changnon, 1992) and precipitation patterns (Shepherd et al., 2002).

This background illustrated the presence of weather in daily lives and mobilities; the overall scientific consent on the occurrence and anthropogenic nature of climate change; and its impact on society in general and on urban areas in particular. Yet although the influence of weather on daily mobility has been pervasive and its societal relevance in terms of climate change never more pronounced, current interdisciplinary scientific debate on how weather shapes daily mobility contains several areas that are under-investigated and require further research to support policy-making. First, various scholars have investigated the, undeniably important, impacts of extreme weather events (e.g. extreme precipitation, storm, lightning, hail, snow and heat) on transport infrastructures (e.g. safety, maintenance, capacities and disruptions) (e.g. Transportation Research Board, 2008). In contrast, we currently know much less about how (the much more frequent) normal fluctuations in weather conditions affect individual mobility choices that form the basis for all travel. Second, while recent climate change evidences are clearer than ever before, we have yet to develop elaborative knowledge on how these changes may affect people's daily mobility choices and travel patterns. This requires establishing direct linkages between regional climate change projections and travel behavioural patterns. Third, as explored in this background, we have only started investigating the relationships between the designs of built up areas and microclimate conditions. It is necessary to further develop this knowledge, and to integrate it into the context of travel behaviour. Such integration provides an alternative perspective on the role of urban form in travel behavioural research and will result in alternative climate-sensitive recommendations for urban planning. Fourth, although various earlier studies investigated the effects of separated weather parameters (e.g. Hanson and Hanson, 1977; Sabir, 2011), we have yet to develop an understanding of how weather conditions affect our mobility choices in interaction with each other. For instance a cooling breeze in summer may affect travel behaviour in a very different way than the exact same wind speed transporting snow on an ice-cold winter day. Fifth, we need to better understand the interactions between weather, socio-demographics, built-environments and mobility choices, and investigate the different exposures and vulnerabilities to weather between different population categories (e.g. based on age, gender, ethnicity, etc.), different mode user groups (environmentally-exposed active mode users versus the more sheltered users of motorised modes), and differently exposed geographical contexts. Finally, while various studies have investigated weather effects on travel behavioural decisions, we know much less about its effects on peoples' subjective experiences of weather, place and emotions during travel. The research presented in this thesis will address these knowledge gaps by integrate existing insights from different disciplines and providing new empirical evidences.

1.2 Conceptual framework

In this section a conceptual framework is proposed, from which the effects of weather and climate on mobility behaviour and experience can be analysed within the spatiotemporal situations in which these decisions and experiences unfold. Hereto, use is made of a time-geographical framework (Hägerstrand, 1970). Time geography departs from individuals' paths through time and across space in order to take part in activities at different locations and times. These space-time paths may result from individuals' resources and preferences, and may be limited by capability (i.e. individuals' biological, instrumental, cognitive or physical limitations, such as the requirement to eat, or rest), coupling (i.e. when presence of other people or objects is required), and authority constraints (i.e. regulatory restrictions, such as shop closing hours). These resources, preferences and constraints are closely linked to individuals' personal and household backgrounds. Socio-demographics, such as age, gender, ethnicity and health conditions, may affect preferences (e.g. regarding the use of transport modes, activity and destination choices, the environment, urban/rural life, or the different seasons) or form constraints. For instance elderly people or people with a high or very low body-mass index (BMI) may be physically constraint in their mobilities. Socio-economic and household backgrounds may supply resources and restrictions (e.g. having a job may restrict your available leisure time; owning a car may allow you to expand your range of movement).

While moving or being stationary, individuals find themselves in unique spatiotemporal situations. In both cases, time-geography teaches us that spatiotemporal situations are highly dynamic (Dijst, 2013). Naturally, environments change (gradually or abruptly) while individuals move from one place to another, for instance when driving out of a busy city centre into a quiet natural area. But also when stationary, the surrounding environment is dynamic, as other individuals, living organisms or objects (including weather and micro-climate conditions, such as heat, cold, wind, rain, precipitation, sunshine, shadows and clouds), all with their own time-space paths, enter, exit, shape and reshape these spatiotemporal travel situations. This requires conceiving place from a dynamic rather than static point of view: a shift from what Malkki (1992) calls 'sedentarist' metaphysics to 'nomadic' metaphysics, in which flows rather than fixity are considered the normal state of affairs (e.g. Castells, 1996; Cresswell, 2006). Following such flow perspective, Dijst (2013) describes these spatiotemporal travel situations along the lines of four interrelated dimensions: built environments, social environments, mobile objects and natural processes. In this thesis mobility will be viewed in relation to these four dimensions simultaneously. For instance as a bicycle trip to work during a hectic morning rush hour with many other people (social environment), bicycles, cars, exhaust fumes (mobile objects), through a densely built urban area (built environment), on a dark, rainy, winter day (natural processes). No elements can possibly better illustrate the dynamics of place than changing weather conditions. Consider for instance the contrast between a deserted park on a stormy autumn day and the exact same park as a lively epicentre of outdoor activities on the year's first warm spring afternoon. Or an empty beach access road in winter and the same road congested on a balmy, sunny summer morning. Weather conditions and the urban built environment cannot be seen separate from each other. Knowledge on urban microclimates has shown that built environments and microclimate conditions are intrinsically related. For instance, due to several processes – indicated with letters in Figure 1.5 and further explained below – considerable differences in temperature (up to 10°C on clear nights) may arise between densely built urban areas and cooler surrounding natural areas. Compared to natural areas, densely built urban areas cool less effectively at night due to heat stored in building surfaces (b) and reduced radiation into the open sky (f vs e), while warming up more quickly during the day due to multiple reflections of solar radiation (a), heated building surfaces (b), and a lack of evapotranspiration from green plants (d), although the warming up may be counteracted by building shadows (c) (Steward and Oke, 2012; Theeuwes et al., 2014).

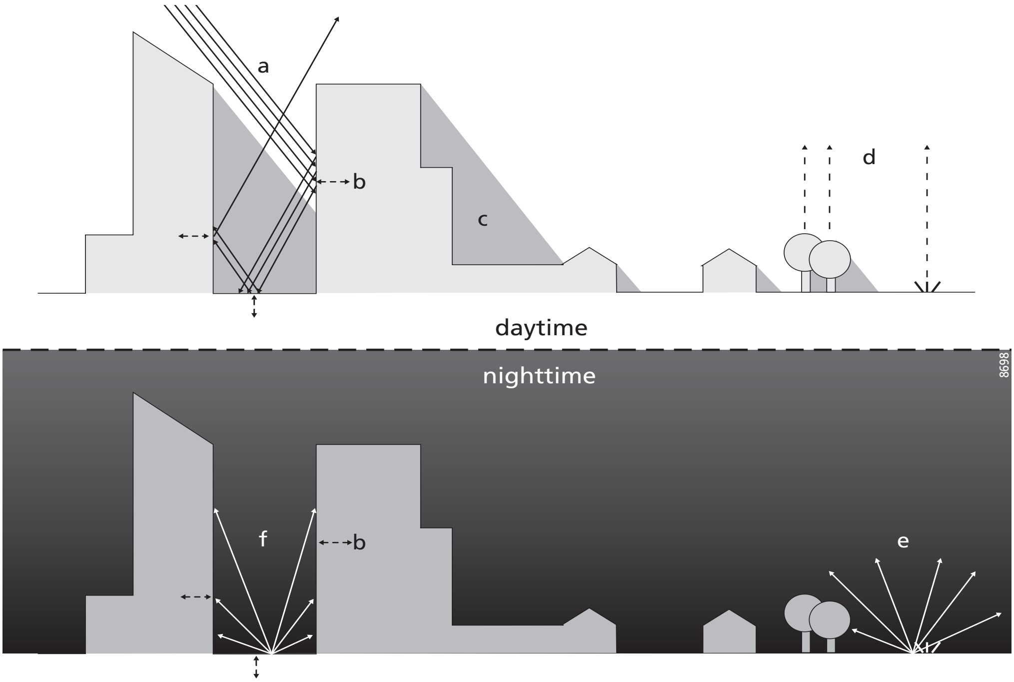

Figure 1.5 Urban microclimate processes (individual letters explained in text). Source: Helbich et al., 2014

On their time-space paths, individuals encounter spatiotemporal situations as a sequence of events. Each situation follows upon earlier situations and leads to new situations. This implicates that the trip context, in itself and in relation to previous and following trips and destinations, should be strongly considered. For instance, when returning home one most likely has to take the transport mode that one left home with. Or when having less time available until the next situation, one may choose a faster transport mode or a nearby destination. Also, several studies point out that weather affects travels towards recreational destinations more strongly than travel towards utilitarian destinations (e.g. Hanson and Hanson, 1977; Sabir, 2011; Flynn et al., 2012). Utilitarian trips, such as trips to work, study or for errands are (1) often very important, (2) often on set locations and on set times, and/or (3) often constitute habitual behaviour (e.g. Verplancken et al., 1997), all of which make utilitarian trips less open to be cancelled or otherwise changed from the ordinary. The same counts for trips made together with others: compared to trips made alone, these trips are more difficult to cancel, change or reschedule, due to the earlier mentioned coupling constraints.

The time-geographical framework used in this research considers mobility not only in terms of behavioural decisions (e.g. transport mode choices, travel frequencies and travel distances), but also in relation to experiences of weather, place and emotions during travel. Hereto, travel is conceived beyond the classic notions of the time and cost of moving in Euclidean space from location A to maximise a utility at location B, a way of rethinking mobility proposed by the New Mobilities Paradigm (e.g. Sheller and Urry, 2006). In his book “On the Move” Cresswell (2006) wonders how spatial and social sciences can leave such movement from A to B as a blank space, while it is obviously full of meaning, experience and emotion. In analogy to e.g. Tuan’s (1977) humanistic conceptualisation of how location or *space* become *place* when people form a bond or attach meaning to it, Cresswell argues that empty movements become mobility where these movements are experienced and meaningful. The incorporation of this human dimension is relatively new to time geography and the transport world. Only recently, empirical studies have started linking travel behaviour to emotional experiences (e.g. McQuoid and Dijst, 2012) and subjective or emotional well-being (e.g. Ettema et al., 2010; De Vos et al., 2013). However, these existing and expanding strands of literature have not yet taken into account the role of weather. From studies outside the transport world it is known that weather has profound impacts on (thermal) comfort (e.g. Nikolopoulou and Steemers, 2003; Thorsson et al., 2004, 2007; Eliasson et al., 2007), moods and emotions (for a review see Kööts et al., 2011), but there is a strong need to integrate these insights into the transport context.

Related to this human dimension, is the consideration of mobility and weather as embodied practises and processes. The perspective of embodiment starts from the human body in understanding how individuals experience the world and feel about themselves in this world (e.g. Merleau-Ponty, 1962; Longhurst, 1997). The relationships between weather and the human body have been examined extensively in biometeorological and medical sciences (e.g. Lambert et al., 2002; Rusticucci et al., 2002; Schneider et al., 2008). Other studies have investigated the differential embodied exposures and vulnerabilities to weather between different population categories, such as the more intense sensations of cold and hot thermal conditions amongst women (e.g Karjalainen, 2012; Kenawy and Elkadi, 2012) and older age groups (e.g. Tuomaala et al., 2013) compared to men and younger age groups. Comparison studies find different behavioural responses to similar weather conditions, such as Swedes being much more receptive to sunshine than sun-avoiding Japanese, which could be attributed to different cultural or climatologically defined preferences to weather, sun, tanning and beauty-ideal (e.g. Knez and Thorsson, 2006; Thorsson et al., 2007). Bodily exposures to weather and subsequent experiences of place and emotions during travel may also differ with regard to the chosen transport modes, trip durations and travel speeds. It may for instance be expected that environmentally exposed active transport mode users – especially cyclists who, compared to pedestrians, are subjected to additional generated winds at speed, and who have fewer options to take shelter against for instance rain or wind – are more intensely affected by weather, than users of sheltered, and often climate-controlled, motorised transport modes.

This brings us to a conceptual framework (Figure 1.6) in which *mobility* – encompassing behaviours as well as experiences – is considered with regard to the individual's background and the dynamic *spatiotemporal travel situation,* consisting of built environments, mobile objects, social environments and natural processes (including weather). As such, this thesis will consider climate and weather conditions, along with other elements of the spatiotemporal situation (i.e. spatiotemporal / trip attributes) and personal background (i.e. personal / household attributes) as independent variables. Mobility behaviours (i.e. choices for transport modes and travel frequencies, distances and durations) and mobility experiences (i.e. of weather, places and emotions) are considered as dependent variables

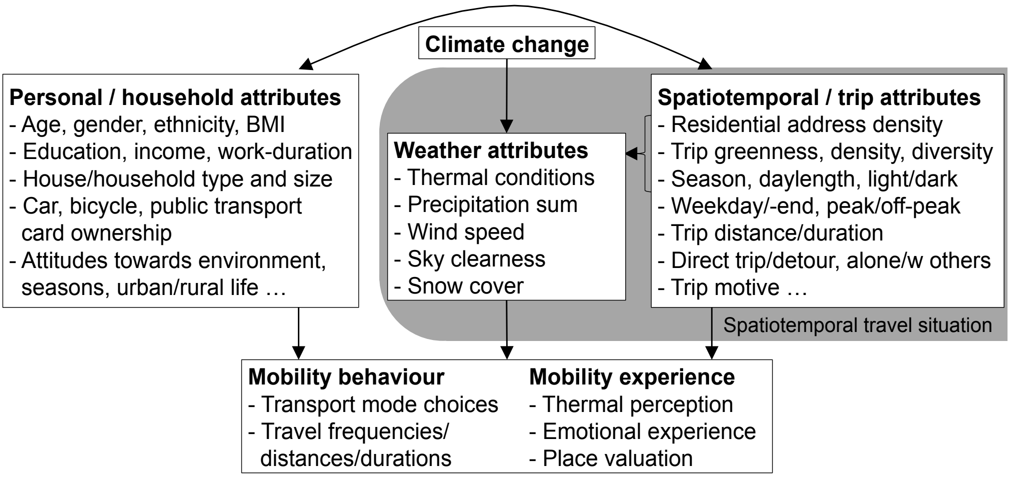

Figure 1.6 Conceptual model

1.3 Research aim and questions

With the increasing societal interest in climate change mitigation and adaptation, the effects of weather and climate on the transport sector have become more important than ever before. This is reflected in a wide range of studies on the effects of weather (mostly its extremes) on transport infrastructure performance, safety, and maintenance (e.g. Transportation Research Board, 2008). However, theoretical and empirical research is needed to further advance our knowledge on the effects of normal weather conditions, and projected changes thereof, on individual daily mobility. Therefore the aim of this research is:

To develop a comprehensive understanding of the impact of current and projected weather on mobility choices and of subjective experiences of weather, place and emotions during daily mobility in the Randstad Holland.

This aim will be addressed along the lines of the following five research questions:

1. What are the current insights and research gaps on the effects of everyday weather conditions on individual daily travel behaviour?

Before exploring the relationships between climate, weather and daily mobility empirically, a thorough investigation of the existing literature needs to be performed. With the increasing societal interest in climate change, scholars from various scientific disciplines – e.g. studies in transport, health, biometeorology, urban climatology, environmental psychology, urban planning and landscape architecture – have given insights into the relationships between weather and daily travel behaviour. Studies often link existing mobility or physical activity datasets to public weather conditions, assessing the effects of weather conditions, such as air temperature, precipitation sum, sunshine and wind speed, on transport mode choices and outdoor activities. Findings generally indicate that warm, sunny, calm and dry weather conditions stimulate outdoor activities and the use of active over motorised transport modes while cold, cloudy, wet and windy weather has opposite effects (e.g. Hanson and Hanson, 1977; Khattak and De Palma, 1997; Thorsson et al., 2007; Sabir, 2011; Flynn et al., 2012; Creemers et al., 2014). However, so far, these insights have been largely separated over the different disciplines. There is a strong need for a systematic and comprehensive review, which maps and integrate these fragmented insights. This review critically discusses the existing studies against their methodological, contextual and behavioural backgrounds. Additionally, from a cross-comparison of similar studies with different climate backgrounds, it will be investigated whether weather conditions lead to different behavioural outcomes in different climate regimes. Finally, a list of knowledge gaps and shortcomings will be identified which urgently require further research. Several of these research gaps and shortcomings will be addressed with the following four empirical research questions.

2. How will projected 2050-climate changes affect seasonal transport mode shares and travelled distances in the Randstad Holland?

While many existing studies analyse the effects of weather on travel behaviour, only a limited number of studies include in their analysis an explicit examination of the effects of future climate change projections. Two exceptions of studies that extrapolate individual weather parameter effects according to future climate change projections include: Aaheim and Hauge (2005), who find evidence for potential future reductions in Bergen (Norway) car usage (benefiting public transport and active modes) for a wetter 2030-2050 climate; and Wadud (2014), who finds a modest (0.5%) projected increase in London cycling for a slightly warmer projected 2041 climate. In contrast to these two studies, we examine with this second research question the effects of climate change on transport modes with respect to the different seasons. There are two reasons for this seasonal distinction. First, as introduced in section 1.1 of this introduction, regional climate change, especially in terms of precipitation patterns, may manifest itself differently during the different seasons. Second, in the different seasons weather changes may have a different meaning for travel behaviour. Where during winter an increase in temperatures may be beneficial to the use of active transport modes, in summer a similar increase in temperature may have a smaller or even negative effect when it may get uncomfortably hot (e.g. Phung and Rose 2008; Lewin 2011; Miranda-Moreno and Nosal, 2011; Ahmed et al., 2012).

3. How do weather conditions affect daily cycling frequencies and durations, and the exchange between cycling and other transport modes.

After establishing how and to what extent climate change may affect seasonal travel patterns overall, in a next step we zoom in to the effects of daily weather conditions on individual daily travel behaviours. The question is specifically focused on cycling. First, because cycling holds many environmental, social, accessibility, and health benefits to society. Second, because existing studies demonstrate that, of all transport mode users, the exposed cyclist appears most strongly affected by weather conditions (e.g. Sabir, 2011). These weather exposures may have an important temporal dimension. For instance one may tolerate cycling through heavy rain or cold for a very short, but not for a longer duration. In addition to its effects on mode shares and cycling frequencies, this research question therefore addresses the effects of weather on cycling durations. Most existing studies on weather and cycling analyse the singled-out effects of individual weather parameters. In reality however, weather conditions always co-occur. For instance, a cooling wind may be perceived as pleasant when it is hot, while being unpleasant when it is cold. With this third research question, we specifically address how combined weather conditions affect cycling. Hereto use is made of the thermal indices Physiological Equivalent Temperature and Mean Radiant Temperature, which combine different weather parameters – e.g. air temperature, wind speed and solar radiation – and more closely than air temperature approximate bodily experiences of thermal conditions (Mayer and Höppe 1987; Matzarakis and Mayer, 1996). Knowledge on calculating and interpreting these indices was acquired through interdisciplinary collaboration with expert meteorologists from Gothenburg, Sweden.

4. To what extent and how do weather conditions affect transport mode choices, thermal perceptions and emotional travel experiences?

In this next step we zoom into the – in section 2.2 introduced – subjective experiences of travel. This fourth research question integrates both theoretically and empirically three strands of knowledge, which have so far been largely separated over different disciplines. First, there are the earlier described transport studies assessing the effects of weather on travel behaviour. Second, thermal comfort studies have examined the relationships between objectively observed and subjectively experienced weather conditions, often reporting considerable discrepancies between the two (e.g. Nikolopoulou and Steemers, 2003; e.g. Nikolopoulou and Lykoudis, 2007; Lenzhölzer and Wulp, 2010). Third, various, mostly psychological, studies have examined the effects of weather on moods and emotions, generally indicating positive effects on moods and emotions during mild, dry, calm and sunny weather and negative effects during cold, hot, wet and cloudy weather (e.g. Albert et al., 1991; Cunningham, 1979; Schwarz and Clore, 1983; Denissen et al., 2008; Ciucci et al., 2011; Kööts et al., 2011). We integrate these three responses to weather – i.e. transport mode choice, thermal perception and emotional travel experience – into one statistical analysis and identify the mediating mechanisms between them. For instance it will be examined whether different transport mode users or population categories (i.e. based on age, gender, and ethnicity) have distinctive thermal perceptions and subsequent distinctive emotional responses to weather.

5. To what extent and how do weather conditions affect transport mode choices, thermal perceptions and en-route place valuations?

In the final step, we built forward on the integrated theoretical and empirical relationships between weather, transport modes, thermal perception, and travel experiences. However, this time with a main focus on the way different transport mode users value place while travelling under different weather conditions. Intuitively weather may play an important role in the way we perceive and value place. For instance a route through a forest may be experienced much more lively, colourful and beautiful on a sunny autumn day, than on a grey, wet and windy winter day. However, existing empirical research on the effects of weather on place perception is very limited, inconsistent, and mostly focussed on valuations of aesthetics in parks. For instance, parks are experienced as more beautiful during spring and autumn (Mambretti, 2011) and with higher air temperatures and lower wind speeds (Eliasson et al., 2007), but others found no significant effects (Knez et al., 2009). With this fifth research question we elaborate on this limited knowledge and address how weather, directly and through thermal perception, affects peoples' en-route place valuations, not only in terms of aesthetics but also with regard to liveliness and friendliness. Also, it will be investigated how and to what extent peoples' en-route place-valuations differ between different geographical contexts (i.e. in terms of greenness, density, diversity), between active and motorised transport mode users, and between different population categories.

1.4 Research design

This thesis is based on a three-stage research design: (1) a systematic literature search; (2) an analysis of existing Dutch National Travel Survey data linked to climate projections; and (3) an analysis of self-gathered Greater Rotterdam travel diary data linked to meteorological records and spatial data. This section discusses the first two stages briefly, and the third stage, because it comprises newly self-gathered data, more elaborately.

A systematic literature search forms the basis for addressing research question 1, which is the focus of chapter 2. A combination of search terms, which on the one hand includes 'weather' or 'thermal comfort' and on the other hand a variety of search terms reflecting travel behavioural aspects (e.g. 'travel', 'behaviour', 'activities', 'transport', 'cycling', 'walking', 'recreation', 'commute'), has been used to map the existing peer-reviewed and grey literature in respectively Scopus and Google Scholar. A final non-exhaustive set of 54 studies is presented in a search matrix in chapter 2. Relevant studies published after the publication data of this paper in August 2012, have been included in the introduction and/or literature sections of the chapters 3 through 6.

To answer research question 2, use is made of a Randstad Conurbation subsample of existing Dutch National Travel survey data (Mobiliteitsonderzoek Nederland – MON), datasets widely used to study the Dutch transport context, including studies with a focus on weather (e.g. Sabir 2011; Creemers et al., 2014). Advantages of using this existing data include: (1) its public availability; (2) its relatively large sample size (40,000-66,000 respondents per year, each performing several trips); and (3) the detailed account of travel behavioural patterns (e.g. transport modes, travel times, travel distances, trip purposes). Disadvantages are that the data sets: (1) were not originally designed for studying the effects of weather, hence interesting elements like whether destinations are indoors or outdoors could not be analysed; (2) provide no account of subjective travel experiences; and (3) have occasionally changed in structure and ownership over the years, which could lead to inconsistencies. Because of the latter, solely data from the period 2004-2009 has been used for being an uninterrupted period without large changes in the data or its ownership. From this period, seasons were selected which could be characterised as typical present and projected 2050 climates, and differences in travel patterns between the selected seasons were assessed. The selections were based on Royal Dutch Meteorological Institute (KNMI) climate change projections originally calculated in 2006 and revised in 2009 (KNMI, 2009). These projections were largely similar to latest 2014 Dutch climate change projections (KNMI, 2014b) sketched out at the start of this introduction. Limitations of the research design to analyse projected climate change effects from present day variations in seasonal travel patterns (discussed into more detail in chapter 3), include the dependence on limited existing climate variety within the 6-year data period, and the uncertainty in climate change as well as long-term societal trends.

Research questions, 3, 4 and 5 will be answered based on self-gathered travel diary data, enriched with weather data and spatial data. The data enrichment processes will be explained in the methods sections of the chapters 4, 5 and 6. The main reason for setting up our own fieldwork and not to pursue with analysing existing data, is to have an original dataset specifically tailored to address the relationships between climate, weather, travel behaviour and travel experience. The research consists of four phases: a questionnaire and three subsequent waves of travel diaries in summer, autumn and winter (Figure 1.7), together representing a complete range of weather conditions (see chapter 4 for an overview). The questionnaire provides a detailed account of the respondent's personal context (section 1.2), including, in addition to standard socio-demographic and household characteristics, unique information on ethnicity (including having origins in different climate regimes), health conditions (e.g. length, weight, body mass index), and personal attitudes (i.e. towards transport modes, the environment, seasonality, weather, weather forecasts, and urban versus rural lifestyles). The travel diaries (a copy is included in attachment A), in addition to standard information on travel behaviour (e.g. transport modes, departure/arrival times and locations, trip motives, etc.), provide unique information on the trip context (e.g. whether travelling direct or via a detour; or alone or in company). However, the most important addition to regular travel diaries is the inclusion of unique questions regarding respondents' subjective experiences of weather, place and emotions during travel. The direct inclusion of subjective information into travel the diary design is inspired by a methodology developed by personality and social psychologists termed Ecological Momentary Assessments (EMA) (Stone and Schiffman, 1994). The main idea behind EMA is that respondents report on perceptions or experiences (in our case of weather, place and emotions) repeatedly (in our case each trip), on-site (in our case in pen-and-paper travel diaries), and close in time of experience (in our case while travelling or directly afterwards). The main advantage of EMA is its accuracy, because it does not rely on recalled information and subsequent potential reconstructive processes (Moskowitz and Young, 2006). An additional advantage in our case is that respondents' experiences in terms of weather, place and emotions, can now directly be linked to travel behavioural choices and framed within the contexts of travel situations.

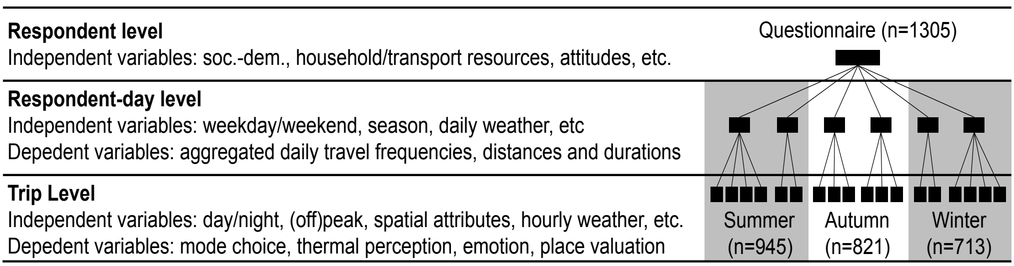

Figure 1.7 Structure of the fieldwork

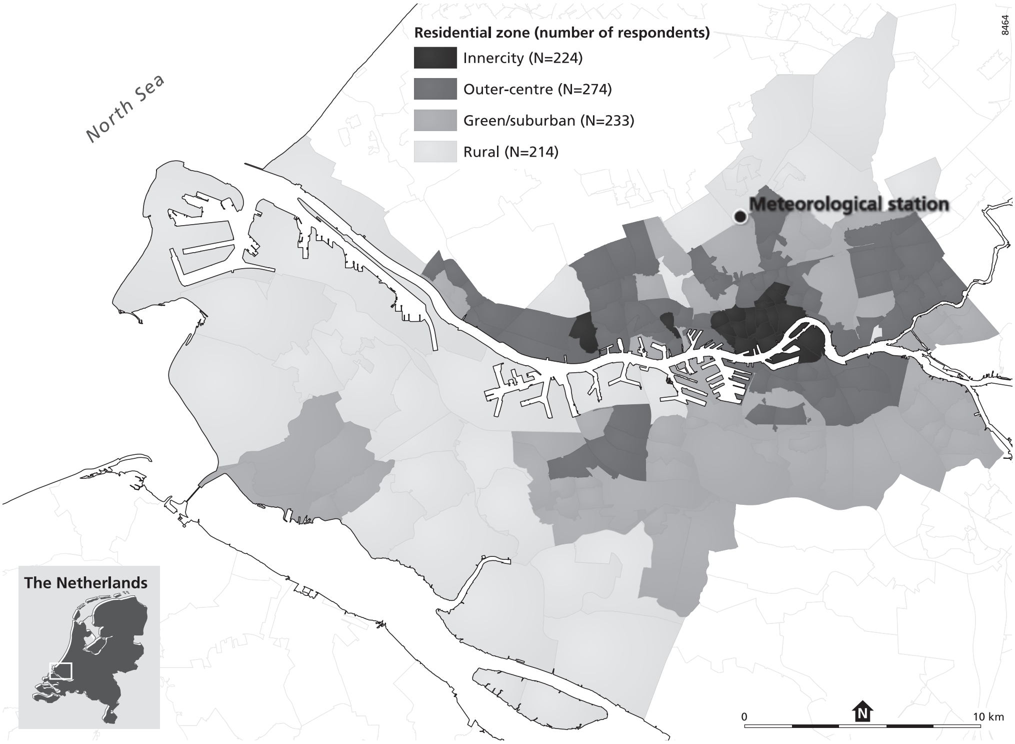

Figure 1.8 Greater Rotterdam study area

The fieldwork is situated in Greater Rotterdam, a coastal port region in the densely populated and economically viable Randstad-conurbation (Figure 1.8). The rationale for selecting Greater Rotterdam is fourfold. First, the area is characterised by rich population diversity in terms of ethnicity, age cohorts, and socio-economic status. Second, the area comprises a large diversity in built environments (i.e. ranging from modern post-World-War-II high-rise areas downtown to a mix of compact historic towns, suburban satellite towns and rural villages in its periphery). Third, with its coastal location and its temporal (Maritime) climate characterised by mild winters (average lows of 1 ˚C and highs of 6 ˚C), warm summers (average lows of 12 ˚C and highs of 21 ˚C), and relatively stable seasonal precipitation patterns (KNMI, 2013), Greater Rotterdam is subjected to a large variance in weather conditions. Finally, regional policy-makers actively promote policies on sustainable transport and climate change adaptation, which provides opportunities for knowledge dissemination. From an existing Internet panel (GFK Intomart), a final 945 respondents[1] of 18 years and older were randomly assigned 6 days to fill out their travel diaries: two in summer, two in autumn and two in winter. The sample was equally distributed over four residential environments (i.e. innercity, outer-centre, green/suburban and rural). We oversampled older age groups (≥65) and non-native Dutch to anticipate typically lower response rates for these groups (Adler et al., 2002).

1 Out of 1953 respondents who were contacted, 1305 (67% response rate) participated in the questionnaires. After dropout and filtering for reliability 945 respondents successfully completed the first wave of travel diaries (summer); 821 the second (autumn); and 713 the third (winter) (Figure 1.7). Because dropout rates appeared random rather than biased on several key socio-demographics (see chapter 4), all 945 respondents records were included.

Several multivariate statistical modelling techniques are used to answer the empirical research questions 2 through 5. In these multivariate models, the effects of weather on travel behaviours and experiences are analysed along with – and thereby controlled for – various background characteristics from the person, spatiotemporal and trip contexts. Multinomial Logit models (MNL) are used to analyse the effects on transport mode choices, while Tobit and Negative binomial models are used to analyse travel distances and trip frequencies. The latter two, in contrast to regular continuous and count data modelling techniques (such as Odds Least Squares and Poisson regression), are able to successfully handle a large number of zeros in the data, which in our case result from respondents not travelling, or not travelling with a specific mode. The research questions 4 and 5 are answered by means of Structural Equation Modelling (SEM): a modelling technique which combines factor and regression models, and which has the ability to accommodate several dependent variables, including their mediating mechanisms, into one statistical analysis. To account for the nested hierarchical structure of the data of trips, days and respondents (Figure 1.7) – all models applied to the fieldwork data make use of standard error clustering techniques to handle within-cluster dependency issues.

1.5 Thesis outline

The research presented in this thesis consists of five academic articles, which have either been published in international peer-reviewed scientific journals or have been submitted for review. As a result, some unavoidable overlap exists between the different chapters, most notably when the topic of climate, weather and transport is introduced, when relevant existing literatures are discussed, and when the study area and data are described. To minimise the overlap, some cross-references between the chapters are included, for instance when sample compositions are discussed.

Table 1.1 outlines the topics, data sources, variables, and analysis techniques used in the five academic articles, each presented in a separate chapter, and each devoted to answering one of the five research questions. Chapter 2 (RQ1), published in *Transport Reviews* (2013) presents a systematic interdisciplinary review of the existing literature, including a cross-comparison of studies from different climate regimes in search for climate patterns in travel behaviour. It identifies major research gaps, which form input for subsequent chapters. Chapter 3 (RQ2), based on the Dutch National Travel survey data, provides an analysis of seasonal climate change effects on transport mode choices and travelled distances. The article has been published in a special issue on 'Weather, Geographical Contexts and Travel Behavior' in the *Journal of Transport Geography* (2013). Chapter 4, 5 and 6 are all based on the Greater Rotterdam fieldwork. Chapter 4 (RQ3) presents the analysis of integrated daily weather conditions on cycling. The article is an outcome of international and interdisciplinary research collaboration with meteorologists and micro-climatologists from Gothenburg, Sweden. It has been published in *Weather, Climate, and Society* (2014), an interdisciplinary journal, which, like us, aims to bridge the divide between meteorology/climatology and social sciences. Chapter 5 and 6 both integrate the relationships between weather, thermal perception, transport mode choices and travel experiences in Structural Equation Models. Chapter 5 (RQ4), submitted to *Transportation Research, Part A: Policy and Practise,* has a specific focus on the effects of weather on emotions during travel. Chapter 6 (RQ5) deals with the way different transport mode users value their spatial route environments and has been submitted to a special issue on 'Geographies of Activity-Travel Behaviour' in the *Journal of Transport Geography.* The final chapter 7 reconsiders the answers to the five research questions, discusses their significances for urban and transport theory, discusses implications for adaptive urban and transport planning in the context of climate change, and draws avenues for future research.

Table 1.1 Thesis outline

Ch.	Topic and RQ's	Data sources	Indep. variables	Dep. variables	Analyses
2	- RQ1 - Review of the literature - Identification of research gaps - Identification of climate patterns in travel behaviour	- Systematic Scopus and Google Scholar search matrix	- Weather - Personal, spatial, temporal and trip contexts	- Transport modes - Travel volumes times and distances - Destination choices - Outdoor activities	- Systematic review - Findings cross-comparison
3	- RQ2 - Seasonal climate change and transport mode choices and distances	- Dutch National Travel survey (2004-2009) - Climate change projections - Weather data	- Seasonal climate projections - Personal, spatial temporal and trip contexts	- Transport mode choice (per season and motive) - Travel distance per person per day (per mode and motive)	- Multinomial Logit model - Tobit model - (SPSS and Stata)
4	- RQ3 - Integrated daily weather conditions and cycling	- Rotterdam fieldwork (Aug 2012-Feb 2013) - Weather data	- Daily weather - Personal, spatial, temporal and trip contexts	- Transport mode choice - Cycling frequency per person per day - Cycling duration per person per day	- Multinomial logit model - Negative binomial model - Tobit model - (Stata)
5	- RQ4 - Weather, thermal perceptions, transport mode choices and emotional travel experiences	- Rotterdam fieldwork (Aug 2012-Feb 2013) - Weather data - Spatial data	- Hourly weather - Personal, spatial, temporal and trip contexts	- Mode choice - Thermal perception - Emotional travel experience	- Structural Equation Model - (MPlus)
6	- RQ5 - Weather, thermal perceptions, urban form, transport mode choices and place valuations	- Rotterdam fieldwork (Aug 2012-Feb 2013) - Weather data - Spatial data	- Hourly weather - Personal, spatial, temporal and trip contexts	- Mode choice - Thermal perception - En-route place valuation	- Structural Equation Model - (Mplus)

Appendix 1A Travel diary

Table 1A.1 Copy of travel diary (translated from Dutch)

I am at a destination…

Arrival time: ……. hour …… minutes

I arrived at the following address:

- ○ home ○ other: street: ……………………………………………… nr. ………
- ○ work (regular)
- ○ study (regular) place: ………………………………………………

This address is the following type of destination:

○ home	○ at somebody else':
○ work/study	○ culture/entertainment/horeca
○ shopping (groceries etc.)	○ sportsaccomodation
○ shopping (other)	○ park/water/nature
○ service (bank/doctor…)	○ other: ………………………………

At this address I do the following:

○ domestic task	○ chauffeuring
○ work/study	○ something else (social visit / leisure)

Answer the following questions only when your destination is in the open air

I performpredominantly the following activity:
○ laying ○ sitting ○ standing ○ walking ○ sports (incl. running)

I am located predominantly: ○ in the sun ○ not in the sun
I am located predominantly: ○ in the wind ○ not in the wind

The temperatyre at this destination feels for me:

○	○	○	○	○	○	○	○	○
very cold	cold	cool	somewhat cool	com-fortable	somewhat warm	warm	hot	very hot

I am on the move…

Departure time: ...... hour ……. minutes

To reach my destination I take the following transport modes

	walking	bicycle	car	bus/tram	metro	train	other
first:	○	○	○	○	○	○	○
there after	○	○	○	○	○	○	○
there after	○	○	○	○	○	○	○
there after	○	○	○	○	○	○	○
there after	○	○	○	○	○	○	○

Fellow travellers	○ none	○ partner/kids	○ friends/family	○ other
This movement is:		○ routine	○ scheduled	○ impulsive
I chose deliberately for a detour:			○ yes	○ no
My trip is predominantly:			○ in the sun	○ out of the sun

I experience my travel surroundings predomently as:

very little green	○	○	○	○	○	very green
sheltered	○	○	○	○	○	open
beautiful	○	○	○	○	○	ugly
lively	○	○	○	○	○	boring/monotonous
very busy	○	○	○	○	○	very quiet
friendly atmosphere	○	○	○	○	○	distant atmosphere

I experience the weather during my trip predomently as:

very sunny	○	○	○	○	○	heavily clouded
very dry	○	○	○	○	○	very wet
very little wind	○	○	○	○	○	very windy

The temperatyre at this destination feels for me:

○	○	○	○	○	○	○	○	○
very cold	cold	cool	somewhat cool	com-fortable	somewhat warm	warm	hot	very hot

During my trip I feel predominantly:

sad	○	○	○	○	○	happy
anxious	○	○	○	○	○	without fear
satisfied	○	○	○	○	○	irritated
calm	○	○	○	○	○	nervous
alert	○	○	○	○	○	not alert
energetic	○	○	○	○	○	tired

2 Impact of everyday weather on individual daily travel behaviours in perspective: a literature review

Lars Böcker, Martin Dijst, and Jan Prillwitz, Utrecht University
Transport Reviews, A Transnational Transdisciplinary Journal, 33(1): 71-91,

Abstract

In the light of growing societal interest for climate change adaptation and mitigation, insights into the meaning of weather conditions for travel behaviours—particularly walking and cycling—have become very important. Recently, various studies from transport, health and biometeorological disciplines have touched upon the relevance of weather for daily activities and travel, yet a review and critical assessment of the existing knowledge are lacking. Hence, the aim of this review is first to bring together these contributions and provide a systematic and comprehensive overview concerning the impact of weather conditions on daily travel activities. Second, the methodological, contextual and behavioural backgrounds of the studies will be discussed. The major conclusion is that the existing studies present an incomplete and fragmented picture of the impact of weather on travel behaviour, which makes effective planning for climate change a harsh job. In the conclusions, some lines for future research will be recommended.

Keywords: travel behaviour; daily activities; climate change; weather; review

2.1 Introduction

By now, most scientists agree on the occurrence of climate change and the—at least partial—responsibility of human activities for these changes (Intergovernmental Panel on Climate Change [IPCC], 2007; National Research Council, 2010). Although uncertainties exist in terms of degree of change and magnitude of effects (Byatt et al., 2006; Carter et al., 2006; Stern, 2007; Tol, 2006), the changing climate will have significant effects for society. This is reported for domains such as agriculture, water management, (health) insurance (IPCC, 2007; Stern, 2007) and the attraction of tourism destinations (Amelung and Viner, 2006; Bigano et al., 2006; Hamilton et al., 2005; Matzarakis and De Freitas, 2001; Nicholls and Amelung, 2008). However, relatively little attention has been paid to the impact of climate change and changing weather patterns on the transport sector (Koetse and Rietveld, 2009). In view of the continuous exposure of transport activities to weather conditions, this is a remarkable fact.

Most studies on the relationship between climate, weather and transport focus on network performance of transportation systems, including work on accidents, disruptions, traffic speeds and maintenance costs (for reviews, see Jaroszweski, et al., 2010; Koetse and Rietveld, 2009; Transportation Research Board, 2008). For example, impacts of extreme heat, frost, storm, fog, rain and snow on rail (Chapman et al., 2008; Duinmeijer and Bouwknegt, 2004), air (Changnon, 1996; Eads et al., 2000; Krozel et al., 2011; Kulesa, 2002) and road infrastructures (Brodsky and

Hakkert, 1988; Chung, et al., 2005; Edwards, 1996; Eisenberg, 2004; Jones et al., 1991; Levine et al., 1995; Martin et al., 2000; Satterthwaite, 1976; Stern and Zehavi, 1990) have been investigated. In comparison with its effects on network performance, the effects of weather on individual travel behaviours on the micro-level—e.g. people's daily choices for outdoor and indoor activities, destinations and transport modes—received much less attention. Additionally, most studies focus on weather extremes, while less often paying attention to the effects of normal weather conditions on our everyday, often habitual, travel behaviours.

It is the challenge of this paper to map and critically discuss the knowledge on everyday weather and individual travel behaviours. We have formulated two related objectives to meet our demands. First, the aim is to supply a systematic and comprehensive overview of the existing empirical studies. Second, the studies on which this knowledge is based will be critically discussed against their methodological, contextual and behavioural backgrounds. To the authors' knowledge, no elaborative overview over impacts of weather conditions on individual daily travel behaviour exists up to date, although some reviews briefly discuss the interactions between weather and daily mode choices (Heinen et al., 2010; Koetse and Rietveld, 2009). Moreover, such an overview is relevant for the achievement of policy goals to enhance sustainable and healthy transportation via weather-exposed walking and cycling—at present, as well as in a potentially changing climate.

First, a brief overview of the main findings from the studies regarding the meaning of different weather aspects for travel activities will be provided. Second, an extensive critical review systematically evaluates the studies, their findings and shortcomings. Third, a final section discusses the review, draws conclusions on main consequences and research gaps and highlights implications for further research.

2.2 Relevance of Precipitation, Temperature and Wind for Daily Activities and Travel

For this literature review, we performed a systematic Scopus search with the following search terms: (1) 'weather' or 'thermal comfort' in title, abstract or keywords and (2) at least one term out of various travel behaviour aspects (including travel, behaviour, activities, transport, cycling, walking, recreation, commute, etc.) in title or keywords. Out of a potential 10,259 studies, we included studies analysing the effects of everyday weather conditions (not incidental weather extremes such as tornados or hurricanes) on individual everyday travel behaviour characteristics such as trip generation and choices for activities, destinations, transport modes, routes and departure times (not multi-day tourism). Studies solely analysing impacts on infrastructure maintenance, accident rates and the performance of infrastructure systems were excluded. Additionally, we performed a Google-Scholar search with similar search terms and selection criteria, to map relevant unpublished literature in this field. Eventually, a non-exhaustive set of 54 studies (Table 2.1) was selected from transportation science, geography, biometeorology and health. The following paragraphs provide an overview of findings regarding the effects of precipitation, temperature and wind.

Table 2.1. Overview of the reviewed studies

			Transportation science and geography																																				Biometeorology									Health					
			peer-reviewed literature																														grey literature							peer-rev.						grey			peer-rev.					
			Hanson & Hanson, 1977	Rose, 1986	Dwyer, 1988	Keay, 1992	Hanbali & Kuemmel, 1993	Changnon, 1996	Khattak & De Palma, 1997	De Palma & Rochat, 1999	Nankervis, 1999	Hassan & Barker, 1999	Knapp & Smithson, 2000	Bergström & Magnusson, 2003	Rietveld & Daniel, 2004	Keay & Simmonds, 2005	Maze et al., 2006	Goetzke & Rave, 2006	Kilpeläinen & Summala, 2007	Winters et al., 2007	Guo et al., 2007	Parking et al., 2008	Müller et al., 2008	Aultman-Hall et al., 2009	Datla & Sharma, 2010	Cools et al., 2010	Sabir, 2011	Miranda-Moreno & Nosal, 2011	Heinen et al., 2011	Call, 2011	Shih & Nicholls, 2011	Tang & Thakuriah, 2012	Thomas et al., 2012	Saneinejad et al., 2012	Richardson, 2000	Aaheim & Hauge, 2005	Hoffmann & O'Mahony, 2005	Burke et al., 2006	Phung & Rose, 2008	Ahmed et al., 2010	Clifton et al., 2011	Zacharias et al., 2001	Zacharias et al., 2004	Thorsson et al., 2004	Thorsson et al., 2007	Nikolopoulou & Lykoudis, 2007	Lin, 2009	Brandenburg & Amberger 2001	Brandenburg et al, 2004	Eliasson et al 2007	Cervero & Duncan, 2003	Tucker & Gilliland, 2007 (review)	McGinn et al 2007	Chan & Ryan, 2009 (review)	Spinney & Millward, 2011	Flynn et al., 2012
Meteorological attributes	measure-ment themes	objective weather	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■
		subjective weather																	■																										■	■					■				■			
		absolute weather	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■
		relative weather			■																■				■			■																												
		recorded weather	■	■	■	■	■	■			■	■	■		■	■	■	■	■	■	■	■	■	■	■		■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■
		stated weather							■	■	■			■					■							■																										■		■		
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		regional stations	■	■	■	■	■	■			■	■	■	■	■	■	■	■	■	■	■	■		■	■		■	■	■	■	■	■	■	■		■	■	■	■	■	■								■		■	■	■	■	■	■
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Mobility attributes	explained variables	modes	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■
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Precipitation

Precipitation may influence people's daily activities. A Halifax time-diary study (Spinney and Millward, 2011) reports negative precipitation effects on sports and outdoor-active-leisure and positive precipitation effects on time spend on home-based, non-active, indoor activities such as media consumption. Two extensive physical activity study reviews (Chan and Ryan, 2009; Tucker and Gilliland, 2007) confirm overall negative precipitation effects on physical activities although many of the reviewed studies—the majority of which makes use of automated measuring techniques such as accelerometers—do not distinguish between indoor and outdoor physical activities. Studies from Chicago (Dwyer, 1988) and Vienna (Brandenburg and Arnberger, 2001) analyse visits to urban recreational destinations and find lower attendances on days with higher precipitation.

Precipitation affects trip-making also. Several studies analyse precipitation effects on car traffic, using automated traffic recordings. Considerable traffic reductions are reported with snowfall for suburban/rural highways in northern US states (Call, 2011; Hanbali and Kuemmel, 1993; Knapp and Smithson, 2000; Maze et al., 2006), Alberta, anada (Datla and Sharma, 2010) and Scotland (Hassan and Barker, 1999). Car traffic reductions with rainfall are reported for Scotland (Hassan and Barker, 1999), for Melbourne mostly at weekends (Keay and Simmonds, 2005) and for Chicago in summer (Changnon, 1996).

Others analyse public-transport ridership statistics. Hofmann and O'Mahony (2005) detect slight decreases in Dublin bus usage on rainy days. For Chicago, Tang and Thakuriah (2012) find decreasing bus ridership with rain and snow, whereas Guo et al. (2007) detect decreasing ridership of bus and train. An exception is heavy snow, during which train ridership increases, indicating a switch back from car to public transport due to difficult driving conditions. In an earlier Chicago study, Rose (1986) finds no significant rain and snow impacts on transit ridership.

The above-mentioned studies conclude negative precipitation effects on trip generation by motorized transportation. In contrast, a national travel survey study from the Netherlands reports a positive relationship between precipitation and car and public-transport trip generation, resulting from large-scale switching from active (open-air) to motorized transport modes (Sabir, 2011). Similar activeto-motorized mode switching due to precipitation, although to a lesser extent, is reported by studies on mode shares from Bergen, Norway (Aaheim and Hauge, 2005) and Toronto (Saneinejad et al., 2012). Also studies from Belgium (Cools et al., 2010; Khattak and De Palma, 1997) and Geneva (De Palma and Rochat, 1999) find stated mode choice adaptations with precipitation.

As of its direct exposure to weather, many studies focus entirely on active transportation. Precipitation is mentioned as one of the most important reasons not to cycle (Bergström and Magnusson, 2003; Nankervis, 1999). Cross-sectional studies from Canada (Winters et al., 2007) and the UK (Parkin et al., 2008) reveal lower aggregated levels of cycling for areas with higher annual precipitation, although they admit other physical factors such as hilliness have larger impacts. Others conclude similar negative precipitation effects on cycling using reported cycling counts from German municipalities (Goetzke and Rave, 2011), Melbourne (Richardson, 2000) and Vermont (Flynn et al., 2012) or revealed cyclist counts from Montreal (Miranda-Moreno and Nosal, 2011), Vienna (Brandenburg et al., 2004), Melbourne (Keay, 1992; Nankervis, 1999; Phung and Rose, 2008) and the Netherlands (Thomas, et al., 2013). Two Australian studies (Keay, 1992; Phung and Rose, 2008) conclude a non-linear relationship with immediate sharp declines in bicycle counts from light precipitation, followed by more marginal reductions from heavier precipitation. Contrastingly, another Australian study (Richardson, 2000) finds few effect of light rain on cycle flows. Congruently, Nankervis (1999) discovers that light rain mainly affects clothing behaviour, whereas only heavy rain affects ridership. Remarkably, Cervero and Duncan (2003), based on household activity survey data from San Fransisco, find no precipitation effect on cycling, whereas they do find an effect on walking.

While many studies show the relevance of precipitation for trip generation, transport mode and destination choices, few analyse also the effects of precipitation on a wider array of travel decisions. Three stated adaptation studies conclude adverse weather effects on route choice and, most-profoundly, adjustment of departure times (Cools et al., 2010; De Palma and Rochat, 1999; Khattak and De Palma, 1997), indicating people anticipate on differences in expected travel times. Finally, Aaheim and Hauge (2005) find reductions in travelled distance due to precipitation, indicating people choose closer destinations and/or cancel trips to further destinations.

Precipitation does not affect travel choices in the same way in all situations. Some car traffic studies find much lower impacts of precipitation on professional (commercial) compared with ordinary personal traffic (Call, 2011), weekday compared with weekend traffic (Changnon, 1996) and peak-hour compared with offpeak traffic (Hanbali and Kuemmel, 1993). Similar temporal differentiations in relative weather impacts are found for cycling counts (Ahmed et al., 2010; Brandenburg et al., 2004). Overall, this seems to indicate a larger effect on leisure compared with utilitarian trips. This conclusion is supported by most studies measuring trip purpose directly (Sabir, 2011; Saneinejad et al., 2012). For commute trips, respondents only adapt departure times, while for shopping and leisure also mode/destination changes or trip cancelling were reported (Cools et al., 2010). A single exception is a German study by Goetzke and Rave (2011), demonstrating significant precipitation effects on cycling to work, but not on cycling for leisure.

Effects may also differ for different population categories and between different geographical contexts. Bergström and Magnusson (2003) find that Swedish women mention precipitation more often as a reason not to cycle than men. Keay (1992) detects considerable female cyclist reductions during light rain in Australia, while male cyclist reductions only occur during heavier rainfall. Chan, Ryan, and Tudor-Locke (2006) find mediating effects of gender and bodyweight for the impact of snowfall on physical activity. Khattak and De Palma (1997) report more distinct weather-related mode changes amongst people with flexible working hours. Wilcox et al. (2000) point at a role of ethnicity: women in rural areas perceive adverse weather as a stronger barrier than older and more ethnically diverse women in urban areas. Aaheim and Hauge (2005) find larger precipitation effects on mode choice in the Bergen city centre compared with the outskirts, resulting from a more exclusive weather-independent car use in suburban areas. Phung and Rose (2008) demonstrate that cycling in suburban and weather-exposed areas is more sensitive to precipitation than cycling in inner-city and sheltered areas.

Temperature

Many of the reviewed studies look at the effects of warmer/colder periods by analysing seasonality. Analysing travel-to-school mode choice in Dresden, Germany, Müller et al., (2008) find a threefold cyclist increase in summer over winter, mostly at the expense of car and public transport. Other studies report similar seasonal cycling patterns (Bergström and Magnusson, 2003; Nankervis, 1999). Additionally, people do more physical activities in summer than in winter (Chan and Ryan, 2009; Tucker and Gilliland, 2007). Contrastingly, Khattak and De Palma (1997) and De Palma and Rochat (1999) in Brussels and Geneva find no significant seasonal changes in mode choice; however, their exclusive focus on car commuters, who may not be very sensitive to weather, may be a reason for this. Apart from weather variations, seasonality affects society in different ways (i.e. the distribution of holidays) that may interfere with travel behaviours. The above-mentioned studies often acknowledge this, but do not correct for it.

Others look at temperature effects directly. Some point out that temperature effects are generally lower than precipitation effects (Cools et al., 2010; Sabir, 2011). Nevertheless, these European studies conclude that temperature has significant positive effects on walking and especially cycling, and negative effects on car and public transport. Contrastingly, some of the earlier-mentioned mainly North-American car and public-transport studies show decreasing travel volumes during colder weather (Guo et al., 2007; Shih and Nichols, 2011; Tang and Thakuriah, 2012) or especially during colder weather combined with precipitation (Datla and Sharma, 2010) or snow, low visibility and heavy wind (Maze et al., 2006). An explanation for this difference between North American and European studies, as found earlier also for precipitation, may be the lower popularity of walking and cycling in the first (Pucher, 2004).

Other studies confirm temperature effects on open-air transportation. Most of the previously discussed cyclist studies show that warmer weather increases cyclist rates (Bergström and Magnusson, 2003; Brandenburg et al., 2004; Hanson and Hanson, 1977; Keay, 1992; Nankervis, 1999; Phung and Rose, 2008; Richardson, 2000). Other studies, mostly from hotter climates, find that not only low temperatures, but also high temperatures through heat thresholds between 25 and 30 °C are disadvantageous for physical activities (Baranowski et al., 1993; Tu et al., 2004) and cycling (Ahmed et al., 2010; Keay, 1992; Phung and Rose, 2008; Richardson, 2000). In Toronto, Mirnada-Moreno and Nosal (2011) find that temperatures above 28 °C combined with high humidity, negatively affect cycling. In Montpelier, Vermont, Aultman-Hall et al. (2009) find a similar parabolic effect of temperature on the number of pedestrians.

Studies also confirm similar temperature effects on outdoors activities. Higher temperatures (up until certain heat-thresholds), especially when combined with calms, are positively associated with observed outdoor place attendances in Chicago (Dwyer, 1988), Vienna (Brandenburg and Arnberger, 2001), Montreal (Zacharias et al., 2001), San Francisco (Zacharias et al., 2004), Gothenburg (Thorsson et al., 2004), Athens (Nikolopoulou and Lykoudis, 2007), Japan (Thorsson et al., 2007) and Taiwan (Lin, 2009). Spinney and Millward (2011) show positive temperature effects on both outdoor-active-leisure and outdoor-active-sports activities in Nova Scotia. Tucker and Gilliland (2007) and Chan and Ryan (2009) in their literature reviews show positive temperature effects on physical activity levels.

Temperature effects on travel behaviour differ for trip-purposes, population categories and geographical contexts. Effects for discretionary travel purposes such as leisure are stronger than for non-discretionary trips such as commuting (Aaheim and Hauge, 2005; Sabir, 2011; Thomas et al., 2012). Additionally, Aaheim and Hauge (2005) find that for errands travelled distances are reduced with higher temperatures, whereas for recreational purposes trip distances increase. With regard to individual backgrounds, some studies stress the higher impact of heat on vulnerable population groups such as elderly (Díaz et al., 2002), although no direct link to travel behaviours is made.

Wind

Although intuitively wind plays an important role in daily travelling, compared with precipitation and temperature it is often overlooked. Guo et al. (2007) find that higher wind speeds decrease Chicago bus ridership, whereas no significant effect has been found for rail. Maze et al. (2006) find an 80% decrease in Iowa rural highway car traffic during snowy weather when combined with 40 mph wind, compared with only a 20% reduction during clear snowy weather with low-wind speeds.

Saneinejad et al. (2012) in Toronto find significant positive wind impacts on car use compared with other modes.

Most studies document wind impacts on cycling. Aaheim and Hauge (2005) find wind as a deterrent for cycling mentioned by most respondents in Bergen. In a cross-sectional comparison of Dutch municipalities Rietveld and Daniel (2004) find a weak negative correlation (20.15) between average annual wind speed and cycling. Flynn et al. (2012) in Vermont and Heinen et al. (2011) in the Netherlands find that wind negatively affects bicycle commuting. Thomas et al. (2012) in another Dutch study find negative wind effects on cycle flows. Others point at the different effects of light and strong wind. Sabir (2011) finds no changes in Dutch modal split shares for moderate wind speeds between 1 and 4 Beaufort (Bft). Only in the case of heavy wind (of approximately 5 Bft or higher), cyclist shares decreases from 30% to less than 25%, mostly increasing the share of walking. Similarly, two Australian studies (Keay, 1992; Phung and Rose, 2008) report cycling declines only for strong winds. Only one study, amongst students in Melbourne, finds no significant wind effects on cycling (Nankervis, 1999).

Physical activities other than cycling seem to be less affected by wind. Studies amongst pedestrians in Brisbane (Burke et al., 2006) and Montpelier, Vermont (Aultman-Hall et al., 2009) cannot confirm significant wind effects on walking. From the physical activity studies reviewed by Tucker and Gilliland (2007) and Chan and Ryan (2009), some find negative wind impacts on physical activities, although most did not detect significant results or did not account for wind.

A few studies point out that wind effects differ for trip purposes and personal backgrounds. In Flanders, Cools et al. (2010) report that half of their respondents mention storms as a reason to postpone or cancel shopping and leisure trips, whereas for commute trips, storms hardly lead to cancellations and changed departure times. Chan et al. (2006) identify mediating effects of bodyweight on the impact of moderate-to-heavy wind on physical activity, with lean people's activity levels being more negatively affected than obese people's.

Similarities and Dissimilarities

Results from the reviewed studies show a potential impact of weather conditions on predominantly trip generation, destination and mode choices. The presented results provide some similarities. Generally, warm and dry weather provide ideal conditions for outdoor leisure activities and active open-air transport modes, whereas rain, snow, windy and cold weather result in switches to sheltered transport modes. Most studies also agree on a higher relative impact of weather on recreational compared with utilitarian trips.

However, findings also reveal dissimilarities. First, the degree of weather impact varies widely. Some studies find strong associations, whereas others detect no significant results for all or some weather parameters. Studies contradict in view of the relative impacts of light and heavy rain on travel choices. Second, studies contradict in the direction of associations. For example, some studies mention wet and cold weather to increase car and public-transport volumes, whereas others detect decreases. Another example is heat, which in some studies is regarded as generally favourable for active transportation, while others identify threshold temperatures above which conditions become unfavourable.

Dissimilarities between studies may result from location—earlier, we mentioned travel-culture differences between America and European countries. Additionally, dissimilarities may relate to climatological differences, anticipated in the following hypotheses. Compared with temperate climates, continental climates generally have larger seasonal contrasts (hotter summers, colder winters), but smaller day-to-day weather fluctuations. Consequently, we expect larger effects from seasonality on travel behaviours in continental climates, whereas day-to-day weather effects are larger in temperate climates. Additionally, we expect physical-activity-heat-thresholds to be higher in countries with hotter summers, as more people may be used to heat.

2.3 Empirical Studies Assessed

The preceding section introduced various studies on the relationship between weather and travel. This section critically discusses studies based on: (1) their representations of meteorological attributes, including their analyses of singled-out or combined weather parameters; (2) their measuring of mobility attributes and modelling themes and (3) the climatological and global/local geographical focus of studies. Table 2.1 presents an overview.

Representation of Meteorological Attributes

Almost all reviewed studies solely make use of objective accounts of weather and correlate these with daily activities and travel behaviour (Table 2.1). It must be mentioned that various studies correlating weather with subjective interpretations of thermal comfort, emotion, affect and mood (for an overview see Kööts et al., 2011) are not included in this review, because they do not investigate behavioural responses. From all reviewed studies, only five include also subjective interpretations of weather. Three studies of urban park attendances in Sweden and Japan (Eliasson et al., 2007; Thorsson et al., 2004, 2007), one study of leisure activities in the USA (McGinn et al., 2007), and one study of driving behaviour and schedule changes amongst car drivers in Finland (Kilpeläinen and Summala, 2007) triangulate absolute weather data with subjective weather ratings. All five studies find discrepancies between objective and subjective weather data, where subjective weather ratings have a higher explanatory value for travel and activity behaviours than objective data.

Almost all reviewed studies, approach the topic solely from an absolute perspective (Table 2.1) and as such consider weather as an objectively measurable “state of the atmosphere” (Gómez-Martín, 2005, p. 572), based on its absolute characteristics “in a given place at a given time” (p. 572). Few studies view weather also relatively, identifying weather at present relative to preceding weather or succeeding weather expectations. One Chicago public-transport study (Guo et al., 2007) finds higher negative impacts of bad weather on Saturday ridership compared with Sunday. They give the potential explanation that bad Saturday weather leads to postponement of recreational trips till Sunday. Other examples illustrate the importance to situate weather effects relative to season. Dwyer (1988), explaining urban forest attendances in Chicago, correlates warm/sunny weather to increased attendances. They find much larger positive effects in spring compared with if the exact same weather conditions occur in summer. Datla and Sharma (2010) show that negative effects of adverse snowy conditions on car traffic volumes are stronger in autumn and early spring compared with during the more expected occurrence of the exact same weather conditions in mid-winter.

With regard to data collection, some analyses make use of stated preference techniques. Khattak and De Palma (1997), De Palma and Rochat (1999) and Cools et al. (2010) ask respondents to state behavioural responses to hypothetical weather conditions. Stated adaptation has the advantage that it can be conducted relatively easily and quickly with surveys, while presenting respondents all potentially interesting weather types, including extreme weather conditions. Disadvantages are possible discrepancies between respondents' stated and actual behaviours, and potentially different interpretations of the same hypothetical weather scenarios. Characterizing weather simply as 'severe', without further specification (De Palma and Rochat, 1999; Khattak and De Palma, 1997), leaves too much room for interpretation for respondents as well as for the reader.

Most studies use revealed accounts of weather (Table 2.1), based on often publically available external sources, most notably national meteorological institutes. Data are typically linked to revealed or reported travel behaviours. Hereby, behavioural and meteorological data need to be matched accurately, taking into account spatial and temporal resolutions. Random mismatches may arise when observed mobility patterns are located too far away from weather stations, especially when it comes to often highly localized precipitation. Structural mismatches may arise when observed mobility patterns occur in cities and are linked to weather data from stations typically located outside cities. According to theories on urban microclimates, considerable differences may exist between cities and the surrounding countryside with regard to temperature (Hidalgo et al., 2008; Mills, 2009; Oke, 1973, 1982; Steeneveld et al., 2011), potentially also with regard to cloud coverage (Changnon, 1992) and precipitation patterns (Shepherd et al., 2002).

With regard to temporal resolutions, reviewed studies often make use of daily weather data—often the regular format of publically available meteorological data. However, daily weather data not always reflect actual weather at the moment a trip or activity takes place. Exceptions are most biometeorological studies (Lin, 2009; Thorsson et al., 2004, 2007), which make use of their own precise meteorological measurements, and a Dutch travel survey study by Sabir (2011), which links mobility data to more accurate hourly weather data.

However, temporal matching is more complicated. Most studies look at actual weather conditions, whereas for travel decisions, people may also refer to expectations of future weather. Expectations are more important for trips planned in advance or with a long duration. Travel decisions made in the morning (i.e. taking a bicycle to work) may constrain travel behaviour later the same day (having to take the bicycle back) (Burke et al., 2006). Hanson and Hanson (1977) detect no effect of cloudiness on mode choices for short activities, whereas they do detect an effect on the daytrip to work, most likely caused by an uncertainty about possible rain during the return trip. This has implications for selecting temporal weather resolutions. These may not always reflect timeframes of travel decision-making, a problem encountered by Sabir (2011). It is difficult to uniformly advise the best time unit of analysis. Hourly (or more accurate) weather data are suggested for analysing spontaneous behaviours (such as visiting a park) or for addressing precise meteorological or physiological processes such as urban microclimates and site/time-specific weather perceptions. However, when analysing (planned or routine) day activities such as going to work, daily weather data may be preferred. If the purpose is to assess climate change effects on aggregated travel patterns, a seasonal timeframe could be chosen.

In their weather expectations, people may also refer to weather forecasts. Surprisingly, only two of all reviewed studies take into account the role of weather forecasts. In their study of car commuters in Brussels, Khattak and De Palma (1997) find no relationship between weather forecast inquiry and travel behaviour, whereas Kilpeläinen and Summala (2007), in their study amongst Finnish car drivers, detect an important role of weather forecasts for changes in travel planning. These two studies focus solely on car drivers; weather forecasts may play potentially a much larger role for open-air transportation and activities.

Weather Parameters in Isolation or in Combination

Popular and scientific literatures, as well as daily weather forecasts, often refer to the weather parameters temperature, precipitation and wind. Whereas most of the reviewed studies focus on precipitation and temperature, only some studies also analyse wind. Precipitation is covered by most transportation studies, some of the health studies, but remarkably by none of the biometeorology studies (Table 2.1). With regard to precipitation, the majority of studies look at effects of rain. In contrast to the literature on road network performances and traffic safety on a system level (see for a review Koetse and Rietveld, 2009), all but a few behavioural studies in this review (Chan and Ryan, 2009; Cools et al., 2010; Guo et al., 2007; Kilpeläinen and Summala, 2007) leave other forms of precipitation, such as snowfall, accumulated snow, hail or fog, uncovered. Other weather parameters such as sunshine, cloud cover, radiation, air pressure and humidity are also largely excluded. Here, most thermal comfort studies and some other reviewed analyses (Brandenburg et al., 2004; Chan and Ryan, 2009; Hanson and Hanson, 1977) are an exception.

In order to measure the impact of weather, most studies single out the effects of certain parameters. In reality, however, weather parameters always co-occur and their impacts and perception may very well be interrelated. An increasing wind during hot weather may be evaluated as pleasant and stimulating for walking and cycling, whereas the same increase in wind during cold weather may be perceived as highly uncomfortable, especially in combination with precipitation. A few analyses account for these interaction effects of weather parameters and evaluate their impact on travel behaviour. Nikolopoulou and Lykoudis (2007) detect a positive effect of increasing wind on attendances of a Greek seashore plaza in summer, while a negative effect is found in winter, indicating a positive association of wind as refreshing in warm temperatures and negatively as additional chill in cold temperatures. Phung and Rose (2008) find significant negative impacts of various gradations of wind under the condition of light rain (a frequently occurring combination of weather parameters) on cycling counts in Melbourne. These results put into perspective previously described marginal effects of wind in comparison with temperature and precipitation, suggesting a potentially greater importance of wind for travel behaviour.

Another way to combine weather parameters is by making use of weather types. Based on a clustering of coexisting weather conditions into commonly occurring seasonal weather types Clifton et al. (2011) innovatively represent combined weather conditions in their analysis of transport mode choices in Sydney. The analysis indicates the relevance of weather types for travel behaviour, but is unfortunately too preliminary and explorative to provide solid conclusions. Other studies combine weather parameters into composed indices. Creating combined weather scores is common practice in weather forecast broadcasts (i.e. barbeque weather grade) and can be found in scientific publications on climate and tourism (Yu et al., 2009), but is rather unique in research on daily travel behaviour. Based on researcher's intuitions Nankervis (1999) in a Melbourne cyclist study and McGinn et al. (2007) in a study of leisure-time physical activities in the USA, combine the weather parameters' temperature, wind and precipitation into a weather score. These combined weather scores show statistically significant impacts on behaviour, although in the Melbourne case just air temperature has a higher explanatory value.

Instead of subjective interpretation, some studies use objective meteorological data to compose a comprehensive weather index. Burke et al. (2006) in their study of pedestrian counts in Brisbane as well as some health studies on physical activities reviewed by Chan and Ryan (2009) analyse combined effects of temperature and humidity by using the Canadian-based HUMIDEX or its American equivalent, the Heat Index. A few other health studies utilize the wind chill factor, a combination of temperature and wind (Chan and Ryan, 2009). Phung and Rose (2008) and Ahmed et al. (2010) measure apparent temperatures, which include air-temperature and humidity as well as the chilling effect of wind. Accounting for biometeorological insights into the relationship between atmospheric conditions and physiological processes in the human body (Rusticucci et al., 2002; Schneider et al., 2008), most of the reviewed thermal comfort studies (Lin, 2009; Thorsson et al., 2004, 2007) operationalize an indicator based on the human heat balance equation. This physiological equivalent temperature (PET) integrates radiation in addition to temperature, humidity and wind, and is the most inclusive and accurate of all indicators in representing the way the human body perceives temperatures. However, the complexity of the PET makes its application on (publically) available weather data more complicated. Some analyses compare the explanatory value of the PET with (traditional) measures of air temperature and show that the PET is the better indicator in models for active transport modes (Brandenburg and Arnberger, 2001; Brandenburg et al., 2004) or attendances of urban recreational sites (Nikolopoulou and Lykoudis, 2007; Thorsson et al., 2004). Although relatively common in many health and thermal comfort studies, indicators of perceived temperatures such as the PET have hardly been used in travel behaviour research (Table 2.1).

Mobility Attributes and Modelling Themes

All reviewed studies show—either directly or indirectly—the relevance of weather conditions for the use of one or more transport modes (Table 2.1). Even studies towards physical activities or the use of outdoor recreational sites show how weather may influence being active and/or outdoors and give as such indirectly an insight into the propensity to walk or cycle. Of the studies addressing the use of transport modes directly, some address trip generation, whereas others look at mode shares, which may lead to different outcomes when, for instance, total travel demand is affected by weather conditions, especially when some of the mode shares are marginal. Remarkably, all except for two studies (De Palma and Rochat, 1999; Khattak and De Palma, 1997) look at mode choice from a 'mono-modal' perspective. In reality, however, trips are often multimodal; they frequently consist of different segments with different transport modes. Studies avoid this problem by analysing the main mode of transport only (Aaheim and Hauge, 2005; Sabir, 2011). However, from a weather perspective, the relatively short sections of waiting at or travelling to/from a bus stop, train station or even a parked car may be also relevant, since these are the moments the traveller could be exposed to the weather.

Conclusions regarding interdependencies between weather and travel behaviours other than mode choice and trip generation are much more limited. The few reviewed stated adaptation studies (Cools et al., 2010; De Palma and Rochat, 1999; Khattak and De Palma, 1997; Kilpeläinen and Summala, 2007) look at a wide range of interrelated travel choices, including transport modes, departure times, routes, destinations, distances and trip purposes. Some analyses give an insight into the role of weather for the frequencies of visits to specific recreational destinations, for example, studies towards the use of urban forests (Brandenburg and Arnberger, 2001; Brandenburg et al., 2004; Dwyer, 1988) or public squares (Eliasson et al., 2007; Lin, 2009; Thorsson et al., 2004, 2007). Weather-related differences in the use of locations may indicate that cyclists change their destinations in order to adjust routes to weather conditions based on the differential physical aspects of these routes, such as shading and shelter to wind (Ahmed et al., 2010; Phung and Rose, 2008). Finally, some studies give an insight into the relationship between weather and travelled distances (Aaheim and Hauge, 2005; Müller et al., 2008; Sabir, 2011).

As mentioned earlier, the role of independent variables, such as personal, trip and geographical characteristics, as a mediating context for the relevance of weather is poorly covered. Many studies do not gather information on personal, trip or geographical characteristics (Table 2.1), often because they are performed on an aggregated level, using observations of (automated) counts of car traffic, transit ridership, cyclists or pedestrians. Some aggregated analyses, however, do analyse the effects of independent background characteristics by indirectly linking the timing and location of trips to socio-demographics on a neighbourhood level, urban form attributes or site/time-specific leisure or commute usage. Other studies perform an analysis on the individual level in which case can be linked directly to personal and trip characteristics. However, hereby often use is made of the existing travel surveys, which are often not designed with analysing weather effects in mind. Interesting dependent or independent variables may often be uncovered, such as: ethnicity, health, lifestyles and weather attitudes; whether destinations are outdoors or indoors; or whether use is made of weather forecasts. Consequently, the majority of studies solely focus on trip purposes, typically concluding a higher weather sensitivity of recreational trips compared to utilitarian trips (Aaheim and Hauge, 2005; Hanson and Hanson, 1977; Sabir, 2011). Some studies investigate the role of multiple socio-demographic variables or geographical contexts; however, these factors are mostly used only as control variables (Aaheim and Hauge, 2005; Sabir, 2011) rather than mediating variables in the relationship between weather and travel. Hence, the potentially varying importance of weather for different population categories in different geographical contexts remains mostly unaddressed, with a few notable exceptions mentioned in the overview of the literature earlier in this paper.

Most studies make use of longitudinal mobility data collections, often from the existing survey or count data. Generally, findings in these studies reflect travel patterns precisely. However, to account for all necessary weather variances, analyses should be conducted over longer time periods; this is not always the case (Chan and Ryan, 2009; Hanson and Hanson, 1977). Other studies make use of cross-sectional comparisons between different geographical sites, combining these with site-specific annual weather data. In order to assess weather effects, it is important to have enough variance between sites. This is not always the case: for instance, Rietveld and Daniel (2004) in their cross-sectional comparison of Dutch municipalities could not address temperature effects because of a rather equal spread of temperatures over the country. Most studies make use of multivariate models in which case they either address the relative impacts of individual weather parameters or the impacts of weather parameters compared with background variables. Studies make use of a wide variety of multivariate modelling techniques, including multinomial logit regressions for mode shares and OLS, Poisson or Tobit regressions for trip generation and destination choice. With their chosen modelling techniques, studies often wrongfully assume linear relationships between weather and travel.

Study Locations

Most studies analyse travel behaviour in urban and suburban areas, whereas travel behaviours in rural areas are less extensively covered. The impacts of weather on urban and rural areas may be distinctly different. On the one hand, weather may play a more important role in rural areas due to fewer buildings and shelter options areas may be more exposed to weather. On the other hand travelling in rural areas, at least in the Western world, is more dominated by the car, which appears to be less affected by weather than other modes. On a global scale, the variance in climate regimes covered by the reviewed studies is rather limited. According to the well-known 1918 Köppen–Geiger classification (Geiger and Pohl, 1954), based on monthly averages of precipitation and temperature, five main climate regimes can be identified worldwide: equatorial, arid, temperate, continental and polar. When looked at the reviewed studies, almost the entire sample is located in North-West Europe, North-America and Australia, representing mainly temperate climates with fully humid and warm summers and continental climates with relatively cold snowy winters but either warm or hot temperatures in summer (Table 2.1). Other climate regimes such as Mediterranean versions of the temperature climate as well as entire equatorial, arid and polar climates are virtually uncovered, with the exception of studies from Greece (Nikolopoulou and Lykoudis, 2007) and Taiwan (Lin, 2009). In the light of global climate change and distinctly warmer urban microclimates, it would be particularly interesting to look at travel and activity patterns in these mainly hotter, moister or dryer climates.

Earlier we hypothesized that different climatologic backgrounds may alter the meaning of weather conditions in peoples' daily lives. For the two dominant climate regimes covered by the review, we perform a cross-comparison of studies' conclusions. When comparing seasonality studies, we find indications for our first hypothesis that seasonality is larger in continental compared with temperate climates. Studies from continental climates—including most of the North American as well as some of the North/Central European studies (Norway, Sweden and Austria)—often mention large societal impacts of cold snowy winter periods (Aaheim and Hauge, 2005; Datla and Sharma, 2010; Guo et al., 2007; Thorsson et al., 2004) in contrast to much warmer summers. Nevertheless, seasonal differences in modal split or trip generation are not more prominent than for temperate climate studies. A reason for this might be that most temperate climate studies in this review are from Western European regions with traditionally higher uses of public transport and active transport modes; those are potentially more affected by weather. When looking at studies on individual weather parameters, we can confirm our second hypothesis that in temperate climates the impacts of daily weather fluctuations on travel behaviours are larger compared with continental climates. However, it is again questionable whether this effect should be attributed to climate or societal differences.

A specifically interesting comparison can be made when looking at heat. As mentioned earlier, studies from various areas with hot summers highlight parabolic temperature effects on physical activities and travel behaviours (Nankervis, 1999; Nikolopoulou and Lykoudis, 2007; Phung and Rose, 2008). When comparing heat thresholds above which physical activities, cycling and walking reduce, at first it appears that these are more or less stable between 25 and 30 °C. Thermal comfort studies—mostly from temperate climates in Europe—generally show that the most comfortable temperatures for being outdoors range between 18 and 21° PET (Nikolopoulou and Lykoudis, 2007; Thorsson et al., 2007). In contrast, the single study in our sample from a hot-humid equatorial climate (subtropical to tropical), Taiwan, finds the most thermally comfortable temperature to vary between 21.3 and 28.5° PET. This suggests that people in a distinctly hotter climate adapt to hotter conditions in their outdoor behaviours as well as in their thermal preferences, confirming our third hypothesis that heat thresholds may be higher and hotter climates.

Climatological differences may become culturally embedded. Thorsson et al. (2007) point at differences between positive effects of hot weather conditions on attendances at sunlit parts of outdoor recreational areas in Sweden and the effects of similar weather conditions on shade-seeking in Japan. Here, contradicting results are related to climatologically and culturally defined attitudes towards heat, sun and staying outdoors in general. After a long winter, the relatively short Swedish summer is much more valued compared with the Japanese situation. Additionally, cultural attitudes towards exposure to sun in relation to beauty-ideal and tanning are very different in Asian cultures and in Europe (Knez and Thorsson, 2006; Thorsson et al., 2007). Another example of attitudes defined by climate and culture can be found in the Netherlands, where even in windy, rainy or cold weather conditions, a substantial part of the population still uses bicycles, resulting from a high degree of familiarity with a tradition of cycling and the specific weather conditions (Sabir, 2011).

2.4 Conclusion and Discussion

Worldwide, climate change ranks high on the political agenda. This has generated a series of questions from society and policy-makers to scientists, regarding issues of adaptation and mitigation. An important policy aim is the promotion of healthier and more environmentally, socially and economically sustainable transportation via walking and cycling. Because of the typical weather-exposure of these modes, an overview of effects of weather on individual often-habitual travel behaviours is crucial, particularly in view of potential climate change. It was our objective of this paper to present and to critically assess the existing knowledge in this field.

Our review allows us to draw the following conclusions. Individual weather parameters have profound impacts on travel behaviour. Warm and dry weather conditions influence outdoor leisure activities and the use of active transport modes positively. Rain, snow, windy, cold and hot weather (above 25–30°C) often result in a switch from open-air to sheltered transport modes and decrease the number of visits to outdoor destinations. Departure times, travel times and routes are also influenced by these weather parameters. Not all effects seem to be linear and equal in all situations. Impacts of weather are larger for recreational than for utilitarian trips. A cross-comparison of studies reveals differences in travel patterns and weather preferences that can—at least partially (also societal differences play a role)—be attributed to climate. Studies from continental compared with temperate climates indicate larger seasonal contrasts and smaller day-to-day weather variances that seem to work their way through in travel patterns. Limited evidence from (sub)tropical climates suggests people here may have higher heat tolerance compared to those in colder climates. Policy-makers are advised to consider changing travel demands due to climate change in infrastructure and land-use planning. Although climate change effects differ regionally and uncertainties exist, some general policy implications can be foreseen from our conclusions. In colder regions, temperature rise may favour healthy and sustainable open-air transportation and physical activities. Contrastingly, usage of these transport modes could be hindered in warm regions or seasons, when uncomfortably hot conditions occur frequently. Here, policymakers are advised to adapt land-use designs to increasing heat, especially in hotter inner-city areas (Smith and Levermore, 2008).

However, in order to give better policy guidance on travel patterns under changing weather conditions, scientific knowledge in this field should strongly be improved. The present set of reviewed studies gives a rather incomplete and fragmented impression. Several methodological, contextual and behavioural arguments can be given for this conclusion. First, most studies single out effects of precipitation, temperature and wind. In reality, however, weather parameters always co-occur, and these combinations dominate daily-life weather perceptions. Although some researchers have made attempts to make use of temperature related integrated weather indices and successfully demonstrated their significance for behavioural responses, an integrative weather type categorization, reflecting the co-occurrence of all relevant weather parameters, is still missing.

Second, most analyses are based on actual and objective weather conditions. For some of our daily activities, however, we refer to our expectations of weather and weather forecasts. Although some studies speculate or even inquire about these aspects, a detailed exploration of the role of expectations and weather forecasts for travel or activity behaviour is yet to be achieved. This also accounts for the use of subjective interpretations of weather. We explored that people's subjective interpretations of weather may be related to comfort aspects. In addition, these subjective interpretations may be linked to weather-related assessments of speed, effort, safety or aesthetics during trips. The few studies analysing subjective weather interpretations find that these factors have higher explanatory value for behavioural responses than objectively measured weather. At first glance, this finding may seem self-evident and of less use. Nevertheless, it implicates there is not just one attractive weather type, but a strong dependency on the person and the type of activities he/she is doing. Additionally, some studies demonstrate that subjective weather experiences are culturally/climatologically embedded into distinct weather preferences and responses, consequently intermediating travel outcomes for different population categories between or within countries.

Third, most of the study locations are situated in the Western world, characterized by temperate or continental climate regimes. Studied populations are almost exclusively located in urban areas, whereas the impact of weather on rural daily life is largely overlooked. However, the majority of meteorological data used in the reviewed studies were retrieved from weather stations located in rural areas, which, in the light of large microclimatological differences between and within cities and countryside, may prove problematic. Due to cultural, economic, social and demographic differences between countries and geographical settings at lower spatial scales, the mediating effects of individual characteristics, such as age, gender, health, ethnicity and work flexibility for the impact of weather on behaviour should be taken into account. This issue has hardly been addressed in the existing empirical studies.

Given the incomplete and fragmented knowledge on the impact of climate change and weather conditions on travel behaviour, we recommend a few lines for future research. First, future research should give priority to comparative studies from different climatologic and geographical contexts, but with the same methodological and data-collection techniques. To some extent, climatological aspects are already addressed in thermal comfort and health studies, but still need to be comprehensively implemented in travel behaviour research. Comparisons could also be made between the impact of weather on travel behaviours in rural, suburban and urban areas as well as between microclimate variances at street level, which may hold important implications for policies and land-use designs, specifically those aimed at sustainable accessibility and liveability of urbanized regions. In addition to comparative studies, analyses should also include in-depth case studies in—up to date virtually uncovered—Mediterranean, arid or equatorial climates, to better account for issues such as heat, drought and humidity. Studies could also try to incorporate projections of future climatologic developments into their analyses, as previously demonstrated by two of the reviewed studies (Aaheim and Hauge, 2005; Ahmed et al., 2010).

Second, future analyses should also address sufficiently people's perceptions and experiences of weather. This line of research carries various aspects. As observed, people experience not single weather parameters, but the combined and interrelated effects of weather. Future analyses should not only single out weather parameters, but also incorporate combined weather effects, for instance, through the use of weather types as explored by Clifton et al. (2011). Additionally, rather than assuming linear relationships, research may identify weather thresholds connected to people's perceptions and experiences. Finally, future studies should try to link the relationships between weather and travel behaviour to physical/mental health, moods, well-being and emotions (see, e.g. Kööts et al., 2011) and as such connect this field of knowledge to research and policies on environmental psychology, health and liveable environments.

Third, more attention should be paid to the mediating roles of personal backgrounds and socio-demographic characteristics. As pointed out earlier, perceptions and experiences of weather conditions may vary between persons of different ethnic backgrounds, lifestyles, age-cohorts, genders and health conditions, between or within countries. Understanding the meanings of these backgrounds for daily activities and travel patterns can contribute to solutions for contemporary societal problems, such as: ageing, health and (im)mobility; obesity and physical (in)activity amongst children or ethnic/cultural disintegration.

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3 Climate change impacts on mode choices and travelled distances: a comparison of present with 2050 weather conditions for the Randstad Holland

Lars Böcker, Jan Prillwitz and Martin Dijst
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Abstract

In the light of climate change, scholars from various disciplines recently addressed the role of weather conditions for travel behaviour. However, existing studies lack assessments of combinations of weather parameters and direct links to projected climate change. With this paper, we investigate potential effects of climate change on mode choice and distances travelled in the Randstad Holland. Based on approximate combinations of weather conditions projected for 2050, we select seasons from the last decade, to represent current and future climate conditions. By using data from the Dutch National Travel survey for the selected seasons, we analyse travel behaviour under 2050-climate conditions compared to travel behaviour under present climate conditions. Results show increasing usage and travelled distances for open-air transport modes in milder and wetter 2050-winters, mainly at the expense of the car, whereas in hotter summers with more extreme precipitation patterns reversed effects are observed. Year-round analyses of effects from 2050-climate conditions show a "flattening out" of seasonal differences in modal split, while for cycling mode shares and distances travelled significantly increase.

Keywords: climate change, weather, transportation, mode choice, travel distance, Netherlands

3.1 Introduction

With the increasing societal interest in climate change adaptation in addition to mitigation, studies from different disciplines have addressed the effects of weather on transportation. The majority of studies focuses on network performance and safety of road, rail and air infrastructure networks (see for reviews, e.g. Transportation Research Board, 2008; Koetse and Rietveld, 2009). Fewer studies address the relevance of weather conditions for travel and activity behaviours on an individual level (for an extensive and critical review of these studies see Böcker et al., 2013a). Additionally, studies often focus on incidental weather extremes, whereas the role of normal weather variations on habitual travel behaviours is often overlooked.

Initially, contributions focused mostly on car travel (e.g. Khattak and De Palma, 1997; De Palma and Rochat, 1999), but in the light of environmental and health issues, also active transportation attracted a great deal of interest (e.g. Nankervis, 1999; Bergström and Magnussen, 2003; Brandenburg et al., 2004; Aaheim and Hauge, 2005; Sabir, 2011). These studies, although sometimes contradicting, give useful insights into the separate roles of weather parameters – temperature, precipitation and, to a lesser extent, wind – for mode choices: Warm and dry weather stimulates choices for active open-air modes walking and cycling at the expense of the car, whereas rainy, snowy, windy, cold or extreme hot weather conditions have opposite effects. However, most studies lack an assessment of combinations of co-occurring weather parameters and an integration of projected climate change effects. Additionally, the relevance of weather for aspects of travel decisions other than mode choices, such as travelled distances, has received far less attention. Finally, climates and weather conditions differ highly between countries. As a consequence, analytical results on the impact of weather parameters on mode choices and travelled distances from studies in Australia, Norway, Switzerland and other countries do not automatically apply on countries characterised by other climate and weather attributes, like the Netherlands.

To address these shortcomings, this paper aims to assess the potential effects of climate change – focusing on average seasons, which include both normal and extreme weather conditions – on habitual seasonal travel behaviours regarding the selection of transport modes and travelled distances. The research is situated in the Dutch metropolitan Randstad region, characterised by a warm-temperate climate with warm summers, mild winters and moderate year-round precipitation patterns (Geiger and Pohl, 1954). To evaluate climate change effects, seasons from the last decade are selected to represent combinations of weather conditions normal to the climate at present and as projected for 2050 by the Dutch Meteorological Institute (KNMI, 2009). Drawing on the Dutch National Travel survey (MON), we carry out seasonal analyses of travel behaviour under 2050-climate conditions compared to travel behaviour under present-climate conditions. In this paper, we first summarize the main findings from the literature on weather and mode choice. Next we describe the data and methods, followed by a documentation of main findings on modal shifts in the perspective of projected climate change. The final section provides conclusions and discussion.

3.2 Literature

This section briefly summarizes some of the relevant literature on the role of weather parameters for transport mode choices and travelled distances. For a more comprehensive review, see Böcker et al. (2013a) on the meaning of weather for individual activity and travel behaviours.

In the field of weather influences on travel behaviour, some studies look at annual variance in mode choices and relate this to seasonal weather patterns. For example, Müller and others (2008) find seasonal variations in travel-to-school trips with shares of walking and especially cycling more than doubling in summer compared to winter at the expense of car and public transport. Other studies report similar seasonal changes in the shares of cycling (Nankervis, 1999; Bergström and Magnussen, 2003) or other physical activities (Chan and Ryan, 2009). However, seasonal patterns cannot solely be attributed to weather. As some of the respective studies pointed out but did not control for, observed patterns may also result from factors like day/night length and the distribution of holidays.

Other scholars investigate the relationship between weather and travel choices by singling out respective impacts of different weather parameters, most notably precipitation and temperature. With regard to precipitation, studies from different national contexts and amongst different transport mode user groups generally point out that precipitation increases the use of motorized transport modes – most notably the private car – at the expense of active transport modes – most notably cycling (e.g. Bergström and Magnussen, 2003; Aaheim and Hauge, 2005; Sabir, 2011). According to some scholars, the relationship between precipitation and mode choice is nonlinear;

however, related findings are contradicting: Keay (1992) and Phung and Rose (2008) find sharp declines in cycling with light precipitation, followed by lesser reductions with heavier precipitation, whereas Nankervis (1999) and Richardson (2000) document that only heavy precipitation has a negative effect on cycling. In addition to affecting mode choices, Aaheim and Hauge (2005) indicate precipitation negatively affects travelled distances. They do not specify for which modes.

In addition to precipitation, many projects investigate the relevance of temperature for mode choices. Comparison studies of relative explanatory values of weather parameters for travel behaviour changes point out that temperature generally seems to have a less distinct impact on mode choice than precipitation (Aaheim and Hauge, 2005; Cools et al., 2010; Sabir, 2011). Nevertheless, analyses in various national contexts find that higher temperatures significantly contribute to shares of active transport modes at the expense of the car and, to a lesser extent, public transport (e.g. Hanson and Hanson, 1977; Aaheim and Hauge, 2005; Sabir, 2011). Some scholars document parabolic effects of temperature, where not only low, but also high temperatures exceeding 25–30 °C thresholds, have negative effects on walking (Aultman-Hall et al., 2009) and cycling (Keay, 1992; Richardson, 2000; Phung and Rose, 2008; Ahmed et al., 2010). With respect to travelled distances, Aaheim and Hauge (2005) show negative effects of increasing temperatures on distances travelled for errands and positive effects on distances travelled for recreation, but again without specifying transport modes used.

Where almost all of the above-mentioned studies analyse weather parameters separately, Nankervis (1999) also investigates combined effects of co-occurring temperature, precipitation and wind, stressing that a combination of low or very high temperatures with precipitation and wind is most negative for cycling. The vast majority of analyses evaluate weather effects on mode choices without including a direct assessment of climate change. One notable exception is a study from Bergen, Norway (Aaheim and Hauge, 2005), which extrapolates weather effects on present-day mode choices into a projected 2030–2050 climate. Results for the Bergen city centre show a decreasing car usage under wetter and warmer future climate conditions. Active transport mode shares increase for work trips, while public transport usage increases for errands. Outside the city, climate change affects mode choices much less, mainly because of the current and future domination of car use.

From these findings it becomes clear that mode choices are clearly affected by temperature and precipitation. Based on the generally positive effect of temperature on active transport modes it may be expected that a warmer future climate will increase shares of walking and especially cycling at the expense of mostly car use. Given the nonlinearity of this effect pointed out by some studies, these increases may be larger for winters than for summers. However, with the higher relative importance of precipitation over temperature indicated by some articles, positive effects on active transport modes may be relativised in all seasons, if temperature rise is accompanied by an increase in precipitation. Whilst the literature gives indications for the effects of weather on transport modes, evidence of the effects of weather on travelled distances is mostly lacking, leaving us with the intuitive interpretation that daily distances travelled by active modes may increase when temperature and precipitation levels are suitable for walking and cycling.

3.3 Research design

Our research is set up in the Randstad Holland: a densely populated area around the four largest Dutch cities Amsterdam, Rotterdam, The Hague and Utrecht. It is the area of specific interest to the larger CESAR-project (Climate and Environmental change and Sustainable Accessibility of the Randstad) on sustainable urbanisation and accessibility in which this study is embedded (http://climateplanning.tk). Based on Randstad weather records (KNMI, 2011) and four climate change scenarios for this region with varying global temperature rise (+1 to +2 ˚C) and variations in prevailing wind patterns (KNMI, 2009), we estimate present and projected 2050 seasonal averages (Table 3.1). At present, the Randstad experiences a warm-temperate climate characterised by mild winters, warm summers and moderate, relatively stable year-round precipitation patterns. In 2050, winters will become much milder and wetter, springs will be warmer and a little wetter, summers are expected to be hotter with more rain over fewer days, and autumns will become warmer.

Table 3.1 Randstad climate statistics for the available seasons

	Winter[a]			Spring			Summer			Autumn		
	Temp. in ˚C	Precip. days[b]	Precip. in mm	Temp. in ˚C	Precip. days[b]	Precip. in mm	Temp. in ˚C	# Wet days[b]	Precip. in mm	Temp. in ˚C	Precip. days[b]	Precip. in mm
Present	3.3	49	191	8.9	45	171	16.6	41	200	10.2	50	230
2050 (range)	4.2 to 5.6	49 to 50	199 to 218	9.8 to 11.5	43 to 45	173 to 182	17.5 to 19.4	33 to 40	162 to 212	11.1 to 12.9	45 to 50	217 to 244
2004	*Incomplete travel survey*[c]			9.5	32	106	17.0	54	319	10.9	51	186
2005	**3.6**	**50**	**173**	**9.8**	**57**	**167**	16.9	46	306	***12.0***	***43***	***217***
2006	2.8	41	130	9.1	53	234	***18.5***	***38***	***214***	13.6	42	210
2007	6.7	57	246	11.7	30	223	17.2	53	293	10.3	49	187
2008	***5.1***	***47***	***212***	***10.2***	***49***	***159***	17.3	54	280	**10.2**	**50**	**282**
2009	2.2	43	133	10.8	39	133	**17.4**	**43**	**207**	*Incomplete travel survey*[d]		

Selected seasons representing present climate are presented in **bold** and those representing 2050 climate in ***bold italics***
Source: Based on KNMI weather records for Randstad weather station De Bilt (KNMI, 2011)
a Winter consists of January and February of the indicated year plus December of the preceding year
b Number of days with ≥0.1mm of precipitation
c Travel survey data for December 2003 is lacking, as we have only data from January 2004 onwards
d Data from October 2009 onwards are lacking in the Dutch National Travel Survey

In order to analyse climate change effects on habitual travel patterns, we select entire seasons from the period 2004–2009 (the period for which we have survey data available) with (a) weather conditions that are in line with today's climate, and (b) currently unusual seasons with weather conditions projected to be normal in 2050 (KNMI, 2009). Selected seasons (Table 3.1) represent patterns in temperature and precipitation as accurately as possible. To address both amount and distribution of precipitation, we include total seasonal sums as well as numbers of precipitation-days (≥0.1 mm). For temperature, seasons with temperatures at the higher end of the projected 2050-bandwidth are preferred, as underlying climate scenarios for these are more likely to occur (KNMI, 2009). Winter 2004/2005, spring 2005, summer 2009 and autumn 2008 represent the present-day climate year. Winter 2007/2008, spring 2008, summer 2006 and autumn 2005 represent 2050. For the spring and summer selections, precipitation is ranked higher than temperature as of its higher importance for mode choices detected from the literature (Aaheim and Hauge, 2005; Cools et al., 2010; Sabir, 2011). Hence for the present climate, warmer-than-average spring 2005 and summer 2009 are preferred over colder-but-too-wet 2006 (spring) and 2005 (summer), whereas for 2050 colder-than-projected spring 2008 is preferred over warmer-but-too-wet (2007) or -too-dry (2009) alternatives. To test robustness, we performed a sensitivity analysis in which we analyse the effects for above-mentioned alternative spring and summer seasons.

Trip-based mobility patterns for the selected seasons are analysed from Dutch National Travel Survey data (Mobiliteitsonderzoek Nederland) from 2004 till 2009 – a dataset used in earlier research (e.g. Sabir et al., 2011). The annual number of respondents varies from around 66,000 in 2004 to 40,000 in 2009. From a sub-sample of participants living in the Randstad region with the age of 18 years and older, we select heads of households and their partners only. We analyse trip-based mode choices and the number of kilometres travelled per person per day for four different transport modes: car, public transport (train, bus, tram, metro), walking and cycling. Other transport modes (mopeds, motorcycles, etc.) have been excluded from the analyses.

In the multivariate part of our study, we analyse the marginal effects of climate change on mode choice and travelled distances as well as its relative contribution compared to other variables. Hereto a climate change dummy variable has been computed that compares the representative 2050-climate year to the representative present-climate year. Climate change effects on travel are analysed along with other individual, household, trip and spatiotemporal attributes listed in Figure 3.1. This in order to verify whether climate change significantly affects travel even when corrected for these various determinants and to assess its relative contribution.

To investigate determinants for mode choices, we use a multinomial LOGIT model. This model is similar to binary logistic regression, except for that it allows for a categorical variable with not just two, but more alternatives. The utility a person derives from each alternative is calculated for each case. Based on the assumption of utility maximisation, for each case the alternative with the highest utility is selected as the alternative that is most likely chosen by the individual. Reference category is the car. From a policy point of view, we are specifically interested into what extent the private car may substitute, or be substituted by, more environmentally friendly transport alternatives under projected climate change.

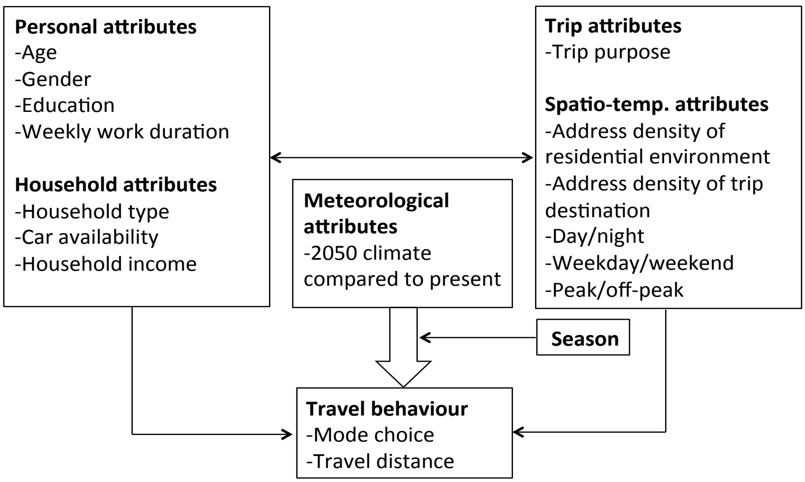

Figure 3.1 Overview of all variables used in the analysis

For travelled distances we look at travelled kilometres per person per day, in total and per transport mode. We are aware that by looking at daily travelled distances we analyse a combination of how far and how often people travel (with a certain mode) and that we cannot analytically distinguish between the two. Nevertheless, we analyse daily distances rather than trip distances, because we are specifically interested in this indicator from a societal point of view: Daily personal car kilometres are relevant for road planning and environmental issues, whereas bicycle or walking kilometres are interesting for bicycle or pedestrian infrastructure planning and an estimation of health benefits.

For our analysis of daily travelled distances, use is made of a TOBIT model. Trip distance cannot be negative and shows excess of zeros – resulting from the fact that many respondents may not use a specific transport mode on a day. A standard OLS-regression would not perform well under these circumstances. It would predict non-existing negative values and it would analyse all observed values in the same way, whereas in reality the observed zeros result from a different underlying behavioural mechanism (i.e. not travelling at all, rather than travelling a very short distance). A TOBIT model is therefore preferred (Greene, 1997). It introduces a latent (unobservable) dependent variable that, similar to OLS, is predicted by a set of independent variables via their respective coefficients. The model runs under the condition that whenever this latent variable is positive, the observed variable is equalled to the latent variable. Otherwise the observed variable is equalled to zero. Likewise, the model statistically differentiates between the two underlying behavioural mechanisms.

3.4 Climate change, mode choices and travelled distances

3.4.1 Descriptive results

Figure 3.2 presents trip-based seasonal modal splits of heads of households and their partners in the Dutch Randstad for a present and 2050-climate. In both scenarios, people use the car for the majority of trips. However, active transport modes of walking and – well known for the Netherlands – cycling also have considerable shares, especially in comparison to non-European Western countries such as the US and Canada (Pucher, 2004). Under present climate conditions, mode shares of the car are considerably higher in winter compared to summer, whereas for active transport modes and especially cycling, a reversed picture can be observed. This is in line with existing research, documenting the attractiveness of summer over winter (e.g. Bergström and Magnussen, 2003; Müller et al., 2008) and warmer over colder weather (e.g. Aaheim and Hauge, 2005; Sabir, 2011) for active transport modes.

Under projected 2050-climate conditions, these explicit seasonal modal split variations seem to slightly level out (see Figure 3.2). As climate change effects in Figure 3.3 demonstrate, attractiveness of active (especially cycling) over non-active transport modes (especially the car) increases in winter, but decreases in summer. Warmer 2050 winters seem to positively affect active transport modes, outweighing a potential negative effect of increasing precipitation. This is different from previous findings, given the dominance of precipitation over temperature in explanatory value for travel behaviour found in the literature (Aaheim and Hauge, 2005; Cools et al., 2010; Sabir, 2011). In contrast to winter, hotter summers, with potential negative effects of increased heavy precipitation, show a decreasing use of active transport modes. Another explanation are the potentially too warm weather conditions for walking and cycling. The shoulder seasons spring and autumn show shifts within rather than between using active and non-active transport modes. As a result of the contrary seasonal effects, net annual shifts in mode shares due to climate change are relatively low. Nevertheless, an overall positive effect on cycling at the expense of car use can be observed.

Compared to trip-based mode shares, the respective shares of daily distances travelled by active modes are rather small (Figure 3.4), resulting from a typical use of active modes for shorter distances. However, seasonal patterns of active mode shares are roughly similar, with longer distances covered in summer and shorter distances in winter. The picture for mode shares of the car is slightly different. Under present climate conditions, car distances are not lowest in summer, but in autumn. Distance-based mode shares for public transport are also considerable, with largest shares in winter and autumn.

In view of climate change effects on distances (Figure 3.5), winter patterns are largely similar to observed effects on trip-based mode shares: walking and cycling distances increase at the expense of non-active modes, particularly public transport. For changes in summer, contradicting patterns can be detected: while trip-based shares of non-open-air transportation increase, distance-based shares decrease. Changes in distances travelled by active transport modes differ, with a slightly increasing share of cycling distances and decreasing walking distances. For the shoulder seasons, shifts within rather than between openand non-open-air transportation seem to take place: in spring, distance shares for public transport and walking go up at the expense of car and cycling; in autumn, a large increase in distance share of the car at the expense of public transport can be detected. In all seasons, but especially in autumn, absolute shifts in mode shares due to climate change effects are much more prominent for non-open-air than for open-air transport modes, potentially stemming from the dominance of larger distances travelled by non-open-air modes. Over all seasons combined, the net climate change effect on mode shares in terms of travelled distances seems to be not very pronounced.

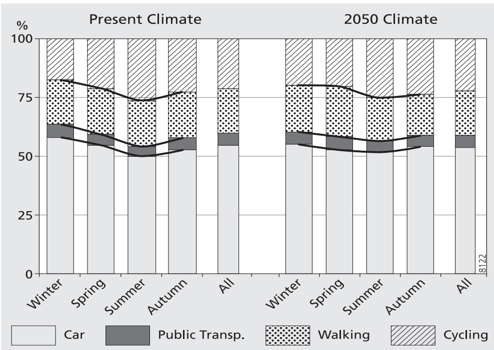

Figure 3.2 Descriptives of seasonal modal split at present and in 2050

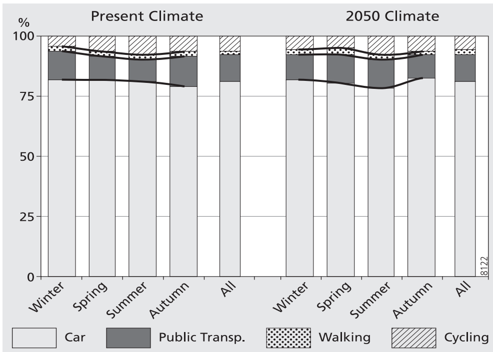

Figure 3.4 Descriptives of daily distance shares travel-led by different modes for present and 2050

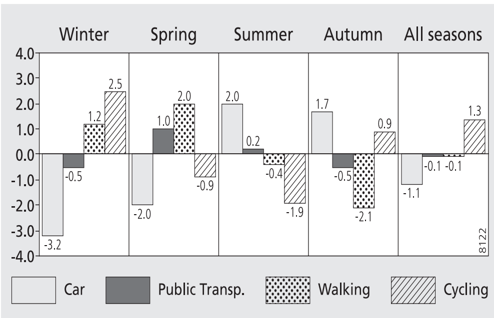

Figure 3.3 Descriptives of absolute seasonal modal split changes due to climate change

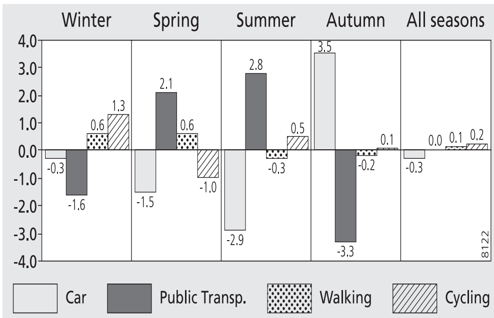

Figure 3.5 Descriptives of absolute daily distance share changes due to climate change

3.4.2 Multivariate analysis

Mode choice

Table 3.2 presents a summary of climate change effects on transport mode choices, based on five multinomial LOGIT models – one full-year model and one for each season. Not displayed in Table 3.2, the underlying complete models also incorporate the other independent variables (see Appendix A for a complete model example). Verification indicates that the effects of these socio-demographic, household, trip and urban form characteristics on mode choices are in line with existing research (e.g. Hanson, 1982; Seskin and Cervero, 1996; Dieleman et al., 2002). For the effects of climate change, the multinomial LOGIT models in Table 3.2 can be interpreted as follows. Signs in front of estimated regression coefficients (B) indicate whether climate change leads to an increase or decrease in the probability a transport mode is used compared to the car. Statistically significant effects are marked with star signs. Odds ratios show the probability a transport mode is used (compared to the car) in a future climate. When the odds of selecting a certain transport mode in 2050 are equal to the odds of selecting it at present the odds ratio is 1 (1:1), hence no effect of climate change is observed. The closer to zero, the lower is the probability a transport mode is chosen in a 2050 climate compared to present. The higher the odds-ratio, the higher is this probability.

Table 3.2 Summary of multinomial LOGIT models on seasonal climate change effects on mode choice

	Climate change effects on mode choice (ref. = car)					
	Walking		Cycling		Public transport	
	B	OR	B	OR	B	OR
Winter	.180 ***	1.198	.256 ***	1.292	.181 *	1.199
Spring	.154 **	1.166	.027	1.027	.414 ***	1.512
Summer	-.082	.922	-.166 ***	.847	-.138	.871
Autumn	-.271 ***	.762	-.085	.918	-.233 **	.792
All seasons	.006	1.006	.073 ***	1.075	.024	1.025
Modal quality: Pseudo R^2 (McFadden) .172 (winter); .169 (spring); .151 (summer); .163 (Autumn); .157 (all seasons)						

*p<0.10; **p<0.05; ***p<0.01
B = Estimated regression coefficient
OR = Odds ratio for selecting mode compared to the reference category car

For winter, the projected 2050-changes in climatologic conditions have significant positive effects on mode choices for walking, cycling (both with a 99% confidence level) and public transport (with 90% confidence) in reference to the car (Table 3.2). In comparison to the representative winter season for the contemporary climate, the season representing 2050 showed a substantial temperature rise from 3.6 °C to 5.1 °C and a modest total precipitation rise from 173 to 212 mm over slightly fewer wet days (50 compared to 47, see Table 3.1). Apparently, this leads to a higher attractiveness of the open-air modes walking and cycling, mostly at the expense of car usage.

For spring, significant positive climate change effects can be identified on public transport (with 99% confidence) and walking (with 95% significance) in reference to the car. The effect on cycling is positive, but not significant. Also in spring, car use seems to become less attractive; however, positive effects on walking and especially cycling seems to be less pronounced than in winter. Like in winter, the increase in walking and cycling seems to be a consequence of the modest temperature rise from 9.8 °C to 10.2 °C, while precipitation remained rather stable (167–159 mm), although falling over a smaller number of days. As mentioned earlier, a sensitivity analysis has been performed to analyse three alternatively selected season combinations which better match projected temperature rise but were not selected because of being too wet or too dry. First, when changing present-spring from 2005 to colder/ wetter 2006, analysed future-compared-to-present temperatures increase while precipitation decreases. As a result, no changes take place for public transport and cycling, but remarkably the positive effect on walking is no longer significant. A potential explanation is that in the original analysis we measured a considerable drop in number of wet days (beneficiary for walking and cycling), whereas in alternative 1 this drop in wet days (and consequently the positive effect on walking and cycling) is smaller. Second, when changing 2050-spring from 2008 to the warmer 2007 with more precipitation over fewer wet days, the positive effect on cycling (non-significant in the original analysis) becomes highly significant. Third, when changing to the warmer/dryer 2009, the positive effect on cycling becomes highly significantly as well, while the positive effect on public transport looses its significance. It seems that warmer 2050 spring temperatures, especially when combined with less precipitation and fewer wet days, are more positive for cycling in reference to the car and public transport.

In summer, identified shifts in mode choice are mainly opposed to changes observed for winter. The models show a significant negative climate change effect on cycling (with 99% confidence) and non-significant negative effects on walking and public transport, all in reference to car usage. To put these figures in perspective: in summer we analyse increasing temperature from 17.4 °C to 18.5 °C and slightly increasing precipitation from 207 to 214 mm over a smaller number of days (from 43 to 38). In contrast to winter, temperature rise in summer leads to a significant decrease in cycling and public transport and an increase in car usage. In contrast to our descriptive findings, multivariate results document a higher decrease in cycling compared to walking. This may be related to the greater opportunities pedestrians have to protect themselves against direct sun by walking in the shade or in covered and acclimatised areas. Also for summer a sensitivity analysis has been performed. Substituting the hotter-than-average 2009 present-summer by milder/wetter 2005, analysed future-compared-to-present-temperatures increase while precipitation decreases. As a result, the negative effect on cycling looses its (strong) significance, while the negative effect on public transport becomes significant. Compared to the original analysis, conditions are clearly less negative for cycling. Nevertheless, when looked at the alternative in itself, even under decreasing precipitation, it appears that climate change effects on cycling in reference to the car are still not positive. This indicates a potential negative effect of heat.

For autumn, negative significant climate change effects on trip-based mode choice are detected for walking (with 99% confidence) and public transport use (with 95% confidence) in comparison to car use. For cycling, although the sign is negative, no significant result can be observed. Compared to the contemporary season, the 2050-autumn is characterised by an increase in temperature from 10.2 °C to 12.0 °C and a precipitation decrease from 282 mm to 217 mm over fewer days (from 50 to 43). Observed reductions in active transport mode usage (at least significant for walking) are surprising in view of increasing temperatures and decreasing precipitation, since both changes in conditions are expected to enhance active transport modes according to the literature. A hypothesis could be that on sunny and dry days people prefer to visit natural and recreational areas at a large, non walkable or cycleable distance and poorly accessible by public transport modes.

Over the course of a whole year, climate change effects are generally less pronounced than in the separate seasons. This is the result of positive and negative seasonal effects levelling out each other and it indicates the relevance of analysing climate change on a seasonal level. Nevertheless, it seems that climate change year-round has a clear significant positive impact on cycling (with a confidence level of 99%) and positive, but insignificant impacts on walking and public transport, all in reference to the car. These results are in line with the descriptives.

Travelled distances

Table 3.3 presents a summary of climate change effects on daily travelled distances, based on twenty TOBIT models (one per mode for each season and for the full year). Again, not displayed are the underlying complete models that include the other independent variables (see Appendix B for a complete model example) – the effects of which are largely in line with the mode choice models as well as with existing research (e.g. Seskin and Cervero, 1996; Dieleman et al., 2002). Table 3.3 can be interpreted as follows: signs in front of the beta coefficients indicate whether a climate in 2050 compared to at present, increases or decreases daily distances travelled with the respective transport modes. The beta coefficients themselves can be interpreted somewhat similarly to OLS regression, with the exception that the linear effect is on the unobserved latent variable, not the observed outcome. They should be interpreted as a combination of two processes: the change in distance travelled and the change in the probability of using a certain mode at all. Due to the use of separate models, coefficients cannot be compared across modes.

Table 3.3 Summary of TOBIT models on seasonal climate change effects on travelled distances

	Climate change effects on distance travelled per person per day for different modes							
	Walking		Cycling		Public Transport		Car	
	Coeff.	S.E.	Coeff.	S.E.	Coeff.	S.E.	Coeff.	S.E.
Winter	2.448**	1.124	6.035**	2.893	-40.243	29.534	-32.126**	13.593
Spring	1.050	1.235	-9.756**	4.250	45.357	35.932	-28.583*	16.736
Summer	-1.194	1.199	-0.702	3.771	-6.572	38.873	13.766	15.771
Autumn	-2.368**	1.102	1.052	3.406	-48.803	32.712	48.954***	16.249
All seasons	-0.206	0.562	3.692**	1.736	-25.437	16.301	-4.463	7.440
Model quality: Pseudo R^2's (McKelvey-Zavoina) range from .066 to .096 for walking; .066 to .121 for cycling; .192 to .253 for public transport; and .233 to .274 for the car								

*p<0.10; **p<0.05; ***p<0.01
Coeff. = Beta coefficient
S.E. = Standard Errors

When compared to the effects on mode choice (Table 3.2), climate change effects on travelled distances (Table 3.3) provide a somewhat comparable picture. Nevertheless some differences exist, both in terms of directions of impact and significance levels. In line with the effects on mode choice, milder but wetter 2050 winters show significant increases in travel distances for walking and cycling (both with 95% confidence) and decreases for travel distances by car (significant with 95% confidence). Also public transport distances decrease, although non-significantly, whereas earlier a positive effect was found in the usage of public transport compared to the car. It seems likely that this mode is used when, due to precipitation, walking and cycling have become less attractive transport modes.

Results for spring show a negative significant effect on daily cycling distances (with 95% confidence) and distances covered by car (with 90% confidence), whereas walking and public transport distances are positively but non-significantly influenced (Table 3.3). As in winter, under slightly warmer 2050 spring conditions the car looses attractiveness in number of trips and in travelled distances. The increase in mode choice for walking and public transport (Table 3.2) is also reflected in travelled distances. This is not the case for cycling. Compared to pedestrians, it is expected that cyclists experience larger inconvenience while cycling during precipitation. Not only is the direct impact of precipitation larger due to higher speeds; cyclists also lack sufficient opportunities (e.g. umbrellas, shelters) to protect themselves satisfactorily.

In summer, no significant effects on travelled distances can be detected from the increase in heat and more extreme distribution of precipitation. Nevertheless, the direction of effects is in line with the rising attractiveness of the car found earlier in Table 3.2. Increasing distances travelled by car are met by decreasing distances travelled by other modes. In comparison with the other transport modes, the car offers good opportunities for protection against rain and heat while travelling.

In autumn, a similar pattern arises as from mode choice models. Under warmer and overall slightly dryer autumn conditions, significantly shorter distances travelled by foot (with 95% confidence) and longer distances travelled by car (with 99% confidence) can be observed, while effects on cycling (positive) and public transport (negative) distances are non-significant. Except for cycling, the results are similar as for summer.

As for mode choices, year-round climate change effects on travelled distances are less pronounced than for the individual seasons. But again, also here a positive significant impact on daily distances travelled by bicycle can be identified. For all other modes effects are negative but non-significant. Positive effects on cycling distances in the overall warmer and wetter 2050 climate are more pronounced than found earlier in the descriptives (Figure 3.3).

3.5 Conclusions and discussion

The aim of this paper is to assess potential climate change effects on people's decisions for transport modes and travelled distances. In contrast with most existing studies on weather and mode choices, we analyse not only trip-based mode choices, but also daily distances travelled with these modes. This gives a more complete understanding of the impacts on travel demand. In order to assess climate change effects, we compare habitual travel behaviour under a mix of normal and extreme weather conditions as projected for 2050 to that at present. Hereto, we look on a seasonal level at combinations of temperature and precipitation, both in terms of averages and distributions. After controlling for various socio-demographic, household, trip and spatial/temporal characteristics, we find evidence for the relevance of climate change effects on mode choices and distances travelled in the Dutch metropolitan Randstad region. Although effects have been observed for all transport modes, it seems that some are more climate-sensitive than others. In general, climate change is especially relevant for switches between the active open-air modes, walking and cycling, and the non-active non-open-air modes, private car and public transport.

Multivariate analyses demonstrate that 2050 climate change in the Randstad Holland has positive effects on choices for cycling (significant) and walking and public transport (both non-significant) at the cost of car usage. Daily distances travelled decrease for all modes (non-significant) except for cycling (significant increase). However, these general results hide large seasonal variances. A projected milder and slightly wetter 2050-winter shows an increase in usage of active open-air transport modes, both in terms of number of trips and travelled distances, whereas usage of especially the car, is reduced. In contrast, the hotter 2050-summer with more intense precipitation and drought shows a decreasing usage of active transport modes, both in of number of trips and travelled distances, contributing mostly to significant higher car use levels. These results are in line with previous research, documenting strong positive temperature effects on active transport modes under cold conditions and weak positive, or even negative, effects under warm or hot conditions (Phung and Rose, 2008; Nankervis, 1999; Aultman-Hall et al., 2009). In addition to a potential negative effect of heat, more voluminous precipitation in the 2050-scenario may also lower attractiveness of walking and cycling in summers. The car seems to be an ideal 'travel coat' for protection against rain and other precipitation but offers often as well private climate control to create a preferred microclimate while travelling.

Although not all signs are significant, the shoulder seasons show in general results in line with those of the preceding season. As in winter, in spring the active transport modes and public transport are more often chosen for a trip than the private car. The same is applicable to daily travelled distances, except for cycling, which shows as for car driving a decrease compared to the present spring. It seems that cyclists experience less opportunities to protect themselves against precipitation. Pedestrians can easily use an umbrella or choose for larger stores or covered shopping areas. They also could opt for public transport for reaching their destination. As in summer, in autumn walking, cycling and public transport are less often chosen compared to the private car and show relatively small daily travelled distance. Only daily distance for cycling will be (non-significantly) increased in the year 2050.

For 2050, a net increase in cycling distances and the attractiveness of cycling compared to car use can be observed. Depending on the degree of change, this might be good news for policy-makers who would like to stimulate environmental, social, health and accessibility benefits for society. However, they should be aware of important seasonal differences. Winter seems to become a season in which active modes will be used more often than now. However, hotter 2050-summers with heavier precipitation at times, will become increasingly the seasons in which active modes will lose ground to the private car. Ceteris paribus, this might have a negative impact on air quality in cities and could lead to more congestion on roads.

In this paper we predict climate change effects on 2050-mobility patterns. This comes with some uncertainties. First, variability exists between presently analysed seasons and projected climate change trajectories. This uncertainty is addressed, through the selection of seasons representing weather patterns within or nearby climate bandwidths projected by four climate scenarios (KNMI, 2009), complemented by a sensitivity analysis for differently selected alternative seasons. Alternatives show some clearly different travel outcomes, which – although logically explained by weather differences – indicate clear significant sensitivity and hence the need to interpret results carefully. Second, in the course of several decades, mobility trajectories may alter significantly, because of societal changes (i.e. global energy prices, economic recession/ growth, demographic transition and technological advancements, for instance in ICT's). Results in this paper, although corrected for various background characteristics, should be interpreted carefully as additional effects of projected weather changes rather than absolute mobility outcomes.

In this paper we aimed specifically at analysing trends in habitual travel behaviours for the general population over the course of entire seasons. Future research could further specify this topic into a few directions: First, in addition to analysing entire seasons, research may address behavioural responses to specific future climate days – a hot dry summer day, a summer storm, a typical mild winter day. Such analysis could also be focused more on the effects of weather extremes on travel behaviours or to the effects of these extremes on people's conceptions of climate change. Second, research could address whether climate change has different effects for the (im)mobility of different population categories, by looking at mediating effects of personal or geographical backgrounds. Additionally, comparable studies are recommended based on surveys from other countries in different climate regimes, as well as from countries in similar climates regimes but with different geographical/cultural backgrounds. Finally, further research may address how climate change not only affects mode choice and travelled distances, but also other interrelated travel decisions such as destination choices.

Acknowledgements

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Appendix 3A Full mode choice model

Table 3A.1 Multinomial LOGIT model for mode choice for all seasons

	Multinomial LOGIT model for mode choice per trip (ref. = car)					
	Walking		Cycling		Public transport	
	B	OR	B	OR	B	OR
Intercept	-.264 **		1.380 ***		-.140	
Age (ref.=30-49)						
18-29	-.166 ***	.847	-.283 ***	.753	.188 **	1.207
50-64	.189 ***	1.208	.165 ***	1.180	.151 **	1.163
65-75	.289 ***	1.335	.216 ***	1.241	.157	1.169
75+	.164 **	1.179	-.460 ***	.631	.241 *	1.273
Male (ref.=female)	-.128 ***	.880	-.119 ***	.888	-.163 ***	.849
Education (ref.= higher)						
lower education	-.078 **	.925	-.268 ***	.765	-.472 ***	.624
middle education	-.002	.998	-.167 ***	.846	-.268 ***	.765
Work duration (ref. <12h/w)						
>30 hours/week	-.490 ***	.612	-.614 ***	.541	-.378 ***	.685
12-30 hours/week	-.304 ***	.738	-.190 ***	.827	-.431 ***	.650
Household type (ref. = fam. 2 workers)						
family 1 or no worker	.130 *	1.139	-.139 **	.870	.198	1.219
couple 1 worker	-.188 **	.829	-.496 ***	.609	-.100	.905
couple 2 workers	-.036	.965	-.259 ***	.772	.278 ***	1.320
couple no worker	-.497 ***	.608	-.639 ***	.528	-.218	.804
single and worker	-.053	.948	-.257 ***	.773	.274 **	1.315
single no worker	-.240 **	.787	-.634 ***	.530	.300 *	1.350
other	.004	1.004	-.100 **	.904	.442 ***	1.555
Household annual income (ref. <15.000)						
15.000 to 30.000 euros	.092	1.096	.261 ***	1.299	.101	1.106
30.000 euros or more	.011	1.011	.133 **	1.143	.192 *	1.212
unknown	.148 **	1.159	.198 ***	1.219	.208 *	1.231
Car availability (ref. = no car)						
2 cars or more	-2.748 ***	.064	-3.193 ***	.041	-4.499 ***	.011
1 car and main driver	-2.401 ***	.091	-2.575 ***	.076	-3.587 ***	.028
1 car. not main driver	-1.815 ***	.163	-1.745 ***	.175	-2.371 ***	.093
Trip purpose (ref. = work/study)						
errands/shopping	1.311 ***	3.709	.364 ***	1.439	-.957 ***	.384
visiting family/friends	.488 ***	1.629	-.262 ***	.769	-.778 ***	.459
leisure	2.297 ***	9.943	.596 ***	1.814	-.309 ***	.734
Geographical context						
address density residence	.112 ***	1.119	.056 ***	1.057	-.030 **	.971
address density destination	.037 ***	1.038	.009	1.010	.332 ***	1.394
Temporal context						
weekday (ref. = weekend)	.261 ***	1.299	.370 ***	1.448	.140 *	1.150
night (ref. = day)	-.031	.969	-.379 ***	.685	.114 *	1.121
peak (ref. = off-peak)	-.123 **	.884	.282 ***	1.326	.912 ***	2.489
Climate change						
2050 climate (ref. = current)	.006	1.006	.073 ***	1.075	.024	1.025
Model quality: Pseudo R^2 (McFadden) = 0.157						

*p<0.10; **p<0.05; ***p<0. 01
B = Estimated regression coefficient
OR = Odds ratio for selecting mode compared to the reference category car

Appendix 3B Full travel distance model

Table 3B.1 TOBIT model on determinants of travel distance for all seasons

	TOBIT models on travelled distance per person per day in 0.1km for different modes[a]							
	Walking		Cycling		Public Transport		Car	
	Coeff.	S.E.	Coeff.	S.E.	Coeff.	S.E.	Coeff.	S.E.
Constant	-1.989	1.864	10.191	5.723	-663.284 ***	56.048	-519.716 ***	27.571
Age (ref.=30-49)								
18-29	-3.556 ***	1.173	-12.223 ***	3.593	93.783 ***	27.910	-5.159	14.954
50-64	2.726 ***	.840	7.779 ***	2.543	26.625	22.745	-40.703 ***	10.832
65-75	3.924 ***	1.300	3.315	4.064	-10.751	41.111	-73.808 ***	18.291
75+	3.315 **	1.473	-33.232 ***	4.939	-75.557	46.088	-62.001 ***	21.824
Gender (ref.=female)								
male	-1.909 ***	.665	.893	2.053	-20.081	18.389	49.463 ***	8.911
Education (ref.= higher)								
lower education	-4.187 ***	.781	-18.277 ***	2.389	-243.461 ***	23.060	-49.394 ***	10.143
middle education	-1.771 **	.739	-12.983 ***	2.264	-119.774 ***	20.371	-37.790 ***	9.502
Work duration (ref. <12h/w)								
>30 hours/week	-11.652 ***	1.059	-23.370 ***	3.248	209.427 ***	32.515	144.998 ***	14.174
12-30 hours/week	-6.554 ***	1.129	-1.841	3.418	61.898 *	35.464	52.243 ***	15.310
Household type (ref.= family. 2 workers)								
family 1 or no worker	.413	1.483	-14.081 ***	4.555	19.850	45.118	-1.047	18.945
couple 1 worker	-1.844	1.478	-19.071 ***	4.508	-.704	44.048	106.818 ***	18.832
couple 2 workers	-1.079	1.131	-14.600 ***	3.402	69.605 **	31.083	42.881 ***	13.814
couple no worker	-2.907 *	1.607	-23.007 ***	4.933	-29.899	51.038	117.671 ***	21.653
single and worker	-.275	1.376	-11.355 ***	4.123	72.107	36.543	73.196 ***	17.748
single no worker	-.269	1.811	-28.403 ***	5.697	100.151	54.283	129.499 ***	25.936
other	-1.230	1.108	-4.700	3.267	93.874 ***	32.037	-3.454	13.718
Household income (ref.<15,000)								
15,000 to 29,999 euros	.469	1.142	13.991 ***	3.714	-27.613	32.973	-11.467	17.571
30,000 euros or more	1.173	1.191	12.167 ***	3.859	31.959	34.583	9.165	17.867
unknown	-.208	1.242	8.135 **	4.029	-2.926	35.844	-51.235 **	18.835
Car ownership (ref.=no car)								
2 cars or more	-11.415 ***	1.111	-71.176 ***	3.496	-782.662 ***	33.823	737.295 ***	18.712
1 car and main driver	-8.365 ***	.927	-40.067 ***	2.909	-587.588 ***	26.332	612.946 ***	16.951
1 car. not main driver	-6.165 ***	1.088	-18.740 ***	3.342	-335.332 ***	28.434	459.175 ***	18.975
Geogr./temp. context								
address density residence	1.078 ***	.173	-1.192 **	.553	30.358 ***	4.483	-23.986 ***	2.576
weekend	-6.035 ***	.628	11.021 ***	2.025	178.042 ***	20.673	-51.785 ***	8.435
Climate change								
2050 climate (ref.=current)	-.206	.562	3.692 **	1.736	-25.437	16.301	-4.463	7.440
Model summary								
Likelihood ratio Chi^2	901***		953***		1738***		4056***	
Ps.R^2 (McKelvey-Zavoina)	.070		.072		.205		.247	

*p<0.10; **p<0.05; ***p<0.01
Coeff. = Beta coefficient
S.E. = Standard Errors
[a] Most independent background variables are included as predictors in the TOBIT models, except for trip-level variables that cannot be defined on the daily level (i.e. trip purpose, peak-hour and destination address density

4 Integrated Weather Effects on Cycling Shares, Frequencies, and Durations in Rotterdam, the Netherlands

Lars Böcker, Utrecht University, and Sofia Thorsson, Gothenburg University
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Abstract

With the increasing societal interest in climate change, health, accessibility, and liveability and subsequent policy aims to promote active transport modes over car usage, many scholars have investigated the relationship between weather and cycling. Existing studies, however, hardly address the effects of weather on cycling durations and often lack assessments of the combined effects of different meteorological variables and potential nonlinearity of these effects. Drawing on travel diary data from a panel study of 945 Greater Rotterdam respondents (the Netherlands), this paper investigates and compares the effects of different meteorological variables, singly as well as combined, on cycling frequencies, cycling durations, and the exchange between cycling and other transport modes. Results show linear negative effects of precipitation sum and wind speed and nonlinear bell-shaped effects of thermal variables on cycling and opposite effects on car usage. Out of three thermal variables investigated, mean radiant temperature (radiant heat exchange between humans and the environment) and physiological equivalent temperature (an index combining the effects of air temperature, mean radiant temperature, air humidity, and wind speed) better explain cycling behavior than just air temperature. Optimum thermal conditions for cycling were found on days with maximum air temperatures around 24°C, mean radiant temperatures around 52°C, and physiological equivalent temperatures around 30°C. Policy and planning implications are highlighted that could reduce cyclists' exposures to disadvantageous weather conditions such as heat, precipitation, and wind, at present and in a potentially changing climate.

Keywords: Weather, transportation, cycling, mean radiant temperature (T_{mrt}), Physiological Equivalent Temperature (PET), Rotterdam (Netherlands)

4.1 Background

Recently, scholars and policy makers have shown increasing interest in climate change adaptation and mitigation. Although large uncertainties and regional variations exist, climate changes (i.e., overall warmer temperatures and changes in precipitation patterns) have been projected and can already be observed today (e.g., Stocker et al., 2013). These weather changes are expected to have an impact on daily lives, especially those aspects that take place outdoors. One sector that may be particularly affected is the transportation sector (Koetse and Rietveld 2009). Of particular interest are the effects on cycling, which provide large societal benefits in terms of CO2 emission reduction and improved accessibility, liveability, and health. Intuitively, cycling should be highly affected by weather due to cyclists' direct exposure. Yet, despite many recent contributions, scientific knowledge about this relationship is still somewhat limited.

Existing studies demonstrate the effects of daily weather [exceptions include, e.g., Sabir (2011), Tin Tin et al. (2012), and Gebhart and Noland (2013), who analyze weather also on an hourly level] on a wide range of travel behaviors, including transport mode choices, trip generation, and to a lesser extent distances traveled [for detailed literature reviews, see Koetse and Rietveld (2009), Heinen et al. (2010), and Böcker et al. (2013a)]. Findings generally indicate that warm sunny or dry weather enhances walking and cycling, while cold, wet, or windy weather has the opposite effects—the effects typically being larger for recreational than for utilitarian purposes (e.g., Hanson and Hanson 1977; Nankervis 1999; Bergström and Magnusson 2003; Aaheim and Hauge 2005; Gallop et al., 2012; Sabir 2011; Flynn et al., 2012; Sears et al., 2012; Thomas et al., 2013). In contrast, studies pay less attention to time spent traveling. However, the effects of weather may be inherently related to time. People may tolerate traveling in the open air during weather conditions like heat, cold, or heavy rain for a short period of time, but may not want to expose themselves for too long.

Studies on weather and travel behavior show two important meteorological shortcomings. First, studies often assume linear weather effects on travel behaviors, whereas in reality these effects may be nonlinear through optimums or thresholds. However, some recent studies demonstrate that not only lower but also high temperatures may negatively affect cycling, for instance above air temperatures of 24°C in Portland (Ahmed et al., 2012), 28°C in Melbourne (Phung and Rose 2008) and Montreal (Miranda-Moreno and Nosal 2011), and 32.2°C in Boulder, Colorado (Lewin 2011). Second, except for a few studies demonstrating the effects of weather on cycling using weather ratings (e.g., Nankervis 1999) or thermal indices (e.g., Brandenburg and Arnberger 2001; Brandenburg et al., 2004), weather and climate change are solely described and discussed in terms of absolute values and trends—in either averages or extremes—of individual meteorological variables, such as air temperature, wind speed, radiation, or precipitation. However, in order to evaluate the impact of weather on people's thermal comfort, health, and well-being, as well as travel behaviors, it is necessary to analyze the combined effects (e.g., Thorsson et al., 2011; Böcker et al., 2013a).

To address these shortcomings in this paper we analyze and compare the impact of precipitation and the single as well as combined (via the physiological equivalent temperature index) impacts of air temperature, mean radiant temperature (radiant heat exchange between humans and environment), air humidity, and wind speed on cycling frequencies, time spent cycling, and the exchange between cycling and other transport modes. This work results from interdisciplinary research collaboration between transportation and climatology scientists with the ambition to integrate and expand on knowledge about the complex link between weather and cycling. This knowledge could be used to give guidance on how to plan and design sustainable, healthy, accessible, and attractive urban areas at present and in a changing climate.

4.2 Data and methods

Selected for this study was the greater Rotterdam area situated on the west coast of the Netherlands. The area is part of the Randstad, the densely populated economic heart of the Netherlands. Typical for the Netherlands, cycling shares are relatively large (around 20%). The region is characterized by a warm-temperate (maritime) climate (Geiger and Pohl 1954) with mild winters (average lows of 1°C and highs of 6°C), warm summers (average lows of 12°C and highs of 21°C), and relatively stable year-round precipitation patterns (KNMI 2013). The rationale for selecting Rotterdam is threefold. First, it is a metropolitan region with a wide variety of population categories (see section 4.2.2). Second, it offers a wide variety of high-density as well as lower-density residential environments (Figure 4.1). Third, the region demonstrates an active policy on sustainable transportation and climate change adaptation.

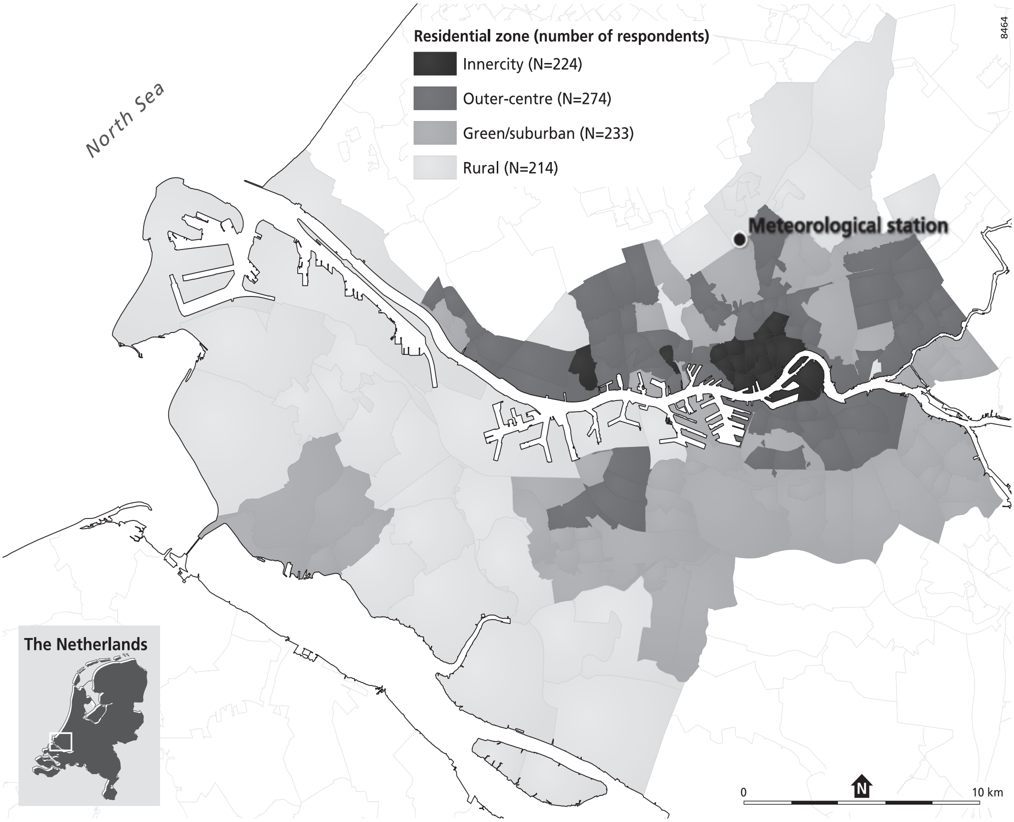


Figure 4.1: Greater Rotterdam study area

4.2.1 Meteorological attributes

Hourly meteorological data (air temperature, air humidity, wind speed, global radiation, and precipitation) for greater Rotterdam were obtained from the Dutch Meteorological Institute (KNMI 2013) from August 2012 through February 2013. The meteorological station is located at the northern edge of Rotterdam (51°57'N, 4°27'E) approximately 20 km from the sea (Figure 4.1). Figure 4.2 describes observed daily maximum air temperature $T_{a(max)}$, average wind speed $W_{s(avg)}$, precipitation sum $P_{(sum)}$, and the occurrence of snow cover on the ground during the study period, along with normal air temperatures for the period 1980–2010. After a wet July month (not included in this research), warmer-than-average sunny weather occurred in late August [with a peak in $T_{a(max)}$ of 34°C; 10°C above average] as well as early September and late October. After a warmer and much wetter than average December month, mid-January provided unusually cold winter weather (up to 10°C below average) with continuous snow cover and frost even during daytime.

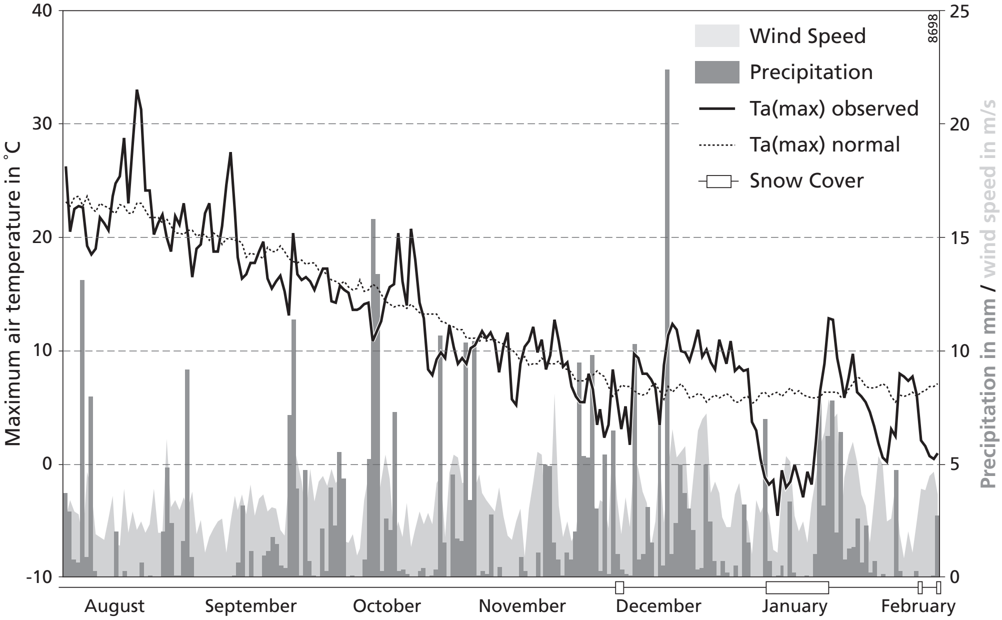


Figure 4.2 Rotterdam weather conditions during survey period. Source: Based on KNMI (2013) publically available weather data

Key: $T_{a(max)}$, observed = observed daily maximum air temperature; $T_{a(max)}$, 1980-2010 = daily maximum air temperature averages for the period 1980-2010

Weather effects on mobility were analyzed using daily meteorological variables aggregated from hourly meteorological data over the 18-h period between 0600 LT and 2400 LT, the time interval in which the majority of mobility takes place (LT is local time). The reason for using daily over hourly variables is threefold. First, some of our analyses (cycling frequencies and total cycling durations) can only be analyzed on the daily level. For uniformity, interpretability, and model comparison it is preferred to also perform the other analyses on the daily level. Second, transport mode choices are often made on the daily rather than instantaneous level. For instance, when deciding in the morning to take the bicycle to work, one probably also keeps in mind the predicted weather later that day when returning home. Third, usage of daily aggregates will allow for better comparison with existing studies, as well as better compatibility with climate change projections. We are aware that weather characteristics aggregated over the course of a day may not always correctly describe the weather experienced at a specific moment. For mode choices, we also tested an analysis with weather variables on the hourly level. This hourly model revealed the same picture and performed roughly the same; hence the daily level model was preferred.

For $W_{s(avg)}$ the daily average (in m s^{-1}) was aggregated; for $P_{(sum)}$ the daily sum is in [2]millimeters. Thermal conditions were investigated using daily maximums rather than averages because these

2 For precipitation we also analyzed the effects of precipitation duration, but in the end total sum was preferred because of better performance in the models.

better describe the type of day. For instance, a clear day with cold (at night) and hot conditions (during the day) may result in a similar temperature average as a cloudy day with mild conditions at night as well as during the day. Thermal conditions were analyzed in three ways: by means of maximum daily *air temperature* [$T_{a(max)}$], *mean radiant temperature* [$T_{mrt(max)}$] and *physiological equivalent temperature* [$PET_{(max)}$].

Mean radiant temperature (T_{mrt}) is one of the most important meteorological variables governing the human energy balance and outdoor thermal comfort (heat load), especially during warm and sunny days (Mayer and Höppe 1987). It is a sum of the exposure to all shortwave and longwave radiation fluxes (direct, diffuse, reflected, and emitted) in a given surrounding area. The value of T_{mrt} is directly influenced by the surface geometry (buildings, vegetation, and topography) and surface materials, which also makes it a good measure to identify built geometries causing increased risks. Compared to T_a, T_{mrt} shows large spatial variations over a short distance during the day (e.g., Thorsson et al., 2011; Lindberg and Grimmond 2011a). The calculation of T_{mrt} was done using SOLWEIG1D (Lindberg 2012), a subversion of SOLWEIG version 2.3 (Lindberg et al., 2008; Lindberg and Grimmond 2011b). SOLWEIG1D calculates the T_{mrt} for a person residing in a specific site (point) and requires observation data on air temperature, air humidity, and solar radiation (global and diffuse components). In addition, geographical information (latitude, longitude, and height above sea level) and information about surface characteristics (sky view factor, albedo, and emissivity) along with information about the proportion of radiation received by the human body in each direction (angular factors) and absorption coefficients for shortwave and longwave radiation are needed. In this study the T_{mrt} was calculated for a person standing/walking in a constantly sun-exposed environment with a sky view factor (SVF) of 0.6 (selected to represent the general SVF for the area). Angular factors were set to 0.22 for radiation fluxes from the four cardinal points (east, west, north, and south) and 0.06 for radiation fluxes from above and below. Standard values of absorption coefficients for shortwave and longwave radiation were used (i.e., 0.7 and 0.97, respectively) (Höppe 1992; VDI 1998). Albedo and emissivity for buildings and vegetation were set to 0.20 and 0.95, respectively according to Oke (1987). For detailed equations and model validation, see Lindberg et al. (2008) and Lindberg and Grimmond (2011b).

Mayer and Höppe's (1987) physiological equivalent temperature index quantifies the combined effect of T_a, W_s, T_{mrt}, and air humidity. A PET value of, for instance, 30°C means that the human body perceives the combined outdoor thermal conditions as a fictive indoor environment with an air temperature of 30°C (Mayer and Höppe 1987). In calculating the PET, characteristics of human beings are set as constants: 80 Watts for internal heat production, 0.9 clo (1 clo = 0.155 m^2 °C W^{-1}) for clothing heat transfer resistance. PET values between 18° and 23°C indicate comfortable conditions. Higher (lower) values indicate increasing probability of heat (cold) stress (Matzarakis and Mayer 1996).

4.2.2 Mobility attributes and modelling techniques

This research draws on travel diary data from a panel study among 945 Greater Rotterdam residents, who were selected with the assistance of a questionnaire agency from an existing Internet panel. Respondents aged 18 years and older were randomly selected from four different types of residential environments in the greater Rotterdam area: inner city, outer center, green/suburban, and rural (see Figure 4.1). We oversampled for non-native Dutch originating from hotter climates (mainly Surinamese, Dutch-Antillean, Indonesian, Turkish, and Moroccan) and older age groups (aged 65 or higher) because of generally lower response rates for these groups in research (Adler et al., 2002), as well as to account for specific weather preferences (e.g., potentially lower heat or heavy wind tolerances among elderly or higher heat tolerances for ethnic groups originating from hotter climates).

Respondents were assigned randomly to six sample days—two in summer (August–September), two in autumn (October–November), and two in winter (December– February)—in which they completed records of all their travel and destination activities. As a result, all days during the data period were covered, with the single exception of the Christmas holiday. Records were only registered during periods that were typically regular working weeks for the respondent, including weekends but excluding holidays. Extra diaries were distributed during hot summer days and cold (snow covered) winter days in order to obtain sufficient response numbers during these interesting but rarely occurring weather extremes. Sample attrition was 13.1% between waves 1 and 2 and 13.0% between waves 2 and 3 and appeared to be random rather than biased when various key socio-demographics were considered. For this reason we also included in our final sample respondents who only completed one or two seasons. Table 1 specifies the composition of the final sample of 945 respondents after cleaning the data for unreliable records and records featuring trips outside the Netherlands subject to different weather conditions. Generally the sample is well balanced with substantial shares for various socio-demographic groups. Additionally, the sample is reasonably representative when compared to the general population in this region, with the exception of lower educated and non-native Dutch being somewhat underrepresented, which is quite typical for Internet surveys (Adler et al., 2002).

Table 4.1: Sample composition and representativeness

		Sample (N=945)	Population [a]
Gender	Male	49.2%	49.2%
	Female	50.8%	50.8%
Age	18-25	8.7%	12.6% [b]
	25-45	33.4%	28.2%
	45-65	42.9%	27.1%
	65-80	13.9%	10.9%
	>80	1.2%	4.1%
Ethnicity	Native Dutch	89.6%	69.2%
	Non-native Dutch	10.4%	30.8%
Education	Higher	35.3%	8% [c]
	Average	35.9%	20% [c]
	Lower	28.1%	72% [c]
	Unknown	0.6%	0% [c]
Household composition and size	Family with child(ren) < age 5	8.4%	-
	Family with child(ren) aged 5-12	9.4%	-
	Dual-earner couple	12.6%	-
	Single-earner couple	7.7%	-
	Non-working couple	12.2%	-
	Working single	16.3%	-
	Non-working single	11.2%	-
	Other (incl. single parent)	22.2%	-
	Average household size	2.37	2.15
Net monthly household income	<2000€	29.5%	-
	€2000-€3000	24.0%	-
	€3000-€4000	19.0%	-
	>€4000	11.1%	-
	Unknown	16.3%	-
	Average in euros	-	€2767

a) Total 2010 population statistics for the Rotterdam Rijnmond COROP region (Source: CBS, 2013)
b) The 12.6% in the total population is aged 15-25 instead of 18-25
c) Statistic for the entire Netherlands population
(-) Data not (publically) available

Our multivariate analysis considered the marginal effects of weather on mode choices, cycling frequencies, and cycling durations, as well as its relative contribution compared to various background variables. These include classical individual and household background variables (e.g., age, gender, income, etc.), spatiotemporal attributes (e.g., residential environment, weekend/weekday, time of the day, etc.), and attitudes that may intermediate the role of weather effects on mobility (e.g., favorite season, environmental concern, and whether a person is more urban or countryside oriented). These are listed in Figure 4.3. Mode choices are analyzed on the trip level, while cycling frequencies and durations are analyzed per person per day. The trip-level attributes of trip purpose and type, as well as the spatiotemporal attributes related to time of the day, are only included in the trip-level mode choice analysis. All other attributes are included in all three analyses.

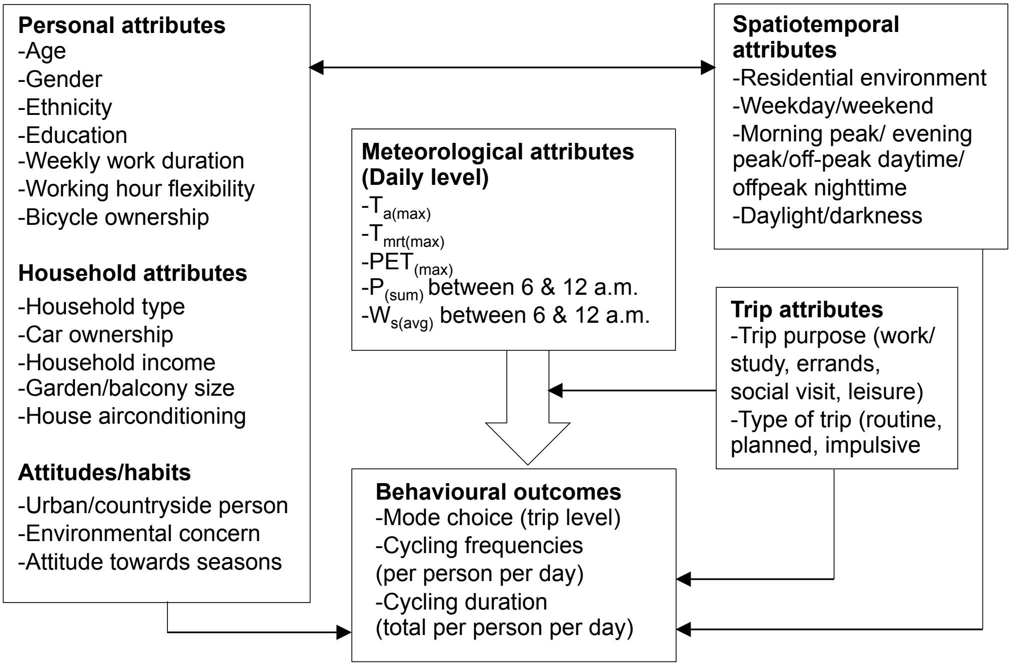
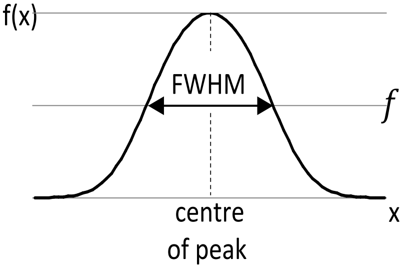


Figure 4.3 Overview of all variables used in the models

Key: $T_{a(max)}$ = maximum daily air temperature; $T_{mrt(max)}$ = maximum daily mean radiant temperature; PET = maximum daily Physiological Equivalent Temperature; $W_{s(avg)}$ = daily average wind speed; $P_{(sum)}$ = daily precipitation sum

To test the effects of weather on mode choices a multinomial LOGIT model was used. This model, based on utility maximization, is similar to binary logistic regression, except that it allows a categorical variable with more than two alternatives. The reference category is the car, allowing for comparison with earlier studies. For daily cycling frequencies and durations, negative binomial and TOBIT models (respectively) were used. These were preferred over standard Poisson (count data) and ordinary least squares (OLS) (interval/ratio data) regression, as they better handle the dependent variables' absence of negative values and excess of zeros due to people not making cycling trips on a day (Cameron and Trivedi 1998; Greene 1997). Because this is a panel study and each respondent performs several trips during several days, trips performed by one respondent may not be strictly independent. To relax the usual requirement of independent observations, all statistical analyses in this paper were performed with the Stata software package "vce-cluster" command (clustered by respondent ID). The estimation of equal robust standard errors per respondent corrects for intragroup correlation (Wooldridge 2002).

For all analyses we estimated separate models for the different trip purposes of work, errands, social visits, and leisure, because existing literature indicates that the weather effects are smaller for utilitarian trips than for leisure (e.g., Aaheim and Hauge 2005; Sabir 2011). However for the overview and focus of the paper these separate trip purpose models will not be presented but only discussed in text. Additionally separate models were estimated for $T_{a(max)}$, $T_{mrt(max)}$ and $PET_{(max)}$, which because of multicolinearity (Pearson r $T_{a(max)}$, $T_{mrt(max)}$ = 0.81; $T_{a(max)}$, $PET_{(max)}$ = 0.96; $T_{mrt(max)}$, $PET_{(max)}$ = 0.90) are analysed one at a time. Finally, to check for potential nonlinear effects, for each of the three thermal variables, we estimated models in two different ways: untransformed (describing a linear relationship) and transformed (describing a bell-shaped relationship). To model the bell-shaped effect, use is made of a Gaussian function (see Figure 4.4), in which *f(x)* indicates the transformed thermal variable as a function of its original, a is the position of the center of the peak (optimal thermal condition for cycling), and b is the full width at half maximum (FWHM) (see Figure 4.4). For each model, various values for a and b were tested until a maximum model log likelihood was reached.



$$f(x) = e^{\frac{-(x-a)^2}{2\left(b/\sqrt{8\ln 2}\right)^2}}$$

Figure 4.4: Gaussian function

4.3 Results

4.3.1 Weather and cycling: Descriptive results

Figures 5, 6, and 7 provide schematic descriptive overviews of the effects of weather on mode choices and cycling frequencies and durations, calculated for the full Greater Rotterdam sample (all trip purposes combined). The modal splits in Figure 4.5 show that, overall, around half of all trips are made by car. As is typical for the Netherlands, cycling also has considerable shares (around 20%). Weather conditions generally seem to have a clear effect on mode choices. Of all transport modes, cycling appears to be the most sensitive to weather.

The three thermal variables have an initially positive effect on cycling shares until a certain thermal optimum. Thereafter the effect is negative. This is congruent with the—sometimes described as parabolic (e.g., Phung and Rose 2008)—effect of T_a on cycling, often indicated but less often empirically demonstrated in the literature. Cycling shares seem to peak on days with $T_{a(max)}$ values between 20° and 25°C, $T_{mrt(max)}$ values between 55°and 60°C, and $PET_{(max)}$ values between

23° and 29°C, which according to the literature should be classified as "slightly warm" (Matzarakis and Mayer 1996). Note that here we refer to maximum temperatures. Cycling in the morning or evening those days may occur during more comfortable thermal conditions. Where cycling peaks, a dip in car usage is observed and to a lesser extent walking, while public transport is affected to a minimum during hot days.

In line with the literature (e.g., Aaheim and Hauge 2005; Sabir 2011), $P_{(sum)}$ and $W_{s(avg)}$ both negatively affect cycling shares in a more linear way, mostly at the cost of car usage. When it comes to the effects of $W_{s(avg)}$, it should be noted that days with high $W_{s(avg)}$ correlate to some extent with rainy (Pearson r = 0.36) and cloudy weather conditions, which may be additional contributors to the here observed decrease in cycling shares.

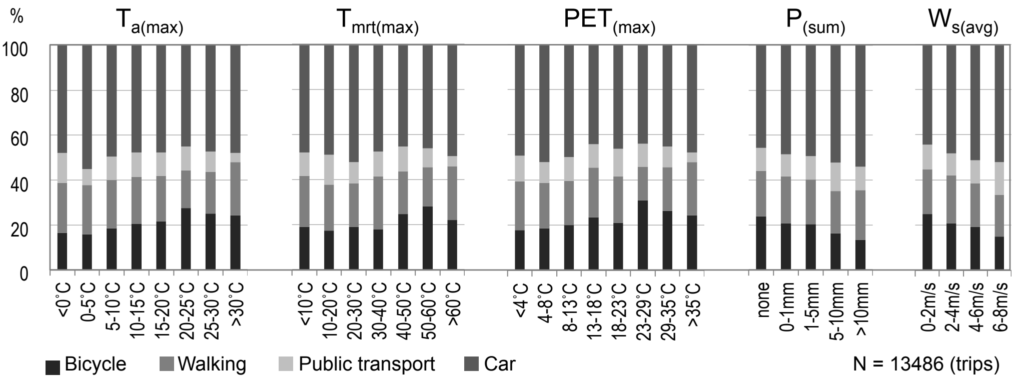


Figure 4.5 Weather effects on modal split

Key: $T_{a(max)}$ = maximum daily air temperature; $T_{mrt(max)}$ = maximum daily mean radiant temperature; PET = maximum daily Physiological Equivalent Temperature; $W_{s(avg)}$ = daily average wind speed; $P_{(sum)}$ = daily precipitation sum

Figure 4.6 presents the effects of weather conditions on the number of bicycle trips per person per day. It represents actual bicycle frequencies (demand) rather than mode shares, discussed above. Generally, weather effects on cycling frequencies show a similar pattern as observed for cycling shares, but the effects seem to be a bit more pronounced. Congruent with the modal split descriptives, daily $P_{(sum)}$—especially on days with over 5 mm of precipitation—and $W_{s(avg)}$ show negative effects.

Regarding thermal conditions, cycling frequencies increase until the same optimum temperatures found earlier for the modal split shares are reached. But rather than the parabolic relationship indicated in the literature, thermal conditions seem to demonstrate a bell-shaped effect on cycling, which flattens out on the lower extreme. This is especially visible when looking at the graphs for $T_{a(max)}$ and $T_{mrt(max)}$. It seems that, at least within the wide range of thermal conditions observed during our study period, a core of weather-tolerant cyclists exists who keep cycling, regardless of the thermal conditions. Remarkably, the $PET_{(max)}$ graph reports a dip in cycling frequencies at days with $PET_{(max)}$ values between 18° and 23°C, which according to the literature should be classified as comfortable thermal conditions (Matzarakis and Mayer 1996). However, the exceptionally high cycling peak in the next class may indicate that the observed anomaly is related to arbitrarily chosen interval classes. Also, it should be noted that here we refer to descriptives that take no account of simultaneous effects of temperatures, precipitation, and wind speeds. These descriptive graphs should therefore be interpreted as indicators of general trends rather than exact representations of individual classes.

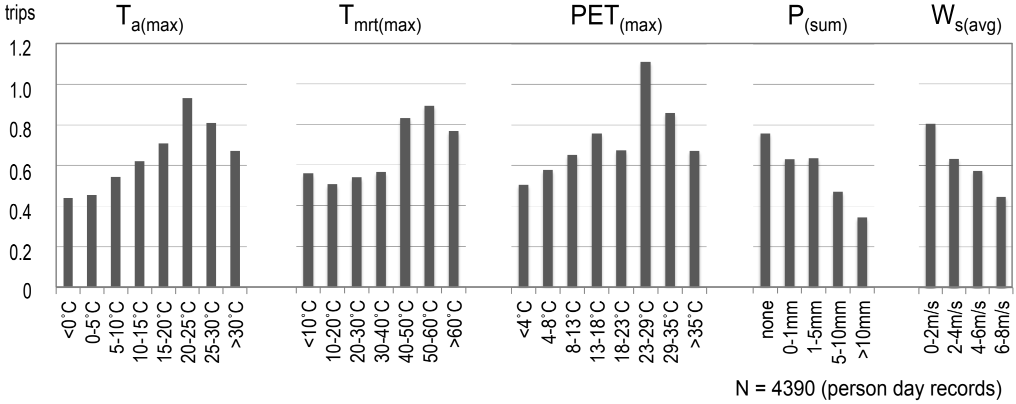


Figure 4.6 Weather effects on number of cycling trips per person per day

Key: $T_{a(max)}$ = maximum daily air temperature; $T_{mrt(max)}$ = maximum daily mean radiant temperature; PET = maximum daily Physiological Equivalent Temperature; $W_{s(avg)}$ = daily average wind speed; $P_{(sum)}$ = daily precipitation sum

Figure 4.7 presents the effects of weather on daily cycling durations. A roughly comparable picture arises for the cycling frequencies, with more or less similar bell-shaped effects for the thermal variables and negative effects for $P_{(sum)}$ and $W_{s(avg)}$. One exception is that the hottest thermal classes for $T_{a(max)}$, $T_{mrt(max)}$, and $PET_{(max)}$ no longer show a decline over the preceding classes. A closer look at the raw mobility data for these hot days revealed that these higher cycling durations are mostly related to distinct leisure activity patterns involving recreational cycling tours and cycling trips to more distant natural recreation areas, including beaches. Overall, the weather effects for cycling durations appear to be even more prominent than for cycling frequencies. This is, for instance, clearly demonstrated when comparing the slope in the graphs for $W_{s(avg)}$. It seems that during calm, dry, and pleasant thermal conditions people cycle not only more frequently, but also longer.

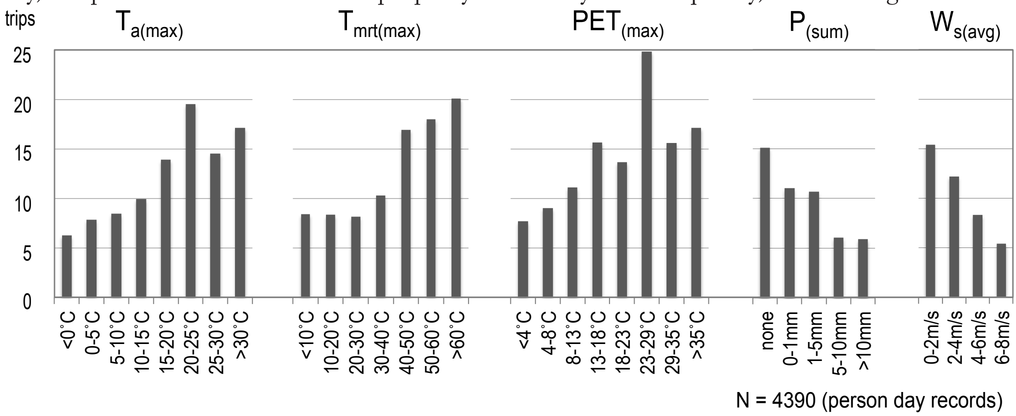


Figure 4.7: Weather effects on time spent cycling per person per day

Key: $T_{a(max)}$ = maximum daily air temperature; $T_{mrt(max)}$ = maximum daily mean radiant temperature; PET = maximum daily Physiological Equivalent Temperature; $W_{s(avg)}$ = daily average wind speed; $P_{(sum)}$ = daily precipitation sum

4.3.2 Multivariate results

This section presents a multivariate analysis of the effects of weather on cycling. Tables 4.2, 4.3, and 4.4 summarize the effects of weather and weather-related parameters on mode choices, cycling frequencies, and cycling durations. To not distract from the main meteorological focus of this paper, the tables do not display the full underlying models, which also include all other independent background attributes[3] listed in Figure 4.3. These full models, as well as the separate models estimated for the different trip purposes[4], can be requested by sending an e-mail to the authors.

Weather effects on cycling shares compared to other transport modes

Table 4.2 presents a summary of the effects of meteorological variables on transport mode choices, as well as the effects of whether or not a trip was made in daylight and whether or not snow cover occurred on the ground. The parameter estimate (B) indicates the change in log odds of choosing a transport mode over the car for a one-unit parameter change. The z statistic indicates the ratio between the parameter estimate and the robust standard errors clustered per respondent. Statistically significant effects have been marked with asterisks. Overall, meteorological variables have a clear effect on the exchange between cycling and the car, even when corrected for various background characteristics, as well as snow cover on the ground and daylight. The exchange between the car and other transport modes is less affected by weather.

Regarding the thermal conditions, the bell-shaped transformed variables for $T_{a(max)}$, $T_{mrt(max)}$, and $PET_{(max)}$ (see section 4.2.2) demonstrate more significant effects and provide better overall model performance than the untransformed originals. This indicates that the effect of thermal conditions on transport mode choice is bell-shaped rather than linear. The positive parameter estimates for the transformed variables imply that the effects of thermal conditions on cycling follow the bell-shaped curve. More precisely, the best model fit was reached for bell-shaped variables with an optimum of 24°C for $T_{a(max)}$ (FWHM = 25°C), 52°C for $T_{mrt(max)}$ (FWHM = 25°C), and 30°C for $PET_{(max)}$ (FWHM = 42°C). These optimums are roughly in line with the optimum intervals found in the descriptives. When comparing the three bell-shaped thermal parameters, $T_{mrt(max)}$ and $PET_{(max)}$ provide higher significance levels and better or similar model fit—indicated by the Wald chi-square statistic[5] —than $T_{a(max)}$. The only thermal variable that is significant on the 99% confidence interval is $PET_{(max)}$. This indicates that combining meteorological variables (T_a, T_{mrt}, humidity, and W_s) within PET seems to lead to a better explanation of the exchange between cycling and the car. However, T_{mrt} is the dominant component within the PET and the most important component of thermal comfort and heat load (Mayer and Höppe 1987). Moreover, the T_{mrt} model as a whole, including $W_{s(avg)}$ as a separate meteorological variable, performs better (higher Wald chi-squared score) than the PET model, in which $W_{s(avg)}$ has been integrated within the $PET_{(max)}$.

3 The respective effects of these sociodemographic, household, trip, and urban form attributes on mode choice outcomes are generally in line with the literature (e.g., Hanson 1982; Cervero and Seskin 1995; Dieleman et al., 2002).

4 In line with the literature (e.g., Hanson and Hanson 1977; Aaheim and Hauge 2005; Sabir 2011), it was shown that mode choices for leisure trips and social visits are more strongly affected by weather conditions than mode choices for utilitarian trips from/ to work, study, and especially errands.

5 The Wald chi-square evaluates to what extent a chosen model performs better than a baseline model in which all estimated parameters are set to zero. If none of the parameters would add anything to the chosen model, the Wald chi-square would be zero. A higher Wald chi-square indicates a better model fit.

In line with the descriptives, $W_{s(avg)}$ and $P_{(sum)}$ negatively affect cycling shares as compared to the car. The $W_{s(avg)}$ effect is significant only in the T_a model (with 90% confidence) and not in the T_{mrt} model. This may be explained by the higher negative correlation between $W_{s(avg)}$ and $T_{mrt(max)}$ (Pearson r = 20.29) than between $W_{s(avg)}$ and $T_{a(max)}$ (Pearson r = 20.17). The significant negative effect of $W_{s(avg)}$ on cycling found in the T_a model may be partially associated with potentially unpleasant or threatening cloudier skies, while in the T_{mrt} model these cloudier skies are better captured by $T_{mrt(max)}$. For $P_{(sum)}$ the negative effects on cycling shares are significant (with a confidence interval of 95% or higher) in all models. Snow cover on the ground seems to affect cycling negatively, potentially related to slippery conditions. However, the effect is not statistically significant, possibly because slippery conditions also negatively affect car usage (nonsignificant positive effects are shown for walking and public transport shares relative to the car). An especially notable observation is the strong positive effect of daylight on both cycling and walking shares in comparison to the car. It seems that after sunset, active transport modes become less attractive. This may partially be related to colder thermal conditions at night, but also to reduced visibility or potential safety issues.

Weather effects on cycling frequencies

Table 4.3 presents a summary of meteorological effects on the number of cycling trips per person per day. Rather than relative cycling shares, this is an analysis of cycling demand in absolute terms.

Table 4.2 Weather effects on transport mode choice

	Multinomial LOGIT model (Car = ref.)					
	Cycling		Walking		Public transport	
	B	z	B	z	B	z
T_a model						
$T_{a(max)}$ (bell-shaped. with optimum = 24˚C; FWHM = 25˚C)	0.284 *	1.76	-0.239	-1.48	0.256	1.32
W_s (avg. 6am – 12am)	-0.061 *	-1.91	-0.044	-1.43	-0.014	-0.33
P_{sum} (6am – 12am)	-0.036 **	-2.41	-0.004	-0.30	0.025	1.31
Snow cover	-0.152	-0.89	0.084	0.57	0.283	1.41
Daylight	0.523 ***	6.21	0.312 ***	3.54	0.101	1.04
*n=13486 (trips); Wald Chi^2=3176***; pseudo R^2(McFadden)=0.21*						
T_{mrt} model						
$T_{mrt(max)}$ (bell-shaped. with optimum = 52˚C; FWHM = 25˚C)	0.245 **	2.11	-0.197 *	-1.83	-0.024	-0.17
$W_{s(avg)}$. (6am – 12am)	-0.050	-1.46	-0.052 *	-1.66	-0.022	-0.53
$P_{(sum)}$ (6am – 12am)	-0.034 **	-2.26	-0.005	-0.39	0.021	1.11
Snow cover	-0.212	-1.40	0.141	1.13	0.137	0.77
Daylight	0.514 ***	6.14	0.316 ***	3.60	0.144	1.45
*n=13486 (trips); Wald Chi^2=3242***; pseudo R^2(McFadden)= 0.21*						
PET model						
$PET_{(max)}$ (bell-shaped. with optimum = 30˚C; FWHM = 42˚C)	0.391 ***	2.60	-0.211	-1.39	0.037	0.19
$P_{(sum)}$ (6am – 12am)	-0.041 ***	-2.73	-0.013	-0.95	0.020	1.04
Snow cover	-0.130	-0.83	0.135	1.03	0.164	0.89
Daylight	0.514 ***	6.12	0.315 ***	3.57	0.139	1.41
*n=13486 (trips); Wald Chi^2=3173***; pseudo R^2(McFadden)= 0.21*						

*p<0.10; **p<0.05; ***p<0.01

Key: $T_{a(max)}$ = maximum daily air temperature; $T_{mrt(max)}$ = maximum daily mean radiant temperature; $PET_{(max)}$ = maximum daily Physiological Equivalent Temperature; $W_{s(avg)}$ = daily average wind speed; $P_{(sum)}$ = daily precipitation sum

The parameter estimate (B) indicates the change in the expected log count of the number of bicycle trips per person per day for a one-unit parameter change. Robust standard errors (S.E.) clustered per respondent and z statistics indicating the ratio between parameter estimates and standard errors are also presented.

Overall, weather seems to have a clear effect on cycling frequencies. In line with the descriptives and the effects on cycling mode shares, thermal conditions demonstrate a bell-shaped effect on cycling frequencies (all significant with 99% confidence). The highest cycling frequencies occur on days with values of 24°C for $T_{a(max)}$, 52°C for $T_{mrt(max)}$, and 33°C for $PET_{(max)}$. This 33°C for $PET_{(max)}$ is slightly higher than the optimums found in the descriptives and the mode choice model. It seems that although cycling mode shares start decreasing above 30°C PET, cycling frequencies in absolute terms start decreasing above 33°C PET—thermal conditions classifying as "warm," two classes above "comfortable" in the literature (Matzarakis and Mayer 1996). Similar to the cycling shares, cycling frequencies $T_{mrt(max)}$ and $PET_{(max)}$ seem to also be better indicators (higher z statistics as well as overall model Wald chi-squared) than $T_{a(max)}$.

As for cycling mode shares, $P_{(sum)}$ shows significant linear negative effects on cycling frequencies (all with 99% confidence). Earlier, a negative effect of snow cover could not be statistically confirmed on cycling shares relative to the car. In contrast, when it comes to absolute cycling frequencies, snow cover demonstrates a highly significant negative effect in all models, suggesting an influence of slippery conditions. It seems that $W_{s(avg)}$ negatively affects cycling frequencies, but these effects are not statistically significant.

Table 4.3 Weather effects on number of cycling trips per person per day

	NEGATIVE BINOMIAL model		
	B	Robust S.E.	z
T_a model			
$T_{a(max)}$ (bell-shaped. with optimum = 24°C; FWHM = 25°C)	0.475 ***	0.116	4.09
W_s (avg. 6am – 12am)	-0.041	0.025	-1.64
P_{sum} (6am – 12am)	-0.040 ***	0.013	-3.13
Snow cover	-0.278 **	0.133	-2.09
*n=4389 (person day records); Wald Chi²=407****			
T_{mrt} model			
$T_{mrt(max)}$ (bell-shaped. with optimum = 52°C; FWHM = 25°C)	0.425 ***	0.079	5.41
$W_{s(avg)}$. (6am – 12am)	-0.020	0.026	-0.77
$P_{(sum)}$ (6am – 12am)	-0.036 ***	0.013	-2.83
Snow cover	-0.379 ***	0.117	-3.24
*n=4389 (person day records); Wald Chi²=428****			
PET model			
$PET_{(max)}$ (bell-shaped. with optimum = 33°C; FWHM = 39°C)	0.544 ***	0.093	5.85
$P_{(sum)}$ (6am – 12am)	-0.037 ***	0.012	-3.01
Snow cover	-0.315 ***	0.118	-2.67
*n=4389 (person day records); Wald Chi²=415****			

*p<0.10; **p<0.05; ***p<0.01

Key: $T_{a(max)}$ = maximum daily air temperature; $T_{mrt(max)}$ = maximum daily mean radiant temperature; PET = maximum daily Physiological Equivalent Temperature; $W_{s(avg)}$ = daily average wind speed; $P_{(sum)}$ = daily precipitation sum

Weather effects on cycling durations

Table 4.4 presents a summary of meteorological effects on total hours cycling per person per day. The parameter estimate (B), similar to standard OLS regression, indicates the predicted change in cycling hours per person per day for a one-unit parameter increase. Robust standard errors (S.E.) clustered per respondent and t statistics indicating the ratio between parameter estimates and standard errors are also presented.

Overall, weather strongly affects daily cycling durations. All included meteorological attributes show significant effects. Generally, the effects of weather on cycling durations show a similar picture as cycling shares and frequencies. Thermal conditions show bell-shaped effects on cycling durations (all significant with 99% confidence). Approximately in line with the descriptives, the longest daily cycling durations occur on days with maximum values of 24°C for $T_{a(max)}$, 52°C for $T_{mrt(max)}$, and 31°C for $PET_{(max)}$. Both $P_{(sum)}$ and snow cover on the ground demonstrate highly significant negative effects on cycling durations (all with 95% or 99% confidence). Also, $W_{s(avg)}$ shows a negative effect on cycling durations, which, in contrast to the cycling frequencies, is significant (with 99% confidence in the T_a model and with 90% confidence in the T_{mrt} model). In line with the descriptives, it seems that $W_{s(avg)}$ affects cycling durations more strongly than cycling frequencies. This indicates that people do still make bicycle trips on windy days but that those trips are shorter than on calm days.

Table 4.4 Weather effects on the number of hours spent cycling per person per day

	TOBIT model		
	B	Robust S.E.	t
T_a model			
$T_{a(max)}$ (bell-shaped. with optimum = 24˚C; FWHM = 25˚C)	0.581 ***	0.108	5.40
W_s (avg. 6am – 12am)	-0.061 ***	0.020	-3.03
P_{sum} (6am – 12am)	-0.026 ***	0.010	-2.64
Snow cover	-0.276 **	0.107	-2.59
*n=4389 (person day records); Wald Chi²=235***; pseudo R²(McFadden)= 0.087*			
T_{mrt} model			
$T_{mrt(max)}$ (bell-shaped. with optimum = 52˚C; FWHM = 25˚C)	0.482 ***	0.076	6.37
$W_{s(avg)}$. (6am – 12am)	-0.038 *	0.020	-1.84
$P_{(sum)}$ (6am – 12am)	-0.022 **	0.010	-2.29
Snow cover	-0.411 ***	0.097	-4.23
*n=4389 (person day records); Wald Chi²=244***; pseudo R²(McFadden)= 0.089*			
PET model			
$PET_{(max)}$ (bell-shaped. with optimum = 31˚C; FWHM = 42˚C)	0.695 ***	0.102	6.82
$P_{(sum)}$ (6am – 12am)	-0.026 ***	0.010	-2.69
Snow cover	-0.299 ***	0.099	-3.02
*n=4389 (person day records); Wald Chi²=240***; pseudo R²(McFadden)= 0.088*			

*p<0.10; **p<0.05; ***p<0.01

Key: $T_{a(max)}$ = maximum daily air temperature; $T_{mrt(max)}$ = maximum daily mean radiant temperature; PET = maximum daily Physiological Equivalent Temperature; $W_{s(avg)}$ = daily average wind speed; $P_{(sum)}$ = daily precipitation sum

4.4 Discussion and conclusions

This paper aims to investigate the complex link between weather and cycling. Drawing on travel diary data from a triple-wave panel study among 945 respondents from Greater Rotterdam, the Netherlands, and after controlling for various individual, household, and trip background characteristics, we analyzed the effects of aggregated daily weather conditions on cycling. Daily weather data produced results similar to those of hourly weather data and were preferred because of uniformity and compatibility and because they are more in line with the moment of transport mode decision-making. To provide a complete picture of cycling behavior, unlike most existing research, an analysis was made not only of cycling frequencies, but also of cycling durations and the exchange between cycling and other transport modes. The results demonstrate a clear overall effect of daily weather conditions on transport mode choices in general and cycling in particular. Congruent with the literature (e.g., Nankervis 1999; Bergström and Magnusson 2003; Aaheim and Hauge 2005; Sabir 2011), daily precipitation sum [$P_{(sum)}$] and average wind speed [Ws(avg)] demonstrate linear negative effects on cycling, mostly benefiting car usage. Cycling durations seem to be more significantly affected by $W_{s(avg)}$ than cycling shares and frequencies. This indicates that on windy days people not only cycle less often, but also for shorter durations. Thermal conditions affect cycling in a nonlinear bell-shaped way. Congruent with some recent studies (e.g., Phung and Rose 2008; Ahmed et al., 2012; Lewin 2011), a thermal optimum for cycling can be identified (days with maximum air temperatures around 24°C). Below and above this temperature cycling shares, frequencies, and durations decrease and car usage increases. Compared to the exposed bicycle, the car offers its user better protection from wind, precipitation, and cold as well as heat.

In contrast with most existing studies on weather and transportation, when analyzing thermal conditions we not only take into account the daily maximums for air temperature [$T_{a(max)}$], but also for mean radiant temperature [$T_{mrt(max)}$], which combines the effects of air temperature (via emission of long-wave radiation from the sky and surrounding surfaces) and solar radiation (direct, diffuse, and reflected), and physiological equivalent temperature [$PET_{(max)}$], which combines the effects of T_a, T_{mrt}, W_s, and humidity. Weather may be perceived as warmer during calms and sunshine than during cloudy and windy conditions, despite a similar Ta. The use of PET and T_{mrt} provides a more comprehensive account of weather conditions, although it should be mentioned that in order to calculate these indices, assumptions needed to be made regarding the urban geometry and human parameters such as shape, heat production, and clothing. Our results demonstrate that $T_{mrt(max)}$ and $PET_{(max)}$ provide better explanations for cycling shares, frequencies, and durations than just $T_{a(max)}$, confirming the importance of combined weather effects. Nevertheless, $T_{a(max)}$, although somewhat weaker, also demonstrates significant effects. In general, T_a may therefore still be a powerful indicator as it is easily interpretable, free of assumptions, widely accessible, and easily compatible with weather forecasts and climate change scenarios.

Insights from this paper are relevant to policy makers in several ways. When analyzing cycling trends over time, as in when evaluating the effects of cycling policies, for example, the insights presented here could be used to disentangle cycling trends from the noise caused by short-term weather fluctuations. Similarly, the insights could be used to improve annual modal split estimations by adjusting for weather conditions—particularly when these are based on origin-destination survey data conducted over the course of less than a full year, or during years with abnormal weather conditions. Additionally, the effects of weather on cycling are relevant in the context of climate change. Most of the year, a warmer future climate may have positive effects on cycling. However, in summer heat may pose a threat. A brief calculation based on Dutch Meteorological

Institute climate change projections for the Netherlands (KNMI 2009) reveals that the number of days with maximum air temperatures of 25°–30°C and 30°– 35°C—days on which optimum conditions for cycling are exceeded—is expected to increase respectively from 24 currently to 30–47 in 2050 and from 4 currently to 7–14 in 2050, depending on whether mild (11°C global temperature rise; no changing prevailing wind patterns) or severe (12°C global temperature rise, changing prevailing wind patterns) climate change scenarios are utilized. A potential future increase in overall precipitation and extreme precipitation events plus changes in solar radiation/cloudiness may further (negatively) impact cycling. Policy makers are advised to consider (thermal) climate adaptations in urban design, for instance through usage of deciduous trees in urban areas and along cycling infrastructures, which provide cooling in summer when foliated—mainly through shading but also through transpiration—while retaining valued sunshine in winter when defoliated (e.g., Lindberg and Grimmond 2011a; Konarska et al., 2014). In addition to alleviating heat and solar radiation, trees can be used to regulate wind and humidity and to protect from sudden (summer) downpours. Wind barriers and precipitation shelter, in the form of trees or other, particularly along main cycling infrastructures, could be additional interventions to reduce cyclists' weather exposures, which may lead to increased bicycle-over-car usage.

This research explores the complex integrated weather effects on travel behavior. Future research could further elaborate this topic into several directions. First, the notions of combined weather and nonlinearity explored in this study could further be investigated. Studies could further explore the effects of precipitation combined with thermal conditions, as well as the existence of (combined) precipitation, wind, or thermal thresholds triggering sudden travel behavior changes. Also, studies may explore the effects of weather variability (e.g., showers versus continuous rain; wind gusts; sunny spells during cloudy days), as well as lagged weather effects (e.g., first warm sunny spring day after a long winter). Second, research could investigate integrated weather effects on other related travel behavior decisions, such as choices for destinations, departure times, speeds, and routes. Such analyses may require other data collection techniques (e.g., smart GIS interfaces), as well as more precise spatial and temporal resolutions. Third, research on the integrated effects of weather on a wide range of (travel) behavioral activities may further focus on the development of new or the fine-tuning of existing meteorological indices to the specific the activities one wants to address. For instance the PET may be better recalibrated to cycling (or other outdoors activities). Fourth, research into the integrated effects of weather should be explored not only objectively, but also in terms of peoples' subjective interpretations of weather in connection with emotional experiences during travel or outdoors activities. Such subjective accounts have been studied qualitatively (e.g., Spencer et al., 2013) but may also be integrated into quantitative travel surveys or diaries. Fifth, to better explore thermal optimums and potential negative effects of heat, especially in the light of climate change, future research is strongly recommended in hotter climate regimes where people experience heat more regularly. Finally, to better guide climate adaptation policies, studies could further investigate the effects of spatial design interventions, such as the usage of trees, wind barriers, and precipitation shelters, on the (experienced) weather exposure of cyclists.

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5 Weather, transport mode choices and emotional travel experiences.

Lars Böcker, Martin Dijst, Jan Faber, Utrecht University
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Abstract

With climate change high on the political agenda, weather has emerged as an important issue in travel behavioural research and urban planning. While various studies demonstrate profound effects of weather on travel behaviours, limited attention has been paid to subjective weather experiences and the psychological mechanisms that may (partially) underlie these effects. This paper integrates theoretical insights on thermal comfort, weather perceptions and emotional experiences in the context of travel behaviour. Drawing on unique panel travel diary data for 945 Greater Rotterdam respondents (The Netherlands), this paper aims to investigate how and to what extent weather conditions affect transport mode choices, thermal perceptions and emotional travel experiences. Our findings point out that observed dry, calm, sunny and warm but not too hot weather conditions stimulate cycling over other transport modes and – via mechanisms of thermal and mechanical comfort – lead to more pleasant emotions during travel. Overall, public transport users have less pleasant emotional experiences than users of other transport modes, while active mode users appear most weather sensitive. The theoretical contributions and empirical findings are discussed in the context of climate change and climate-sensitive urban planning.

Keywords: Weather, thermal comfort, transport mode choice, emotion, Netherlands

5.1 Introduction

With the increased scientific evidence for climate change (IPCC, 2013) and political interest in climate change adaptation and mitigation, weather and climate change have become important issues in transport planning and travel behavioural research. While research initially focussed predominantly on the effects of weather extremes on transport infrastructures (for an overview see e.g. Transportation Research Board, 2008), recently, various scholars have investigated the effects of daily weather conditions on individual travel behaviours, including the use of transport modes (for reviews, see Koetse and Rietveld, 2009 and Böcker et al., 2013a). Many recent studies link objectively measured weather conditions to existing or self-gathered travel behaviour data and generally conclude that higher – but not too high – air temperatures enhance walking and cycling in comparison to motorised transport, whereas precipitation sum and wind speed have opposite effects (e.g. Sabir, 2011; Ahmed et al., 2010; Creemers et al., 2014). In contrast, we know very little about how weather is perceived during travel, how it affects our emotions, and via which mechanisms it affects transport mode choices. Addressing these research gaps is crucial (1) to better understand the effects of weather and changing climate conditions on travel behaviour, (2) to assess its impact on daily emotional wellbeing during travel, and (3) to expand climate-sensitive urban planning (Eliasson et al., 2007; Lenzhölzer and Wulp, 2010) to places and infrastructures of (active) mobility.

Existing knowledge on the experience of weather and its effects on emotions can be found mostly outside, and disconnected from, the field of transport studies. This paper introduces biometeorological insights into the relationships and discrepancies between objectively measured and subjectively perceived weather conditions in terms of thermal and mechanical comfort (e.g. Thorsson et al., 2007; Eliasson et al., 2007; Oliveira and Andrade, 2007), and psychological insights into the relationship between weather, moods and emotions (for a review, see Kööts et al., 2011). We integrate these insights, both theoretically and empirically into the context of travel behaviour, hereby addressing recent calls for a more interdisciplinary approach on this subject (Eliasson et al., 2007; Böcker et al., 2013a). It is our aim to investigate how and to what extent weather conditions affect transport mode choices, thermal perceptions and emotional travel experiences. Hereto, purposely-designed Greater Rotterdam (Netherlands) travel diary data (n=945) – including ecological momentary assessments (EMA) of thermal perceptions and emotions (i.e. happiness, irritation, fear and tiredness) – are connected to local urban form and hourly meteorological data and analysed in structural equation models. This paper first summarizes the main findings from the literature on the effects of weather on transport modes, thermal comfort, and emotions and moods. Second, it introduces the study area, dataset and modelling framework. Third, it describes and explains the main findings in relation to the literature. Finally, it concludes with a discussion of the main findings and its policy and research implications.

5.2 Literature

Over the last few decades, transport research, originating mostly from maritime and continental climates in Europe, North America and Australia, has investigated the effects of temperature, precipitation and wind on transport mode choices (for literature reviews, see Koetse and Rietveld, 2009; Böcker et al., 2013a). Studies typically link (national) travel survey data to publicly available weather records from nearby meteorological stations. Regarding air temperature, studies generally find a positive effect on walking and cycling compared to motorised transport, particularly car usage (e.g. Hanson and Hanson, 1977; Aaheim and Hauge, 2005; Sabir, 2011). However, some others point out that this relationship between temperature and transport mode choice may be nonlinear. Above a certain optimum between 24°C and 30°, high temperatures have been found to negatively affect walking in Montreal (e.g. Aultman-Hall et al., 2009), or cycling in Melbourne (e.g. Phung and Rose, 2008; Ahmed et al., 2010) and the Netherlands (Thomas et al., 2013; Böcker and Thorsson, 2014). When it comes to precipitation sum and wind speed, studies generally agree on more or less linear negative effects on walking and cycling and positive effects on particularly car usage (e.g. Aaheim and Hauge, 2005; Phung and Rose, 2008; Sabir, 2011; Böcker and Thorsson, 2014).

Where transport researchers have mostly analysed the effects of objectively measured weather conditions, biometeorologists and health scientists have also linked people's behavioural responses to weather conditions and their subjective assessments in terms of *thermal comfort*. Hereby, thermal comfort is commonly defined as "that condition of mind which expresses satisfaction with the thermal environment and is assessed by subjective evaluation" (ANSI/ASHRAE, 2004: 2). For instance three studies on urban park attendances in Japan and Sweden (Thorsson et al., 2007; Eliasson et al., 2007), a study on individual psychological weather adaptations in the United Kingdom (Nikolopoulou and Steemers, 2003), and a study on leisure activities in the USA (McGinn et al., 2007), point out that thermal comfort results from combinations of different meteorological variables, such as air temperature, relative air humidity, solar radiation and wind speed. The relationship between weather and comfort has not only thermal aspects. The exposure to wind or precipitation – or a combination of both as wind-driven rain – may have direct implications for comfort levels, for instance related to related to moist in the eyes, flapping clothes, hair disturbances, or even loosing balance and being blown over (e.g. Bottema, 1993; Blocken and Carmeliet, 2004). Such direct physical aspects, often referred to as *mechanical comfort*, have mostly been studied through wind tunnel experiments in the field of wind engineering (e.g. Blocken and Carmeliet, 2004), but are in reality often difficult to disentangle from thermal comfort (Oliveira and Andrade, 2007).

To acquire insights into the relationships between weather and emotions during travel, we need to draw on existing psychological knowledge of weather and longer-term moods (e.g. Kööts et al., 2011). Mood has often been linked to seasonality, for instance via the cyclical syndrome Seasonal Affective Disorder (Rosenthal et al., 1984), usually referring to winter depression. Also amongst the general population, scholars have confirmed the idea that moods are worst in winter and best in summer (e.g. Springer and Roslow, 1935; Oyane et al., 2008), although also empirical evidences for mood dips outside winter exist (e.g. Ozaki, 1995; Huibers et al., 2011). Other studies link moods directly to individual weather conditions. First, the number of sunshine hours and the level of solar radiation have been found to increase mood levels (e.g. Cunningham, 1979; Schwartz and Clore, 1983; Howarth and Hoffman, 1984; Barnston, 1988; Albert et al., 1991; Denissen et al., 2008; Ciucci et al., 2011). More specifically sunshine has been found to reduce sadness (Ciucci et al., 2011), cynicism, doubtfulness (Howarth and Hoffman, 1984), tiredness and sluggishness (Denissen et al., 2008), and increase optimism, concentration (Howarth and Hoffman, 1984) and mental activeness (Albert et al., 1991). The relationship between exposure to sunshine and positive mood is strongly embodied: exposure to sunlight, via the production of vitamin D3 in the skin, influences levels of serotonin in the human brain and elevates mood and energy levels (Lambert et al., 2002; Lansdowne and Provost, 1998). In addition to sunshine, higher air temperatures have been found to increase general levels of mood (e.g. Cunningham, 1979; Barnston, 1988; Denissen et al., 2008). More specifically Howarth and Hoffman (1984) point out that higher air temperatures increase levels of concentration and very low temperatures (under -8°C) increase feelings of aggressiveness. Both heat (e.g. Palamerek and Rule, 1980; Bell, 1981) and extreme cold (Schneider et al., 1980) can be seen as sources of discomfort that may lower the barrier for people to behave aggressively. Compared to air temperature and sunshine, psychological mood research paid relatively little attention to the effects precipitation and wind speed. Nevertheless, Denissen et al. (2008) document a link between wind and negative aspects of mood; Barnston (1988) finds that rain reduces morale and increases irritation; Schwartz and Clore (1983) link rain to a lack of positive mood aspects; and Howarth and Hoffman (1984) find rain to increase scepticism.

The above-mentioned three strands of literature on the effects of weather on respectively travel behaviour, weather comfort and emotions, can be brought together into a travel situational framework. Hereto, we need to theorise about the causalities between transport mode choices, thermal perceptions, and emotional experiences. First, because the literature indicates that thermal perceptions play an important role in experiencing comfort, emotional experiences can be seen as a consequence of thermal perceptions. Second, both thermal perceptions and emotional experiences reported during the trip can be seen as consequences of the different environmental exposures resulting from the transport mode choices, which are made in advance of a trip. In this travel situational framework, the effects of weather conditions on mode choices, thermal perceptions and emotional travel experiences cannot be viewed separately from other contextual factors, such as personal, household, trip and spatiotemporal contexts. For instance, thermal comfort studies indicate that women (e.g Karjalainen, 2012; Kenawy and Elkadi, 2012) and older people (e.g. Tuomaala et al., 2013) experience cold weather as colder and warm weather as warmer than men and younger age groups. Also peoples' physical activity levels and clothing (e.g. Havenith et al., 2002) as well as peoples (culturally defined) weather preferences and attitudes towards being outdoors and staying in the sun (e.g. Knez and Thorsson, 2006; Thorsson et al., 2007) may play a role in the way people perceive weather and in the way it affects their emotional experiences. Finally, the exposure to weather, and therefore its effect on peoples' emotional travel experiences, may differ between different spatial configurations within the city. For instance, some studies demonstrate that green, wind-exposed or shadowed environments are perceived as colder than concrete, sunlit or wind-sheltered environments (e.g. Nikolopoulou and Lykoudis, 2007; Phung and Rose, 2008; Lenzhölzer and Wulp, 2010), although others point out that the relationships between urban form and microclimate conditions may differ significantly between different seasons (e.g. Theeuwes et al., 2014).

5.3 Methodology

5.3.1 Study area and data

The study area for this research is Greater Rotterdam: a coastal port region in the west of the Netherlands, which is part of the densely populated and economically important Randstad Holland region (Figure 5.1). The region has a maritime climate with mild winters (lows: 1°C; highs: 6°C), warm summers (lows: 12°C; highs: 21°C), and precipitation ranging from 158 mm in spring to 258 mm in autumn (KNMI, 2013). The rationale for selecting Greater Rotterdam as a study area is threefold: First, the area has a diverse population in terms of socio-demographics, socio-economic status and cultural backgrounds. Second, the area offers a large variety of spatial environments, ranging from post-Second-World-War mid- and high-rise areas in the city centre to a mix of compact historic towns, lower-density satellite towns, and villages in surrounding areas. Third, local politicians pursue and promote active policies regarding both climate change mitigation and adaptation, which makes the region interesting in terms of knowledge dissemination.

This study is based on a travel diary survey (used in two earlier studies: Böcker and Thorsson, 2014; Helbich et al., 2014) conducted from August 2012 to February 2013. From an existing Internet panel, 945 respondents aged 18 or older were randomly assigned six regular days[6] (two in summer, two in autumn and two in winter), to participate in a travel diary research. Following Moskowitz and Young (2006) an ecological momentary assessment (EMA) methodology was used, which implicates that respondents report repeated measurements of weather perceptions and emotional experiences in on site travel diaries, which can then directly be linked to reported travel behaviours. Respondents were distributed equally over different residential environments (see Figure 5.1) and we oversampled for people aged 65 or older and people with non-western ethnicities, because of lower expected response rates and unique weather preferences for these groups. Although representativeness has never been a primary aim, our sample represents the Greater Rotterdam population relatively well on several key socio-demographic statistics like gender, age and household size (CBS, 2013), except for an underrepresentation of lower educated

6 Regular days contain weekends and weekdays, but exclude respondents' vacations or days of illness.

and non-western ethnicities, which is quite typical for internet panels (Adler et al., 2002). For more information on the sample composition, see Böcker and Thorsson (2014).

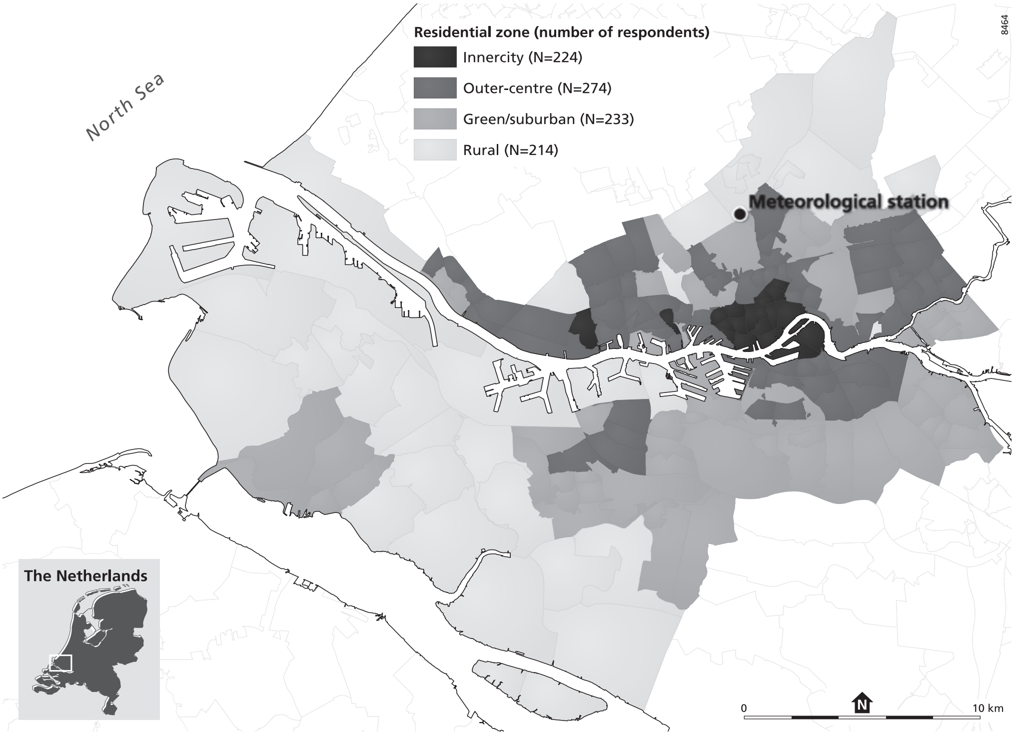

Figure 5.1 Study area Source: Böcker and Thorsson, 2014. Administrative level: 4-digit postal codes.

The trip data from the travel diaries are enriched with external data in two steps. First, through geocoding of trip origins and destinations based on Dutch cadastral data (2014) and subsequent shortest path estimations based on ESRI street data (2008), trip data are spatially linked in ArcGIS to route-specific urban form and land use characteristics. Following Schlossberg et al. (2006), a 200m buffer is used, which is small enough to capture most of the nearby surroundings that have most impact on the traveller, while giving some margin with regard to peoples' potential route deviations from the calculated shortest paths. From a 100m^2-cell grid three urban form and land use indicators are extracted: address density (number of residential and non-residential addresses per cell); greenness index (surface-area proportion of green space); and a Shannon index for building usage diversity (a value of 0 refers to one single building usage; higher values refer to areas with more mixed building usages like residential, offices, shops and public services) [7] . Second, trip data are linked to hourly meteorological data from a local Royal Dutch Meteorological Institute (KNMI, 2013) weather station (Figure 5.1). Our analysis includes the effects of hourly average air temperature, precipitation sum, wind speed, and clearness index. The latter indicates whether sky conditions are clear (values close to 1) or cloudy (values close to 0) and is defined as the ratio

7 Building usage diversity and address density are extracted from the 2014-dataset 'Basisregistraties, Adressen en Gebouwen (BAG)'. Greenness is extracted from the 2001-dataset 'Landelijk Grondgebruiksbestand Nederland (LGN)'.

between the observed and the theoretical maximum incoming solar radiation given the specific time and location on the earth's surface (Crawford and Duchon, 1999). Additionally, we control for whether or not snow-cover had been accumulated on the ground, as this may have affect travel behaviours and emotions. During the survey period, the Greater Rotterdam area had been subjected to a wide range of weather conditions (Figure 5.2), such as dry and warmer-than-average weather (with a peak of 34°C) in late August; warmer-than-average but very wet weather in December; and colder-than-average weather in mid-January with sub-zero maximum air temperatures and permanent snow-cover on the ground.

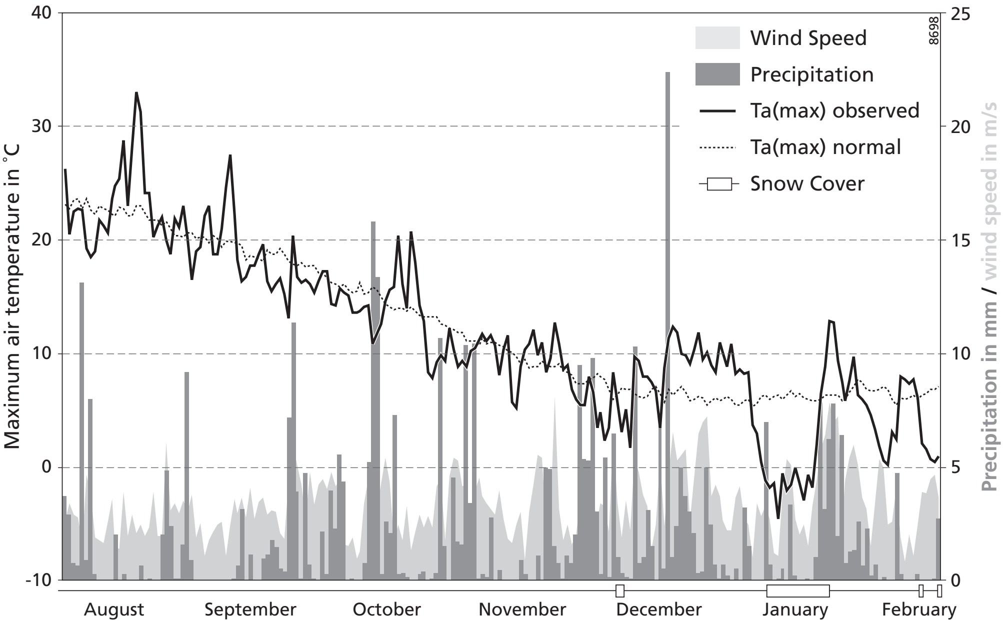

Figure 5.2 Rotterdam weather conditions during survey period Source: Helbich et al., 2014

5.3.2 Multivariate modelling techniques

In our multivariate analyses use is made of Structural Equation Modelling (SEM), via the software package Mplus. SEM enables us to analyse the effects on emotional travel experiences in a *factor* model based on four separate items – i.e. happiness, fear, irritation and tiredness – covering several emotional dimensions including positive/negative affect and level of activeness. Hereto, respondents were asked to rate in their travel diaries for each trip on 5-point Likert scales to what extent they felt sad or happy; fearless or fearful; satisfied or irritated and energetic or tired. In advance of the modelling, a principal component analysis was conducted, which revealed a one-factor solution for emotional travel experiences on which happiness loads positively and fear, irritation and tiredness load negatively.

Additionally, SEM allows integrating this emotional travel experience factor model as a dependent variable into a *regression* model. But unlike regular regression analysis, SEM models may contain more than one dependent variable. In our regression model we analyse the effects of weather on (1) transport mode choices, (2) thermal perception, and (3) emotional travel experience, whereby we define the mediating mechanisms between these three dependent variables to be based on the causalities discussed at the end of section 2. Hereby we control for various contextual factors, including socio-demographic (e.g. age, gender and ethnicity), attitude (e.g. towards summer, urban living, the environment), socio-economic (e.g. income, education), transport resource (e.g. car/bicycle ownership), trip (e.g. trip purpose, distance) and spatiotemporal (e.g. address density, building usage diversity, greenness, week/weekend, peak/off-peak) attributes. This results in the final SEM modelling framework presented in Figure 5.3.

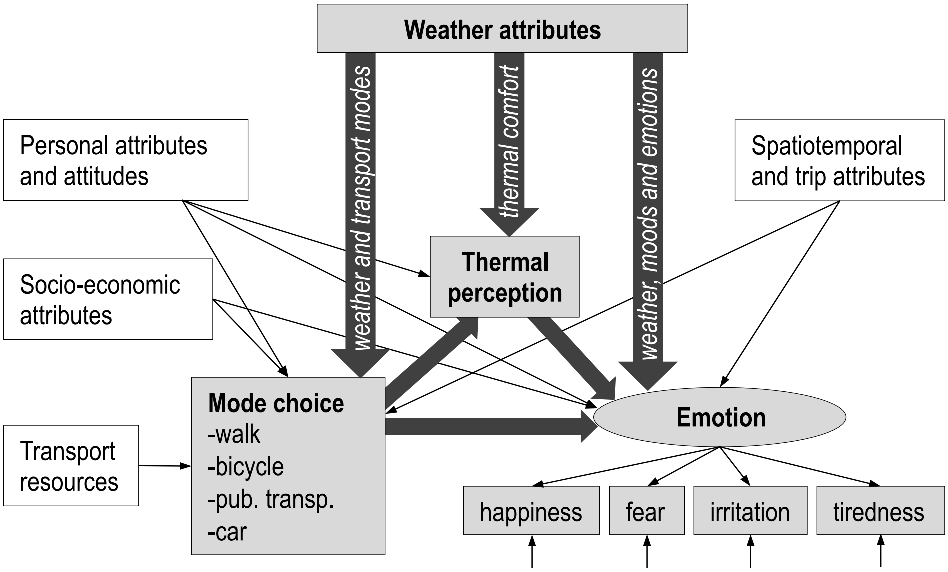

Figure 5.3 SEM modelling framework

5.4 Analysis

5.4.1 Descriptive analysis

This section provides a descriptive overview of the effects of objectively measured weather on the three dependent variables in this study: thermal perceptions, transport mode choices, and emotional travel experiences. Table 5.1 demonstrates the relationship between objectively measured air temperature and peoples' subjective thermal perceptions. Naturally, colder conditions are experienced as colder and warmer conditions as warmer. Overall, it appears that people perceive air temperatures as most comfortable at 15-20°C. Considerable thermal discomfort during travel is perceived from 0-5°C downwards (too cold) and from 25-30°C upwards (too hot). However, in line with the literature (e.g. Thorsson et al., 2007) clear discrepancies can be observed between objectively measured thermal conditions and thermal perceptions. These are illustrated by the bandwidths of subjective thermal interpretations during similar air temperature intervals. Based on these figures, it could be hypothesised that similar air temperatures are perceived differently under different combinations of weather conditions, amongst different people using different transport modes, and/or in different geographical settings. Via our SEM model in section 4.2 we will further examine this hypothesis.

Table 5.1 Distribution of subjective thermal experience for different air temperature intervals

		Percentage of respondents who perceive thermal conditions as…									thermal comfort
		very cold	cold	cool	slightly cool	comfort-able	slightly warm	warm	hot	very hot	score a
Objective T_a	<0˚C	29%	57%	9%	2%	4%					-3,1
	0-5˚C	4%	48%	29%	8%	12%					-2,3
	5-10˚C		24%	40%	19%	17%					-1,7
	10-15˚C		8%	30%	28%	32%	2%				-1,1
	15-20˚C			11%	19%	49%	12%	8%			-0,1
	20-25˚C				1%	27%	18%	40%	11%		1,3
	25-30˚C					7%	8%	44%	31%	10%	2,2
	≥30˚C					4%	2%	14%	47%	33%	2,9
Total		**3%**	**17%**	**21%**	**14%**	**25%**	**6%**	**10%**	**4%**	**1%**	**-0,8**

a) Perceived thermal comfort score: -4 = very cold; 0 = comfortable; 4 = very hot

Figure 5.4 compares the mean modal split averages for different classifications of hourly weather conditions. In congruence to the literature (e.g. Aaheim and Hauge, 2005; Sabir, 2011) higher hourly air temperatures lead to an increased usage of open-air active transport modes, especially cycling, while car and public transport shares decrease. However, the relationship between air temperature and transport modes is not entirely linear. In line with other studies (e.g. Phung and Rose, 2008; Ahmed et al., 2010; Thomas et al., 2013; Böcker and Thorsson, 2014) it seems that above a thermal optimum between 20 and 25˚C, the above-mentioned positive effects of air temperature flatten out, or when it comes to cycling even reverse. Also when air temperatures fall below zero, walking and public transport shares increase while car usage decreases, potentially related to slippery road conditions. When looked at the effects of sky clearness, it can be seen that clear, sunny sky conditions (higher CI values) increase active transport modes over car and public transport usage, while dark or heavily clouded sky conditions (lower CI values) have opposite effects. Finally, in congruence to the literature (e.g. Aaheim and Hauge, 2005; Sabir, 2011),

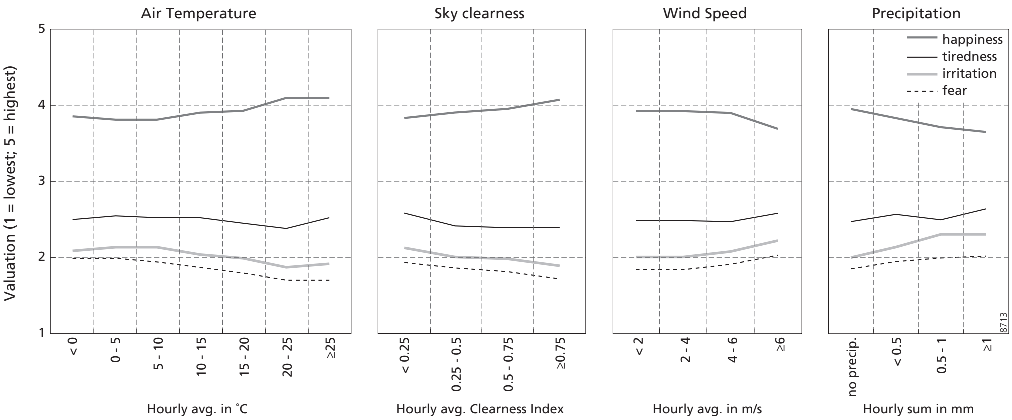

Figure 5.4 Weather and modal split

precipitation sum and higher wind speeds (above 4-6m/s) decrease the usage of active over motorised transport modes. An exception is walking, which increases for the higher precipitation classes. A potential reason for this could be that during rainy weather people prefer nearby over further away destinations (e.g. the small grocery shop around the corner compared to a big supermarket), and therefore are more likely to walk.

Figure 5.5 indicates the effects of hourly weather conditions on emotions experienced while travelling. Positive effects of an increase of air temperature and sky clearness can be observed on happiness reported during trips, and more or less equal or negative effects on tiredness, irritation and fear. These findings are in line with the literature on weather and moods demonstrating that higher air temperature and sunshine enhance positive affects like happiness and enthusiasm while decreasing negative affects like fear, irritation and disgust (e.g. Cunningham, 1979; Denissen et al., 2008; Howarth and Hoffman, 1984) and aspects of fatigue like tiredness and sleepiness (Goldstein, 1972; Howarth and Hoffman, 1984). An exception is our finding that above 25°C happiness no longer increases, fear no longer decreases and tiredness and irritation even increase. This indicates that not only cold but also hot weather conditions may negatively affect emotions, as suggested in some earlier studies (e.g. Schneider et al., 1980; Bell, 1981). In contrast to air temperature and sky clearness, precipitation sum and wind speed (although only above 4-6m/s) have negative effects on emotional experiences, which is in congruence with e.g. Schwartz and Clore (1983).

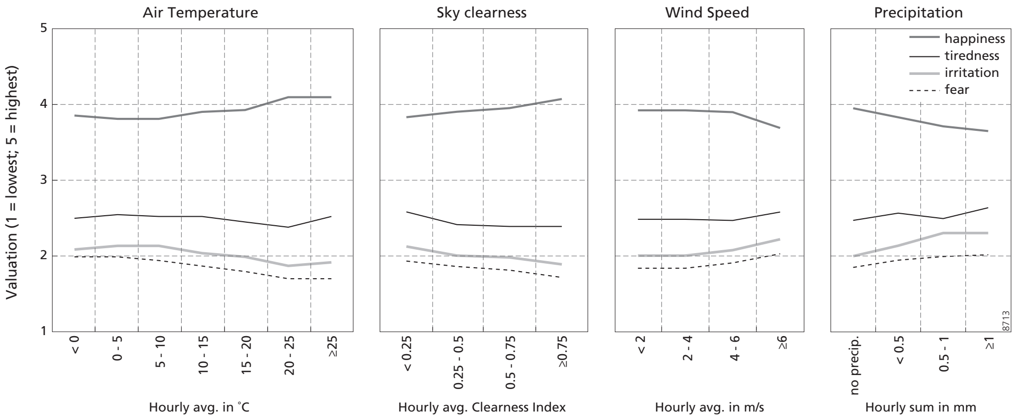

Figure 5.5 Weather and emotional travel experiences

5.4.2 Multivariate analysis

Table 5.2 presents four SEM-models. The models are similar, but each utilizes another dependent dummy variable for mode choice. The three columns in each model present standardized coefficients and their significance levels for the three dependent variables: mode choice, thermal perception (Tfeel), and emotional travel experience (emotion). The factor model in the upper section of Table 5.2 indicates that the item happiness loads positively on emotion and the items tiredness, irritation and fear load negatively. The regression model has been constructed, based on the paths presented in Figure 5.3. The models fit rather well to the data, as indicated by a Root

Table 5.2 Full-sample structural equation models for the different transport modes

	SEM: Standardized coefficients: estimator=WLSMV[a], cluster=person-id[b], N = 11759 trips											
	Model 1: Walking			Model 2: Cycling			Model 3: Public transport			Model 4: Car		
	Walk	Tfeel	Emotion	Bicycle	Tfeel	Emotion	Pub. tr.	Tfeel	Emotion	Car	Tfeel	Emotion
Factor model												
Happiness			.877			.878			.877			.877
Irritation			-.827***			-.827***			-.827***			-.827***
Fear			-.768***			-.768***			-.768***			-.768***
Tiredness			-.657***			-.657***			-.658***			-.657***
Regression model[c]												
Personal and attitudes												
Age	.071***	-.021	.108***	-.114***	-.028**	.116***	-.066	-.020	.105***	.063**	-.024*	.113***
Male (D)	-.037*	.036***	.073*	-.069*	.033**	.074**	.058	.035***	.076**	.077***	.033**	.073**
Nonwestern ethn. (D)	.005	-.007	.011	-.073**	-.010	.014	.068**	-.008	.017	.018	-.007	.012
BMI: Obese (D)	-.061***	.007	.014	-.057*	.005	.013	.007	.008	.011	.105***	.004	.014
Summer person (D)	.019	-.022*	.046	-.014	-.023*	.047	-.005	-.022*	.046	.017	-.023*	.047
Environm. conscious	.028	-.005	.143***	.094***	-.001	.141***	-.018	-.005	.143***	-.094***	-.002	.141***
Rural-oriented	-.026	.017	-.009	.074**	.021*	-.013	-.038	.018	-.014	-.013	.018	-.011
Socio-economic												
Educ. middle (D)	-.026		-.004	.008		-.005	.004		-.004	.034		-.004
higher (D)	.018		-.093*	-.036		-.091*	-.085*		-.099**	.056		-.09*
Hh-income €3-4K (D)	-.015		.068*	-.042		.068*	.009		.068*	.031		.067*
>€4K (D)	-.017		.017	.010		.016	-.037		.013	.003		.016
unknown (D)	-.029		-.031	-.011		-.032	.044		-.029	.007		-.032
Transport resources												
# Cars in hh	-.042**			-.125***			-.274***			.274***		
Pub-tr. card (D)	.002			.057*			.255***			-.194***		
Bike for city (D)	-.031			.302***			.037			-.135***		
sports/e-bike(D)	-.038			.341***			-.059			-.145***		
Trip attributes												
Travel together (D)	.012		.031	-.198***		.039*	.034		.035*	.149***		.036*
Detour (D)	.051***		.001	.030**		.002	-.016		.002	-.077***		.001
Weekend (D)	.017		.048*	-.002		.049*	-.078**		.042	.022		.049*
Peak hour (D)	.005		-.025*	.013		-.025*	.043*		-.021	-.026*		-.025*
12AM-6AM (D)	.004		.007	.031**		.006	-.006		.007	-.025**		.007
Trip for work (D)	-.717***		.037	-.391***		.016	.167***		.016	.217***		.009
errands (D)	-.201***		-.126***	.017		-.136***	.145***		-.124***	.124***		-.132***
social (D)	-.078***		-.079***	.014		-.083***	-.136***		-.094***	.119***		-.079***
Travel distance	-.081***		-.024	.018		-.028	-.062**		-.033*	.117***		-.024
Trip environment												
Building diversity[d]	.019		.020	-.005		.021	-.017		.019	-.006		.020
Address density	.068***		-.017	.000		-.014	.043		-.010	-.132***		-.018
Green % (log-transf.)	-.025		.031	.059**		.027	-.129***		.019	.025		.030
Weather												
Ta >25˚C (D)	.017	.144***	-.042**	-.005	.144***	-.041**	-.013	.144***	-.043**	-.003	.144***	-.041**
>15–≤20˚C (D)	.025	-.298***	-.020	-.026	-.299***	-.017	.076***	-.300***	-.011	-.03*	-.297***	-.020
>10–≤15˚C (D)	.031*	-.493***	-.015	-.062***	-.496***	-.010	.050*	-.495***	-.008	-.002	-.494***	-.014
>5–≤10˚C (D)	.031*	-.691***	-.038	-.072***	-.694***	-.032	.071**	-.693***	-.028	-.008	-.691***	-.037
>0–≤5˚C (D)	.002	-.557***	-.020	-.064***	-.560***	-.016	.008	-.557***	-.018	.039**	-.559***	-.019
≤0˚C (D)	.034	-.672***	.038	-.026	-.673***	.042	.035	-.673***	.044	-.015	-.671***	.037
Psum	.010	-.014**	-.042***	-.031*	-.016**	-.040***	.029**	-.015**	-.038***	.000	-.014**	-.041***
Ws	-.020	-.071***	-.031	-.014	-.072***	-.031	.034	-.072***	-.028	.026	-.072***	-.031
Snowcover (D)	.021	.000	-.035	-.065	-.003	-.031	.039	-.001	-.031	.001	.000	-.034
CI ≥.5–<.75 (D)	.004	-.026***	-.009	.024	-.025**	-.010	.047**	-.028***	-.005	-.026	-.025**	-.010
≥.25–<.5 (D)	.021	-.050***	-.023	-.010	-.051***	-.022	.040	-.052***	-.018	-.009	-.05***	-.022
<.25 (D)	.025	-.046***	-.046**	-.006	-.046***	-.044**	.012	-.046***	-.044**	-.013	-.045***	-.045**
darkness (D)	.002	-.059***	-.053**	-.067***	-.062***	-.050**	.019	-.059***	-.051**	.061**	-.061***	-.051**
Mediators												
Walk/bike/pub./car (D)[d]		-.015**	.051		-.050***	.042		.025*	-.088**		.038***	-.034
Tfeel			.118***			.121***			.120***			.117***
Model quality												
Dep. var. R^2	.647	.692	.125	.349	.693	.126	.395	.692	.131	.398	.692	.125
Model Chi²(df.)	301(156)***			312(156)***			321(156)***			290(156)***		
RMSEA / CFI / TLI	.009 / .989 / .982			.009 / .988 / .980			.009 / .990 / .983			.009 / .988 / .980		

a Estimator is Weighted Least Squares Means and Variance adjusted. Significance: *p<.1; **p<.05; ***p<.01

b Clustered sampling technique has been applied, which deals with the trip data that are clustered within respondents

c Reference categories for dummy variables (D): female; ethnicity=native-Dutch; BMI=not obese; favourite season is not summer; educ.=lower; hh-income<€3000; no pub-tr. card; bike=none; weekday; off-peak; 6AM-12AM; trip purpose=leisure; Ta>20≤25˚C; CI≥.75

d Mediator transport mode is walk (yes vs. no) in walking model, bicycle (yes vs. no) in cycling model, etc.

Mean Square Error of Approximation (RMSEA) well below the critical .05 level and Comparative Fit (CFI) and Tucker Lewis indices (TLI) well above the critical .95 levels.

Mode choices

Table 5.2 presents the effects on transport mode choices in the first column of each model. Overall, the models explain the variance in transport mode choices relatively well (i.e. 65% for walking, 35% for cycling, and 40% for public transport and car usage), for instance when compared to other Dutch studies (e.g. Sabir, 2011: 32%; Böcker et al., 2013b: 16%).

The relatively high explained-variances in this study may be contributed to the inclusion of a detailed set of weather conditions, personal attitudes, and trip specific details (i.e. travel companion and route-environmental attributes) in addition to the standard control variables. In this paper we will focus on the effects of weather conditions on mode choices. The effects of other socio-demographic, socio-economic, transport resource and trip-specific background variables on mode choices are largely in line with earlier studies (e.g. Cervero and Seskin, 1995; Dieleman et al., 2002; Bühler, 2011).

When controlled for all of the above, weather appears to have a relatively modest impact on mode choices. On the plus side, because of this controlling the remaining effects reflect better the true effects of weather on mode choices. In line with our descriptive findings and earlier studies (e.g. Aaheim and Hauge, 2005; Sabir, 2011; Creemers et al., 2014), precipitation sum ($P_{(sum)}$) has a negative effect on cycling and a positive effect on public transport usage. Wind speed (W_s) and snow cover have no significant effects. Also daytime sky clearness (Clearness Index –CI) does not have a clear significant effect on transport mode choices. Only during darkness, when CI values cannot be estimated, we observe an increase in car usage at the cost of cycling. A reason could be that the car is relatively more comfortable, faster and safer during darkness. Finally, air temperature has a nonlinear effect on transport mode choices. Lower air temperature intervals, when compared to the optimal 20-25°C riding temperature, have a negative effect on cycling and a positive effect on walking and public transport usage. However, not only lower but also higher air temperatures above 25°C may negatively affect cycling, although this effect cannot be statistically confirmed. This may indicate a negative impact of heat on cycling found in some earlier studies (e.g. Lewin, 2011; Ahmed et al., 2010).

Thermal perceptions

Table 5.2 presents the effects on subjective outdoors thermal perceptions in the second column of each model (indicated by 'Tfeel'). In accordance with the SEM modelling framework (Figure 5.3), thermal perception is regressed on personal attributes, weather conditions, and the mode choice. Socio-economic factors, transport resources and trip attributes are not expected to influence the way people perceive outdoor thermal conditions. The effects of trip environments on thermal perceptions were tested, but were found non-significant and reduced the model fit. These paths have therefore not been specified. Overall, the models explain a large share of the variance in thermal perceptions (around 69%).

Most of the variance in thermal perceptions can be explained by a combination of observed weather conditions. Obviously, a dominant relationship exists between air temperature and thermal perception. Under lower air temperature intervals people perceive thermal conditions as colder, under air temperatures above 25°C people perceive air temperatures as hotter. Additionally, however, thermal perceptions are affected positively by sky clearness and negatively by wind speed and precipitation. It is thus the combination of higher air temperatures, sunshine, dry and/or calm weather that makes people perceive thermal environments as warmer, and the combination of low air temperatures, cloudy, dark, wet and/or windy weather that makes people perceive thermal environments as colder. These findings are in line with several thermal comfort studies on urban park attendances (e.g. Thorsson et al., 2007), but are now confirmed for everyday travel.

Section 4.1 briefly explored the discrepancy between observed and experienced thermal conditions. Table 5.2 confirms our expectation that thermal experiences during travel differ between different people. Our findings are in line with existing biometeorological insights that women (e.g Karjalainen, 2012; Kenawy and Elkadi, 2012) and older age groups (e.g. Tuomaala et al., 2013) experience thermal environments overall as colder and less comfortable than men or younger age groups. Compared to native Dutch people, people with a non-western ethnicity, often originating from warmer climate backgrounds, have colder thermal experiences, however this effect is non-significant. This non-significance may be related to the relatively small share of non-western ethnicities in the sample (10,4%). In line with e.g. Tuomaala et al. (2013), obesity was not found to influence thermal conditions. Finally, weather preferences seem to play a role. People who reported summer as there favourite season perceive thermal conditions as colder, than those who have other favourite seasons. In contrast to Eliasson et al. (2007) we could not statistically confirm a difference in thermal sensation between urban and rural-oriented people.

In line with our expectations transport mode choices significantly affect the way people perceive thermal conditions. Weather-exposed active mode users, especially cyclists, perceive colder air temperatures as colder and therefore less comfortable than users of motorised modes. Especially the weather protected and climate-controlled car user seems to experience less discomfort related to cold weather conditions. Unfortunately, because of the limited sample of extremely warm days in our data, we were not able to run a separate SEM model specifically for hot days to investigate whether during hot weather these relationships would be the same. However, additional descriptive comparisons give an indication that during hot weather (above 25°C) different transport mode users' thermal experiences are more similar.

Emotional travel experiences

Table 5.2 presents the effects on the construct of emotional travel experiences in the third column of each of the four models. As pointed out in the factor model at the top of Table 5.2, emotional travel experience is constructed on the positively loaded item happiness and the negatively loaded items irritation, fear and tiredness. The models explain less of the variance in emotional travel experiences (around 13%) than of the variances in transport modes and thermal perceptions. This comes as no surprise, as emotional experiences may be affected by many other factors not included in the model.

First, we will investigate the effects of personal backgrounds on emotional travel experiences. This analysis shows that emotional travel experiences differ between people. Men and older people report more pleasant emotions than women and younger people. These findings are in line with meta-analyses in the field of subjective well-being, which report modest but significant positive effects of age (e.g. Stock et al., 1983) and amongst men (e.g. Haring et al., 1984; Inglehart and

Rabier, 1986), although others found no significant gender or age effects (for an overview see Diener et al., 1999). Additionally, reported emotional travel experiences are less positive amongst lower income groups – in congruence to e.g. Clark and Oswald (1996) and Ferrer-i-Carbonell (2005) – and amongst higher educated. The latter may be related to more demanding study or job responsibilities, higher stress levels, hastier travel patterns and/or increased multitasking, all of which may negatively impact on emotions during travel. When looked at personal attitudes, environmentally conscious people appear to have more pleasant emotions during travel, which could be related to a more harmonic or relaxed way of life.

In addition to personal backgrounds, Table 5.2 presents the effects of trip-characteristics. Most importantly, emotional travel experiences seem to be related to trip purpose. As expected, people experience more pleasant emotions during leisure trips as compared to social and especially errands trips. The more voluntary and potentially relaxed character of leisure may be a reason for this. Surprisingly, no significant differences can be identified between leisure and work trips. It could be that controlling for weekends and travelling during peak hour already captures this variation. As expected, people experience significantly less pleasant emotions on weekdays and during peak hour, although these effects are relatively small. Also longer distance trips lead to slightly less pleasant emotions, but this effect is only significant when controlled for whether or not people travel by public transport. Additionally, people experience marginally more pleasant emotions when travelling together. Travelling deliberately via a detour has no significant effect on emotional travel experiences. Also urban form characteristics of the trip environment have no significant effect on the way people experience emotions during travel. Although it should be mentioned that detailed data on spatial variation may have gone lost due to our spatial matching process – i.e. the lack of route information, buffer size, and aggregation of spatial characteristics over the course of entire trips.

Also weather affects emotional travel experiences. Unlike most existing studies, who look at the direct effects of weather on long-term moods (e.g. Cunningham, 1979; Denissen et al., 2008), we identify how weather affects short-term emotional experiences during travel: directly, as well as indirectly, via thermal sensation. Regarding the *direct* effects of weather parameters on emotions, the model confirms the descriptives and the literature. In line with several studies on the relationships between weather and mood (e.g. Cunningham, 1979; Albert et al., 1991; Denissen et al., 2008; Ciucci et al., 2011), low sky clearness indices representing cloudy weather result in less pleasant emotional travel experiences, while sunny weather conditions – known for increasing happiness-enhancing serotonin in the brain (e.g. Lambert et al., 2002; Lansdowne and Provost, 1998) – lead to more pleasant emotions. Also during darkness, when sunshine is absent and sky clearness cannot be calculated, people experience less pleasant emotions. The latter may also be related to possible tiredness during early mornings and late evenings, or potential reduced feelings of safety in the dark. As expected, and in congruence with Schwartz and Clore (1983), Denissen et al. (2008) and Barnston (1988), precipitation and wind speed negatively affect emotional experiences, although the effect of wind speed cannot be statistically confirmed. When it comes to the direct effects of air temperature, hot weather (above 25°C), has a negative effect on emotions during travel. This gives evidence for a negative impact of heat on emotional well-being as indicated by few studies on weather and moods (e.g. Schneider et al., 1980; Bell, 1981). Colder air temperatures have no direct significant effect on emotions. Instead, temperature affects emotion mostly *indirectly* via thermal perception. Colder thermal perceptions strongly negatively affect emotions during travel. Also wind speed, precipitation sum and low sky clearness have indirect negative effects on emotional travel experiences via lower thermal perceptions, in addition to their earlier discussed direct effects.

When comparing the four different models, it appears that emotional travel experiences differ amongst different transport mode users. As for the effects of weather, both direct and indirect mechanisms can be identified. *Directly*, public transport users experience less pleasant emotions, compared to the other transport modes. This is in line with literature reporting the lowest travel satisfaction amongst public transport users compared to other transport modes (e.g. Friman et al., 2013). However, we observe no positive effect of car usage on emotional travel experiences, as indicated by existing studies mentioning the pleasure, comfort and freedom associated with car usage (e.g. Mokhtarian and Salomon, 2001; Steg, 2005; Jakobsson, 2007; De Vos et al., 2013). In contrast to existing studies (e.g. Friman et al., 2013) our SEM model reveals no significant *direct* effect of the use of active transport modes on emotional travel experiences. *Indirectly* however, weather-exposed active mode users, because they experience thermal environments as colder and less comfortable, have less pleasant emotional travel experiences. On the other hand, car users benefiting from more self-created comfortable thermal environments experience indirectly more pleasant emotions.

5.5 Conclusions and discussion

With climate change adaptation and mitigation high on scientific and political agendas, over the last decade many studies investigated the effects of weather on travel behaviour, especially on the use of healthy, environmentally friendly, congestion reducing, but weather-exposed active transport modes. However, in these existing transport studies, subjective experiences of both weather conditions and emotions during travel have been largely underexplored. It was our aim to investigate how and to what extent weather conditions affect transport mode choices, thermal perceptions and emotional travel experiences. Hereto, greater Rotterdam (The Netherlands) diary data on travel behaviour and ecological momentary assessments (e.g. Moskowitz and Young, 2006) of thermal perceptions and emotions during travel, connected to local urban form and weather data, were analysed in structural equation models (SEM).

By integrating biometeorological and wind engineering knowledge on weather comfort and psychological knowledge on weather and moods into the context of travel behaviour, this paper makes two important theoretical contributions to the existing transport literature. First, while controlling for the effect of weather on transport mode choices – i.e. warm, but not too hot, calm, dry and sunny weather conditions stimulate cycling over motorised mode usage (especially public transport) – our findings demonstrate that weather conditions and weather perceptions form an integral part of the emotional travel experience. Two important mechanisms are revealed: A *direct* mechanism demonstrated by the negative effects of precipitation, wind speed and cloudy or dark sky conditions on emotional travel experiences, which indicates the role of *mechanical (dis) comfort* associated for instance with the threat of clouds, the effort of moving against the wind, the discomfort of getting wet or having wind blown in your face, or worse, combinations of the above. An *indirect* mechanism, mediated by thermal perceptions, highlights the role of *thermal (dis)comfort*, which is associated with increased air temperature and decreased precipitation, sky clearness and wind speed. This results in warmer thermal perceptions while travelling, and by that in more pleasant emotions. For temperatures above 25°C the effects are trickier: although positively contributing to warmer thermal perceptions and therefore indirectly to more pleasant emotional experiences, we also observe a compensating direct negative effect on emotions, which indicates a neutral or potentially negative effect of heat on emotions.

Second, our findings demonstrate that thermal perceptions – which show discrepancies with objectively measured weather conditions – and emotional travel experiences differ across transport mode user groups and population categories. Again direct and mediated effects can be distinguished. Directly, public transport users have less pleasant emotional travel experiences, especially when compared to active transport modes. Additionally, pedestrians and especially cyclists, being highly exposed to air temperatures, wind and precipitation, perceive thermal travel environments as colder and less comfortable, which indirectly affects their emotional experiences. On the contrary, car drivers, travelling inside weather-protected and often climate-controlled indoor environments, experience less discomfort related to cold and have indirectly more pleasant emotional travel experiences. Besides transport modes, also personal backgrounds affect thermal perceptions and emotional travel experiences. For instance, women and older people perceive thermal travel environments as colder, which indirectly affects negatively their emotional travel experiences.

The insights generated in this paper are valuable for policy makers in several ways. When aiming to stimulate the use of sustainable but environmentally-exposed active transport modes, it is more important than for car or public transport policies, to look beyond instrumental factors, such as time and financial costs, and pay close attention to weather- related perceptions and emotions. In this research this has become clear via the observation that active mode users' thermal perceptions and emotional experiences appear more strongly affected by weather than those of motorised modes. This implies that in cities, in which people have become increasingly mobile and travel constitutes a relatively large share of daily life, factors that contribute to pleasant or unpleasant emotional travel experiences have direct implications for the quality of urban living. Especially our findings that hot weather and precipitation may negatively impact upon emotional travel experiences, already at present, should be accounted for into adaptive urban planning strategies for a projected warmer future climate with increases in heavy precipitation. This can be achieved through the implementation of climate-sensitive urban design strategies, such as the consideration of shadowing and ventilation effects of street layouts or the use of heat-alleviating deciduous trees (e.g. Konarska et al., 2014), or the provision of (vegetated) walls and roofs as shelters from wind and precipitation. Moreover, we advise policy makers and urban planners to expand such climate-sensitive urban design strategies from its general uses in landscape architecture and specifically implement it into public places and along infrastructures that are frequented by weather-exposed active mode users and climate-vulnerable societal groups like elderly people.

Further research is recommended to advance the integrated interdisciplinary knowledge presented in this paper in several directions. First, studies may further explore the complexity of causalities between weather perceptions, emotional experiences and travel behaviour. For instance it may be explored whether travel behaviours not only affect, but are also affected by, weather perceptions and emotions. Hereto, studies with a similar ecological momentary assessment methodology of repeated connected measurements may more explicitly use the longitudinal structure of the data and for instance relate transport mode choices at one point in time to experiences at previous points in time. Second, studies may further elaborate on the different weather exposures between social groups; especially the effects on potentially vulnerable target populations, such as elderly, young people, or ethnic groups, each with their distinctive sensitivities and preferences towards weather and mobility. Third, empirical studies from different cultural and climatological backgrounds are needed to verify our findings in different climate contexts. For instance, peoples' weather perceptions and emotional or behavioural responses to weather, may differ considerably in warmer climate regimes where people deal with heat, not occasionally, but during the course of entire seasons, for instance through developing habits like having a siesta. Fourth, in addition to global climate differences, studies should investigate different behavioural and emotional responses to weather on smaller geographical scales (i.e. between regions, cities, neighbourhoods or even streets) and link these differences to local (urban) microclimate conditions, due to for instance built densities, land use designs, water and vegetation patterns (e.g. Steward and Oke, 2012). Finally, it may be investigated if, and to what extent, the here explored effects of weather on comfort and emotional travel experiences are reflected in people's attitudes towards transport modes. For instance, one may generally dislike public transport, but prefer it to cycling when it is cold, rainy or windy. If this is the case, such knowledge could benefit policy makers to better predict and guide transport mode decisions under various present and future climate conditions.

6 En-route weather and place valuations for different transport mode users.

Lars Böcker, Martin Dijst, Jan Faber, Marco Helbich, Utrecht University
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Abstract

With the increasing societal interest in climate change, mostly separated strands of literature have investigated the travel-behavioural, thermo-sensational and environmental-psychological effects of weather on people in everyday life. This research conceptually and statistically integrates these fragmented insights. Drawing on unique Greater Rotterdam (The Netherlands) travel diary data enriched with hourly meteorological and spatial route attributes, we analyse how weather affects different transport mode users' en-route place valuations in terms of liveliness, friendliness and aesthetics. Our main findings indicate that windy, cloudy, cold (<15°C) or to hot (≥25°C) weather conditions negatively affect en-route place valuations, either directly or through lower thermal comfort. Active mode users generally value their route surroundings more positively than motorised transport modes, however they also appear more strongly affected by weather in their thermal experiences and place valuations. Policy makers are advised to expand climate-sensitive urban planning along active transport mode infrastructures.

Keywords: Weather, thermal comfort, mode choice, place valuation, Netherlands

6.1 Introduction

With climate change high on the political agenda, weather and climate have emerged as important topics in travel behavioural research and transport planning. On the one hand, transport forms an important contributor to climate change through greenhouse gas emissions (e.g. Chapman, 2007). On the other hand, as of its direct exposure to weather, the transport sector is also highly affected by climate change (e.g. Koetse and Rietveld, 2009). In this light, various studies investigated the effects of weather on daily travel behaviours, including choices for active and motorised transport modes, destinations and travel distances (for detailed reviews see Koetse and Rietveld, 2009; Böcker et al., 2013a). While most of these studies focus on objective weather and behaviour, much less is known on how weather is subjectively experienced and how it affects the experience of place during travel. Exactly this knowledge, on subjective experiences of weather and place during travel, is crucial to better understand transport mode decisions and to support *climate-sensitive urban planning* (Eliasson et al., 2007; Lenzhölzer and Wulp, 2010) – especially with regard to the facilitation of infrastructures for healthy and sustainable, but weather-exposed, active transport modes.

The relationships between weather, travel and subjective experiences of weather and place, have been addressed in three separated strands of literature. First, transport scientists have investigated the *travel-behavioural* effects of objectively measured weather conditions on transport mode choices. Studies generally conclude that cold, cloudy, wet and windy weather conditions stimulate motorised transport, while warm, sunny and dry weather conditions increase usage of active modes – with typically larger effects for leisure than for utilitarian trips (e.g. Hanson and Hanson 1977; Sabir 2011; Creemers et al., 2014). Regarding temperature, some studies added that not only cold, but also hot weather above optimums between 25-30°C may negatively affect walking (Aultman-Hall et al., 2009) and cycling (e.g. Ahmed et al., 2012; Lewin, 2011; Miranda-Moreno and Nosal, 2011).

A second set of, mostly biometeorological, studies have investigated the *thermo-sensational effects* of objectively observed weather conditions on subjective weather experiences. It is indicated that we experience thermal (dis)comfort as a combination of different meteorological variables, including air temperature, wind speed, humidity and solar radiation. However, studies also observe considerable discrepancies between measured and subjectively experienced weather (e.g. Nikolopoulou and Steemers, 2003), which could be related to personal or cultural backgrounds (e.g. Knez and Thorsson, 2006; Thorsson et al., 2007), clothing and physical activity levels (e.g. Havenith et al., 2002) or site-specific spatial configurations. Green, shadowed and/or wind-exposed environments are generally perceived as colder than concrete, sunlit and/or wind-sheltered environments (e.g. Nikolopoulou and Lykoudis, 2007; Phung and Rose, 2008; Lenzhölzer and Wulp, 2010).

A third, but very limited, selection of studies investigates the *environmental-psychological effects* of weather on place perception and valuation. From a philosophical viewpoint Yuriko Saito (2005:160) explores the multisensory effects of weather on aesthetic experiences of everyday environments: "Our experience of a fierce autumn wind is not simply the feeling of wind against our body; the way in which fallen leaves swirl around, the dynamic swaying of tree branches, the rustling sound they make, the slightly musty smell coming from half-decaying leaves accumulated on the ground, and the rapid movement of clouds all contribute toward our experience of this windy weather". Some quantitative studies also investigated the role of weather or seasonality on experiencing aesthetics. Mambretti (2011) finds that two urban parks in Zurich, Switzerland, are experienced as more beautiful during spring and autumn, compared to summer and winter. Two studies from Gothenburg, Sweden, link aesthetics directly to weather. Eliasson et al. (2007) conclude that urban parks are experienced as more beautiful with higher air temperatures and lower wind speeds, while Knez et al. (2009) find no significant effects of weather conditions on aesthetic experiences. Apart from aesthetics, also social aspects of place valuation (Cattel et al., 2008) may be affected by weather. Pleasant mild to warm, sunny, dry and calm weather conditions may enhance social interactions, liveliness, friendliness and safety in outdoor public space, as these conditions increase the outdoor presence of people (e.g. Zacharias et al., 2001; Thorsson et al., 2007; Lin, 2009) and positively affect emotions (Kööts et al., 2011).

So far, despite recent calls for a more interdisciplinary approach (Eliasson et al., 2007; Böcker et al., 2013a), insights into the interdependencies between the above-outlined three strands of literature are lacking. It is this paper's aim to integrate these separated insights both conceptually and statistically. This way we examine how weather experiences, mode choices and en-route place valuations influence and compensate each other. We analyse the direct and mediated (by thermal comfort) effects of hourly air temperature, precipitation sum, wind speed and sky clearness on different transport mode users' en-route place valuations in terms of liveliness, friendliness and aesthetics, while controlling for various personal, trip, temporal and spatial attributes (i.e. address density, building diversity, percentage green). Hereto, we analyse unique travel diary data from a panel study amongst 945 Greater Rotterdam respondents (The Netherlands), enriched with spatial and meteorological data, by means of Structural Equation Models. The paper first describes the study area and methods used. The results section describes and explains the model outcomes. A concluding section summarizes and discusses the main findings and draws implications for future research and policy regarding the role of climate-sensitive urban planning.

6.2 Research design

6.2.1 Study area and data

This study is situated in Greater Rotterdam, the Netherlands (Figure 6.1). This coastal harbour region is part of the Randstad conurbation: the densely populated and economically vital metropolitan region, which in addition to Rotterdam contains the cities of Amsterdam, The Hague, and Utrecht. The region has a maritime climate, characterised by mild winters (lows: 1°C; highs: 6°C), warm summers (lows: 12°C; highs: 21°C), and relatively stable seasonal precipitation patterns (ranging from 158mm in spring to 258mm in autumn) (KNMI, 2013). Greater Rotterdam was selected for this study because of three reasons: First, the area consists of a large variety of spatial environments, ranging from largely post-WWII mid- and high-rise inner-city areas, to compact historic towns and newer lower-density satellite towns and villages in the outskirts. Second, the area has rich population diversity in terms of age, ethnicity and socio-economic status. Third, the region pursues active policy on sustainable transport and climate-sensitive urban planning.

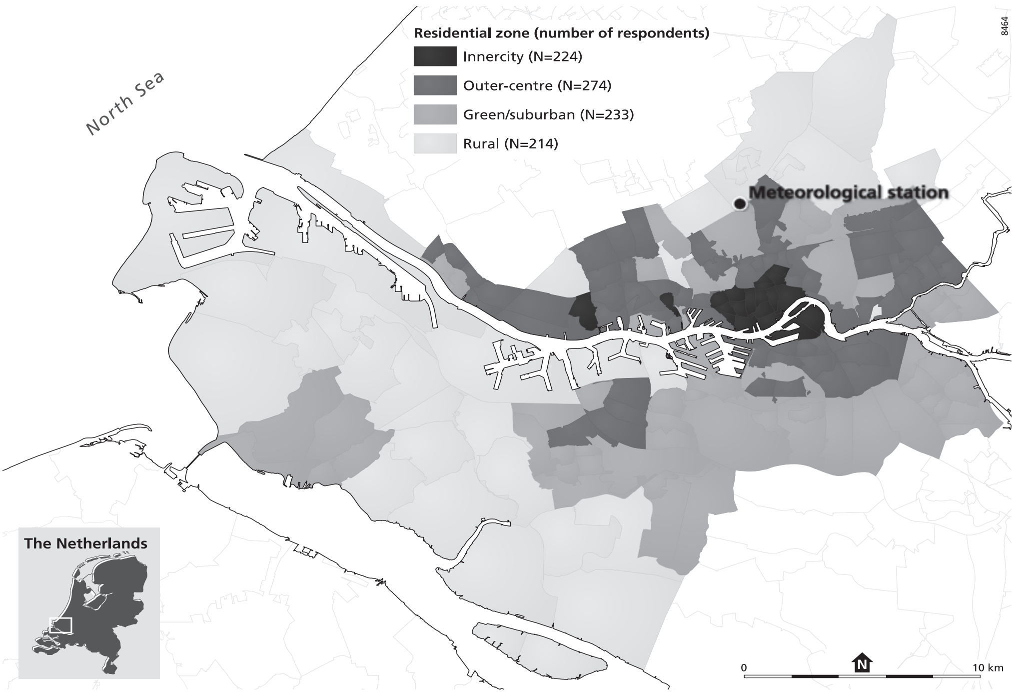

Figure 6.1 Greater Rotterdam study area. Source: Böcker and Thorsson, 2014. Administrative level: 4-digit postal codes.

We conducted a travel diary survey (used in two earlier studies: Böcker and Thorsson, 2014; Helbich et al., 2014) from August 2012 to February 2013 amongst 945 respondents, aged 18 and older, from different Greater Rotterdam residential environments (Figure 6.1). Respondents were randomly assigned two regular[8] days in summer, two days in autumn and two days in winter, to report their travel behaviours and experiences, first on-site in travel diaries and later online. We oversampled for non-native Dutch and older age groups (≥65 years) in anticipation of lower response rates for these groups. Our sample represents the Greater Rotterdam population relatively well on several key socio-demographic statistics like age, gender and household size (CBS, 2013), except for an underrepresentation of lower educated and non-native Dutch people (for more information on the sample composition, see Böcker and Thorsson, 2014).

Next, the travel survey data are enriched with spatial route attributes. Hereto, trip origin and destination addresses are geocoded via Dutch cadastral data (2014) on a 6-digit postal code level, containing roughly 17 addresses per spatial unit. Utilizing a geographic information system (GIS) and 2008-street data provided by ESRI, origins and destinations are linked along the street network using shortest-path analysis. Following Schlossberg et al. (2006), each trip path has been buffered with a radius of 200m. This 200m buffer is large enough to capture the area had people taken slightly different routes, while it is small enough to capture mostly the nearby surroundings in a direct line of sight that are most relevant to the traveller. Subsequently, route specific attributes describing the traversed environments are extracted. Hereto, each trip buffer is intersected with a grid having a spatial resolution of 100m superimposed on the study area. This spatial scale keeps GIS computation time modest, while details about local urban form elements remain preserved (e.g., open spaces). For each cell three indicators are extracted: building usage diversity, address density, and greenness index. The building usage diversity refers to the mix of building usages (i.e. office, shop, public service, etc.) and is operationalized based on the Shannon index. A Shannon index value of 0 refers to a cell with only 1 building usage while higher values represent cells in which building usages are more diverse. Address density refers to number addresses (residential and non-residential) per cell. Greenness index[9] refers to the surface-area proportion of green space.

Finally, the travel survey data are linked to hourly meteorological records obtained from a Royal Dutch Meteorological Institute measurement station (KNMI, 2013) located inside the study area, just north of Rotterdam (Figure 6.1). We include in our analysis the effects of hourly average wind speed (in m/s), precipitation sum (in mm) and air temperature (in °C)– the three most commonly used meteorological variables in existing studies. Additionally, we analyse the effect of the hourly clearness index: the ratio between the observed and the theoretical maximum incoming solar radiation given the specific time and location on the earth's surface (Crawford and Duchon, 1999). High values (closer to 1) represent clear sky conditions, while lower values (closer to 0) represent cloudier weather. Finally, we control for whether or not snow-cover has been accumulated on the ground, as this may have direct effects on travel activities as well as place valuations. Figure 6.2 provides a brief background of climate conditions during the survey period. Late August (with a peak of 34°C), early September and late October had above average temperatures ($T_{a(max)}$ observed, compared to the 1980-2010 normal) and were relatively sunny. December was relatively warm too (+10°C), but very wet. In contrast, mid-January was very cold with snow, ice and daily maximums well below 0°C.

8 Regular days contain both weekdays and weekends, but exclude periods in which the respondent was ill or on holiday, in which case new days were assigned.

9 Building usage diversity and address density are extracted from the 2014-dataset 'Basisregistraties, Adressen en Gebouwen (BAG)'. Greenness is extracted from the 2001-dataset 'Landelijk Grondgebruiksbestand Nederland (LGN)'.

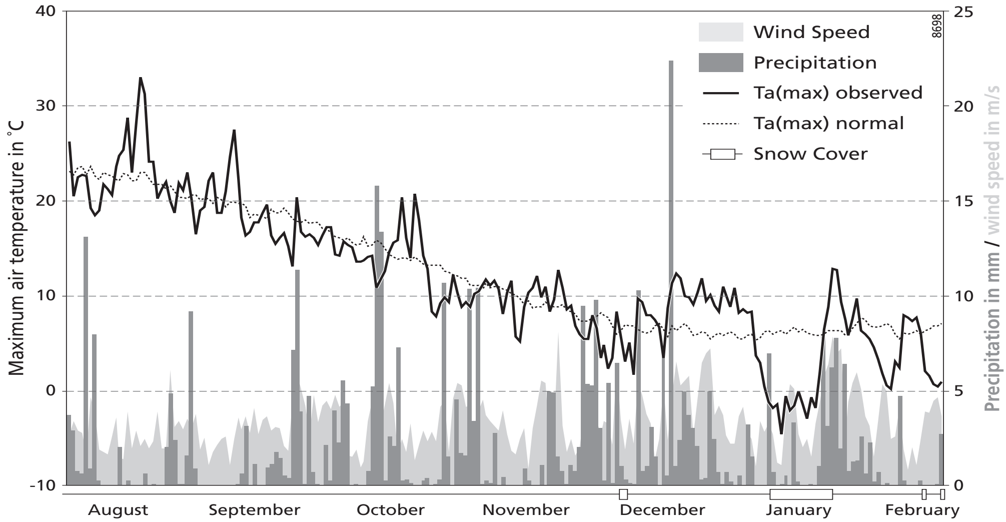

Figure 6.2 Rotterdam weather conditions during survey period . Source: Helbich et al., 2014

6.2.2 Multivariate modelling techniques

One of our ambitions in this paper is to statistically integrate the behavioural, thermo-sensational and environmental-psychological mechanisms when mediating the effects of weather on en-route place valuations. A major complication is that, apart from a large set of independent personal, spatiotemporal and weather variables, we have not one, but three interrelated dependent variables: transport mode choice, thermal experience, and en-route place valuation. In the multivariate part of the analysis, we therefore make use of Structural Equation Modelling (SEM), via the software package Mplus. Unlike regular regression, SEM allows for multiple dependent variables in one model and also accommodates mediating mechanisms that connect the three interrelated dependent variables.

SEM basically consists of two parts combined into one analysis: a *factor model* and a regression model. The factor model constructs our dependent variable en-route place valuation, based on the three items covering both physical and social appeals of place: aesthetics, liveliness and friendliness. Hereto we asked respondents to rate on 5-point Likert scales their overall impression of spatial route surroundings from ugly to beautiful; dull to lively; and distant to friendly. A principal component analysis was conducted before, revealing a one-factor solution in which all three items are positively loading. In the *regression model* we analyse the effects of the independent personal (e.g. age, gender, ethnicity), socio-economic (e.g. income, education), transport resources (e.g. car/bicycle ownership), spatiotemporal (e.g. week/weekend, peak/off-peak, and the earlier discussed spatial attributes), trip (e.g. purpose, distance) and weather variables on mode choice, perceived temperature and en-route place valuation, as well as the relationships between the three dependent variables. Causality between the three dependent variables is conceptualised theoretically. Perceived temperatures and en-route place valuations during the trip are treated as consequences of the mode choice decision made in advance. En-route place valuations are analysed as a consequence of perceived temperatures, because biometeorological research indicates the importance of the thermal environment in general comfort levels (e.g. Thorsson et al., 2007; Knez et al., 2009) and place assessment (Eliasson et al., 2007).

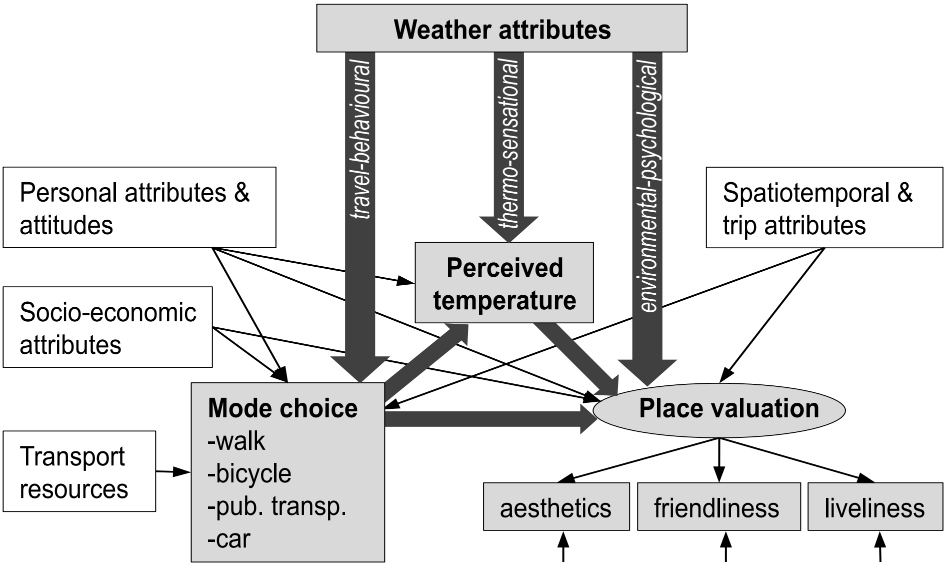

Figure 6.3 SEM conceptual model

Based on these causalities the conceptual model in Figure 6.3 has been specified. Because of the hierarchical nature of the panel data, we applied a clustered sampling technique, which estimates robust standard errors for all observations (trips) belonging to the same cluster (respondent), and lifts the constraint that all observations need to be independent.

6.3 Results

6.3.1 Descriptive results

First, we will explore how people's subjective en-route place valuations are related to objective spatial route characteristics (Figure 6.4). It appears that green route environments are valued higher in terms of aesthetics. This is congruent with studies indicating the direct aesthetic qualities of urban parks and green spaces (e.g. Sheppard and Harshaw, 2002; Smardon, 1998). Although less pronounced than with aesthetics, greener routes are also experienced as friendlier. A reason could be that green areas invite active mode users to socially interact (Hansmann et al., 2007 and Korpela et al., 2014). The relationship between greenness and liveliness is less clear: green areas and areas with a lack of green are experienced equally lively. In contrast to green areas, routes with higher address densities and building diversities – are perceived as less aesthetic. These reduced aesthetics could be related to a lack of green space in urban environments, but may also be related to the lack of aesthetically attractive historic inner-city areas in Rotterdam, due to major Second World War bombings, On the plus side, denser and more diversely built environments are valued higher in terms of liveliness, possibly thanks to more people (Carmona et al., 2003; Cattel et al., 2008), objects, sounds and smells in busy urban environments. These more diverse and densely built environments are valued as slightly less friendly, which could be related to a faster and/or more individualised life in the city compared to the countryside.

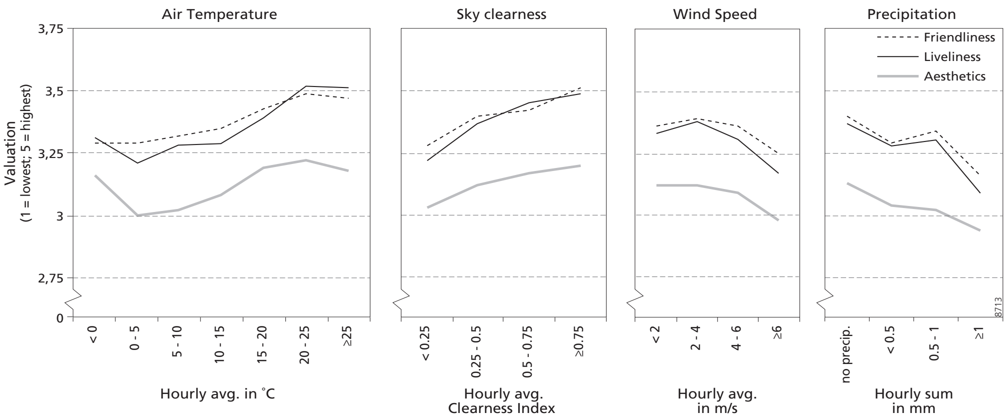

Figure 6.4 Valuation of different route environments

Figure 6.5 indicates the effects of hourly weather conditions on en-route place valuations. Overall, aesthetics are valued lower than liveliness and friendliness. Nevertheless, when considering the slopes of the graphs, it appears that weather conditions have a relatively similar effect on all three items of place valuation. Overall, people's en-route place valuations increase with higher hourly air temperatures and sky clearness, and decrease with precipitation and wind speeds above 4 m/s. The observed positive effect of air temperature and negative effect of wind speed on experienced aesthetics are congruent with Eliasson et al., 2007. Weather effects on experienced liveliness have not been studied before, but could be explained from increased outdoor presence of people during warm, dry, calm and sunny weather conditions (e.g. Zacharias et al., 2001, Thorsson et al., 2007; Lin, 2009).

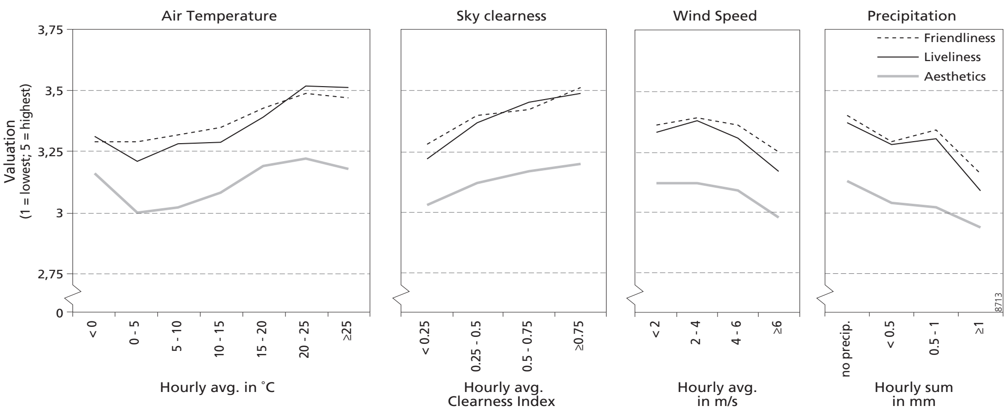

Figure 6.5 Weather and en-route place valuation

The effects of weather on en-route experiences could also be mediated by people's emotional states (Knez et al, 2009). From another study we know that dry, sunny, calm and warm but not too hot weather leads to more positive emotions during travel (Böcker et al., forthcoming). These positive emotions may make spatial surroundings look more beautiful, and may also result in more and more-pleasant social interactions with travel companions or strangers and, hence, higher valuations of liveliness and friendliness. Regarding air temperature, Figure 6.5 demonstrates that valuations of place aesthetics, friendliness and liveliness, are relatively positive during sub-zero temperatures, while flattening out or even turning negative above 25°C. The first could be related to the long period of cold, but attractive sunny and snow-covered winter weather mid to late January 2013. The latter could indicate a potential negative effect of heat on comfort levels (e.g. Zacharias et al., 2001, Nikolopoulou and Lykoudis, 2007; Lin, 2009), which may mediate en-route place valuations (e.g. Eliasson et al., 2007; Knez et al., 2009).

6.3.2 Multivariate results

Table 6.1 presents four full-sample structural equation models, which are identical except that each contains another dependent variable for mode choice. The four models contain three columns, which present the standardized coefficients and their significance levels for the three dependent variables mode choice, perceived temperature (Tfeel), and en-route place valuations (Place-v). The factor model indicates that all items load positively on en-route place valuations. Specified according to the arrows in Figure 6.3, the regression model contains the effects of weather along with other independent variables on the three dependent variables, as well as the mediating effects between the dependent variables: perceived temperature on en-route place valuations; and mode choice on perceived temperature and en-route place valuations. All models fitted well, with Root Mean Square Error of Approximation (RMSEA) values well below the critical level of 0.05 and Comparative Fit Index (CFI) and Tucker Lewis Index (TLI) values around or above 0.95.

Mode choices

Indicated by the R2 values, the models specified in Table 6.1 explain transport mode choices relatively well[10]: 65% of the variance in walking, 35% in cycling, 39% in public transport and 38% in car usage. Before we turn to the effects of weather on mode choices, first the effects of other independent variables will be briefly summarised. According to our expectation and in line with the literature (e.g. Seskin and Servero, 1996; Dieleman et al., 2002; Bühler, 2011), the most important predictors of transport mode choices are transport resources, trip distance, trip purpose, and whether people are travelling alone or in company. The number of cars in the household increases car usage; public transport card membership increases public transport usage and cycling; and bicycle ownership (particularly of sports or electric bikes) increases cycling over car usage. Short-distance trips are more often performed by active modes; long distance trips more often by motorised modes. Regarding trip purposes, leisure trips have a relatively high share of walking and a relatively low share of car usage; work trips a relatively high share of motorised modes. Compared to car users, cyclists are more likely to travel alone.

Other background characteristics, such as socio-demographics and spatiotemporal trip environments have a smaller impact on mode choices. Nevertheless some significant effects can be identified: Non-western immigrants cycle less; older people cycle less and travel more by foot and

10 For instance compared to earlier Dutch studies taking into account the effects of weather, but not in relation to subjective experiences of place and weather (e.g. Sabir, 2011; Böcker and Thorsson, 2014).

Table 6.1 Full-sample structural equation models for the different transport modes

	SEM: Standardized coefficients: estimator=WLSMV$_a$, cluster=person-id$_b$, N = 11759 trips											
	Model 1: Walking			Model 2: Cycling			Model 3: Public transport			Model 4: Car		
	Walk	Tfeel	Place-v	Bicycle	Tfeel	Place-v	Pub. tr.	Tfeel	Place-v	Car	Tfeel	Place-v
Factor model												
Aesthetics			.719			.723			.721			.723
Friendliness			.676***			.668***			.671***			.675***
Liveliness			.550***			.555***			.554***			.550***
Regression model$_c$												
Personal and attitudes												
Age	.071***	-.021	-.043	-.114***	-.028**	-.018	-.067	-.020	-.034	.064**	-.024*	-.017
Male (D)	-.037*	.035***	-.002	-.069*	.032**	-.001	.058	.035***	-.005	.079***	.033**	.008
Nonwestern ethn. (D)	.005	-.007	.011	-.073**	-.010	.020	.069**	-.008	.015	.018	-.007	.016
BMI: Obese (D)	-.062***	.007	-.031	-.057*	.005	-.036	.007	.008	-.042	.106***	.004	-.020
Summer person (D)	.019	-.022*	-.029	-.014	-.023*	-.024	-.005	-.022*	-.026	.017	-.023*	-.021
Environm. conscious	.028	-.005	.043	.094***	-.001	.038	-.019	-.005	.047*	-.095***	-.002	.028
Rural-oriented	-.026	.017	-.029	.074**	.021*	-.042	-.039	.018	-.036	-.014	.018	-.036
Socio-economic												
Educ. middle (D)	-.026		-.065	.008		-.070*	.004		-.069*	.034		-.062
higher (D)	.019		-.087**	-.036		-.080*	-.087*		-.087**	.056		-.072*
Hh-income €3-4K (D)	-.015		.036	-.042		.037	.010		.034	.032		.039
>€4K (D)	-.017		.043	.010		.039	-.037		.038	.003		.040
unknown (D)	-.029		.045	-.011		.042	.045		.043	.007		.042
Transport resources												
# Cars in hh	-.043**			-.127***			-.258***			.261***		
Pub-tr. card (D)	-.001			.053*			.248***			-.177***		
Bike for city (D)	-.029			.294***			.025			-.124**		
sports/e-bike(D)	-.029			.350***			-.075			-.148***		
Trip attributes												
Travel together (D)	.012		.032	-.198***		.054**	.034		.036	.151***		.065***
Detour (D)	.051***		.073***	.030**		.079***	-.016		.081***	-.079***		.066***
Weekend (D)	.017		-.041	-.002		-.038	-.079**		-.042	.022		-.033
Peak hour (D)	.005		.009	.014		.008	.043*		.012	-.027*		.004
12AM-6AM (D)	.004		-.038***	.032**		-.040***	-.006		-.037***	-.025**		-.042***
Trip for work (D)	-.201***		-.152***	.017		-.188***	.147***		-.180***	.126***		-.161***
errands (D)	-.078***		-.059***	.014		-.074***	-.137***		-.079***	.121***		-.047**
social (D)	-.082***		-.071***	.018		-.087***	-.063**		-.088***	.118***		-.060***
Travel distance	-.717***		.086**	-.391***		.001	.168***		-.032**	.220***		.005
Trip environment												
Building diversity$_d$	.019		-.035	-.005		-.031	-.018		-.033	-.006		-.033
Address density	.068***		-.011	.000		.001	.043		.003	-.134***		-.027
Green % (log-transf.)	-.025		.028	.059**		.017	-.130***		.017	.025		.028
Weather												
Ta >25˚C (D)	.017	.144***	-.033*	-.005	.144***	-.031*	-.014	.144***	-.031*	-.003	.144***	-.033*
>15–≤20˚C (D)	.025	-.298***	-.025	-.026	-.299***	-.016	.076***	-.300***	-.018	-.030*	-.297***	-.023
>10–≤15˚C (D)	.031*	-.493***	-.064**	-.062***	-.496***	-.049*	.050*	-.495***	-.057**	-.002	-.494***	-.053*
>5–≤10˚C (D)	.031*	-.691***	-.081**	-.072***	-.694***	-.063*	.071**	-.693***	-.073**	-.008	-.691***	-.068**
>0–≤5˚C (D)	.002	-.557***	-.070**	-.064***	-.560***	-.058**	.009	-.557***	-.070**	.040**	-.559***	-.053*
≤0˚C (D)	.035	-.672***	-.039	-.025	-.673***	-.024	.033	-.673***	-.031	-.016	-.672***	-.027
Psum	.010	-.014**	-.039***	-.031*	-.016**	-.034***	.030**	-.015**	-.036***	.000	-.014**	-.037***
Ws	-.020	-.071***	-.020	-.014	-.072***	-.022	.034	-.072***	-.022	.026	-.072***	-.017
Snowcover (D)	.022	.000	.034	-.065	-.003	.045	.039	-.001	.040	.001	.000	.038
CI ≥.5–<.75 (D)	.004	-.026***	-.024	.024	-.025**	-.026	.047**	-.027***	-.021	-.026	-.025***	-.028
≥.25–<.5 (D)	.021	-.050***	-.039*	-.010	-.051***	-.034	.041	-.052***	-.033	-.009	-.050***	-.036*
<.25 (D)	.025	-.045***	-.038	-.006	-.046***	-.033	.012	-.046***	-.033	-.013	-.045***	-.036
darkness (D)	.002	-.059***	-.139***	-.067**	-.062***	-.131***	.020	-.059***	-.138***	.062**	-.061***	-.124***
Mediators												
Walk/bike/pub./car (D)$_d$		-.015**	.177***		-.049***	.105***		.025*	-.048		.038***	-.208***
Tfeel			.061*			.069**			.060*			.074**
Model quality												
Dep. var. R^2	.646	.692	.113	.349	.693	.109	.385	.692	.104	.381	.692	.133
Model Chi^2(df.)	286.799(130)***			289.150(130)***			270.867(130)***			298.347(130)***		
RMSEA / CFI / TLI	.013 / .972 / .947			.012 / .974 / .949			.012 / .973 / .948			.013 / .970 / .941		

a Estimator is Weighted Least Squares Means and Variance adjusted. Significance: *p<.1; **p<.05; ***p<.01

b Clustered sampling technique has been applied, which deals with the trip data that are clustered within respondents

c Reference categories for dummy variables (D): female; ethnicity=native-Dutch; BMI=not obese; favourite season is not summer; educ.=lower; hh-income<€3000; no pub-tr. card; bike=none; weekday; off-peak; 6AM-12AM; trip purpose=leisure; Ta>20≤25˚C; CI≥.75

d Mediator transport mode is walk (yes vs. no) in walking model, bicycle (yes vs. no) in cycling model, etc.

by car; and men and obese people are more likely to travel by car instead of active transport modes. In addition to classic socio-demographic factors, we also included in our models the effects of personal attitudes: people who highly consider the environment in everyday life choices (environm. conscious) cycle more often and make less use of the car; people oriented towards rural rather than urban amenities (rural-oriented) are more likely to cycle. Regarding trip environments, congruent with Seskin and Servero (1996) trips through densely populated areas have a relatively high share of walking and a relatively low share of car usage and trips through green areas have a relatively high share of cycling and a relatively low share of public transport.

Regarding temporalities, public transport shares are higher during peak hour and night-time trips have a relatively high share of cycling and a relatively low share of car usage. Unlike most existing studies, we included in our models also whether trips are made directly or via a detour. It appears that trips via a detour are more likely performed by active transport modes and less likely by car.

Weather appears to have a modest impact on mode choices. This modest impact is not surprising, because we introduced in our analysis many new control variables. This controlling ensures that the presented effects better describe the relationship between weather and mode choices. Some interesting significant effects appear. In congruence to the literature (e.g. Aaheim and Hauge, 2011; Sabir, 2011; Creemers et al., 2014) and the descriptives, lower air temperature (T_a) classes significantly reduce cycling shares, while the shares of walking and public transport increase. A negative parameter sign for temperatures above 25°C compared to reference temperatures of 20-25°C, although not significant, may even indicate a potential negative effect of heat on cycling, as found by several earlier studies (e.g. Ahmed et al., 2012; Lewin, 2011; Miranda-Moreno and Nosal, 2011). Precipitation sum ($P_{(sum)}$) positively affects public transport usage, mostly at the cost of cycling. The effects of wind speed (W_s) and snow cover are not significant. In contrast to the descriptives, sky clearness indicated by the Clearness Index (CI) does not have a clear significant effect on transport mode choices.

Perceived temperatures

The effects on subjectively perceived outdoor thermal conditions are presented in the second column of each of the four models in Table 6.1 indicated by "Tfeel". Subjectively perceived outdoor thermal conditions will be regressed on the independent personal and weather variables, as well as on the dependent variable mode choice (see Figure 6.1). Regarding the effects on perceived outdoor thermal conditions, the four models for the different transport modes are more or less similar and differ mostly with respect to the effect of the mediator transport mode. The explained variances for perceived temperatures are large (69%).

First of all, perceived outdoor thermal conditions appear to be strongly related to observed weather conditions. In comparison to the reference temperature 20-25°C, the lower an air temperature class, the more negative its standardized coefficient, while temperatures above 25°C show a significant positive effect. However, when controlled for this strong effect of observed air temperature, it appears that, with the exception of snow cover, also the other weather variables have strong significant effects. Congruent with several thermal comfort studies (e.g. Eliasson et al., 2007; Thorsson et al., 2011), increased cloudiness – indicated by lower Clearness Index (CI) classes – and higher wind speed lead to colder thermal experiences. In addition, and this has not been studied before, we also found that darkness and larger precipitation sum leads to colder thermal experiences.

In addition to the weather, several personal attributes and attitudes were found to influence thermal experiences. Women, older people and persons who indicated summer as their favourite season, all perceive thermal conditions significantly colder. These findings are congruent with biometeorological insights, indicating higher thermal cold discomfort amongst women (e.g. Karjalainen, 2012; Kenawy and Elkadi, 2012) and lower thermal sensation values for older age groups (e.g. Tuomaala et al., 2013). Obesity was not found to affect perceived temperatures, which is in congruence to earlier studies showing very marginal effects of body mass index (BMI) on thermal sensation (e.g. Tuomaala et al., 2013). The model also shows that people with a non-western ethnicity, often from warmer climate regimes, perceive thermal conditions as colder than native Dutch people, but this effect is not significant.

Finally, it appears that perceived outdoors thermal conditions are affected by mode choice. When cross-comparing the different transport mode models, it becomes clear that active transport mode users, especially weather-exposed cyclists, experience thermal conditions as significantly colder than the more weather-protected users of motorised transport modes. Of all transport mode users, car drivers, sheltered by the protected thermo-regulated environment of their private car, are directly affected by weather conditions only while walking from or towards their parked car. As a result they perceive outdoor temperatures as least cold.

En-route place valuation

The effects of en-route place valuations (Place-v) are presented in the third column of each model in Table 6.1. The R^2 values for en-route place valuations are lower than for the previous dependent variables. This is no surprise as place valuations are highly subjective and could be affected by many unknown external factors outside the model. Nevertheless, the models explain around 10-13% of en-route place valuations and some interesting significant effects can be identified. Before we turn to the effects of weather, we will first briefly summarise the effects of other background factors on people's en-route place valuations.

Descriptively we found that route environments have an effect on people's impressions of their travel surroundings in terms of aesthetics, liveliness and friendliness (§3.1). In contrast, address density, building diversity and percentage of green surface have no significant effect on the place valuation construct when tested multivariately. Also personal background characteristics have no clear significant effect on en-route place valuations. Only for education a significant effect can be observed. Higher and middle educated people seem to have a less positive impression of their travel surroundings than lower educated, possibly related to more critical assessments of place and aesthetics in general, or to hastier or more routinized travel patterns and/or multitasking, which could all result in less attention for spatial surroundings (e.g. Katz and Aakhus, 2002).

In contrast to the marginal effects of personal backgrounds and static spatial attributes, en-route place valuations are more significantly affected by dynamic attributes of trip environments, as well as by various situational trip attributes. People value their travel surroundings higher when accompanied by others, compared to when travelling alone. A reason could be that spatial experiences are enhanced when people can share them with others. Another reason could be that the very presence of acquainted fellow travellers distracts people's attention away from physical spatial surroundings. Subsequently, people's place-valuations might be affected by social interactions with fellow travellers, which may directly improve valuations of friendliness and liveliness. Place valuation is also higher during trips deliberately made via a detour. It could be that trips via a detour are often made via scenic or pleasant routes, selected specifically by the respondent for aesthetic qualities or qualities related to the social atmosphere.

Temporalities also matter. People value place more negatively during the night-time hours between 12am and 6am. Possible explanations could be related to reduced daylight and absence of people on the streets, which may affect aesthetics, friendliness or liveliness. No significant differences can be observed between weekdays and weekends, or between peak and off-peak travel. However, potential variations for these temporal aspects may be captured within the strong effects of trip purpose. People value their spatial surroundings much more during leisure trips than during errands, social and particularly work trips. There may be several reasons for this. From another study we know that people have generally more positive emotions during leisure trips (Böcker et al., forthcoming), which may subsequently mediate cognitive processes like place valuation (e.g. Blaney, 1986; Kuiken, 1991). Another reason could be that work or errands trips are often more of a routine, often with the same transport mode and via the same routes. During such routine trips through well-known spatial environments, people may pay less attention to their spatial surroundings, compared to possibly more spontaneous or exciting leisure trips. A final reason could be that during leisure trips, people have more time to select more pleasant routes, and/or to more intensely enjoy the qualities of the spatial surroundings.

In addition, also the dynamics of weather play an important role. The multivariate results largely confirm the descriptives in the literature described in section 2.1. Air temperatures between 20-25°C (reference category in Table 6.1) result in the most positive place valuations. Colder air temperatures (below 15°C), as well as hot air temperatures (above 25°C) have significant negative effects. People's en-route place valuations are negatively affected by precipitation, cloudy sky conditions and, most dominantly, darkness. In contrast to earlier research (Eliasson et al., 2007) as well as our descriptive results, when controlling for all of the above, wind speeds have no significant effect on place valuation. In addition to the direct effects of weather on en-route place valuations we tested also the indirect effects via subjective thermal experiences. Warmer thermal experiences (as a combination individual backgrounds and weather conditions described in §4.2.2) have a significant positive effect on place valuations.

Finally en-route place valuations vary significantly between the different transport mode users. Our results demonstrate that active transport mode users have more positive place valuations than users of motorised transport modes. There may be several reasons for this. First, positive place valuations may be related to the satisfaction with travel in general. Existing studies demonstrate that usage of active transport modes contributes to higher levels of travel satisfaction than motorised travel (see e.g. De Vos et al., 2013 for a review). Second, compared to car and especially public transport users, active mode users – at least in the Dutch context of pedestrian/bicycle friendly infrastructure – may have more freedom to select pleasant routes or even which side of the road to travel. Also while pedestrian and bicycle routes often lead straight through parks or old inner-city areas, car drivers are usually confined to – less unique and more monotonous/boring – spatial environments around arterial roads or highways. Third, active transport mode users are more directly and intensely connected to their spatial surroundings. Wunderlich (2008:139), for instance, describes walking as "principal mode of perceiving and living (embodying) urban places", through which "we sense and develop a sense of place". This intense and detailed experience of the spatial environment may result in a more positive valuation of it. In contrast, car users are more distanced from the outdoors spatial surroundings. Particularly in an urban environment, the attention that car drivers pay to the spatial surroundings will be mostly related to the driving task and other traffic. Additionally, the interior space of the private car – equipped with technologies in safety, communication, entertainment, climate control and noise isolation – forms a private bubble serving as a mobile home or work location (e.g. Laurier, 2002). Finally, while travelling at higher speeds motorised mode users see spatial surroundings in less detail and are less easily able to stop, which distances them from their spatial surroundings (Graham and Marvin, 2001; Peters, 2003).

6.4 Conclusion and discussion

With the increasing societal interest in climate change, scholars from different, mostly separated, scientific disciplines have investigated the travel-behavioural, thermo-sensational and environmental-psychological effects of weather on people in everyday life. Addressing recent calls for a more integrated interdisciplinary approach (Eliasson et al., 2007; Knez et al., 2009; Böcker et al., 2013a), this research aims to conceptually and statistically integrate these fragmented insights. Drawing on unique Greater Rotterdam (The Netherlands) travel diary data enriched with hourly meteorological and spatial route attributes derived by means of GIS-analysis, we analyse how weather affects different transport mode users' en-route place valuations in terms of liveliness, friendliness and aesthetics, while controlling for personal/household, trip and spatiotemporal attributes in Structural Equation Models.

Our findings demonstrate that weather forms an integral part of en-route place valuations. Lower (<15°C) or too high (≥25°C) air temperatures, precipitation and cloudy or dark sky conditions, have *direct* significant negative effects on en-route place valuations. This could for instance be related to reduced presence of people outdoors affecting liveliness or friendliness; lower light intensities affecting aesthetics; or less pleasant emotions mediating place valuations in general during these weather conditions. In addition to this direct effect, our findings reveal that warm, clear, dry and calm weather conditions result in warmer thermal experiences, and *indirectly* in more positive place valuations.

Besides the effects of weather, this paper shows that en-route place valuations differ substantially between the different transport modes. Being more intensely and intimately connected to their physical surroundings while travelling, active mode users have overall more positive en-route place valuations than public transport and especially car users. However, during cold, wet and windy weather this closer connection may also have its backside. Active mode users – more exposed to these disadvantageous weather conditions than more protected motorised mode users – perceive thermal travel environments as colder, indirectly lowering their place valuations. Besides weather and mode choice, other trip-specific situational factors appear to play an important role in place valuations. For instance people value their travel surroundings more when travelling during daytime, in company, for leisure, or via deliberate detours.

In contrast, place valuations seem less affected by static spatial route attributes (i.e. greenness, building usage diversity and address density). Although our descriptive findings suggested a relationship – i.e. greener route environments are associated with higher aesthetic and friendliness valuations; densely and diversely built environments with lower aesthetic but higher liveliness valuations – our multivariate analyses show no significant relationships between objective route environments and overall subjective place valuations. This may be a result of our data matching process. Because we have only origin and destination data available, and not the actually taken routes, we had to model people's shortest routes and apply a 200m buffer in case people take slightly different routes. Also we link en-route place valuations to spatial attributes averaged over the course of an entire route. Due to this broad buffer and/or aggregations we may have lost some detailed spatial variation.

The insights generated in this paper could be valuable for policy makers in several ways. First, our findings on subjective place valuations of travel environments give insights into travel beyond the traditional instrumental factors like time and cost, but as a value in itself affected by the dynamics of travel environments. These insights could help policy makers to better understand how and why travel demand for different transport modes fluctuates with the dynamics of time, place and weather. Second, as travel is an important aspect of our increasingly mobilised world, our findings on different transport mode users' en-route place valuations, translate directly into liveability of urban areas and the subjective wellbeing of its mobile residents. While weather-protected motorised mode users' place valuations are less affected by weather conditions, urban planners, depending on their local climate's present and projected future challenges, are advised to particularly consider active transport mode users' exposures to cold, heat, precipitation and/or wind. This supports the importance to expand climate sensitive urban planning from its uses in landscape architecture (e.g. Lenzhölzer and Wulp, 2010; Eliasson et al., 2007) to the transport domain. Examples may include the implementation of deciduous trees (e.g. Konarska et al., 2013), precipitation shelters and/or wind barriers in outdoors urban places or along infrastructures frequented by cyclists or pedestrians, and could enhance liveability and usage of such outdoor environments.

This study provides a new interdisciplinary exploration into the relations between weather, urban form, travel and people's experiences of weather and place. To better cater practitioners in their adaptive policy and design strategies, future research could elaborate these themes into several directions. First, the relationship between objective spatial configurations of route environments and subjective place valuations should be further explored. It is important that en-route place valuations are directly linked to accurate GPS tracked route environments. In conjunction, the sensitivities of multiple buffer sizes on the statistical model may be evaluated. Also route environments should not only be applied to trips as a whole, but also to separate trip segments to address detailed spatial configurations on smaller spatial scales – i.e. the neighbourhood or even street level. Second, to properly address the effects of microclimate conditions the effects of weather on place valuations should be linked, not only to weather data from the nearest (often rural) meteorological station, but also to detailed local microclimate data gathered throughout the urban fabric. Third, research may further explore the potentially different vulnerabilities to weather of different social groups. In this study we found some evidence that women and older aged people have colder thermal experiences. However, the effects of these and other attributes like ethnicity need to be further explored, not only on thermal experiences but also on place valuations. Finally, research may analyse the effects of weather on place valuations in direct conjunction with other interrelated subjective experiences, such as travel satisfaction or emotional state.

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7 Conclusions and discussion

7.1 Background: Climate, weather, urban form and daily mobility

Intuitively, weather plays an important role in everyday mobility. When we are travelling on foot or by bicycle; cycling towards a train station; waiting at a bus stop; walking towards a parked car; or driving under slippery road conditions. How often do we not expose ourselves to cold, heat, sun, rain, snow or wind, on our journeys to work, friends, shops or leisure destinations? Yet, although the influence of weather on daily mobility in everyday life can be pervasive, scientific debate on the relationships between climate, weather and transport has so far largely been focused on the effects of extreme weather events on road, air or rail infrastructure maintenance, accident rates and traffic flows. In contrast, despite many recent contributions, we still know much less about how climate and weather shape individual mobility in everyday life. Therefore the following aim (Figure 7.1) was formulated for this research:

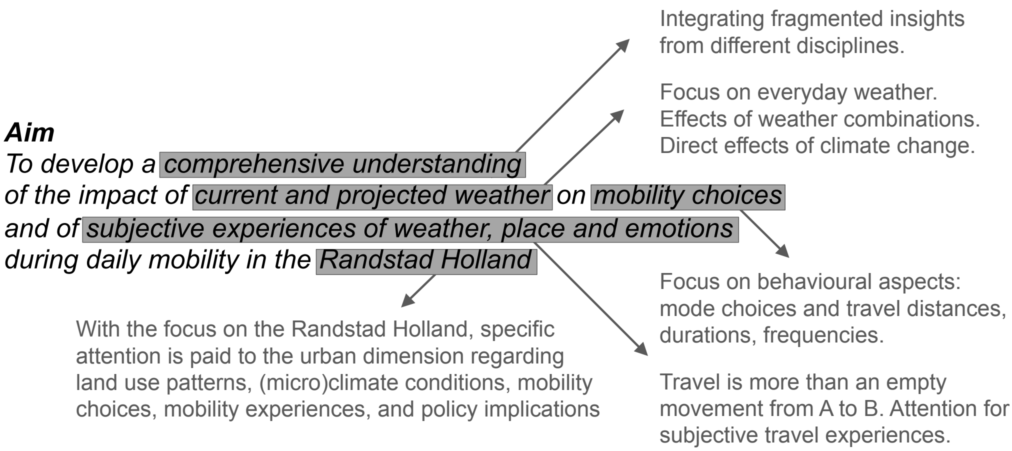

Figure 7.1 Aim and foci

With this aim this research is positioned amidst five theoretical debates held within different scientific disciplines: the debates on (1) weather and travel behaviour amongst transport scientists (e.g. Hanson and Hanson, 1977; Sabir, 2011; Creemers et al., 2014); (2) weather and physical activities amongst health scientists (e.g. McGinn et al., 2007; Chan and Ryan, 2009; Spinney and Millward, 2011); (3) weather and outdoors (thermal) comfort amongst biometeorologists (e.g. Nikolopoulou and Steemers (2003); Knez and Thorsson, 2006; Thorsson et al., 2007); (4) urban microclimates amongst urban climatologists; and (5) weather, moods and emotions amongst environmental psychologists (e.g. Cunningham, 1979; Denissen et al., 2008; Ciucci et al., 2011). This research provides empirical knowledge on the effects of everyday weather on transport mode choices, travel distances, durations and frequencies, which confirms existing knowledge in transport sciences on the relationship between weather and travel behaviour. Moreover, by integrating insights from all of the above-mentioned disciplines, this research enlarges existing transport knowledge with currently underexplored insights on: (1) the direct effects of seasonal climate change on travel patterns; (2) the effects of the interactions between different weather parameters;

(3) insights into the effects of weather on the experience of weather, place and emotions during travel; and (4) the different effects that weather has on different people and mode users in different urban environments. By adding weather conditions as a new dynamic layer to urban form, and intrinsically relating it to urban form through microclimate linkages, this research sheds new light on the relationships between weather, urban form and travel behaviour.

Apart from these theoretical contributions, this research centres itself in one of today's most prominent societal debates. With renewed evidence for global temperature rise, precipitation variability, and increased frequencies of extreme weather phenomena (e.g., IPCC, 2013), climate change is more than ever before an important topic amongst scientists, policy makers as well as the general population. As an important contributor to green house gas emissions, as well as being largely exposed to weather, the transport sector is evidently related to climate change in a complex manner (e.g. Koetse and Rietveld, 2009). Both mitigation and adaptation strategies are crucial (IPCC, 2013). It has become clear that climate change can only be dealt with through the simultaneous implementation of both mitigation and adaptation measures. With regard to transport policy and planning this leaves the tricky question of how to stimulate the carbon-neutral, healthy active transport modes walking and cycling, while at the same time protecting these environmentally-exposed active mode users from adverse current and projected weather conditions wherever possible. In this respect, the insights into the effects of climate and weather on individual daily mobility provide useful insights into: (1) how mobility decisions are shaped by current weather conditions, (2) how mobility patterns may change in a future climate, and how (3) mobility affects emotional experiences and place valuations under different weather conditions. These insights are necessary in order to understand the weather exposures and vulnerabilities of different people and mode users; to design climate-sensitive urban planning in urban public places and along active mode transport infrastructures; and to guide transport mode decisions under present and future climate conditions.

This thesis consists of a collection of five research articles which all address the relations between climate, weather and daily mobility. This concluding chapter provides an overview of the main findings and a discussion of their significances for urban and transport theory, policy and planning. The chapter ends with a research agenda to address research limitations, newly generated questions, and remaining knowledge gaps.

7.2 Synopsis

In order to address the aim of this research (Figure 7.1) five research questions have been formulated in the introduction of this thesis. This section summarizes and interprets the main findings from the chapters 2 through 6 that have provided answers to these research questions.

1. What are the current insights and research gaps on the effects of everyday weather conditions on individual daily travel behaviour?

A systematic literature review of transport, health and biometeorological studies on the effects of weather on any form of travel or activity behaviour, brought together the following existing insights in chapter 2. Individual weather parameters have profound impacts on travel behaviour. Overall, the reviewed studies' findings indicate that warm, dry, calm and sunny weather positively affect outdoor leisure activities and the use of active over motorised transport modes, while rain, snow, windy, and cold weather have reverse effects. Studies that control for this typically report smaller weather effects on utilitarian than on recreational trips, which may be related to the importance of these trips, the way these trips are often fixed in time and place, and the habitual behaviour often associated with these trips. A geographical cross-comparison of findings revealed that studies from temperate climates report relatively large weather-related day-to-day variances in travel behaviour; that studies from continental climates report relatively large seasonal contrasts; and that limited evidence from (sub)tropical climates indicates higher heat tolerances than in cooler climates. It seems that these differences can partially be explained by the climatological differences between the study sites: i.e. warm to hot weather conditions throughout the year in (sub)tropical climates; large contrasts between hot summers and cold snowy winters in continental climates; relatively unstable daily weather fluctuations in temperate climates. However differences may also be related with different (transport) cultures.

The literature review also revealed several methodological, contextual and behavioural shortcomings. First, except for a few studies using thermal indices that combine different weather parameters to explain activity or travel behaviour (e.g. Brandenburg et al., 2004; Thorsson et al., 2004, 2007), most studies single out the effects of precipitation, temperature and wind, and ignore the fact that in reality weather parameters always co-occur and these combinations dominate daily-life weather perceptions. Additionally, studies often ignore the potential existence of thresholds or non-linearities that may characterise the relationships between weather and mobility. A few exceptions for instance report sudden decreases in cycling or outdoor activities above certain wind speeds (e.g. Sabir, 2011) or find evidence that not only cold, but also hot weather above 25–30°C may negatively affect active mode usage or outdoor activities (e.g. Tu et al., 2004; Aultman-Hall et al., 2009; Ahmed et al., 2010). Second, where most existing studies link mobility behaviours to objectively measured weather conditions, much less attention is paid to how peoples' travel behavioural choices could be linked weather forecasts and to peoples' expectations, perceptions and emotional responses to weather. Exactly this kind of subjective knowledge, when linked to socio-demographics, cultural backgrounds or transport mode choices, may give a better understanding of why weather has different effects on different people, different types of activities, and different transport mode users. Third, the current literature provides very few insights into the effects of weather on daily mobility in non-western countries and polar, desert or (sub)tropical climates. On a smaller spatial scale studies look largely at mobility in urban regions, but often neglect to consider the distinct microclimates formed within urban regions, for instance when linking urban mobility to rural meteorological weather records without reflecting on the potential bias. Some of these and other shortcomings have been addressed with the following four empirical research questions in this thesis.

2. How will projected 2050-climate changes affect seasonal transport mode shares and travelled distances in the Randstad Holland?

This second research question addresses two knowledge gaps in chapter 3: the lack of direct analyses of climate change effects on daily mobility (season-specific effects in particular); and the one-sided approaches of analysing transport mode choices solely through trip shares and not through travelled distances. To answer the research question, approximate combinations of the projected weather conditions (KNMI, 2009) were used to select seasons from the last decade representing current and 2050-climate conditions. Based on Dutch National Travel Survey data, Randstad Holland mobility patterns for these select current and future seasons were compared. Multivariate analyses that control for sociodemographic, household, and spatiotemporal trip backgrounds, indicate a significant overall increase in bicycle usage and travelled distances in a warmer and somewhat wetter 2050 climate, while other modes appear less strongly affected. The relatively large effect on cycling can be explained by large weather-exposure of cyclists, certainly when compared to protected car users, but even when compared to pedestrians who may be more flexible to seek cover from rain, wind, cold or heat by using umbrellas or moving inside covered, heated or shaded areas.

Besides the year-round climate change effects, the analyses show clear seasonal differences. Active mode usage and travelled distances (again especially for cycling) increase in milder, wetter 2050-winters (mainly over car usage). In contrast, hotter 2050-summers, with more extreme precipitation patterns, demonstrate reversed effects. These climate change effects seem to level out to some extent the classical seasonal modal split pattern of higher active mode usage in summer and lower active mode usage in winter, currently observed in many temperate and continental climates (chapter 2), including the Randstad Holland (chapter 3). Although these seasonal climate change effects cannot be used to derive conclusions on the respective effects of separate weather parameters, they could be used to form hypotheses regarding the effects of precipitation and air temperature. It seems that under relatively cold winter conditions an air temperature increase leads to a relatively large increase in active open-air mode usage (large enough at least to exceed to a potentially negative effect of a marginal increase in overall precipitation sum), while under warmer summer conditions combined with increased extreme precipitation a similar air temperature increase does the contrary. A hypothesis could be a nonlinear relationship between air-temperature and transport mode usage, sometimes indicated, but not often empirically investigated, in the existing literature (as described above in answer to research question 1). This has been further examined when analysing the effects of individual and integrated weather parameters in answer to research questions 3 through 5.

3. How do weather conditions affect daily cycling frequencies and durations, and the exchange between cycling and other transport modes.

Three knowledge gaps motivate the formation of this third research question in chapter 4: the surprisingly (given the temporary nature of weather exposures) limited knowledge on the effects of weather on travel durations; the limited attention for potentially nonlinearities in weather effects; and the limited knowledge on how combinations of weather conditions affect mobility. Although also examining the exchange with other transport modes, this research question specifically addresses cycling, because of the large societal benefits and earlier-found weather-sensitivity of this mode (chapter 3). Analyses of self-gathered Greater Rotterdam travel diary data (n=945) connected to local weather records, demonstrate linear negative effects of precipitation sum and wind speed, and bell-shaped effects of thermal conditions on cycling shares, frequencies and durations and opposite effects on car shares. Confirming the hypothesis of a nonlinear relationship between thermal conditions and mode choice (chapter 3), an optimum air temperature for cycling was identified around 24°C. This is in line with earlier findings from Portland (Ahmed et al., 2010), but somewhat lower than the 28°C and 32°C found in Melbourne (Phung and Rose, 2008) and Boulder, CO (Lewin, 2011). These different findings may be related to hotter summers, but also to a more incidental and recreational cycling profile in the latter two study areas. Compared to cycling shares and cycling frequencies, our findings indicate that weather affects cycling durations more strongly. A reason might be that people have more aversion against cycling for longer than for cycling for shorter durations under unpleasant weather conditions. This could be an indication that temporality plays an important role in weather exposures.

In addition to air temperature, two thermal indices were introduced in collaboration with meteorologists to capture the combined effects of air temperature, solar radiation, humidity, and/or wind speed. These Physiological Equivalent Temperature and Mean Radiant Temperature appear to better explain cycling shares than just air temperature, which confirms interplay of the different weather parameters. These thermal indices approximate more closely than air temperature the bodily experiences of thermal conditions (Mayer and Höppe 1987; Matzarakis and Mayer, 1996). Nevertheless, they are still constructed based on objectively measured weather parameters. With the following research questions 4 and 5 this thesis also introduces respondents' subjectively perceived thermal conditions while travelling.

4. To what extent and how do weather conditions affect transport mode choices, thermal perceptions and emotional travel experiences?

This fourth research question addresses in chapter 5 the limited existing knowledge on how weather is perceived during travel, how it affects emotional travel experiences, and how it has potentially different effects on different population categories and transport mode users. Moreover, by integrating (both theoretically and empirically) fragmented interdisciplinary insights on weather and mobility (chapter 2), weather and subjective comfort (e.g. Nikolopoulou and Steemers, 2003, Thorsson et al., 2004, 2007) and weather, moods and emotions (e.g. Kööts et al., 2011), it is investigated how peoples' responses to weather in terms of transport mode choices, thermal perceptions and emotions affect and compensate each other during daily mobility. To answer this research question, use was made of the same Greater Rotterdam dataset mentioned above, which includes in addition to mobility choices also subjective Ecological Momentary Assessments – i.e. a methodology of measuring respondents subjective responses in real-time and on-site (Moskowitz and Young, 2006) – of weather perceptions and emotional travel experiences.

Confirming the existing literatures addressed in research question 1 and the empirical findings in answer to research question 3, results demonstrate that observed dry, calm, sunny and warm but not too hot weather conditions stimulate cycling over other transport modes. Moreover these advantageous weather conditions contribute, either directly or indirectly, to more pleasant emotional travel experiences in terms of happiness, irritation, fear and tiredness. The direct effects indicate the implications of weather conditions on what some earlier studies refer to as mechanical (dis)comfort (e.g. Oliveira and Andrade, 2007), for instance associated with the extra energy of moving against the wind and/or the discomfort of having wind and rain blown in your face. The indirect effect runs via the experience of thermal conditions and indicates a role of thermal comfort. Under a combination of higher air temperature and sky clearness, and lower precipitation and wind speed, people perceive subjectively thermal travel environments as warmer and more comfortable. This confirms our expectation, addressed in answer to research question 3, that bodily experiences of thermal conditions involve interplay of different co-occurring weather conditions. On their turn, warmer subjective thermal perceptions were found to contribute to more pleasant emotional travel experiences. An exception are air temperatures above 25°C, under which negative effects on emotional experiences were found. This indicates a potentially negative effect of heat on mental states, as found in existing mood research (e.g. Schneider et al., 1980).

Thermal perceptions and emotional experiences are not universal across the entire sample, but differ by trip purpose, transport mode and across population categories. People have overall more pleasant emotional experiences during weekend, off-peak and leisure trips, which could for instance be explained by reduced crowdedness or a more relaxed and voluntary character of these trips. Compared to other transport modes, public transport users have less pleasant emotional experiences. This is in line with lower satisfaction with travel rates amongst public transport users found in the literature (e.g. Friman et al., 2013), which could be explained by a lack of freedom and privacy associated with public transport, or the potential waiting, uncertainty and discomfort of changing connections. In this respect, it seems remarkable that no elevated emotional experience can be found amongst car users, which is usually found to score highest on satisfaction (e.g. Steg, 2005; Jakobsson, 2007; De Vos et al., 2013). However, when the relationship with weather is taken into consideration, it appears that car users in their emotional experiences benefit indirectly from overall higher levels of thermal comfort, resulting from their weather protected and usually thermo-regulated indoor car environments. In contrast environmentally exposed active mode users perceive thermal conditions as colder and less comfortable, which has an indirect negative effect on their emotional experiences. Thermal perception and emotional travel experiences were also found to differ between different population categories. Women and older people perceive thermal travel environments as colder, which has indirect negative effects on their emotional travel experiences. These differences are in congruence with a few existing studies demonstrating higher thermal sensitivities for these groups (e.g Karjalainen, 2012; Kenawy and Elkadi, 2012; Tuomaala et al., 2013), and provides another indication for the embodied effects of weather on humans.

5. To what extent and how do weather conditions affect transport mode choices, thermal perceptions and en-route place valuations?

This fifth research question in chapter 6 builds forward on the data and insights developed in answer to research question 4, however it address the relationships between weather, weather perceptions and travel experiences from an explicit geographical point of view: one of the remaining shortcomings addressed in the literature presented in answer to research question 1.

Overall, the results demonstrate that en-route place valuations (in terms of liveliness, friendliness and aesthetics) are mostly affected by dynamic rather than static spatial attributes. While static spatial route attributes, such as greenness, building usage diversity and address density have no significant effects on en-route place valuations, it appears that people value their travel surroundings more positively when travelling accompanied by others, for leisure, during daytime, or with a detour.

In line with this, also the dynamics of weather play an important role. Overall, precipitation, lower or too high (≥25 ˚ C) air temperatures, and a lack of sunshine have direct negative effects on en-route place valuations. Besides these direct effects, warm, clear, dry and calm weather conditions – similarly as with emotional travel experiences – result in warmer thermal perceptions and indirectly into more positive place valuations. Several explanations can be given for these relationships. First, existing studies reveal that the above-mentioned disadvantageous weather conditions reduce outdoor public space attendances (e.g. Thorsson et al., 2004, 2007), which may make route environments less lively. Second, as explored in answer to research question 4, weather may trigger less pleasant emotional experiences. Less pleasant emotions experienced by the respondent may filter the way s/he values place in general (Knez et al., 2009), while less pleasant emotional experiences by surrounding others could generate a more distant social atmosphere and affect the way people value en-route friendliness. Third, some weather elements like sunshine could make urban or natural surroundings look brighter or more colourful, which could positively affect the way routes are valued in terms of aesthetics. As with emotional travel experiences, the effects of weather on en-route place valuations differ substantially between different transport modes. Active mode users – being more intensely and intimately connected to their travel environments – value travel surroundings overall more positively. However, when weather conditions are considered, active mode users perceive thermal environments as colder and less comfortable (indirectly negatively affecting their place valuations), especially when compared to protected and often climate-controlled car users.

Table 7.1 Overview of direct and mediated climate and weather effects on daily mobility

	Climate and weather effects on mobility behaviour	Weather effects on mobility experience
Directly on individual	• Active compared to motorised mode usage decreases in summer but increases year-round and in winter under warmer, wetter 2050 climate conditions (ch3). • Warm (but not too hot), dry, sunny and/or calm weather positively affects active mode usages, distances and frequencies, while cold, hot, cloudy, wet and windy weather stimulate motorised mode usage (ch4–6). • Thermal conditions measured as combinations of weather parameters better explain mobility behaviour than just air temperature (ch4)	• Via thermal and mechanical (dis)comfort, warm (but not too hot), dry, sunny and/or calm weather may negatively affect emotional experiences (ch5) and en-route place valuations (ch6). • Sunshine may boost feelings of happiness, directly via chemical processes in the human body. However, exposure to sunshine may also directly lead to tiredness, sunburn or headache, and subsequent negative emotional experiences (ch5). • Weather perceptions vary with socio-demographic factors. For instance women and older people perceive cold weather as colder (ch5–6).
Via built environment	• Snow-cover, or other adverse weather conditions, may generate slippery road conditions or network disturbances and may indirectly reduce the demand for long distance, car, bicycle and/or public transport travel, while increasing the demand for short-distance travel and walking (ch2, ch4).	• Daytime sky clearness could enhance brightness and colours, which could positively affect en-route place valuations in terms of aesthetics (ch6) • Pedestrians may be more flexible than cyclists to take shelter against wind, precipitation or uncomfortable temperatures under, inside and along buildings, walls, trees and buildings (ch5–6).
Via social environment	• Weather may affect mode or destination-specific travel volumes, congestions, and network performances. These may indirectly affect mobility choices (ch2).	• Warm (but not too hot), dry, sunny and calm weather positively affects outdoor public place attendances (ch2), as well as people's emotional experiences (ch5). This may generate busier and friendlier social atmospheres, and positively affect valuations of liveliness and friendliness (ch6).
Via mobile objects	• New communication technologies may enable people to use detailed weather forecasting technologies (e.g. shower detecting radar) on the move, which may enable people to avoid rain showers when cycling, walking or selecting routes (ch7).	• Active mode users are more intensely exposed to weather than for instance car drivers, protected by mobile objects, such as the cocoon of the private car, windscreen wipers, heating and air-conditioning (ch5–6). • Pedestrians may be more flexible to protect themselves against precipitation with mobile objects like umbrellas (ch2).

Climate, weather and daily mobility in the context of dynamic spatiotemporal situations

The introduction of this thesis introduced a time-geographical framework, in which mobility behaviours and experiences are understood from the interactions between individuals (with their own unique personal backgrounds) and the dynamic spatiotemporal situations in which mobility unfolds. Following Dijst (2013), these spatiotemporal situations consist of four interrelated dimensions: (1) built environments, (2) social environments, (3) mobile objects and (4) the natural processes, such as climate and weather. Various multivariate analyses were employed to analyse the relationships between climate, weather and mobility while controlling for these personal backgrounds and multidimensional spatiotemporal situations. However, while answering the five research questions it has become clear that not only mobility itself, but also the relationships between climate, weather and mobility, need to be understood in interaction with the other spatiotemporal dimensions. Table 7.1 provides an overview of the relationships between climate, weather mobility behaviours and mobility experiences examined throughout this thesis, and distinguishes where weather conditions affect the individual directly and where they do so in interaction with the built environment, socio environment and mobile objects.

7.3 Implications

Theory

The insights from the empirical analyses presented in this thesis on climate and weather effects on individual daily mobility behaviours and experiences have a number of implications for current theoretical discussions on climate, weather and transport, as well as on transport research in general. When climate and weather are linked to transport, for instance in popular media, but also in most existing scientific research, what usually comes first to mind are the incidental situations of extreme weather. Without denying the functional as well as symbolic importance of these extreme weather events, this research in addition shows empirical evidence for the substantial relationships between recurring normal everyday weather fluctuations and individual daily mobilities. Moreover, it is argued that these relationships are more complex than originally thought. It is demonstrated that the often singled-out and linear effects of weather parameters on mobility behaviours in existing studies are oversimplified. Instead of singled-out effects, this research shows that people perceive and experience weather as a combination of temperature, sunshine, wind and precipitation, and that it is these weather combinations that better explain mobility behaviours. Instead of linear relationships, empirical evidences are found for nonlinear bell-shaped temperature effects on cycling shares, frequencies and durations, as well as descriptive indications for wind and precipitation thresholds above-which the use of active transport modes suddenly drops.

Weather conditions are often conceived as exogenous, external factors. However this does not mean that the effects of weather on mobility can be viewed separately from the personal, trip, and spatiotemporal contexts in which trips are situated. This research analyses the effects of weather on mobility not only when controlled for, but also in relation to, individuals' personal backgrounds, preferences, resources and constraints (Hägerstrand, 1970) and spatiotemporal travel situations in which trips are situated (Dijst, 2013). This has lead to important alternative insights into the heterogeneous effects of weather on the mobility of different population categories. Our results confirm the insights from some existing studies that women and older people are more sensitive to cold weather conditions (e.g. Karjalainen, 2012; Kenawy and Elkadi, 2012; Tuomaala et al., 2013), and demonstrate that this is also the case with regard to the experience of weather during daily mobility. Additionally our research provides new insights into the so far underexplored role of ethnicity. Although no significant effects could be determined due to limited immigrant subsamples, our results indicate that non-native Dutch, often with a background in warmer climate regimes, experience thermal environments as colder and therefor less comfortable. With regard to trip backgrounds, in congruence to some existing studies (e.g. Hanson and Hanson, 1977; Sabir, 2011) it is shown that weather has weaker effects on utilitarian than on recreational trips, for instance related to the relative importance, spatiotemporal fixity, and/or often habitual behaviour associated with utilitarian trips (e.g. Verplancken et al., 1997). Moreover, by including natural processes (i.e. weather, seasonality, day/night rhythms) and other dynamic processes (i.e. weekdays/weekends, peak/offpeak) as integral components of spatiotemporal travel situations, this research provides an alternative, more dynamic (Castells, 1996; Cresswell, 2006; Dijst, 2013), perspective on the role of urban form in travel behavioural research. Our results point out that these spatial dynamics (including the weather) have a greater influence on peoples' mobility experiences th an static classical urban form characteristics, such as density, diversity and design. This does not implicate, however, that we question for instance the well-documented relevance of urban form characteristics for travel behaviour. On the contrary, it enhances the importance of urban form, but in a different ways. It is for instance important, and even more so in the context of a potentially climate change, to investigate how mobility behaviours and experiences are affected by microclimate conditions resulting from land use configurations, built densities, built materials and vegetation patterns. In this respect, one of our other papers (not included in this thesis) demonstrates stronger weather effects on cycling in low density rural areas, compared to more centrally located, compact, high density inner-city areas (Helbich et al., 2014). These differences can be attributed to the colder microclimates, the higher weather exposures, and/or the longer distances in rural areas.

Where most existing studies on weather and transport relate mobility behaviours solely to objectively measured weather conditions, this research in addition explores weather and mobility from a subjective dimension. This involves two shifts in thinking: The first is to rethink mobility beyond simple empty movements from A to B (New Mobilities Paradigm – e.g. Cresswell, 2006; Sheller and Urry, 2006), as a dynamic analogy to thinking about the meaningful notion of place beyond the empty Euclidean space (e.g. Tuan, 1977). The second is to conceive the effects of weather as a wide range of multisensory bodily experiences (e.g. Merleau-Ponty, 1962), such as the smell of wet surfaces after drought, the touch of wind in your face, the taste of raindrops dripping into your mouth, the threatening sound of thunder, or the aesthetic visual perception of sunshine (Saito, 2005). It may even be argued that weather affects bodily sensations beyond the five traditional senses through thermo-sensational processes in the body (Lenzhölzer, 2010). Together these multisensory bodily experiences lead to subjective evaluations of thermal and mechanical comfort (Oliveira and Andrade, 2007). By integrating weather related travel behavioural, bio-meteorological and environmental-psychological insights, our results show that peoples' behavioural responses to weather are intrinsically related to weather perceptions and weather-related experiences of place and emotions during travel. It is shown that warm but not too hot, dry, calm and sunny weather conditions not only stimulate active over motorised mode usage (in congruence to e.g. Sabir, 2011, Creemers et al., 2014), but also result in higher perceived thermal comfort and more pleasant emotional experiences and place valuations during travel. Moreover, these weather-related mobility experiences appear to be mediated by mode choice, in the sense that weather exposed active mode users are more sensitive to especially cold weather conditions than protected motorised mode users.

These findings provide alternative new insights into the expanding debate on travel, satisfaction and well-being (e.g. Ettema et al., 2010; De Vos et al., 2013), which is currently largely investigated without considering the role of weather. With pleasant weather being a common explanatory factor for both active mode shares and pleasant emotional travel experiences, it may even be stated that neglecting the role of weather could potentially lead to spurious associations between active mode usage and pleasant emotional experiences. At least, including the role of weather could lead to a more nuanced and inclusive picture of travel and wellbeing, especially when considered in the context of potentially changing climate conditions.

An important question that remains is what implications the here explored effects of climate and everyday weather on daily mobilities, have on mid and long term decisions regarding holiday choices, car ownership, and (secondary) housing preferences. According to Alan Pred's life path – daily path dialectic, the 'details of everyday life are rooted in past intersections of individual path and institutional project' (Pred, 1981:13), implying that decisions and experiences during the daily time-space paths affect more structural decisions in the longer run – an insight and language Pred borrowed from Time Geography (Hägerstrand, 1970) and Structuration Theory (Giddens, 1979). In this research we found indications for potentially increasing car uses in warmer future summers and decreases in milder future winter. However, how exactly these potential trends may affect mid term decisions regarding car ownership remains unclear. Another interesting question is how daily mobility encounters with weather affect our annual holiday choices? For instance, interesting evidences have been found for late-summer rushes on sun destination last minute bookings in response to a continuously cold and rainy summer (Gössling and Hall, 2006). In return, weather encounters during vacation – e.g. having gotten accustomed to warm, dry sunny weather for a period of several weeks – may have consequences for weather preferences, daily travel behaviours, and daily travel experiences upon returning home. Gradual, structural changes in climate conditions may also affect leisure, tourism and secondary home ownership in the longer run. In temperate and continental climates, warmer projected climate conditions may restrict snow and ice related domestic tourism in winter, but stimulate domestic summer holiday behaviour and secondary home ownership over warmer international destinations. Climate change may also affect the attractiveness of residential, work and leisure destinations within countries or even within urban regions. In hotter projected summers, it may be questioned if people would still choose densely built, sparsely vegetated inner-city areas as places to live, work, shop and recreate, or whether they would rather search for cooler alternatives, such as air-conditioned indoors shopping complexes or forested and water-rich natural areas outside cities.

Policy and planning

The introduction of this research positioned transport as one of the most important contributors to green house gas emissions, and at the same a time a sector that is highly exposed to and affected by (changing) weather conditions. The research presented in this thesis has dealt primarily with the latter process. Therefore, the results of this research have policy and planning implications for adaptation strategies with regard to both current and projected weather conditions. However, because of this reciprocal relationship between climate and transport, the policy and planning implications outlined in this section will also be considered from a mitigation viewpoint where applicable. While many existing studies have focussed on the impact of weather extremes on transport, this researched specifically demonstrated the effects of normal everyday weather conditions on daily mobility, although also more extreme weather conditions like heat have been explored. This section outlines the policy and planning implications of the relationships between weather and daily mobility investigated in this research with regard to a variety of domains, such as: travel demand modelling; the planning of transport infrastructures; the stimulation of active transport mode usage; mental and physical health; the planning of urban land uses; the provision of housing; and landscape architecture.

Empirical findings in this research demonstrate significant effects of normal weather conditions on transport mode shares, travel frequencies and travelled distances. Although the effects of weather on these mobility behaviours may be relatively small in comparison to some of the control variables like car ownership, even these relatively small weather-induced changes (e.g. an increase in travelled distances by car by a few per cent) may have large implications for traffic flows and road congestion, especially in densely populated urban regions like the Randstad Holland. Policy makers are therefore advised to take into account the here explored positive effects warm, sunny, dry and calm weather on active over motorised mode usage. For example, when analysing cycling trends to evaluate the effects of cycling policies, insights from this research can be used to clear the trends one is interested in from the noise caused by daily weather fluctuations. Or when analysing or comparing modal split statistics cross-sectionally or longitudinally, it may be important to control for weather effects at the time and location of measurement. Travel demand modelling may also need to consider the gradual changes of everyday weather conditions in the longer run. Results from the Randstad Holland point out that policy makers in this region may need to prepare for the accommodation of induced cycling demand in a warmer, albeit slightly wetter, future climate. This may be good news for policy makers who aim to promote the use of healthy active transport modes. However they should be aware of the important differences between winters during which active mode usages seem to increase and summers that show opposite effects, likely due to increased heat or more extremes in precipitation. Although climate change effects differ regionally and uncertainties exist, similar seasonal trends may be expected in other temperate and continental climates.

Policy makers and transport planners are advised to take two important steps in order to successfully consider current and future weather conditions in transport planning, as well as to perform sustainable transport planning in a more general sense. One step is to adapt the traditional transport models, upon which most of today's transport planning is based, by including besides the car also other transport modes, and by including preferably also different seasonal models and climate change scenarios. Transport related cost benefit analyses might also need to be improved by including multiple mode alternatives (Hosking et al., 2011). Another step is to view mobility beyond instrumental factors such as time and cost, and to pay closer attention to perceptions and emotional experiences during travel. Perceptions and emotional experiences with regard to weather are important components of this. This more subjective perspective on mobility is especially important, when the aim is to stimulate active transport modes. In comparison to motorised mode users, pedestrians and cyclists are more closely and intimately connected to their physical outdoors surroundings, because they are travelling with lower speeds, by means of self-generated physical effort, and in exposure to the open air. As a result, this research shows more positive emotional experiences and route valuations amongst active mode users, but at the same time also higher weather sensitivities, for instance with regard to combinations of cold, wet and windy weather conditions. In addition, this research finds also higher weather sensitivities amongst women and elderly people and indications for different weather preferences amongst people with ethnic backgrounds in warmer climate regimes. These findings illustrate that it is important to differentiate urban and transport policies in accordance to different mode users and population categories. The latter may gain particular importance in the context of an ageing society or an increasingly multi-ethnic society resulting from (climate change-related) migrations.

Climate and weather have often been linked to health, generally through the negative impacts of climate change on society, such as heat related mortality rates, natural disasters, famine, reducing quality and quantity of drinking water, or infectious deceases (IPCC, 2014). In addition to these direct effects, the results in this research provide several alternative societal implications of the relationships between weather and health in interaction with mobility. The effects of weather and climate change on the use of active transport modes and outdoors physical leisure activities, examined or discussed in this research, have indirect implications for peoples' levels of physical activeness and related issues with obesity, which ranks as one of the biggest health problems in the western world (Hosking et al., 2011). Where most studies on the effects of climate and weather on health are focussed on physical health, this research advises policy makers to consider also the implications for mental health. In today's highly mobilised world, in which travel constitutes an important part of everyday life, peoples' mobility experiences and place valuations in relation to weather conditions may translate directly into implications for people's mental health and the quality of living. In particular the finding of negative effects of air temperatures above 25°C on emotional experiences, may lead to concern in a warmer projected future climate. The effects of current and future heat on both mental and physical health issues may have additional implications when considered in interaction with other atmospheric processes, such as pollen, aero-allergen, ozone and other air pollutant levels, which are all higher with warmer temperatures (Hosking et al., 2011). These implications may be further amplified in urban regions like the Randstad Holland, as a result of concentrated traffic and industrial pollutant sources, limited ventilation, and potentially warmer urban microclimate conditions.

The issue of microclimate conditions introduces the last set of policy and planning implications related to this research. By examining the relationship between urban form and travel behavioural from the dynamic perspective of weather, this research has important implications for urban planning that are best labelled as climate-sensitive urban design in landscape architecture (e.g. Eliasson et al., 2007; Lenzhölzer and Wulp, 2010). Although the weather may not be changed directly, careful urban planning on multiple geographical scales with climate consequences in mind may contribute to more desirable microclimate outcomes, and may as well affect peoples' weather exposures in outdoors urban places.

On an urban system level, it may be debated whether to prefer compact or lower density designs. Densely built, sparsely vegetated, and poorly ventilated compact innercity areas are often associated with the higher innercity air temperatures (mostly at night) compared to surrounding rural areas. However recent microclimate knowledge reveals that especially in summer shading casted by compact urban designs may reduce daytime urban heat (Theeuwes et al., 2014). Moreover, our own results from a parallel paper indicate that not only air temperatures, but also precipitation and wind speeds have generally smaller effects on cyclists in compact urban areas compared to those in more weather exposed rural areas (Helbich et al., 2014). Based on these new evidences, and in line with the known benefits of compact urban designs for car-independent mobility, urban planners are advised to consider compact over lower density urban designs. Ideally, such compact urban designs are combined with citywide provision of connected rather than separated green areas. This can provide urban cooling, improve air quality, and facilitate outdoors recreation and physical activity at close proximity, which diminishes physical activity barriers and the need for motorised transport. Such urban design measures may especially be considered when it comes to residential areas with larger concentrations of vulnerable populations, such as the elderly.

On a neighbourhood level, urban planners may adapt climate sensitive street designs that consider the orientation towards the sun, shading patterns and natural ventilation. In addition, use may be made of deciduous trees, wind barriers and precipitation shelters in urban public places and especially along environmentally exposed active mode infrastructures. Deciduous trees provide shade and cooling to pedestrians and cyclists when foliated in summer, while preserving valued sunshine when defoliated in winter (e.g. Lindberg and Grimmond, 2011b; Konarska et al., 2013). Well placed wind barriers and precipitation shelters along active mode infrastructures – e.g. along highly-exposed bridge stretches or where gaps between buildings create wind tunnels – could reduce cyclists' weather exposures at strategic locations that may otherwise be perceived as barriers to active mode usage.

Finally, climate sensitive designs may be implemented on the individual level in and around the house, ideally by involving citizens in the process, which has the additional benefit of raising microclimate awareness. Measures may include passive cooling of buildings through insulation, material use and light surface painting amongst others (Santamouris and Asimakopoulos, 1996). In contrast to active cooling through air-conditioning, these measures do not generate anthropogenic heat outlet into outdoors urban environments, and they reduce rather than increase energy use (Chapman et al., 2009). Another example could be the stimulation of green over paved garden designs, especially with regard to street facing gardens. Apart from its cooling effect, recent findings from the Netherlands point out that street-level green uses on eyesight have direct positive effects on street users' valuations of aesthetics and thermal comfort (Klemm et al., 2013).

7.4 Recommendations for future research

Through usage of multiple quantitative methods applied on existing and self-gathered mobility datasets linked to external urban form, climate and weather data, this interdisciplinary research provides important innovative insights into the relationships between climate, weather, dynamic spatial contexts, and individual daily mobility behaviours and experiences. Nevertheless, there are a few methodological and theoretical shortcomings to this research, as well as some important issues that remain underexplored. This final section will identify these shortcomings and simultaneously present recommendations for future research that could address these shortcomings and other important issues.

By linking revealed mobility patterns to revealed weather conditions, our coverage of weather and climate conditions is limited to the range of weather conditions to which respondents were subjected during the survey periods. With regard to the seasonal climate change analyses (chapter 3), this implicates that we were dependent on the extent to which projected future climate conditions manifested itself already at present – not only as isolated episodes, but prolonged over the course of entire seasons in the last decade. Although we were able to select seasons safely within the bandwidths of both current and projected future climate conditions, it was not possible to run multiple alternative milder and more extreme climate change scenarios, which would have been desirable to address the uncertainty of climate change projections as well as to provide policy makers with a more differentiated picture. With regard to the analyses of everyday weather (chapters 4, 5 and 6), our weather coverage is limited to the August 2012 – September 2013 survey period (e.g. Figure 4.2). Despite active oversampling strategies on hot days at the start of the survey period, data coverage on warm (> 25°C) and especially hot weather conditions (> 30°C) is somewhat limited. From this present data we were able to identify negative heat effects on emotions and the use of active transport modes overall, which provided important contributions to the existing literature. However, limitations in hot weather coverage made it difficult to provide a differentiated picture of the behavioural and psychological responses to heat with regard to smaller subsamples, such as for transport modes, trip purposes or population categories like elderly or non-western ethnicities. In order to get more detailed insights into the effects of less recurrent weather conditions like heat or other weather extremes, future studies may need to adopt in addition methodologies other than revealed behavioural research, such as stated adaptation techniques or qualitative research. Besides its limited coverage, hot weather conditions observed in our survey period constituted mostly isolated peaks of exceptionally warm weather conditions. It may be questioned to what extent the observed behavioural and psychological responses to such relatively short and exceptional periods of hot weather reflect how people would respond to hot weather conditions on a more structural basis. In this respect, and certainly in the light of climate change, it is crucial to expand future research to include currently largely underexplored Mediterranean, arid and equatorial climate regimes. It needs to be further explored how people in structurally warmer climates may have developed different weather preferences, experiences, adaptations or practises. Examples could be higher heat tolerances (Knez and Thorsson, 2006), cooler dwellings, or different daily rhythms of spending energy, such as through the practise of having siestas.

One of the strengths of this research is its contribution to a better understanding of the complexity of the relationships between weather and daily mobility. Our analyses provide alternative insights that the effects of weather on daily mobility are not necessarily linear as often assumed. To this end, we found empirical evidence for non-linear bell shaped effects of thermal conditions on transport mode choices, as well as some descriptive indications for the existence of potential thresholds, for instance with regard to certain wind speeds above which bicycle use declines. However, more research into these potential nonlinearities is required to verify our results. In addition, future studies may want to consider that some weather parameters have different dimensions. Wind and precipitation may not only be measured in terms of total sum or average speed, as done in this research, but may also include durations, intensities, intervals or timing. For instance, gusty winds or clearly separated heavy rain showers intermediated by sunny spells may have completely different effects on mobility, than constant winds or continuous drizzle. By introducing thermal indices (chapter 4) and subjective thermal perceptions (chapters 5 and 6) originating from biometeorology into a travel behavioural study, this research has demonstrated that weather conditions affect mobility in combination rather than isolation. However, more transport studies with similar interdisciplinary methodologies are needed to verify our results. In addition, our insights are somewhat limited with regard to how weather interactions affect the individual beyond the perspective of thermal comfort. One could think for instance of the disproportional discomfort of the simultaneous effect of heavy wind and precipitation (Blocken and Carmeliet, 2004, Oliveira and Andrade, 2007). Future research may also further explore the effects of integrated weather conditions by linking mobility to clusters of naturally co-occuring weather conditions, such as a typical clear, sunny, dry, cold winter day or a hot, humid, summer day, referred to as weather types (Clifton et al., 2011).

The time-geographical framework in the introduction of this research describes daily mobilities as the time-space paths of individuals through a sequence of spatiotemporal travel situations (Hägerstrand, 1970; Dijst, 2013). One of the strong aspects of this research is that it considers mobilities in relation to the rich dynamic spatial contexts of present travel situations. One of the shortcomings, however, is that – despite statistically accounting for the independency of trips by the same respondent through clustered standard errors – our analyses largely ignore how mobilities are related to preceding and later travel situations, including preceding and later weather conditions. This temporal relationality may have important implications for the effects of weather. In this respect, an important task for future research is to get a better understanding of peoples' expectations with regard to weather conditions. For instance, an unexpected first warm spring day after a long cold winter period may result in a spontaneous positive effect on active mode usage, outdoor leisure destination visits, weather valuations and travel experiences – much more positive for instance than on a day with the exact same weather conditions in the middle of summer. On a smaller time scale, a sudden dry spell in an otherwise rainy day may result in temporally concentrated pedestrian, cyclist or outdoors leisure activities, because people realise they have to be quick before the rain starts again. One way, in which future travel diary studies could take into account temporal relationality, is to make more explicit use of the longitudinal structure of travel diary data in latent growth curve models. This is a specific type of Structural Equation Modelling, which relates the effects of weather on mobility behaviours (and experiences) at one point in time to its effects on mobility behaviours (and experiences) at previous and later points in time. Besides addressing the role of relative weather, such latent growth curve models could give more insights into the complex causalities (explored in chapters 5 and 6) between mode choices, weather perceptions and mobility experiences in terms of emotions and place valuations. Another way to account for temporal relationality would be to include in addition to present weather conditions: the lagged effects of previous weather (e.g. Creemers et al., 2014); the differences between current weather and long-term averages; and/or the broadcasted weather forecasts for that day. Especially the role of weather forecasts has currently been largely underexplored, both in traditional forms (such as in daily news bulletins), as well as in more dynamic forms, such as the real time weather radar applications on smart phone apps that can be inquired even while on the move.

This research shows that the effects of weather on mobility may differ between different people and across different geographical contexts. Our results provide some interesting indications that women, elderly people, and people with ethnic backgrounds in warmer climate regimes perceive weather conditions as colder and less comfortable. However, due to a limited share of immigrants in our sample (±10%), despite extensive oversampling, it is difficult to statistically confirm the ethnicity effects. Further research with larger elderly and immigrant sample sizes is recommended that includes separate elderly and immigrant (sub)sample models or interaction effects between weather and socio-demographics, in order to find out whether and how weather has different effects on the mobilities of these specific populations. Zooming in on the effects of weather on elderly and immigrant mobilities is crucial in order to get a better perspective on their distinct weather and mobility preferences and vulnerabilities, especially in the light of an ageing and – as a result of international migration – potentially increasing multi-ethnic society. Additional attention may also be devoted to the effects on other vulnerable subpopulations, such as young children or people with reduced physical or mental health. These effects may also directly be related to physical activity contributions and associated health issues like obesity. With regard to the role of geographical contexts this research investigates the relationship between weather and mobility from an explicit dynamic urban perspective. However, one of the main limitations in this respect is that our analysis link urban mobility patterns to weather data from meteorological stations located outside the city. Including local data from urban weather stations was considered but ultimately avoided because of reliability concerns. Our method may have resulted in a bias between measured weather conditions at the rural weather station and observed microclimate conditions by respondents throughout the urban fabric. Further research is recommended, which takes into account urban microclimate conditions more explicitly and accurately in the measurements of weather conditions. This may require using higher spatial and temporal resolutions, and the use of new data gathering techniques. Instead of the data on entire trips linked to nearby rural daily or hourly weather records, studies may want to use GPS-based data on routes, route segments and speeds, linked directly to data from (mobile) local urban weather stations or precipitation radar data. In order to provide an account of mobility experiences, these GPS-tracked mobility data could be linked to repeated Ecological Momentary Assessment of such experiences on smart-phone apps, or to innovative biometric data collection techniques.

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Nederlandstalige samenvatting

Of we nu te voet of op de fiets onderweg zijn naar een eindbestemming, bushalte, station of geparkeerde auto, in de file staan tijdens een druilerige ochtendspits, verblind worden door een laagstaande zon, rijden op een gladde weg, of dat we bij warm zonnig weer op pad gaan, een terrasje pakken of verkoeling aan de waterkant zoeken; tijdens onze dagelijkse verplaatsingen worden we telkens blootgesteld aan een verscheidenheid aan weersomstandigheden. Intuïtief gezien speelt het weer een belangrijke rol in verkeer en vervoer. Mede door de maatschappelijke aandacht voor klimaatverandering is er, met name de afgelopen jaren, veel wetenschappelijke kennis ontwikkeld op dit gebied. Bestaande kennis richt zich met name op de effecten van extreme weersomstandigheden zoals stormen, overstromingen en hittegolven, op de veiligheid, de doorstroming en het onderhoud van het wegennet, openbaar vervoer en luchtvaartnetwerk. Er is echter binnen de wetenschap nog altijd veel minder bekend over de effecten van allerlei normale weersomstandigheden op de dagelijkse mobiliteit van mensen. Precies dit onderwerp zal in dit proefschrift nader worden onderzocht. De hoofddoelstelling hierbij is meer inzicht te krijgen in de betekenis van huidige en toekomstige weersomstandigheden voor dagelijkse mobiliteitskeuzen en voor de subjectieve beleving van weer, ruimtelijke omgeving en emoties onderweg in de Randstad. Deze hoofdvraag zal worden beantwoord aan de hand van de volgende vijf deelvragen, welke opeenvolgend worden beantwoord in vijf wetenschappelijke artikelen die de basis vormen voor dit proefschrift.

1. *Wat zijn de bestaande wetenschappelijke inzichten en kennishiaten met betrekking tot de effecten van alledaagse weersomstandigheden op individueel dagelijks verplaatsingsgedrag en activiteitenpatronen?*

Een systematisch literatuuronderzoek is uitgevoerd om de bestaande wetenschappelijke kennis naar de effecten van het weer op dagelijks verplaatsingsgedrag en activiteitenpatronen uit verschillende wetenschappelijke disciplines te verenigen. Er bestaat algemene consensus dat neerslag, bewolking, wind en lagere temperaturen een negatief effect hebben op wandelen, fietsen en actieve openluchtactiviteiten, en dat ze leiden tot een toename in met name autogebruik. Deze weerseffecten lijken een grotere rol te spelen bij vrijetijdsverplaatsingen dan bij verplaatsingen naar meer verplichte bestemmingen zoals werk, studie en winkels voor dagelijkse boodschappen. Maar er zijn ook duidelijke verschillen. Wanneer studies uit verschillende landen met elkaar worden vergeleken, blijken er geografische verschillen te bestaan die deels verklaard lijken te kunnen worden door klimaat, alhoewel ook andere factoren zoals culturele verschillen een rol kunnen spelen. Studies verricht in gematigde zeeklimaatzones (zoals in grote delen van West-Europa) rapporteren relatief grote dagelijkse weersschommelingen, terwijl studies in landklimaatzones (zoals in de binnenlanden van de VS en Canada) met name de sterke seizoensverschillen accentueren. Enkele studies in warme (sub)tropische klimaatzones (zoals in Taiwan) bieden aanwijzingen dat mensen in warmere klimaten een hogere temperatuurtolerantie hebben.

Het literatuuronderzoek legt ook belangrijke tekortkomingen bloot. Ten eerste besteden studies, een enkele uitzondering daargelaten, voornamelijk aandacht aan de individuele effecten van weerparameters zoals regen, temperatuur en wind, maar niet aan de samenhang hiertussen. Hierbij wordt voorbij gegaan aan de complexiteit van het weer in het dagelijks leven, waarin mensen juist blootgesteld worden aan combinaties van weersomstandigheden. Zo kan wind bijvoorbeeld een aangenaam verkoelend effect hebben op een hete zomerdag, terwijl dezelfde wind op een koude regenachtige dag juist een negatieve rol kan spelen. Ten tweede wordt in veel studies aangenomen dat weerparameters een lineair effect hebben op verplaatsingsgedrag, terwijl dit in werkelijkheid niet het geval hoeft te zijn. Een aantal studies onderkennen dit en rapporteren bijvoorbeeld plotselinge dalingen in fietsgebruik boven bepaalde windsnelheden of vinden dat niet alleen lage, maar juist ook zeer hoge temperaturen een negatief effect hebben op gebruik van actieve vervoerswijzen en openluchtactiviteiten. Ten derde richten studies zich met name op objectief gemeten weersomstandigheden, maar is er veel minder aandacht voor de rol van weerberichten alsmede voor de verwachtingen, percepties en emotionele belevingen die mensen hebben van weer. Juist inzicht in deze subjectieve kwesties is nodig om te begrijpen hoe het weer mensen beïnvloedt, en waarom weerseffecten verschillen tussen verschillende mensen, verschillende sociale groepen, of verschillende vervoermiddelgebruikers. Ten slotte is er een aantal geografische dimensies onderbelicht. De huidige literatuur is sterk gericht op gematigde land- en zeeklimaten in de westerse wereld, terwijl we nog maar weinig weten over de effecten van weer op dagelijkse mobiliteit in niet-westerse landen, poolgebieden, woestijnen en (sub)tropische klimaten. Op kleinere ruimtelijke schaal is er met name aandacht voor mobiliteit in stedelijke regio's. Echter, de gebruikte weersgegevens zijn veelal afkomstig van landelijke weerstations. Dit kan een vertekend beeld geven, aangezien er substantiële verschillen kunnen bestaan tussen microklimaten binnen en buiten de stad.

2. *Hoe zal de te verwachten klimaatverandering in 2050 van invloed zijn op dagelijkse vervoermiddelaandelen en verplaatsingsafstanden in de Randstad voor de verschillende seizoenen?*

Om deze tweede onderzoeksvraag te beantwoorden is een klimaat-effectanalyse uitgevoerd op bestaande mobiliteitsdata (Mobiliteitsonderzoek Nederland, MON). Hiertoe zijn uit de afgelopen decennia vier seizoenen geselecteerd die representatief zijn voor ons huidige klimaat, alsmede vier seizoenen die wat betreft temperatuur en neerslagpatroon in lijn liggen met de KNMI verwachtingen voor het klimaat in 2050. Een vergelijking van mobiliteitspatronen in deze toekomstige ten opzichte van de huidige seizoenen laat zien dat klimaatverandering een effect heeft op mobiliteitspatronen. Van alle vervoermiddelen blijkt de fiets het meest sterk beïnvloed te worden. Dit kan worden verklaard doordat de fietser het sterkst wordt blootgesteld aan het weer, zeker in vergelijking met de beschutte automobilist, maar ook in vergelijking met bijvoorbeeld de wandelaar die eenvoudiger beschutting kan vinden tegen regen, wind, kou of hitte in bebouwde omgevingen of met behulp van attributen zoals een paraplu. De bevindingen laten zien dat in de Randstad over de gehele linie naar verwachting vaker en verder gefietst zal gaan worden. Dit gaat met name ten koste van het autogebruik. Echter, er bestaan wel duidelijke verschillen tussen de seizoenen. Het gebruik van actieve vervoerswijzen stijgt vooral in mildere en enigszins nattere winters van 2050. In het zomerseizoen worden juist omgekeerde effecten geobserveerd. De geprojecteerde hittetoename in combinatie met extremere neerslag lijkt het in de zomer minder aantrekkelijk te maken om te fietsen en te wandelen. Het gebruik van gemotoriseerd vervoer, in het bijzonder de auto, neemt hierdoor in de zomer naar verwachting toe. Door deze tegengestelde seizoenstrends worden de seizoensverschillen in vervoermiddelgebruik zoals we die nu kennen in (hoger gebruik van actieve vervoerswijzen in de zomer ten opzichte van de winter) enigszins afgevlakt.

3. *Hoe beïnvloeden weersomstandigheden de dagelijkse frequentie en duur van fietsen en het fietsaandeel ten opzichte van andere vervoermiddelen?*

Deze deelvraag richt zich specifiek op fietsen, dit in navolging op de eerdere bevinding dat de fiets van alle vervoersmiddelen het sterkst door weersomstandigheden wordt beïnvloed. In plaats van seizoensspecifieke klimaateffecten worden ditmaal de directe dagelijkse weerseffecten onderzocht. Hiervoor is een onderzoek met verplaatsingsdagboekjes uitgevoerd onder 945 respondenten in Rotterdam en omgeving. In deze dagboekjes hielden respondenten gedurende twee dagen in de zomer, twee dagen in de herfst en twee dagen in de winter precies bij waar, hoe laat, met welk vervoermiddel en naar welke bestemmingen zij onderweg waren. Deze data zijn vervolgens gekoppeld aan dagelijkse meteorologische gegevens van het KNMI. De resultaten laten zien dat windsnelheid en hoeveelheid neerslag een lineair negatief effect hebben op fietsfrequenties, fietsduur en fietsaandelen ten opzichte van andere vervoermiddelen, in het bijzonder de auto. De effecten op fietsduur lijken hierbij relatief het sterkst te zijn. Een mogelijke verklaring hiervoor is, dat fietsers het met name onprettig vinden om gedurende langere tijd blootgesteld te zijn aan deze 'negatieve' weerseffecten. Wat betreft de effecten van temperatuur lijkt er sprake te zijn van een non-lineair verband: zowel koud als heet weer hebben een negatief effect op fietsen. Hierbij ligt het omslagpunt rond een maximale dagelijkse luchttemperatuur van 24°C. Om de effecten van temperatuur op fietsen nader te onderzoeken is niet alleen gekeken naar luchttemperatuur, maar ook naar warmtestraling (T_{mrt}) en gevoelstemperatuur (PET). Dit zijn beide indicatoren die weliswaar lijken op luchttemperatuur, maar toch iets anders in elkaar zitten. Ze houden namelijk rekening met samenhangende weerselementen zoals inkomende zonnestraling, windsnelheid en/of luchtvochtigheid en sluiten bovendien beter aan op de werking van de warmtebalans in het menselijk lichaam. De resultaten laten zien dat deze alternatieve thermische variabelen een betere statistische verklaring bieden voor fietsgedrag dan enkel luchttemperatuur. Dit kan een indicatie zijn dat de beleving van warmte door het menselijk lichaam inderdaad voortkomt uit een samenhang van verschillende weersomstandigheden. Om dit nader te onderzoeken wordt met behulp van de laatste twee deelvragen onder andere gekeken naar de subjectieve temperatuurbeleving van respondenten onder verschillende weersomstandigheden.

4. *In hoeverre en op welke manier beïnvloeden weersomstandigheden vervoermiddelkeuzen, temperatuurbeleving en de beleving van emoties onderweg?*

Deze deelvraag richt zich op een van de belangrijkste geïdentificeerde kennishiaten op het gebied van weer en mobiliteit: het beperkte inzicht in de subjectieve beleving van weersomstandigheden onderweg. Om deze deelvraag te beantwoorden worden inzichten uit de drie wetenschappelijke kennisvelden *weer en mobiliteit*, *thermisch comfort* en *weer en emoties,* zowel conceptueel als statistisch geïntegreerd. Ook hiervoor wordt het verplaatsingsdagboekjesonderzoek in Rotterdam en omgeving gebruikt. Naast de eerder beschreven verplaatsingsdata hebben respondenten in deze dagboekjes ook precies bijgehouden hoe zij het weer, emoties en de omgeving onderweg tijdens iedere verplaatsing hebben beleefd. Deze informatie wordt opnieuw gekoppeld aan meteorologische gegevens van het KNMI, maar ditmaal op uurniveau. In een statistische analyse op basis van structurele vergelijkingsmodellen (SEM) worden objectieve weersomstandigheden, subjectieve temperatuursbelevingen, vervoermiddelkeuzen en emotionele mobiliteitsbelevingen aan elkaar gelinkt. De resultaten laten zien dat nat, bewolkt, winderig, koud of juist te heet weer een negatief effect hebben op het gebruik van actieve vervoerswijzen, in het bijzonder de fiets, ten opzichte van gemotoriseerd vervoer. Bovendien leiden deze ongunstige weersomstandigheden onderweg tot een minder prettige beleving van emoties. Hierbij spelen zowel directe als indirecte effecten een rol. De directe effecten hebben te maken met bijvoorbeeld het gebrek aan comfort dat kan optreden als men geconfronteerd wordt met wind en regen in het gezicht, of de extra moeite die het kost om tegen de wind in te fietsen. De indirecte effecten hangen samen met de subjectieve temperatuurbeleving onderweg. Niet alleen hogere luchttemperaturen, maar ook zonneschijn en lagere neerslag en windsnelheid leiden ertoe dat mensen omgevingen als warmer beleven. Dit bevestigt de eerdere verwachting dat temperatuurbeleving een samenspel is van verschillende tegelijk optredende weersomstandigheden. Deze warmere beleving blijkt op zijn beurt een positief effect te hebben op emoties onderweg. Een uitzondering hierop zijn temperaturen boven 25°C, die weliswaar als warmer worden beleefd, maar die een negatief effecten blijken te hebben op emoties. Dit kan belangrijke negatieve gevolgen hebben in een mogelijk warmer toekomstig klimaat.

Behalve deze algemene bevindingen laten de resultaten ook zien dat de beleving van warmte en emoties onderweg sterk kan verschillen voor verschillende bevolkingsgroepen, verschillende type verplaatsingen, verschillende tijdstippen en verschillende vervoermiddelgebruikers. De beleving van emoties onderweg blijkt positiever te zijn tijdens het weekend, buiten de spits, en bij vrijetijdsverplaatsingen. OV-gebruikers hebben vergeleken met andere vervoermiddelgebruikers een minder prettige emotionele mobiliteitsbeleving. Echter wanneer ook weerseffecten in ogenschouw worden genomen, blijkt dat de automobilist van alle vervoermiddelgebruikers de meest aangename warmtebeleving heeft, wat indirect leidt tot een prettigere emotionele mobiliteitsbeleving. Daarentegen blijken de wandelaar en met name de fietser, verplaatsingsomgevingen doorgaans als kouder en daardoor minder prettig te beleven. Ten slotte blijkt thermische beleving te verschillen tussen verschillende bevolkingsgroepen. Vrouwen en ouderen beleven omgevingen als kouder en daardoor minder prettig

5. *In hoeverre en op welke manier beïnvloeden weersomstandigheden vervoermiddelkeuzen, temperatuurbeleving en de waardering van ruimtelijke omgevingen onderweg?*

Deze laatste deelvraag bouwt voort op de gebruikte dataset en statistische analyse bij deelvraag 4, echter er wordt ditmaal specifiek aandacht besteed aan de ruimtelijke aspecten met betrekking tot de relaties tussen weer, temperatuurbeleving en ervaring van de verplaatsing. De waardering van verplaatsingsomgevingen staat hierbij centraal en wordt gemeten op basis van drie aspecten die zowel fysieke als sociale dimensies bevatten: esthetiek, gemoedelijkheid en levendigheid. Allereerst is bekeken in hoeverre de waardering van ruimtelijke verplaatsingsomgevingen samenhangt met fysieke, ruimtelijke kenmerken van de verplaatsingsomgeving, zoals het percentage groen, de adressendichtheid en de diversiteit van gebouwen. Opmerkelijk genoeg hebben deze statische, ruimtelijk kenmerken weinig effect. De waardering van verplaatsingsomgevingen blijkt met name te worden beïnvloed door verplaatsings-specifieke dynamische ruimtelijke aspecten. Mensen waarderen verplaatsingsomgevingen hoger wanneer zij reizen in gezelschap, met vrijetijdsdoeleinden, bij daglicht of wanneer zij bewust kiezen om te reizen via een omweg. In het verlengde hiervan speelt ook de dynamiek van het weer een belangrijke rol. Over het algemeen hebben droog weer, zonneschijn en milde tot warme temperaturen, zowel direct als indirect via temperatuurbeleving, een positief effect op de waardering van ruimtelijke omgevingen. Er kunnen verschillende verklaringen worden gegeven voor deze relaties tussen weer en omgevingswaardering.

Ten eerste is bekend uit de literatuur dat deze gunstige weersomstandigheden leiden tot een hoger gebruik van actieve vervoerswijzen en meer buitenactiviteiten op straat, wat ertoe kan leiden dat ruimtelijke omgevingen drukker en levendiger worden. Daarnaast is eerder gebleken dat deze gunstige weersomstandigheden een positief effect hebben op emoties. Dit kan stimulerend werken op de manier waarop mensen omgevingen in het algemeen waarderen, maar ook hoe gemoedelijk mensen met elkaar omgaan. Ten slotte kunnen sommige weerselementen zoals zonneschijn, bewolking, mist of regen een direct effect uitoefenen op de esthetische kwaliteiten van omgevingen. Zoals ook eerder bleek bij emotionele mobiliteitsbelevingen, verschillen de effecten van weer op ruimtelijke omgevingswaardering sterk tussen de verschillende vervoermiddelgebruikers. Wandelaars en fietsers blijken over het algemeen een hogere waardering te hebben van ruimtelijke verplaatsingsomgevingen dan gebruikers van gemotoriseerde vervoersmiddelen. Dit kan te maken hebben met de open lucht en de lagere snelheden, waardoor zij een hechtere band hebben met de ruimtelijke verplaatsingsomgeving. Dit betekent echter ook dat wandelaars en met name fietsers gevoeliger zijn voor het weer, zeker in vergelijking tot de beschutte automobilist.

Toegevoegde waarde

De inzichten die in dit proefschrift zijn gegenereerd dragen op een aantal wijzen bij aan de theoretische discussies omtrent de relaties tussen klimaat, weer en dagelijkse mobiliteit. Waar zowel binnen de wetenschappelijke literatuur als populaire media vooral veel aandacht bestaat voor de effecten van extreme weersomstandigheden op de transportsector, zijn in dit onderzoek juist vooral de effecten belicht van normale weersomstandigheden op dagelijkse mobiliteit. Het is duidelijk geworden dat deze relaties complexer zijn dan voorheen werd gedacht. De analyses in dit proefschrift laten zien dat er gecombineerde weerseffecten optreden en dat de relaties tussen weer en verplaatsingsgedrag niet altijd lineair hoeven te zijn. Ook laten de resultaten zien dat de effecten van weersomstandigheden op mobiliteit niet uniform zijn, maar substantieel kunnen verschillen voor verschillende bevolkingsgroepen en verplaatsingssituaties. Bovendien wordt, door de toevoeging van natuurlijke (zoals weersomstandigheden, seizoenen, en dag- en nachtritmes) en andere dynamische processen (zoals week- en weekenddagen of spits- en daluren), verplaatsingsgedrag vanuit een meer dynamisch perspectief verklaard dan veelal gebruikelijk is. Maar wellicht is de belangrijkste toegevoegde waarde dat we meer te weten zijn gekomen over de tot dusverre relatief onbekende subjectieve weer- en mobiliteitsbelevingsaspecten. Het is belangrijk hierbij mobiliteit te zien vanuit de betekenis die het heeft voor de reiziger (niet alleen in functionele, maar ook in gevoelsmatige zin), en weerseffecten te beschouwen als lichamelijke belevingen waarbij alle zintuigen betrokken zijn. Het is duidelijk geworden dat combinaties van weerselementen zoals temperatuur, zonneschijn, neerslag en wind een belangrijke rol spelen in zowel emotionele mobiliteitsbelevingen als de waardering van ruimtelijke verplaatsingsomgevingen. Deze inzichten vormen een belangrijke aanvulling op het toenemende wetenschappelijke debat omtrent de relatie tussen reizen en welbevinden, en bieden bovendien nieuwe 'mentale' en 'lichamelijke' perspectieven in de relatie tussen weer en gezondheid.

De bevindingen in dit onderzoek omtrent de relaties tussen weer, ruimtelijke inrichting, verplaatsingsgedrag en mobiliteits-/weerbeleving kunnen ook van waarde zijn voor een aantal beleidsdoeleinden. Hierbij is het belangrijk om zowel klimaatadaptatie doeleinden (bijvoorbeeld het aanpassen van ruimtelijke omgevingen om negatieve gevolgen van weer en klimaat te verzachten) en mitigatiedoeleinden (bijvoorbeeld CO2-reducerende maatregelen om wereldwijde klimaatverandering af te remmen, zoals het stimuleren van het gebruik van duurzame actieve vervoerswijzen ten opzichte van de auto) in beleid te verenigen. Een belangrijke aanbeveling voor beleidsmakers is om meer rekening te houden met de effecten van dagelijkse weersveranderingen op vervoermiddelgebruik. Dit is bijvoorbeeld van belang bij het analyseren van vervoerstrends (zoals bij het evalueren van de effectiviteit van aangelegde fietsinfrastructuur), waarbij correcties moeten worden toegepast voor schommelingen in weersomstandigheden op korte termijn. Daarnaast is het belangrijk om mobiliteit niet alleen vanuit een tijd- en kostenoogpunt te beschouwen, maar meer aandacht te besteden aan zachte factoren zoals mobiliteitsbeleving, welbevinden en gezondheid, welke van invloed kunnen zijn op de waarde van reistijd. Het weer speelt hierbij een belangrijke rol. Op de langere termijn wordt beleidsmakers aangeraden bij de aanleg van fietsinfrastructuur rekening te houden met een mogelijke toename in het fietsgebruik in een toekomstig warmer klimaat. Hierbij is het echter wel belangrijk om de gevolgen van negatieve weersomstandigheden zoals neerslag, wind, kou, en (met het oog op klimaatverandering) met name hitte voor de van nature weinig beschutte wandelaar en fietser zoveel mogelijk te verzachten. Dit kan bijvoorbeeld worden bewerkstelligd door 'klimaatgevoelige' ingrepen in ruimtelijk stedelijk ontwerp. Het gebruik van bedekkende vegetatie rondom wandel en fietsinfrastructuur kan bijvoorbeeld een slimme maatregel zijn om in de zomer verkoeling en beschutting te bieden tegen hitte en plotselinge zware buien, terwijl dit in de winter (wanneer de blaadjes van de bomen zijn) geen belemmering vormt voor waardevolle wenselijke zonnestralen. Andere maatregelen kunnen zijn het gebruik van windschermen en overkappingen, met name op locaties die veel door wandelaars en fietsers worden gebruikt, almede op locaties waar beschutting vaak minimaal is, zoals bijvoorbeeld op bruggen.

About the author

Lars Böcker was born on the 15th of May 1985 in Arnhem, the Netherlands. He finished his secondary education at the Arentheem College in Arnhem in 2003. After completing one year of Earth Sciences in 2004 at Utrecht University, he switched to a bachelor in Human Geography and Planning, also at Utrecht University, which he completed in 2006. During this period he developed his interests in urban and transport geography, which he pursued further during a research master in Human Geography and Planning at Utrecht University and during an exchange period at Lancaster University. This period formed the basis for his master thesis on the mobilities of business travel. He graduated in 2010. It was during this master thesis that he explored the performance and experience of mobility beyond classic notions of time and cost, and familiarised himself with readings on the New Mobilities Paradigm, Actor Network Theory and Time Geography, some of which can be found back in this dissertation. Inspired by conducting research, he started his PhD project in April 2010 at the department of Human Geography and Planning at faculty of Geosciences, Utrecht University. To improve his interdisciplinary understanding of the relationships between weather, urban form and mobility experiences, in 2012, together with colleagues from Utrecht University and Wageningen University, he initiated an international interdisciplinary collaboration with urban climatologists at Gothenburg University, Sweden, which led to a joint publication included as a chapter in this book. Lars currently works as a postdoctoral researcher on issues related to the sharing economy in the transport sector at the Department of Innovation, Environmental and Energy Sciences at the Faculty of Geosciences, Utrecht University.

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