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OLLE JÄRV

Mobile phone based data in human travel behaviour studies: New insights from a longitudinal perspective

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Department of Geography, Institute of Ecology and Earth Sciences, Faculty of Science and Technology, University of Tartu, Estonia and Department of Geography, Faculty of Sciences, Ghent University, Belgium. This dissertation contributes to a joint PhD between the University of Tartu (Estonia) and Ghent University (Belgium).

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CONTENTS

LIST OF PUBLICATIONS

This dissertation is based on five original articles that have been published in international peer-reviewed scientific journals, are forthcoming, or have been submitted. These articles will be referred to in the dissertation by their respective Roman numerals.

This dissertation comprises five academic articles:

I Ahas, R., Mark, Ü., **Järv, O.** and Nuga, M. (2006) Mobile positioning in sustainability studies: the social positioning method in studying commuter's activity spaces in Tallinn. In: Mander, Ü., Brebbia, C.A., Tiezzi, E. (Eds.) *The Sustainable City IV. Urban Regeneration and Sustainability*. WIT Press, Southampton. pp. 127–135.

II Ahas, R., Silm, S., **Järv, O.**, Saluveer E. and Tiru, M. (2010) Using mobile positioning data to model locations meaningful to users of mobile phones. *Journal of Urban Technology* 17(1), 3–27.

III **Järv, O.**, Ahas, R., Saluveer, E., Derudder, B. and Witlox, F. (2012) Mobile phones in a traffic flow: a geographical perspective to evening rush hour traffic analysis using call detail records. *PLoS ONE* 7(11), e49171.

IV **Järv, O.**, Ahas, R. and Witlox, F. (forthcoming) Understanding monthly variability in human activity spaces: a twelve-month study using mobile phone call detail records. *Transportation Research Part C: Emerging Technologies* (Accepted for publication).

V **Järv, O.**, Müürisepp, K., Ahas, R., Derudder, B., Witlox, F. (forthcoming) Ethnic differences in activity spaces as a characteristics of segregation: a study based on mobile phone usage in Tallinn. *Urban Studies* (Under review).

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Author's contribution

I The author is partially responsible for the data collection, processing and analysis and partially participated in writing the manuscript.

II The author is primarily responsible for the development and verification of the anchor point model and partially participated in writing the manuscript.

III The author is responsible for formulating the research questions and composing the study design; is fully responsible for the data collection, processing, analysis and interpretation; and is primarily responsible for writing the manuscript.

IV The author is primarily responsible for formulating the research questions; is fully responsible for composing the study design, data collection, processing, analysis and interpretation; and is primarily responsible for writing the manuscript.

V The author is partially responsible for composing the study design; is primarily responsible for data collection, processing, analysis and interpretation, and for writing the manuscript.

LIST OF ABBREVIATIONS

AAL	The number of annual unique activity locations
AAS	The size of the annual activity space
CA	The call activity for a mobile phone user
CDR	The call detail records of mobile phones
DAL	The number of meaningful daily activity locations
DAS	The size of daily activity space
ICT	Information and communication technologies
MAL	The number of monthly unique activity locations
MAS	The size of monthly activity space
MLA	Multiple linkage analysis
Mtop10	The share of call activities to an individual's 10 most-frequented activity locations, excluding the home location
NAL	The share of "new" or once a year visited activity locations
SDE	Standard deviational ellipse

PREFACE

I can proudly reply to the question – Yes, it is finally finished. I completed my dissertation. To get this far, to reach my destination after so many years, has been a challenge. It is claimed that the harder the route, the more rewarding the triumph. My PhD journey through scientific literature, statistical models and constant learning about both human spatial travel behaviour and life (in its broadest sense) in spatial, temporal and social dimensions would not have been possible without the moral support from my social network and the financial support from different institutions.

I am thankful for the financial support provided by the Institutional Research Grant IUT2-17 of the Estonian Ministry of Education and Science; Estonian Science Foundation Grant ETF7562; EU Regional Development Foundation, Env. Conservation & Technology R&D Program project TERIKVANT 3.2.0802.11-0043; and the Estonian Information Technology Foundation. I am also grateful to the European Social Fund through the Doctoral School of Economics and Innovation, and the Doctoral Studies and Internationalisation Programme DoRa for the additional support to attend and present my work at conferences and to visit Ghent University, which enabled me to enrich the content of my dissertation. Not least, I am thankful to the mobile network operator EMT and Positium LBS for providing the data used in this dissertation.

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Last, but above all, I owe my sincerest gratitude to my parents and to my beloved Kerli. I thank my parents for opening my eyes to the diverse world, for

shaping me to become a (human) geographer, and for always supporting me unconditionally. I am blessed to have Kerli next to me for her tremendous moral support, patience and willingness to delve into extensive discussions about space, time, society and life.

Vabriku Street, Tartu, September 2013

1. INTRODUCTION

1.1. Background

The travel behaviour research of individuals is, broadly speaking, about movement and displacement of people in space and time, which can also be defined as "spatial mobility" or "spatial behaviour" of individuals. In travel behaviour research, there is a wide range of different elements that can be studied, albeit in recent decades, by taking the 'mobilities turn' to heart (Sheller and Urry, 2006), its spatial characteristics have emerged to become the central object of interest (Schönfelder and Axhausen, 2010). Therefore, the spatial perspective in travel behaviour is the focus of this dissertation.

Travel behaviour is comprised of a complex pattern of paths and activities in space and time. It is the outcome of the interconnection between individual factors, interaction with other individuals, and external factors such as the surrounding environment and social structures. According to Pred (1984), combining Giddens' structuration theory (1979) with the concept of time geography developed by Hägerstrand (1970), developments within societies and their fundamental structures are changing human actors and their everyday life practices. In addition, through individuals' daily practice in space, people intentionally or unintentionally produce and reproduce societal structures and systems.

Individual travel behaviour is influenced by socio-economic factors and the needs, life values, preferences, attitudes, prejudices and habits of individuals (Bagley and Mokhtarian, 2002; van Wee, 2009; Van Acker et al., 2010). However, travel behaviour is (re)shaped by underlying external factors, such as the layout of urban structure, land use, infrastructure and micro-scale neighbourhood design (Handy, 1996; Badoe and Miller, 2000), policies and legislation (Cao et al., 2009; Neutens et al., 2011), and cultural habits and societal norms (Stern and Richardson, 2005). Furthermore, travel behaviour is determined by one's social networks and interactions with others (Carrasco and Miller, 2006; Lee and Kwan, 2011); it is further amplified by information and telecommunication technologies (ICT) in both physical and virtual space (Kesselring, 2006; Miranda-Moreno et al., 2012; van den Berg et al., 2013).

The interplay of the individual and society directly or indirectly affects our entire lives continuously (Lefebvre, 1991). The ability to move and to be flexible in space and time impacts our entire life; one's stroll in the park, one's daily commuting routine, weekly leisure activities and long-istance travelling, and residential and occupational mobility or even migration patterns during the course of one's life all hinge upon one's willingness and ability to 'move' in time and space (Cresswell and Merriman, 2010). In recent decades, societal structures in post-industrial countries have changed as a result of the overall growth in prosperity, the shift in the labour market, economic globalisation, politics, and social life, (sub)urbanisation, and the development of mobile technologies, such as in personal cars, airplanes and ICT (Graham, 1998; Urry, 2000). Hence, we witness ever-increasing consumerism, individualisation, diversification of ways of life, social innovations, physical and virtual space mobilities, and space-time compression in the physical world (Kwan, 2007; Cassiers and Kesteloot, 2012).

These developments have increased the complexity of individual travel behaviour while behaviours are becoming more flexible and fragmented in space and time (Hubers et al., 2008; Schwanen et al., 2008) and there is a blending of different mobility forms and activities in terms of multiple residences and long-distance travel for leisure and occupational purposes (Doherty, 2006; Flamm and Kaufmann, 2006a; Limtanakool et al., 2006). In addition, the need for mobility- and adventure seeking is evident (Kesselring, 2006; Mokhtarian et al., 2006), whereas the objective of spatial mobility may be the travel itself as an activity (Mokhtarian and Salmon, 2001; Sheller and Urry, 2006). In developed countries, work-related or mandatory travel constitutes approximately one fifth of all trips and up to one quarter of the total distance people travel; the biggest share of travel is leisure-related (Schlich et al., 2004; McGuckin and Srinivasan, 2005).

From a more social perspective, studies confirm that individual travel behaviour is associated with (the feeling of) personal freedom (Flamm and Kaufmann, 2006a), the level of subjective well-being (De Vos et al., 2013), identity and moral dispositions (Valentine, 2008), and the creation of social status and the formation of power relations in society (Kaufmann et al., 2004; Viry et al., 2009). Consequently, 'being mobile' has become an established ideology in the contemporary world, with the absolute and relative ability to move in spatial, temporal and social dimensions functioning as a new form of capital (Kaufmann et al., 2004; Urry, 2007; Kellerman, 2012). Hence, spatial mobility, per se, has become a decisive condition for social interaction and integration (Urry, 2000).

To date, the conventional approach for studying human travel behaviour has been to collect data using activity-travel diaries predominantly based on short periods of time (up to three days) or to conduct retrospective interviews (Schönfelder and Axhausen, 2010). At the aggregated level, data are usually based on static (traffic) counters and census or register data (Raymer et al., 2007; Leduc, 2008). However, this approach does not meet the need to gain a more comprehensive understanding of human (travel) behaviour. It neglects the mid- and long-term perspectives and does not consider that the intrapersonal variability is equal to or even greater than interpersonal variability on a daily basis (Pas and Koppelman, 1987; Kitamura et al., 2006). Generally, the prolonged perspective has been neglected due to a lack of data for longer periods, the high costs of data collection, the high response burden for the respondents, and a tendency for the responses to be biased (Golob and Meurs, 1986; Richardson et al., 1995; Axhausen et al., 2007).

Better understanding of human travel behaviour and its inter- and intra-personal variability in different temporal horizons would provide new insights into a myriad of different societal issues to plan environmentally, socially and economically sustainable societies (e.g., Batty et al., 2012). For instance, the additional knowledge of population mobility gives urban planners information that can be used to manage (sub)urbanisation and excessive land use, which is also referred as urban sprawl (see Ewing et al., 2007), and to design better neighbourhoods (Handy, 2005; Calabrese et al., 2013). In the context of the growth of excessive travel, CO_2 pollution and dissatisfaction with the quality of life (OECD, 2007; Boussauw et al., 2012), this information enables transportation planners to develop intelligent (public) transportation systems, to improve accessibility (Rose, 2006; Miller et al., 2013; Perchoux et al., 2013), to limit the increasing overall transportation demand and to alleviate traffic congestion (Downs, 2004).

While individual spatial mobility is considered a factor of socio-spatial differentiation and inequality (Urry, 2000; Kaufmann et al., 2004; Kesselring, 2006), comprehensive knowledge of the spatial dimension of human travel behaviour enables us to understand thoroughly the phenomenon of segregation and to reduce the deepening spatial divisions between social groups which lead to tensions and polarisation on both the local and the global scales (Cassiers and Kesteloot, 2012; Dukes and Musterd, 2012).

In recent years, the importance of adopting an intrapersonal perspective and the need to understand travel behaviour from a longitudinal (monthly, yearly) perspective have increased; therefore, new methods and approaches are needed to narrow these research gaps. The implementation of ICT-based accurate sensor technologies is already helping us to better understand and map human mobility in space and time. These technologies are, among others, mobile phone positioning (Zhao, 2000), global positioning systems (GPS) (Herrera et al., 2010), Bluetooth (Eagle and Pentland, 2005), Wi-Fi (Do and Gatica-Perez, 2013) and smart card transactions (Ma et al., 2013).

Because mobile phones are ubiquitous around the world and they are the most mobile of all mobile technologies (Townsend, 2000; Castells et al., 2007; Wilson and Corey, 2011), mobile phone based data are perceived to be a promising means to assess human movements at the individual level (Asakura and Hato, 2004; González et al., 2008), population dynamics at the aggregated level (Reades et al., 2007) and transportation systems (Rose, 2006; Bar-Gera, 2007). Nevertheless, one must acknowledge that mobile phone based data are facing two major challenges: privacy issues and fear of surveillance (Ahas and Mark, 2005; de Montjoye et al., 2013), and the need for further development of current theoretical and methodological approaches to interpret the data (Kwan, 2013).

In light of the above, the theoretical framework of this dissertation is presented next by focusing on three topics. First, an overview of the longitudinal perspective of current human travel behaviour is provided. This is followed by the introduction of the activity space approach and a description of how the spatial dimension of human travel behaviour is being measured. Finally, the implementation of mobile phone based call detail records (CDR) in human travel behaviour research is provided.

1.2. Theoretical framework

1.2.1. Longitudinal perspective in travel behaviour

In the field of human travel behaviour research, there is a substantial body of literature on short-period multiday travel surveys that confirm significant interpersonal day-to-day variability (Hanson and Huff, 1982; Jones and Clark, 1988; Buliung et al., 2008).

Despite individual socio-economical background, however, approximately half of the observed interpersonal variability is explained by intrapersonal variability (Hanson and Huff, 1982; Pas and Sundar, 1995; Susilo and Kitamura, 2005). Therefore, the stability of and variability in travel behaviour emphasises the need to extend study periods (Schönfelder and Axhausen, 2010). Our understanding of weekly travel behaviour patterns, described by stability and routines during working days with significant deviations on weekends, is already being substantially enriched by scholars such as Pas (1988), Schlich and Axhausen (2003), Srivastava and Schönfelder (2003), Spissu et al. (2009), and Tarigan and Kitamura (2009). However, controversial findings (e.g., Buliung et al., 2008; Miranda-Moreno and Lee-Gosselin, 2008) indicate the need for further research.

To date, the investigation of travel behaviour using a longitudinal perspective for monthly and yearly time horizons has been rare (Schönfelder and Axhausen, 2010). Individual travel behaviour during a concurrent study period longer than one month or during temporal (e.g., monthly) study intervals within a year has not been thoroughly studied because of several methodological issues (Golob and Meurs, 1986; Axhausen et al., 2007). Hence, longitudinal inter- and intrapersonal variations and rhythms of human travel behaviour, the development of travel behaviour over time and influencing external factors are not fully understood. Schönfelder and Axhausen (2010) demonstrate that different activities are performed over different durations (daily, weekly, monthly, and yearly), whereas the performance of certain activities varies in terms of timing and/or activity location in geographical space (e.g., Schlich et al., 2004; Nurul Habib et al., 2007). Moreover, due to societal developments affecting our daily lives, Frändberg (2008, p. 24) describe how we can rethink our conceptual framework for studying human daily travel behaviour at the present time by considering time frames beyond just one day or one week time and focusing on more prolonged time horizons.

Longitudinal perspectives, so far, have been studying human travel behaviour by comparing the changes of habitual behaviour over multiple years (Roorda and Ruiz, 2008; Olsson, 2012), exploring the dynamics of long distance mobility (Frändberg, 2008) and observing how travel behaviour changes because of life-course events (Lanzendorf, 2010; Scheiner and Holz-Rau, 2013). These studies are predominantly based on the concept of mobility biography that focuses on life-course trajectories (Lanzendorf, 2010) but does not delve into actual travel behaviour, per se. Hence, the monthly variability of actual travel behaviour and month-to-month comparisons up to a one-year study period or longer has, to the author's knowledge, not been studied for neither the inter- nor the intrapersonal perspective to date. The growing availability of longitudinal data, such as GPS-based (Schönfelder and Axhausen, 2010) and mobile phone based datasets (Silm and Ahas, 2010; Phithakkitnukoon et al., 2012), will enable researchers to study this topic in the near future.

In the current literature, the monthly perspective in human travel behaviour has been typically limited to examining the seasonality affect where months are proxies for the seasons of the year. Findings on how travel behaviour is influenced by seasonality are inconclusive. This is, in part, due to methodological differences in how travel behaviour and its variability are measured (Schlich and Axhausen, 2003) and in the geographical setting of each study. Findings indicate that seasonality affects the variation in time allocated by individuals to home and travel activities (Hirsh et al., 1986), pick-up/drop-off activities and weekend maintenance shopping (Bhat and Srinivasan, 2005) and that seasonality is more influential on leisure activities (Kemperman et al., 2002) such as out-of-home recreation activities during weekends (Bhat and Gossen, 2004) and recreational shopping (Bhat and Srinivasan, 2005). The seasonal variation in human travel behaviour is also evident through the use of (public) transportation: there is higher ridership during the spring and the fall while there is lower ridership during the summer and the winter months due to weather conditions (e.g., Tang and Thakuriah, 2012). Based on time-activity surveys, epidemiologists confirm that seasonality influences time spent on outdoor activities, on (transit) travel and on activities related to paid work (Xue et al., 2004; Wu et al., 2011; Isaacs et al., 2013).

On the other hand, some studies suggest that seasonality does not affect weekly activity-participation patterns (Kitamura and van der Hoorn, 1987) or the average daily number of reported trips per person over a six-week period (Schlich and Axhausen, 2003). Nurul Habib et al., (2007) conclude that an individual's daily travel behaviour remains generally stable over several months. However, these latter studies do not take into account the spatial dimension of human travel behaviour.

In the spatial perspective, the monthly average trip distance from home indicates that individuals' trips are significantly more dispersed in space and destinations are further from home during the summer months (Schönfelder and Axhausen, 2010, p. 156) and that seasonality affects short-term population relocation (Silm and Ahas, 2010). These findings indicate that individuals' need for spatial innovation and variety-seeking behaviour depends on the month of the year.

1.2.2. The activity space approach

To understand, describe and study human travel behaviour from both the spatial and temporal perspectives, geographers and sociologists, among others, have developed a number of different concepts (Horton and Reynolds, 1971; Zahavi, 1979; Golledge and Stimson, 1997; Neutens et al., 2011). However, Hägerstrand's (1970) concept of time geography, which is an essential framework for understanding individual behaviour through interdependent space and time, is often considered the seminal work in the field. With respect to daily travel behaviour, researchers from Lenntorp (1976) to Miller (1991), Kwan (1998) and Neutens et al. (2008) have focused on the individual's perceptual or potential travel behaviour and on accessibility.

Other scholars, such as Dijst (1999; 2004) and Schönfelder and Axhausen (2003; 2010), have focused more on observed travel behaviour. Dijst (2004, p. 30) proposes three levels of individual action space where an individual's (i) perceptual action space is the widest spatial sphere that partially or fully includes one's (ii) potential action space in which (iii) the actual action space is entirely located. The latter denotes visited activity locations that comprise daily bases (such as home and work) that define the structure of the activity and travel pattern of an individual (Dijst, 1999, p. 195). Similarly, Golledge and Stimson (1997) propose the concept of the activity space, which generally delineates the locations within which an individual has direct contact due to one's regular activities, including travel between and around those locations. Based on the latter concept, Schönfelder and Axhausen (2010) suggested that activity space can be defined by six elements: home location, duration of residence, the number of activity locations in the vicinity of the home, trips within the neighbourhood, mobility to and from frequently visited activity locations, and travel between and around the centres of daily life. The concept of activity space is also considered as a network of usual places, indicating the structure of opportunities and accessibilities determined by the location strategies of the household (Flamm and Kaufmann, 2006b) given the strong relationship between one's social network and that person's activity space size (Axhausen, 2007; Lee and Kwan, 2011).

Although the time geography approach emphasises the interdependent study of travel behaviour in a three-dimensional space-time perspective (e.g., Kwan, 2013), this dissertation focuses on a two-dimensional spatial perspective within different time horizons. The latter approach is predominantly applied in travel behaviour research (e.g., Dijst, 1999; Buliung and Kanaroglou, 2006; Schönfelder and Axhausen, 2010). Using a two-dimensional perspective, the spatial aspect of human travel behaviour can be studied using a point-based approach for the enumeration of trips or for unique destinations/locations. Based on this, methods from spatial statistics and computational geometry together with geovisualisation techniques are used to represent and measure an individual's use of space.

Different techniques are used to measure the spatial extent of travel behaviour: (shortest) travelled distance, kernel densities, standard deviational ellipse, standard distance (circle), and the minimum convex polygon method (Buliung and Kanaroglou, 2006; Schönfelder and Axhausen, 2010). The main aim in quantifying the extent of the activity space is to reveal and assess factors affecting human travel behaviour. However, findings are inconclusive whereas influenced by the measuring technique, the dataset applied, and the geographical setting (Schönfelder and Axhausen, 2010). Nevertheless, the extent of human activity space tends to be influenced by age, gender, household type, income and occupation type, working status, private car availability, and the locations of the residence (density) and workplace.

Of course, the quantification of human activity spaces does not always reveal one's actual spatial travel behaviour perfectly due to several reasons. It excludes virtual dimension and other forms of non-physical communication that serve as a substitute for face-to-face contacts to some extent (Schönfelder and Axhausen, 2003). Observed spatial behaviour does not always reflect one's mobility potential (Kellerman, 2012), and the social "content" of the visits may remain obscure in exercises of quantification (Kwan, 2013; Palmer, 2013). Nevertheless, the activity space approach is successfully applied to studying human travel behaviour because it emphasises the spatial and temporal dimensions while providing a good starting point for delving into social processes (Dijst, 1999; Buliung et al., 2008; Kamruzzaman and Hine, 2012; Palmer et al., 2012; Wang et al., 2012).

1.2.3. Implementing mobile phone based data

Mobile phone based data are perceived as a medium to better map, explore and understand human travel behaviour (Asakura and Hato, 2004; González et al., 2008; Palmer et al., 2012). In general, this approach provides a vast amount of data for unique locations of mobile phones in space and time; some datasets are handset-based (e.g., tracing mobile phones) while others that assess the usage capacity of mobile antennae are network-based (e.g., Erlang measure). A handset-based approach can be further divided into active (initiated by the network operator) and passive (automatically stored log data) positioning techniques. Both active (Article I) and passive (Articles II–V) mobile phone positioning techniques are applied in this dissertation while the predominant focus is on the latter.

A handset-based passive mobile phone positioning approach is applied while analysing call detail records (CDR) of mobile phones. CDR data are the log file of the network operator that automatically includes information on all outgoing call activities (CAs): voice calls, short messaging service texts, and Internet and data services conducted by mobile phone users in the network. The use of CDR in human travel behaviour research has demonstrated several advantages over conventional data collection methods, such as registers, static (traffic) movement counters, questionnaires, or travel diary surveys (Ahas and Mark, 2005; Reades et al., 2007; Witlox, 2007; Leduc, 2008).

CDR data have several advantages: (i) the provision of a large sample size (potentially all mobile phone users), (ii) the ability to consider long study periods (from one day up to months and years), (iii) the inclusion of a large study area (potentially a whole country and the entire world when including roaming-data), and (iv) the ability to have the spatial accuracy of a city block in urbanised areas. Moreover, the dataset is cost-effective because it is collected automatically into a database without disturbing respondents or burdening them with obligations, and the data can be processed into movement information in near real time.

However, CDR data has some disadvantages, such as the sampling issues related to phone ownership and its use, the limited availability of socio-economic variables and the access to data for research purposes. One of the most sensitive issues brought up with the use of passive mobile phone positioning data for research purposes is the concern about privacy, ethics and surveillance fear among mobile phone users and the general public (Ahas and Mark, 2005; de Montjoye et al., 2013). Because of this fear, network operators are hesitant to provide data to researchers, despite the exclusion of personal information and the limitations of the positioning accuracy (i.e., a city block). Furthermore, in countries belonging to the European Union, the receiving, storage, processing, and applications of CDR data are strictly regulated by the EU directive on handling personal data and the protection of privacy in the electronic communications sector (European Commission, 2002).

While applying CDR data to examine human travel behaviour, one must acknowledge several factors that may affect the results and bias the conclusions. First, an individual's CA habits and patterns may vary in space and time according to that individual's socio-economic characteristics, preferences, lifestyle, habits and work attributes (Castells et al., 2007). There is a correlation between the use of a mobile phone and the descriptive characteristics of individual spatial behaviour (Miranda-Moreno et al., 2012; Yuan et al., 2012). Second, external factors, such as country differences (e.g., legislation, service costs) and cultural backgrounds influence mobile phone use (Mccartt et al., 2006; Castells et al., 2007; Baron, 2010; White et al., 2010). At the micro level, the use of a mobile phone can be partially or fully restricted in certain places (e.g., in a court or at school). However, CAs at these places prior to or after a certain activity still reflect the location in a person's digital footprint. Moreover, smartphones are becoming increasingly prevalent in our daily lives; this technology provides more precise digital footprints (Chetan Sharma Consulting, 2013). These types of phones are used throughout the day while users simultaneously undertake other activities: smartphones are widely used while they are 'on-the-go', e.g., commuting, walking or using public transport in the USA (Google, 2011). Moreover, despite the prohibitions and restrictions (Mccartt et al., 2006) and the associated hazards of mobile phone use while driving, it is still practiced (White et al., 2010).

Nevertheless, the implementation of CDR data in human travel behaviour research is growing quickly and is being applied in various applications: the identification of an individual's activity locations (Zhou et al., 2007; González et al., 2008; Isaacman et al., 2011) and the assessment of mobility patterns of single individuals (Calabrese et al., 2013), entire populations (Silm and Ahas, 2010) or subgroups, such as foreign tourists (Ahas et al., 2008). Further, it enables the measurement of the influence of social networks on human mobility (Phithakkitnukoon et al., 2012) and the estimation of traffic flows in a transportation network (Steenbruggen et al., 2011). The combination of the ubiquity of mobile phones in our daily lives (Townsend, 2000; Castells et al., 2007; Wilson and Corey, 2011) and the growing body of literature demonstrates that CDR data are suitable for gaining a more comprehensive understanding of human travel behaviour at the aggregated and the disaggregated individual level and in short- and long-term perspectives.

1.3. Objectives and research questions

Although our understanding of individual travel behaviour in space and time has been a constant subject since Hägerstrand (1970) and is thoroughly examined in the short-term (i.e., daily) perspective to date, there are still distinct research gaps as described above. Three aims are the subject of this dissertation: **First**, to complement the existing methodology for data collection and measurement by conceptualising the identification and measurement of human travel behaviour and utilising a novel mobile phone based dataset. This methodological approach enables us to study short- and long-term time horizons at both the individual and aggregate levels. **Second**, to extend the existing knowledge of the spatial dimension of human travel behaviour in the longitudinal perspective by providing new insights from daily, monthly and yearly perspectives. **Third**, to demonstrate how mobile phone based data can be implemented to provide valuable knowledge on social processes and phenomena. Therefore, the overall aim of this dissertation is:

To ascertain how mobile phone based data can help us understand human travel behaviour.

The general aim is further refined into five research questions which are addressed in this dissertation:

1. *How can mobile phone based data be conceptualised to identify and measure human activity locations and movement between these locations?*

This research question will be addressed in Articles I–V. Article I is a first attempt to investigate the applicability of mobile phone data for measuring human spatial behaviour in general. Here, based on a 5-day experiment of active mobile phone positioning data, extraction of activity locations was conducted and daily trip distances were assessed. Based on the knowledge obtained, CDR data, i.e., data received from the passive mobile phone positioning method, were used to develop a model suitable to extract activity locations for the entire population. In Article II, the conceptualisation of the anchor point model and the identification of personal daily anchor points, such as home and work-time, location is presented with the further distinction of regular and random activity locations. The verification of the model's results with the population register data are performed. The anchor point model is the methodological basis for Articles III, IV and V.

Based on the anchor point model, Article III puts forward an alternative methodological approach on how CDR data and the anchor point model can be applied to investigate individuals' movements in space and time between extracted activity locations at the aggregated level. In the last two Articles (IV and V), in addition to home and work-time locations, the extraction of activity locations is then elaborated on further by implementing the multiple linkage analysis (MLA) method for distinguishing an individual's daily meaningful activity locations from other activity locations.

2. *How can mobile phone based data be used to extend our understanding of human travel behaviour for a prolonged time period of one month and one year?*

This research question will be addressed in Articles IV and V. The identical methodological approach is used in both articles; the approach extends the current understanding of human travel behaviour by presenting a conceptual approach for the identification of individual travel behaviour over prolonged time horizons. Article IV explicitly focuses on monthly travel behaviour during twelve consecutive months, whereas Article V explores a person's typical monthly behaviour concurrently with annual spatial behaviour.

3. *What factors influence the spatial characteristics of human travel behaviour from daily, monthly and yearly perspectives?*

This research question will be addressed in Articles I and V. As a first attempt to investigate the applicability of mobile phone based data for measuring the spatial dimension of human travel behaviour, Article I also demonstrates to what extent socio-economic factors affect individual daily movement patterns and activity spaces. Article V presents a more comprehensive overview of how interpersonal factors affect an individual's daily spatial activity and the spatial extent of one's "typical" monthly and annual travel behaviour. Here, emphasis is also placed on the issue of ethnicity and travel behaviour.

4. *How and to what extent are spatial characteristics of human travel behaviour influenced by the monthly variance?*

While this research topic is not possible to study with conventional data collection methods, this research question is the main focus of Article IV. Article IV explores to what extent monthly travel behaviour varies in space over a period of twelve consecutive months by applying mobile phone CDR data. To achieve this, four activity-location-based and two activity-space-based measures are investigated. In particular, the influences of interpersonal and intrapersonal factors along with seasonality are considered to explain the monthly variance. Based on the initial results, the occurrence of intrapersonal outlier months was added in cases for which the spatial extent of travel behaviour was markedly non-typical.

5. *How can mobile phone based data provide complementary knowledge on problematic social phenomena which are complicated to reveal?*

This research question will be addressed through three examples of social phenomena – short-term population mobility, traffic congestion and socio-spatial inequality; these are dealt with in Articles II, III and V, respectively. The comparison of results between the anchor point model and the population register data in Article II suggests that the implementation of the anchor point model is beneficial for assessing short term (e.g., monthly) changes in residential or occupational mobility with relatively low research costs and with minimum time delay. Moreover, the article demonstrates how this approach could be explicitly suitable for urban and transport planners to analyse the spatial distribution of populations, to monitor population processes and to solve problematic societal issues. It is essential in regions or countries where available population register data are out of date or incomplete, and it is an important supplement to census data, which are comprised of very detailed information but with long-term periodicity.

Article III demonstrates how mobile phone based data can be implemented to reveal the spatiotemporal composition of traffic flows within a given road section during a given time frame. This person-based approach cost-effectively provides additional valuable information for transportation planners, which they can use to better manage traffic congestion for an entire road network system by adopting this method as one of the real-time traffic monitoring tools in the near future. Article V conceptualises the implementation of the activity space approach and the mobile phone data in segregation research, which has been predominantly conducted at the aggregated level with fixed areal units. By doing so, Article V demonstrates how the proposed methodology can be embedded into a field of (ethnic) segregation studies and can reveal new insights on activity space based segregation. This approach can help to extend the current understanding of socio-spatial differences and can be used for making policies that aim to foster social cohesion and integration and to restrain socio-spatial inequality.

2. METHODOLOGICAL FRAMEWORK

2.1. Data

The CDR data applied in this dissertation (Article II–V) originates from the largest Estonian mobile network operator, EMT, which has over half a million active clients. The database contains records of all outgoing CAs conducted within the network: voice calls, short messaging service texts, and Internet and data services initiated by the phone owner in Estonia. Each CA record includes the unique ID number of the phone (randomly generated by the operator for every mobile phone), the exact time and date, and the mobile network antenna that provided the network signal for the CA. In Articles IV and V, the supplementary dataset of unique ID numbers is provided by the operator and is incorporated in to the analysis to provide the mobile phone owners' birth year, gender and the preferred language to communicate with the operator.

The CDR data are encrypted to preserve the anonymity and privacy of the mobile phone owners. The random ID number is generated by the operator for every mobile phone (not related to the phone or SIM card number), which is a link between each phone owner and his or her CA. CDR data are recorded in accordance with Estonian legislation for billing purposes by the operator and not for the purposes of this dissertation. Data receiving, storage, processes, and applications in this research follow data security and privacy requirements specified in European Union directive (European Commission, 2002). Moreover, ethical and privacy issues concerning conducted studies (Articles II–V) are consulted with and approved by both the Estonian State Data Protection Agency and by the Ethical Committee of Human Studies at the University of Tartu.

The geographical information for each CA record is obtained from the geographical coordinates of the network antennae. The precision of the spatial accuracy of the CA corresponds to the coverage of a network antenna (Figure 1). The coverage area of a network antenna is not spatially fixed and varies according to the population density and along main transportation corridors, i.e., according to the use of the mobile phone network. In general, the average coverage of all network antennas in Tallinn is approximately 0.8 km^2; in the Tallinn functional urban region (FUR) it is 15.3 km^2. In less inhabited rural areas, network antennas cover greater areas, with an average coverage area of 120 km^2.

This dissertation applies CDR data in different time periods: the study period in Article II is from November 1, 2006 to October 31, 2007; for Article III it is from October 1, 2008 to September 30, 2009; and for Articles IV and V it is from January 1, 2009 to December 31, 2009.

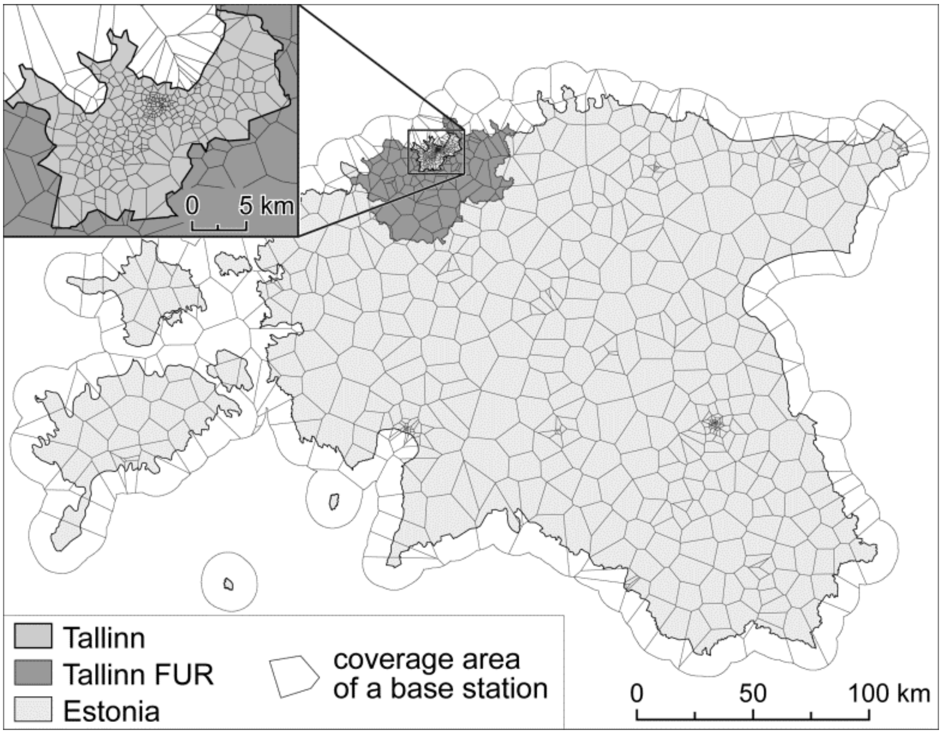

Figure 1. The study area and the distribution of theoretical areas of base station coverage. An enhanced view of Tallinn is shown in the top left (Source: adapted from Article IV, Figure 1).

2.1.1. Complementary data

In Article I, the active mobile phone positioning data and questionnaire describing socio-economic characteristics and travel behaviour are applied. Data were collected as a pilot study, where clients from the EMT network agreed to be located within a 30-minute interval between 7 am and 11 pm from February 18, 2004 to February 22, 2004. For locating mobile phones, the Cell Global Identity and Timing Advance method (Ahas et al., 2007) is used.

In Article II, the Estonian Population Register is used to compare register based residential distributions with the distribution of home anchor points as an output of the CDR data derived from the anchor point model (see Section 3.1) at the municipality level in Estonia. In Article III, stationary loop detector traffic counter data are used to calibrate hourly traffic flow that is derived from CDR data. In Articles IV and V, Population and Housing Census 2011 data from Statistics Estonia are applied to compare the socio-economic background distributions of samples from the CDR dataset with the population data in the Tallinn functional urban region.

2.2. Study area

In general, the study area of this dissertation is the whole country of Estonia, i.e., the entire coverage area of the EMT network (Figure 1). In Article II, the main focus is on the entire country of Estonia, with approximately 1.3 million inhabitants. In Articles I, and III–V, the main focus area is the Tallinn FUR – the largest FUR and the capital city region of Estonia, with approximately 550,000 inhabitants, of whom, 400,000 live in the core city of Tallinn.

Special attention is given to the Tallinn FUR for two reasons: (i) it is the most densely populated region and thus, CDR data enables the best spatial accuracy to evaluate human travel behaviour and (ii) within the last two decades, the region has undergone the most significant changes in Estonia and hence requires improvements to manage increasing mobility and traffic congestion. For example, spatial restructuring includes vast and increasing residential and workplace suburbanisation (Tammaru et al., 2009) in line with dramatic increase in motorisation with the rise in passenger vehicles and the decline of the demand for public transportation (European Commission, 2002).

2.3. Sample

At the time of the research, the penetration of mobile phone subscriptions (per 100 inhabitants) in 2009 was 117% (Statistics Estonia, 2013) while approximately 95% of Estonia's population use mobile phones (TNS EMOR, 2008). For the active mobile phone positioning experiment (Article I), 117 mobile phone owners who use the EMT network were selected. In Articles II and III, all people who own mobile phones and use the EMT network were potential study subjects according to the CDR data; the market share (TNS EMOR, 2008) comprises slightly over 0.5 million mobile phone users. In particular, in Article III, of all of the mobile phone users in the EMT network, only those phone users who conducted CAs in four selected network antennas during the study period, which covered the studied road section of the Tallinn-Tartu highway (E263), were examined.

Articles IV and V focus on mobile phone users who are of working age (between 20 and 64), live in Tallinn FUR and whose workplace is located in Tallinn. Furthermore, their home and workplace anchor points had to remain in the same network base station during the whole study period to analyse individuals' constant state of human travel behaviour without any significant life-course event in the spatial context. To minimise the potential impacts of individuals' CA habits and patterns that could influence the description of an individual's travel behaviour, four additional criteria are set to examine individuals with relatively similar digital footprints. A total of 1,310 mobile phone users meet these criteria. For Article V, the criteria for home location is further limited to Tallinn only, and the sample is comprised of equal shares of those mobile phone users who prefer Estonian as a communication language with the network operator and those who prefer Russian. Hence, in Article V, a total of 560 mobile phone users are examined.

2.4. The measurement of activity locations

In measuring activity locations based on CDR data in this dissertation, a unique activity location denotes the coverage area of an operator's base station where a person has made an outgoing CA. Hence, theoretically activity location indicates a given spatial area where activity location(s) is situated.

In this dissertation, based on theoretical background, several assumptions are elaborated on for applying CDR data in human travel behaviour studies: (i) an anonymous mobile phone in the dataset represents an individual (phone owner); (ii) CAs represent an individual's digital footprint in space and time; (iii) the amount of time spent in a location is strongly correlated with the amount of CAs conducted within a given location; (iv) a one-month time period is sufficient to reveal the extent of an individual's habitual spatial mobility, despite the fact that CAs are not constantly conducted while activities or travel are performed; and (v) a preferred communication language with network operator is a proxy for ethnicity and cultural background.

In addition to enumeration of unique activity locations in given study time horizons, the share of visitation to an individual's 10 most-frequented out of home activity locations (Mtop10) and the share of 'new' (or yearly visited) activity locations (NAL) is examined in Article IV. The former is as an indicator of the concentration of daily life, whereas the latter is as an indicator of variety-seeking behaviour, which is similar to Schönfelder and Axhausen (2010).

2.5. The measurement of activity spaces

The spatial extent of individual activity spaces are measured in Articles I, IV and V. Based on activity locations, the directional distribution tool in ESRI ArcGIS software is applied to calculate the standard deviational ellipse (SDE) at the individual level, and the daily distance travelled is measured to describe the individual activity space in Article I. In this dissertation, the SDE represents the smallest possible spatial area in which activity locations are found with a probability of 95% using a weighted measure based on the number of CAs conducted in each activity location to reflect the physical presence and time spent there.

Of the various methods available for measuring the extent of individual activity spaces, the SDE technique is preferred for several reasons. First, it is less sensitive to spatial outliers compared to some methods (Yuill, 1971), for example, compared to the minimum convex polygon (Burgman and Fox, 2003) or the standard distance circle (Buliung and Kanaroglou, 2006). Second, the two foci of the ellipse better coincide with the underlying structure of the individual activity space with two daily anchor points (home and work/school); hence, the major axis denotes the daily routine link between home and work (or school). Third, despite the tendency of the SDE technique to overestimate the spatial spread, Rai et al. (2007) did not find any additional geometry more applicable to this type of problem.

2.6. Data analysis

In Article I, the Kruskal-Wallis test is applied to assess the influence of an individual's socio-economic background on the characteristics of the individual's activity space. A linear correlation is applied to compare the distribution of home anchor points calculated by the anchor point model to the Population Register data at the municipality level. In Article III, the study sample (road users) is classified in to two groups: commuters and others (non-commuters), and the distance between the home location and the last destination of the day are both calculated according to the shortest path analysis. To eliminate both the diurnal (hourly) and the weekly (day-of-week) rhythms of the CA pattern, a regression model for each pattern is calculated to calibrate the CDR data to data from a stationary loop detector traffic counter.

The K-means cluster technique is used in Articles IV and V to categorise each individual according to the individual's mobile phone usage patterns: the daily CA pattern is based on hourly frequencies, and the weekly CA pattern is based weekday frequencies. In Article IV, a univariate general linear model (GLM) (Garson, 2012) is applied to assess the seasonality of the monthly variability in individual travel behaviour and how individual factors influence the intrapersonal monthly variability in travel behaviour. In Article V, GLM is applied to assess what factors influence human travel behaviour. In addition, a modified Z-score method (Iglewicz and Hoaglin, 1993) is used to examine the occurrence of an individual's outlier monthly travel behaviour; specifically, the method is used to assess the impact of individual factors on the occurrence of intrapersonal outlier travel behaviour by using a binary logistic regression analysis (Article IV) and to exclude markedly different intrapersonal outlier travel behaviour for ascertaining the "typical" monthly travel behaviour (Article V).

3. RESULTS

This chapter presents the main findings from the conceptualisation of the identification and the measurement of human travel behaviour based on mobile phone based data and the empirical analyses. The main findings are presented in the following four sections.

3.1. Identification and extraction of activity locations

Based on the CDR data, background assumptions (see section 2.4), and the main findings from the first experiment with active mobile phone positioning (Article I), the anchor point model is developed. For each individual, the anchor point model (Article II) finds the two most frequently used mobile network base stations where CAs are made on a monthly basis and defines these as everyday anchor points. The model further distinguishes other base stations where an individual has conducted CAs only during one day in a month or during multiple days and defines these activity locations as random activity locations and as secondary anchor points (e.g., child care, grocery shopping, sports), respectively (Article II, Figure 3).

For everyday anchor points, the model distinguishes these into home and work-time (work or school-related) anchor points by taking into account (i) the average time of day and its standard deviations of (outgoing) CAs conducted in each activity location; and (ii) the spatial relationships between neighbouring activity locations. The work-time anchor point is the most important activity location during the daytime, based on the anchor point model. For a majority of individuals, this anchor point is related to work; for children and young people it is most likely related to educational activities. For individuals who have only one predominant everyday anchor point according to the CAs, the model defines this as a multifunctional anchor point (Article II, Figure 3). The latter designates a base station coverage area in which an individual may have a work- or school-related anchor point together with the home location. However, this may also designate solely a home location for those who do not have any other significant activity location, for example, for unemployed or elderly people, the home may be the only anchor point in one's activity space.

A comparison of the residential distribution based on the Estonian Population Register and the distribution of the home anchor points extracted by the anchor point model at the municipality level (n=227) in Estonia reveals a strong linear regression (r=0.99). An additional in-depth pilot questionnaire study with 205 people was conducted to verify the reliability of the anchor point model for finding home and work-time locations (Järv, 2010). Both, home and work-time anchor points were calculated correctly with more than 80% accuracy at the base station level and approximately 90% accuracy at the municipality level.

Several important methodological aspects for improving the identification of activity locations from the CDR data are found during the analysis for future research. For example, an improvement could address the difficulty the model has with people who do not have any spatially fixed work location or who work night shifts and have a different diurnal lifestyle than the model currently assumes. Because of the significant differences in individuals' mobile phone usage (Article II–IV), it is difficult to define the exact frequency threshold of CAs to differentiate other meaningful daily activity locations from other activity locations. Secondary anchor points identified by the anchor point model include both daily meaningful activity locations and other occasionally visited or irregular activity locations.

Therefore, a relative person based approach is further implemented to define an individual's other meaningful daily activity locations (besides home and work-time locations). In Articles IV and V, a multiple linkage analysis (MLA) derived from the mathematical graph theory (Haggett et al., 1977) is applied to reveal the subdominant activity locations that are important or meaningful for the spatial structure. In general, the MLA technique distinguishes the individual's meaningful daily activity locations from all activity locations based on the relative frequency of the CAs in each activity location.

The anchor point model together with the supplementary MLA technique enables us to distinguish four types of activity locations: (i) the home (or multifunctional) anchor point, (ii) the work-time anchor point, (iii) the location of other meaningful daily activities and (iv) the remaining (occasional, irregular or random) activity locations in an individual's activity space.

3.2. Spatial behaviour over a prolonged time period

CDR data derived by the anchor point model and the MLA technique extends our understanding of the spatial dimension of human travel behaviour over a prolonged time period in several ways.

First, human spatial behaviour at the individual level is revealed in terms of variety seeking and the tendency towards habitual routine for working age people. Approximately 17% of an individual's unique activity locations that were visited during a month were 'new' or visited only once during the study year (Article IV, Table 4). However, it is estimated that, on average, 78% of the time that is spent outside the home location is spent in the 10 most frequently visited activity locations.

Second, individuals' daily, monthly and annual activity spaces are conceptualised (Figure 2) and measured in Articles IV and V. The distribution of human activity spaces in all three temporal perspectives are highly skewed towards greater values (mean > median). For individuals living within the Tallinn FUR (Article IV), the median size of the daily activity space (DAS) was 616 km^2, with an interquartile range of 154 to 1,772 km^2, and the median size of the monthly activity space (MAS) was 2,913 km^2, with an interquartile range of 1,167 to 6,638 km^2. In the case of individuals living in Tallinn and for which months with individuals' markedly unusual intrapersonal outlier spatial behaviour were excluded from the calculations, the variability among individuals' activity spaces was significant (Article V). The median size of the DAS was 34 km^2, with an interquartile range of 14 to 115 km^2, the median size of the MAS was 332 km^2, with an interquartile range of 97 to 2,214 km^2, and the median size of the annual activity space (AAS) was 2,715 km^2, with an interquartile range of 679 to 8,774 km^2.

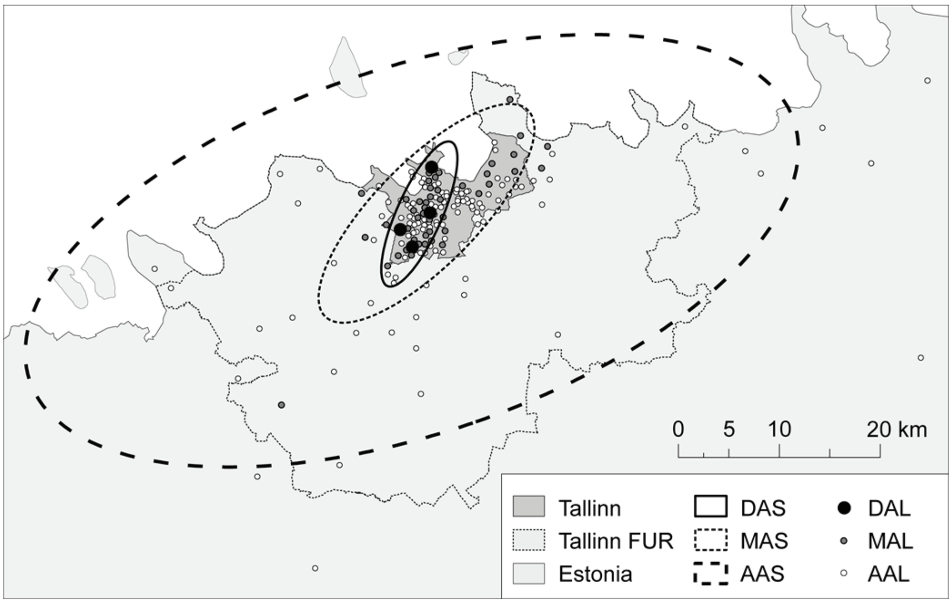

Figure 2. Visualisation of a 43-year-old woman's annual activity space (AAS) based on her visited activity locations (AAL) in 2009. Her monthly (MAL, MAS) and daily (DAL, DAS) spatial behaviour denotes the actual use of space in case of April 2009 (Source: Article V, Figure 2).

Third, despite a limited number of an individual's background attributes, the background attributes explain a significant amount of the interpersonal variability of the activity locations and the size of the activity space for adults living and working in Tallinn (Article V, Tables 3 and 4). In general, the model's overall explanatory power (partial eta squared) in terms of activity locations and activity spaces varies between 0.122–0.718 and 0.217–0.412, respectively. However, mobile phone usage provides a predominant part of the explanatory power for the number of activity locations; the amount of unique activity locations is explained by the average number of conducted CAs, and, in particular, the number of CAs made outside the home and work-time locations.

For the spatial extent of the activity spaces, the influence of phone usage pattern is less evident. However, age and ethnicity explain the size of the MAS, and they explain the size of the AAS even more clearly. The distance between the home and the work-time location affects the size of the MAS only slightly, whereas the distance affects the size of the DAS significantly. For the active mobile phone positioning experiment, the size of the daily activity space is significantly ($p<0.05$) influenced by the individual's education, the individual's lifestyle (suburbanite or city dweller) and the geographical region of the home location (Article I, Table 1).

3.3. The monthly variance in human spatial behaviour

For the analysis of 12 consecutive months of data, a modest monthly variation in the number of activity locations (DAL, MAL, NAL) is evident, while larger variations occur in the sizes of individual activity spaces (DAS, MAS) (Figure 3). The results indicate a strong seasonal impact: compared to the 12-month average, in July, the NAL shows a 35% increase and the sizes of DAS and the MAS more than double. Habitual routine spatial behaviour as indicated by Mtop10 and DAL does not change significantly throughout the year.

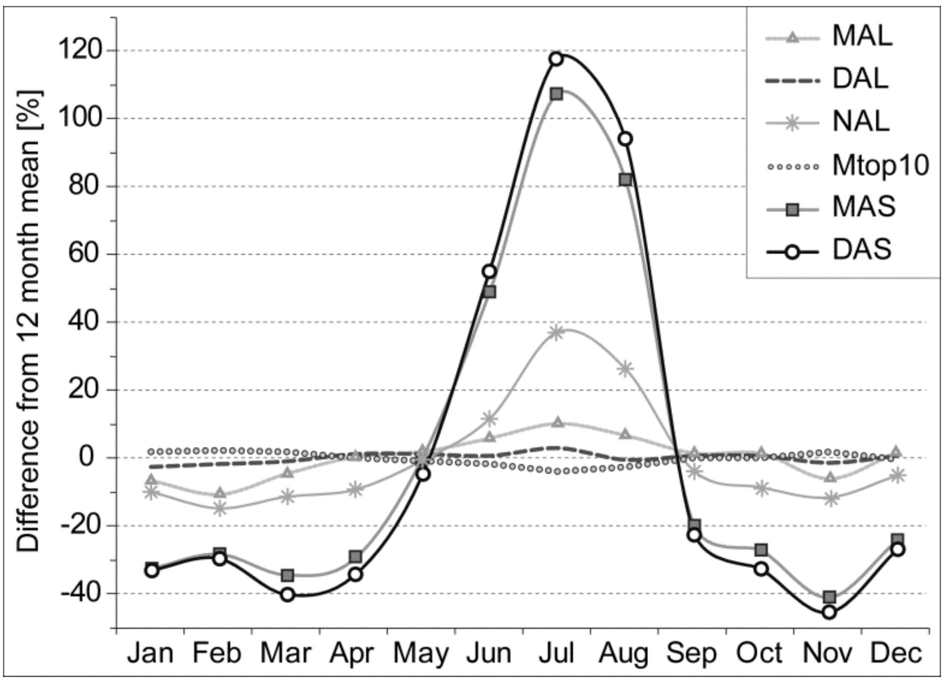

Figure 3. Monthly interpersonal variations in spatial behaviour for various measures compared to the 12-month mean (Source: adapted from Article IV, Figure 4).

However, the assessment of the intrapersonal aspect in human travel behaviour reveals that the seasonal effect (month of year) is actually modest whereas the monthly variance is predominantly explained by an individual, per se (Table 1). Seasonality affects the variety seeking behaviour: the seasonal effect explains 8% and 17% of the monthly variance of the NAL and the size of the MAS, respectively. The distinct impact of seasonality (7%) on the size of DAS is unexpected.

Table 1. Summary of the GLM results indicating which factors describe the monthly variance in individual spatial behaviour for various measures (Source: adapted from Article IV, Table 5).

Independent factors	MAL[a]	DAL[b]	NAL[c]	Mtop10[d]	MAS[e]	DAS[f]
Corrected Model	0.855*	0.340*	0.333*	0.819*	0.654*	0.554*
Individual	0.678*	0.316*	0.271*	0.680*	0.561*	0.500*
Seasonality (month of year)	0.040*	0.001	0.080*	0.039*	0.165*	0.069*
CAs	0.236*	0.001*	0.010*	0.011*	0.000	0.000
CAdays	0.003*	0.000	0.000	0.002*	0.005*	0.002*
notHW	0.197*	0.001*	0.036*	0.158*	0.071*	0.054*

* Coefficients are significant at 0.05 level.
[a] Number of MAL, [b] Number of DAL, [c] Share of 'new' (or yearly visited) activity locations from MAL, [d] Share of CAs to 10 most-frequented activity locations of MAL, [e] Size of MAS, [f] Size of DAS

The intrapersonal variability, however, is not (or only marginally) explained by the limited individual background factors (age, gender, home and work location) available for this study (Article IV, Table 7). A predominant share of the intrapersonal monthly variance is explained by the variation in the mobile phone usage pattern. These results indicate significant intrapersonal variability in individual travel behaviour in the spatial perspective. This is, to some extent, confirmed by the occurrence of intrapersonal outlier months, in which an individual's travel behaviour is markedly non-typical compared to travel behaviour during other months of the year (Figure 4). Intrapersonal outlier travel behaviour in the spatial perspective is related to seasonality; one third of individuals have a markedly different activity space size in the summer (Figure 4, B). Interestingly this is also the case with the size of the DAS. However, during other months of the year, there is a constant number of individuals who have intrapersonal outlier activity spaces: 5–10% of people have outlier DAS sizes, and 10–15% of people have outlier MAS sizes.

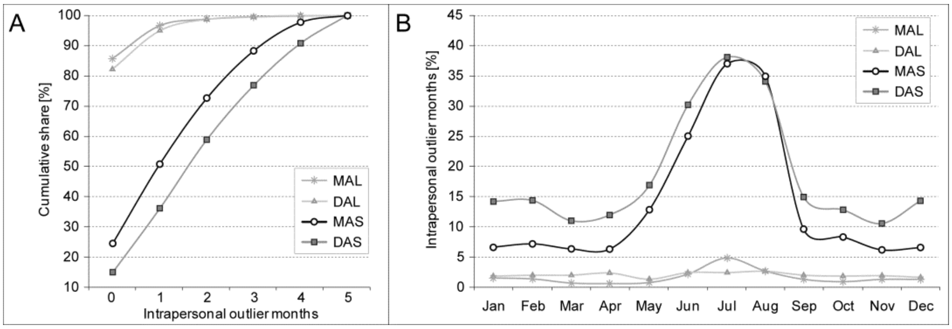

Figure 4. The distribution of individuals with intrapersonal outlier months (A) and the distribution of intrapersonal outlier behaviour by month (B) for various spatial characteristics of human travel behaviour (Source: adapted from Article IV, Figure 5).

3.4. Three case studies

The identification and extraction of activity locations and the examination of human activity spaces over prolonged time periods provide complementary information for several problematic phenomena in society which are complicated to reveal with traditional data collection methods; hence, these results might contribute to practical solutions. This dissertation thoroughly examines three different examples.

Short-term population mobility. In the case of Estonia, mobile phone based data reveals that because of the rapid (sub)urbanisation processes that have occurred within the last two decades (Tammaru et al., 2009), census data with long intervals between data collection are not up to date, and the population register data, *de jure*, does not reflect the distribution of the population, *de facto* (Article II, Table 2). While register data underestimate the population in functional urban regions around larger cities (e.g., Tallinn) due to suburbanisation, the data overestimate the population in degenerated industrial regions (North-East Estonia). There is a strong correlation (r=0.99) between the number of home anchor points and the number of residents based on Population Register in Estonia's 227 municipalities. In addition, work-time locations based on the anchor point model indicate the actual distribution of workplaces of people on a monthly basis, which is otherwise unable to be revealed in Estonia (Article II, Figure 8).

Transportation demand and the composition of traffic congestion. For the road section along the Tallinn-Tartu highway on the administrative border of Tallinn, the composition of road users and movement types that comprise the traffic flow is examined. The results indicate that daily commuting and suburban commuters' trips influence transportation demand by amplifying the evening rush hour traffic to some extent (Article III, Figure 9). However, the dominant share (69%) of trips by all road users is not related to the direct workplace-home movement during the rush hour period (Article III, Table 3). During the most congested time, Friday's afternoon rush hour, the geography of road users' final destinations of the day is distinctive compared to the other days: destinations are farther away from the home location (Article III, Figure 10) and are more dispersed in the geographical perspective (Article III, Figure 11).

A person-based ethnic segregation. For the ethnic inequalities in human travel behaviour in the spatial perspective, the results reveal remarkable differences in the amount of activity locations (Article V, Table 3) and in the sizes of activity spaces (Article V, Table 4) for the Estonian- and Russian-speaking language groups. Moreover, the differences between the individual travel behaviour of the language groups are more evident when the time frame of the study period is longer, i.e., when the share of activities that are not related to daily routine travel behaviour increases and the relevance of the daily habitual home-work link decreases. Furthermore, longitudinal perspective reveals that the geographical distribution of activity locations outside of the individual's daily activity space has distinct patterns: Russian-speakers' visitations tend to concentrate in certain regions, whereas Estonian-speakers visitations are located more equally around the country (Article V, Figure 3).

4. DISCUSSION

This chapter provides a critical discussion about the findings and presents directions for future research. The chapter is divided into three sections based on the three main aims of this dissertation: first, a description of the improvements to the conventional methodology for data collection and measurement, which include conceptualising the identification and measurement of human travel behaviour and implementing novel mobile phone based data; second, an analysis that extends the existing knowledge of the spatial dimension of human travel behaviour in the longitudinal perspective by providing new insights from daily, monthly and yearly perspectives; and third, a demonstration of how mobile phone based data can be implemented to provide valuable knowledge of social processes and phenomena.

4.1. Methodological contribution

One of the main aims of this dissertation is to complement the existing methodology for data collection and measurement of human travel behaviour. Prior to the discussion of identifying activity locations and measuring activity spaces of individuals, several general aspects of applying CDR data in human travel behaviour studies must be addressed.

First, while CDR data are suitable for representing the entire population, one must acknowledge the sampling issues (Article II). People who do not use mobile phones, such as young children and elderly people, are excluded. People who are sensitive to service costs may be underrepresented due to the business model and target customer policies of the network operator that provides the CDR data. For the network operator that provided the CDR data for the current studies, some regional and socio-economic differences were found in terms of the penetration of mobile phone users (TNS EMOR, 2008).

Second, the spatial accuracy of the CDR data depend highly on the heterogeneity of the spatial resolution of the base station network. Hence, the spatial precision of individual travel behaviour can be up to the level of a city block (less than 1 km^2) in the dense urban area, yet very poor in rural regions (more than 100 km^2). This indicates that the CDR data are more applicable in urbanised regions and further, the varying spatial resolution in geographical space must be acknowledged while comparing individuals from different regions.

Third, while activity locations are determined by the CDR data, these defined activity locations are actually theoretical spatial areas where activity locations are situated. Hence, the spatial granularity of CDR data is not suitable for micro-level studies, but it is accurate enough when activity location precisions can be at the level of a city block or neighbourhood. Fourth, study analyses (Articles IV and V) show that individual peculiarities in mobile phone usage in both the temporal and the spatial context have significant effects on human travel behaviour in the spatial perspective (Castells et al., 2007; Yuan et al., 2012). This is notable because the study sample (Articles IV and V) was selected based on rather strict constraints in terms of the frequency and the stability of call activities. This emphasises the need to verify the CDR data with the actual spatial behaviour in the following studies.

4.1.1. Identifying activity locations

First, the active mobile phone positioning experiment was conducted (Article I). The accuracy of active mobile phone positioning compared with the location data from the questionnaire and the GPS is consistent with other studies (e.g., Zhao, 2000; Asakura and Hato, 2004); specifically, active mobile phone positioning data are able to add a supplementary quantitative output layer to the current layers that are based on traditional questionnaires and activity-travel diaries. However, the experiment showed that the active mobile phone positioning approach is similar to the GPS based approach but is not accurate enough when micro-level travel behaviour is considered (Calabrese et al., 2013). Further, similar to the GPS data collection method, the active positioning approach is a resource-consuming method, and it is not reasonable for examining large study samples and/or for a prolonged study period (e.g., Rose 2006).

Based on the knowledge obtained from the latter experiment and other studies (Asakura and Hato, 2004; Ahas and Mark, 2005), the passive mobile phone positioning data were analysed to extract individuals' activity locations to study the dynamics of the entire population. Initially, the anchor point model was developed based on the conceptual models by Golledge and Stimson (1997), Flamm (2004) and Flamm and Kaufmann (2006b). The model is designed to assume that an individual has two daily anchor points: a work or educational location during the day time in addition to a home location. Consistent with other scholars (e.g., Huang et al., 2010; Do and Gatica-Perez, 2013), the verification confirms that the anchor point model is sufficiently accurate in identifying individuals' two most important daily anchor points from the CDR data at the base station level (Article II; Järv, 2010).

However, some disadvantages were found related to the anchor point model and to peculiarities of the CDR data and human mobile phone usage patterns that needs to be improved in future research. For example, the anchor point model may not correctly find home and work-time locations for those individuals who have more than one spatial location to work (or study) and/or who have a different daily habitual routine (e.g., night-shift workers). To some extent, this can be solved and the model can be improved when the land use characteristics are included in the model, such as residential areas. For individuals who do not have a second daily anchor point (e.g., unemployed, elderly people, or those with a home office) or when the type of work is mobile (taxi driver), the anchor point model is able to overcome this problem to some extent by identifying a single dominant, multifunctional anchor point in one's activity space. Because of the poor spatial granularity of the CDR data, a multi-functional anchor point can also be assigned if one's home and workplace is located within one base station coverage area. This is common in sparsely inhabited rural regions.

Another relevant issue is the "switching" of the network signal between neighbouring network antennas to provide the best possible signal for a mobile phone (see Article II). As a result, if an individual stays at one location and makes phone calls, these calls may be handled by multiple neighbouring base stations. Hence, the CDR data may be interpreted erroneously as visitations to different locations. For the anchor point model, the neighbouring relationships of base stations is addressed using a one-month period for calculations, which was found to be long enough to minimise this problem.

However, while the anchor point model calculates a daily anchor point on a monthly basis, the verification analysis by Järv (2010) suggests an additional calculation stage: to find the long-term anchor points as the average of short-term (monthly) anchor points during several months. For example, if an individual goes to spend the summer holidays in a coastal resort for one month, then the model would identify and locate one's home (multifunctional) anchor point to the holiday resort whereas the long-term home anchor point would be located at one's actual location of residence. This improvement of the model would enable the assessment of short-term mobility relative to long-term habitual routine behaviour as a future research direction in tourism studies, for example.

Due to significant peculiarities in mobile phone usage patterns (Articles IV and V) and the ambiguous extraction of secondary anchor points by the anchor point model, the MLA technique was applied to improve the identification of meaningful daily activity locations (DAL) based on the relative frequency of CAs in activity locations. The implementation of the MLA technique was used because of its successful applicability for determining a meaningful connection in air transport networks (van Nuffel et al., 2009) and meaningful commuting flows in an urban system (van Nuffel, 2007).

Although this dissertation did not aim to reveal the actual meanings of meaningful daily activity locations besides home and work-time anchor points, it should be considered in the future. For example, the analysis could be improved by integrating land use data with the anchor point model (Miranda-Moreno et al., 2012) and including additional personal attributes to the CDR data and by combining this with questionnaire-based data. These improvements would open up new directions for future model improvements by increasing the accuracy of the model and extending the classification of activity locations.

4.1.2. Measuring activity spaces

Based on the extraction and identification of individual activity locations, an individual's daily, monthly and annual activity spaces were conceptualised (Figure 3) and measured (Articles IV and V). **Daily activity space** (DAS) delineates meaningful daily activity locations and indicates the spatial extent where an individual performs one's daily habitual travel behaviour. Hence, this is assumed to coincide with the concept of actual activity space (Dijst 1999) and with the concept of actually observed activity space by Schönfelder and Axhausen (2010, p. 127).

Individual **monthly activity space** (MAS) is derived from all visited unique activity locations during a month, and it is assumed that this represents the spatial extent of an individual's spatial behaviour while consisting of both daily habitual routine and variety-seeking behaviour, especially during the weekends (Schlich and Axhausen, 2003). Hence, MAS can be seen as the realisation of one's (potential) action space (Golledge and Stimson, 1997; Dijst, 1999) from a monthly perspective. Individual **annual activity space** (AAS) is derived from all of the visited unique activity locations during one year. This includes all activities performed by a certain temporal (diurnal, weekly, seasonal) pattern, deviations stemming from these natural and societal rhythms and activities conducted once in a year (e.g., Christmas, summer/winter vacation). Therefore, it can be assumed that the AAS indicates the maximum spatial extent one is able or willing to reach for performing activities, especially in terms of long-distance travel and long-durational activities outside one's daily activity space. To this end, the AAS could denote, to some extent, the realisation of an individual's potential spatial mobility (Kellerman, 2012) or motility (Kaufmann et al., 2004). Although realised mobility may not always reflect one's actual mobility potential (Kellerman, 2012), it could be one solid quantitative indicator in human travel behaviour research.

This dissertation did not aim to verify how the size of the MAS and the AAS reflect the actual use of space in the prolonged study period, but rather, the aim was to focus on to what extent which factors affect human travel behaviour. Nevertheless, to verify how well the proposed measures of MAS and AAS coincide with the actual travel behaviour would enable this approach to be implemented in exposure studies where the spatial extent is essential.

4.2. New insights from the longitudinal perspective

Previous studies have focused on weekly rhythms of human travel behaviour (Tarigan and Kitamura, 2009) or have revealed the impact of long-term decisions on daily travel behaviour over the life course (Lanzendorf, 2010). However, less attention has been given to time horizons that remain in-between these perspectives. An exception is the work performed by Axhausen and his colleagues (Schlich and Axhausen, 2003; Nurul Habib et al., 2007; Schönfelder and

Axhausen, 2010). This dissertation offers complementary insights on human travel behaviour in three temporal perspectives.

4.2.1. Daily spatial behaviour

Findings confirm that the structure of daily travel behaviour is predominantly about habitual routine: on a monthly basis the number of meaningful daily activity locations is stable, and the time spent outside the home is predominantly spent in the 10 most frequented activity locations (78% of the time). This finding coincides well with previous research done by Schönfelder and Axhausen (2010, p.148). In addition, these two characteristics of daily travel behaviour remain stable during the 12 months studied. This is consistent with previous studies (Schlich and Axhausen 2003; Nurul Habib et al., 2007) suggesting that months (seasonality) do not affect daily habitual routine.

However, the monthly variability regarding the spatial extent of daily activity spaces is evident (Article IV): on average, the size of the DAS more than doubles in the summer. Interestingly, the impact of seasonality is rather minimal while the predominant factor is the intrapersonal variability, per se, and is not related to age, gender or the spatial location of residence. This is confirmed by the occurrence of intrapersonal outlier travel behaviour on a monthly basis; besides a concentration of intrapersonal outlier travel behaviour in the summer months (June–August), each month some 5–10% of studied individuals have markedly different size DASs. While the number of DALs remains steady, this may indicate the substitution of meaningful activities and/or the relocation of activity locations in space. In the summer, this can be explained partially by vacations and the temporary use of second homes (Silm and Ahas, 2010). Aside from seasonality, a further investigation is needed to explain the intrapersonal variability, specifically, whether it is due to underlying societal factors, the diversification of ways of life (Kesselring, 2006; Van Acker et al., 2010) or due to the implemented methodology.

4.2.2. Monthly spatial behaviour

Despite small monthly interpersonal variations in the number of monthly unique activity locations, a large interpersonal monthly variance exists in the extent of monthly activity spaces (MAS). This coincides with findings of the Atlanta survey in which the mean travel distance from home has a clear seasonal pattern (Schönfelder and Axhausen, 2010, p. 156).

The seasonal effect is a significant factor in explaining the size of the MAS. This is most likely due to fact that it denotes the realisation of an individual's need for variety-seeking behaviour. This is indicated both by the clear seasonal pattern in terms of NAL and the occurrence of intrapersonal outlier travel behaviour. These findings coincide with previous findings, suggesting that leisure or recreational related activities are more influenced by seasonality than by other factors (Kemperman et al., 2002; Bhat and Srinivasan, 2005), especially during weekends (Bhat and Gossen, 2004). However, findings confirm that the monthly variance in individual monthly travel behaviour is predominantly explained by intrapersonal variability, per se, and not by age or gender. Similar to the DAS, the occurrence of intrapersonal outlier travel behaviour on a monthly basis is significant. This finding may be, in part, due to limited information on the socio-economic attributes of the individuals who we studied. Several important attributes explaining travel behaviour differences between individuals were not available for these studies, such as household type, working status or private car availability (Buliung and Kanaroglou, 2006; Schönfelder and Axhausen, 2010). Nevertheless, such a strong intrapersonal monthly variability raises many questions that should be investigated more thoroughly.

The intrapersonal variability in in the DAS and the MAS confirms that there is a necessity for surveys that are able to examine beyond short-term study periods to reveal routine activities with longer periodicities and to define "typical" individual travel behaviour. These results also support the suggestion made by Frändberg (2008) that there is a need to revise the concept of human habitual travel behaviour and to not focus just on a daily perspective but to consider activities with certain weekly and monthly periodicities as a habitual behaviour as well. This is particularly relevant given that daily habitual travel behaviour has become more flexible and fragmented (Hubers et al., 2008; Schwanen et al., 2008) and traditional mobility forms and activities are blending in terms of multiple residences and long-distance travel for leisure or occupational purposes (Flamm and Kaufmann, 2006a; Limtanakool et al., 2006).

In addition, for future research, the monthly perspective in travel behaviour provides a complementary understanding on the variety seeking behaviour of individuals in space and time, which is difficult to reveal with traditional data collection methods. For example, the monthly prospective allows us to examine how individual "typical" daily and monthly travel behaviour are related to one another. Investigating several months concurrently can reveal the optimal month that is the most suitable for describing an individuals' "average" or "typical" travel behaviour.

4.2.3. Annual spatial behaviour

Revealing individual travel behaviour in a one-year perspective by capturing all activity locations has not yet been examined to the author's knowledge. This dissertation provides initial evidence about the extent of individual travel behaviour during the one-year period.

For half of the 560 individuals (between age 20 and 64) living and working in Tallinn, the size of the AAS remained between the range of 700 km^2 to 9000 km^2, whereas the median and mean size of the AAS for all 560 individuals was approximately 3,000 km^2 and 6,000 km^2, respectively. Although not analysed in this dissertation, the flexibility of human travel behaviour or the need for variety-seeking behaviour could be revealed when comparing the AAS against the MAS and the DAS. Based on median values of the sample group, the individual's DAS size comprises only some 10% of one's MAS. Further, the individual's MAS size comprises some 12% of one's AAS.

The size of the AAS clearly demonstrates how different human travel behaviour can be during the long-term study period. Despite not knowing the reasons for such variance, this indicates to what extent an individual has the potential to experience physical environment and social interactions with different people. When mobility in space, time and social dimensions are assumed to be interrelated, and hence mobility is seen as one causal factor for social differentiation or even a new form of capital (Urry, 2007; Viry et al., 2009; Kellerman, 2012), then the size of the AAS could be an indicator to assess social differences and mobility potential in the spatial perspective. Preliminary findings of this dissertation already indicate socio-spatial differences (Section 3.4) that can be the premise for studying socio-spatial inequalities and segregation.

4.3. Complementary knowledge on three social phenomena

The third aim of this dissertation was to provide new insights on social phenomena that are difficult to examine with traditional data collection methods, such as questionnaires, activity-travel diaries or register and census data. To this end, three examples in Estonia were provided as examples of how CDR data and the proposed methodology can provide supplementary knowledge for solving societal problems and challenges.

Considering societal developments (Graham, 1998; Kwan, 2007), particularly the fast development of mobile technologies (Townsend, 2000; Urry, 2007), the population dynamics of short-term mobility has become a decisive aspect for urban and transportation planning and policy-making. The methodology put forward in this dissertation is able to provide, on a monthly basis, the distribution of the population, their activity locations and an estimate of the population dynamics. Information about the population's short-term mobility gives tools to better manage temporal variations in residential and workplace distributions and to provide better public (health, security, transport) and private (grocery, entertainment) services (e.g., Batty et al., 2012). This improves the accuracy for assessing health risks of people and potential exposure to hazards (e.g., Kwan, 2013).

Furthermore, in regions where the demographic processes are unstable or within fast developing stages, the population distribution, *de jure*, may not reflect the situation, *de facto.* As is the case with Estonia (and Tallinn FUR in particular), up-to-date information on short-term mobility can provide an essential starting point for urban planners and policymakers making up-to-date decisions. In cases for which reliable register data are not available (e.g., developing countries), this proposed methodology is the best or only reliable data source to describe the population distribution, in general, and to monitor short-term dynamics, in particular.

For transportation planners, the proposed methodology has a high potential to add to traditional data collection and analysis methods in three aspects. First, it provides a longitudinal study period, and this method can be adopted as one of the real-time traffic monitoring tools. Second, a location based approach is able to reveal the composition of a traffic flow in a given road section and to provide cost-effective information about the road users who comprise traffic congestion. This information can substitute large-scale questionnaires, on-road surveys and large-scale number plate detections for assessing road users' origin and destination. However, it does not help with aspects such as traffic volume and speed, transportation mode split or trip chaining, and therefore, traditional traffic counters are needed. Third, the distribution of peoples' homes, work-places and other meaningful daily activity locations can be linked, distributed into origin-destination movement matrices and used to estimate traffic flows between nodes (e.g., traffic analysis zones) in the transportation network.

The estimation of traffic flows based on a given road section or based on a transportation network perspective at the regional or country level can be an additional input layer to the framework of intelligent transportation systems (Zhao, 2000; Bar-Gera, 2007). In countries (e.g., Estonia) where transportation planning is less advanced, this information is a valuable source to cost-effectively estimate traffic flows. For example, the proposed methodology of this dissertation is already being applied in Estonia to provide an estimate of traffic flows to develop the road network around the city of Tartu (Ramboll, 2009); this is helping to optimise the public transportation systems (Positium, 2008) and to assess regional population dynamics within the functional urban region of the city of Pärnu (Positium, 2010). However, the reliability of the methodology to derive spatial movements of people and activity locations from the CDR data needs to be improved in the future.

If the CDR data could be related to the mobile users' socio-economic background attributes, then the proposed methodology could access much needed social content, and hence, we could rightly refer to it as a "social positioning method", a definition that was already put forward by Ahas and Mark (2005). The great potential of this type of methodology is only now being acknowledged in social sciences (Palmer et al., 2012). A significant contribution can be provided by extending the current understanding of socio-spatial differences based on the heterogeneity of human activity spaces and spatial mobility. Issues, such as segregation, socio-spatial inequality, social isolation, subjective well-being and ecological footprint can be examined. Obviously, this is only one possible source from other ICT based methods (e.g., Batty et al., 2012).

For this dissertation, only limited social attributes were available, such as age, gender and the preferred communication language, which was used as a proxy for ethnicity. As an example, a case study was conducted to emphasise the emerging people-based approach in segregation studies, which makes it possible to reveal socio-spatial inequalities at the individual level (Wang et al., 2012; Palmer, 2013). The results suggest significant ethnic differences in human spatial behaviour, especially beyond the individual daily activity space. Given the Estonian context, these ethnic differences in the spatial dimension of human travel behaviour may be a result of social networks (Lee and Kwan, 2011) that have distinct geographical distributions between two ethnic groups (Silm and Ahas, forthcoming). However, it may also be due to a certain constraint (e.g., language skill) or voluntary choices (e.g., self-preferences). Thus, further research is needed to reveal the underlying causal factors.

Nevertheless, these findings already demonstrate the importance of the proposed methodology for providing complementary insights on socio-spatial inequalities at individual level (Cassiers and Kesteloot, 2012). This dissertation agrees with scholars who are describing the need to go beyond the aggregated data and static spatial units and to focus on human spatial and social mobility in time to improve our understanding of social processes (Urry, 2000; Kaufmann et al., 2004; Kellerman, 2012; Kwan, 2013).

5. CONCLUSIONS

Our understanding of individual travel behaviour in space and time has been a constant subject since Hägerstrand (1970), and has been thoroughly examined in the short-term (i.e., 1–3 days) perspective. However, human travel behaviour for prolonged time horizons has not been studied extensively, which is mainly due to the inadequacy of the available data collection methods and a predominant focus on daily travel behaviour, such as the home-work link. In light of societal developments in the age of the "mobilities turn" (Urry, 2000), initial indications of different temporal rhythms of human travel behaviour (Schönfelder and Axhausen, 2010) and acknowledging the importance of human spatial mobility (Urry, 2007; Kwan, 2013), there is a growing need to fulfil research gaps in terms of human travel behaviour in the prolonged perspective.

The aim of this dissertation was threefold and sought to make conceptual, methodological and empirical contributions. First, one aim was to complement existing methodology for data collection and measurement by conceptualising the identification and the measurement of spatial characteristics of travel behaviour and using novel mobile phone based CDR data. The proposed methodology provides tools to study human travel behaviour in short- and long-term perspectives both at the individual and the aggregate levels. Second, the existing empirical knowledge of travel behaviour in the longitudinal perspective was extended by complementary evidence from daily, monthly and yearly perspectives, and special attention was given to the monthly variance. Third, this dissertation demonstrates three case studies on how the proposed methodology could provide complementary insights on social phenomena that are difficult to examine with traditional data collection methods, such as questionnaires, activity-travel diaries or register and census data. In summary, this dissertation aimed to ascertain how mobile phone based data can help us to understand human travel behaviour. This is obtained by answering five refined research questions; the main results were introduced (Section 3), and the findings were thoroughly discussed (Section 4).

First, to identify and measure human activity locations and movement between these locations based on the large volume of CDR data, the anchor point model was developed (Article II). The model was developed based on knowledge achieved from the first experiment using active mobile phone positioning data that investigated the applicability of mobile phone data for measuring human travel behaviour (Article I). In general, the anchor point model identifies four types of activity locations, and the two most important activity locations are defined as home and work-time anchor points. These anchor points are identified and located with a high accuracy at the base station level, although several aspects can be improved in the future. Based on identified activity locations, it is possible to derive individual movements and to analyse traffic flows (Article III). The anchor point model is further improved by implementing the MLA technique to better extract meaningful daily activity locations from other random activity locations relative to the individual's mobile phone usage pattern (Article IV).

Second, the implementation of mobile phone based data to extend our understanding of human travel behaviour over a prolonged time period was achieved by analysing individual "typical" daily, monthly and annual travel behaviour in terms of the number of unique activity locations visited and the spatial extent of activity spaces (Articles IV and V). Monthly and annual activity spaces have not yet been analysed to the author's knowledge. The prolonged perspective is important because it reveals one's spatial behaviour beyond the daily habitual routine behaviour, and to some extent, the realised spatial mobility could reflect one's actual spatial mobility potential. At the very least, this perspective provides a quantitative indicator for assessing individuals' mobility potential.

Third, despite the limited individual background attributes that were available to these studies, it was found that the influence of individuals' socio-economic factors describing spatial characteristics of human travel behaviour are generally weak, except for the significant effect of language as a proxy for ethnicity (Articles I and V). However, it was found that individual mobile phone usage patterns vary significantly between individuals in spatial and temporal perspectives, describing significant interpersonal variability in human travel behaviour (Articles IV and V). Therefore, one must consider this aspect while using the CDR data in human travel behaviour studies to avoid potential biases in the results due to peculiarities of the data.

Fourth, special attention was given to assess intrapersonal variability in monthly travel behaviour during twelve consecutive months (Article IV). Monthly intrapersonal variability was predominantly explained by the intrapersonal variance, whereas the seasonal effect, per se, remained weak. However, while the seasonal effect was weak for the daily activity space, it was still significant. Moreover, on a monthly basis, some 5–10% of the studied individuals' spatial behaviour is markedly non-typical, and thus, this indicates the need to investigate this phenomenon more in the future. Otherwise, the seasonal variability was the most evident in the case of variety seeking behaviour.

Fifth, three different empirical case studies were conducted to demonstrate how mobile phone based data are able to provide complementary knowledge on social phenomena that is difficult to reveal otherwise. The proposed methodology provides information on short-term population mobility (Article II), which can complement up-to-date census or register based data. However, in cases for which the latter data are not available, mobile phone based methodology may be the only suitable data source to reveal population distribution information. Similarly, this is the case with transportation planning (Article III). The proposed methodology can provide knowledge such as the composition of road users and their trip purpose, to some extent, and it can also provide a rough estimate of the distribution of traffic flows in the transportation network. Finally, in the case of person based activity space segregation, the findings demonstrate the distinct ethnic differences in the spatial behaviour of individuals in both geographical and relative perspectives (Article V). Hence, this study emphasises the importance of delving into person-based segregation to better understand segregation phenomenon in general.

In conclusion, based on the main findings presented and discussed above, this dissertation argues that (i) the call detail records (CDR) of mobile phone users are a valuable addition to traditional data collection methods for revealing the spatial characteristics of human travel behaviour at the individual level, allowing us make a contribution to forming the smart cities of tomorrow at the aggregated level; (ii) the proposed methodology enables us to capture and provide insights on human travel behaviour in the prolonged (monthly, yearly) perspective and narrow the research gap on both the inter- and intrapersonal variability of human spatial behaviour; and (iii) the proposed methodology is suitable for providing complementary knowledge to better understand social processes and to solve problematic social phenomena in terms of population short-term mobility, transportation planning and socio-spatial segregation.

The empirical findings of this dissertation provide a fruitful premise for future research by highlighting several new avenues to explore. For the conceptual and methodological perspective, additional personal attributes should be included in future studies based on CDR data, the anchor point model should be integrated with land use data and combined with questionnaire-based data to further downplay current methodological weaknesses. Another future direction is to add long-term anchor points into the anchor point model and to determine the type of the activity and its duration to improve the reliability of the model. This, in turn, would improve the explanatory power for describing human spatial behaviour in the longitudinal perspective and would provide more knowledge. For example, it would be interesting to focus on intrapersonal variability and on the variability of daily spatial behaviour in particular. Improvements to the methodology would further explain social phenomena up to the point where the underlying causal factors for human spatial behaviour could be revealed.

The verification of how well the spatial extent of daily, monthly and annual activity spaces coincide with the actual use of space and its error assessment would certainly be a relevant direction for future research in human spatial behaviour research.

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SUMMARY IN ESTONIAN

Reisikäitumise uurimine mobiiltelefonidel põhinevate andmetega: pikaajalisest andmestikust tulenevad uued teadmised inimeste ruumikasutusest

Kaasaja ühiskonda iseloomustab inimeste järjest suurenev mobiilsus. Mobiilsust nähakse edukuse ja innovatsiooni alusena, kuid samas kaasnevad sellega transpordi- ja keskkonnaprobleemid. Seetõttu on inimeste mobiilsus üks keskne uurimisteema inimgeograafias ja sotsiaalteadustes tervikuna. Inimeste ruumilise mobiilsuse ja reisikäitumise uurimine on oluline ühiskondlike väljakutsete tõttu, mille lahendamiseks kasutatakse järjest rohkem uusi andmeid, analüüsimeetodeid ja kontseptuaalseid mudeleid.

Inimese reisikäitumine koosneb liikumiste ja tegevuste keerulistest mustritest, mis tekivad inimese, teda ümbritseva keskkonna ning sotsiaalsete struktuuride omavaheliste seoste tagajärjel. Inimese reisikäitumise erinevaid aspekte on traditsiooniliselt uuritud lühiajaliste (1–3 päeva) küsitlusuuringute, reisipäevikute ja transpordiloenduste põhjal, kusjuures eesmärgiks on valdavalt olnud inimeste tavapärase, rutiinse käitumise väljaselgitamine. Uuringute lühiajalisus on tulenenud rakendatud meetodite iseloomust, sest inimeste mitmekordne ja pikaajaline uurimine on keerukas ja kulukas ning seetõttu on reisikäitumise uurimisel käsitletud vähe liikumisi pikaajaliselt. Inimeste reisikäitumise pikaajaline perspektiiv on aga muutunud üha olulisemaks, sest inimeste liikumiste mustrid muutuvad järjest keerukamaks, individuaalsemaks ja vähem rutiinseks ning ajas ja ruumis paindlikumaks. Lühiajalise vaatlusperioodiga ei ole võimalik liikumiste ja tegevuste perioodilisust, iseloomulikku ruumikasutust ja selle varieeruvust tuvastada ega kirjeldada. Samuti näitavad esmimesed teostatud pikaajalised uuringud selgete ajaliste rütmide esinemist inimeste reisikäitumises.

Inimeste reisikäitumise uurimine pikematel vaatlusperioodidel ja pikaajaliste andmestike põhjal on muutunud võimalikuks info- ja kommunikatsioonitehnoloogiate (IKT) arengu, eeskätt GPS-seadmete ja mobiiltelefonide tõttu. Mobiiltelefonide abil on võimalik koguda kuluefektiivselt ja inimest segamata tema digitaalset jäljerida pika ajaperioodi kohta. Käesoleva doktoritöö eesmärk on selgitada välja, kuidas mobiiltelefonide andmed aitavad paremini aru saada inimese reisikäitumisest. Esiteks panustab doktoritöö reisikäitumise uurimise metoodika täiendamisesse, pakkudes välja kontseptsiooni inimese ruumilise käitumise tuvastamiseks ja metoodika selle mõõtmiseks mobiilitelefoni kõnelogiandmete põhjal. Teiseks täiendab doktoritöö praeguseid teadmiseid inimese reisikäitumise ajalisest ja ruumilisest ulatusest ning selle varieeruvusest. Kolmandaks tõestab doktoritöö Eestis teostatud juhtumiuuringute näitel väljatöötatud metoodika rakendamise kasulikkust ühiskonnanähtuste uurimisel, sealhulgas transpordi- ja linnauuringutes.

Doktoritöös arendati välja mobiiltelefonide kõnelogiandmetel (*Call Detail Records*) põhinev ankurpunktide mudel (Artikkel II) varasemast eksperimendist saadud teadmiste alusel. Eksperimendi käigus hinnati inimese reisikäitumist hinnati aktiivse mobiilpositsioneerimise meetodil (Artikkel I). Ankurpunktide mudel tuvastab ja eristab inimese igapäevaselt olulised ja juhuslikud tegevuskohad ning võimaldab nende alusel liikumisi tegevuspõhiselt eristada (Artikkel III). Inimese kõige tähtsamate, elukoha ja tööaja ankurpunktide tuvastamise täpsus on kõrge. Mudeli täpsuse tõstmiseks harva ja/või juhuslike kohtade eristamisega arendati mudelit täiendavalt, rakendades *Multiple Linkage Analysis* (MLA) meetodit (Artikkel IV).

Teise tulemusena selgitati välja inimeste ruumikasutuse parameetrid ja selle varieeruvus päevase, kuise ja aastase ajaperioodi lõikes (Artikkel IV–V). Selleks hinnati unikaalsete tegevuskohtade arvu ja inimeste tegevusruumi ulatust. Kuine ja aastane ruumikasutus võimaldab välja selgitada inimese ruumikasutuse väljaspool igapäevast rutiinset elu- ja töökohavahelist reisikäitumist ning aitab hinnata tema ruumilise mobiilsuse potentsiaali. Üldiselt varieeruvad tegevusruumi ulatused inimeste vahel olulisel määral, kuid tallinlaste näitel on nende igapäevase, kuise ja aastase tegevusruumi ulatuse mediaanväärtused vastavalt 34 km^2, 332 km^2 ja 2715 km^2.

Kolmanda tulemusena selgitati välja sotsiaalsete ja demograafiliste tunnuste mõju inimese igapäevasele, kuisele ja aastasele tegevusruumile. Selgus, et inimese sool, vanusel ning elu- ja töökoha asukohtadel on nõrk mõju tööealise inimese tegevusruumi parameetritele (Artikkel I, IV, V). Samas selgus, et suhtluskeelel mobiilsideoperaatoriga (eesti, vene) kui inimese etnilise tausta näitajal on selge mõju: eestikeelsetel on tegevusruum märkimisväärselt suurem kui venekeelsetel (Artikkel V). Veel tuli selgelt välja, et inimese mobiiltelefoni kasutuse ajalistel ja ruumilistel eripäradel on oluline mõju tulemustele (Artikkel IV–V), mis tõestab, et mobiiltelefoni kõnelogiandmete kasutamisel inimese reisikäitumise uurimiseks tuleb telefonikasutuse ajalisi ja ruumilisi eripärasid kindlasti arvesse võtta.

Neljanda tulemusena selgitati välja reisikäitumise indiviidipõhine (*intrapersonal*) varieeruvus ja sesoonne mõõde (Artikkel IV). Kuigi uuritud inimeste kuude keskmised tegevusruumi näitajad viitasid selgele sesoonsele rütmile, oli sesoonsuse statistiline mõju nõrk ja indiviidipõhise kuise varieeruvuse põhjuseks oli indiviid ise. Sesoonsus mõjutas kõige rohkem inimese juhuslikku reisikäitumist, mida mõõdeti uute tegevuskohtade suhtarvu abil. Samas selgus, et igal kuul on umbes 5–10% inimeste igapäevane ruumikasutus märkimisväärselt erinev nende tavapärasest ruumikasutusest.

Viienda tulemusena näidati, kuidas on väljatöötatud metoodikat võimalik rakendada ühiskonna uurimiseks. Esiteks saab metoodikaga tuvastada ja analüüsida elanikkonna lühiajalist mobiilsust. Seega on tegemist usaldusväärse andmeallikaga, mis võimaldab uurida rahvastiku paiknemist, kui registripõhised andmed puuduvad või on aegunud (Artikkel II). Teiseks saab metoodikaga tuvastada konkreetsetel teelõikudel liikuvad inimesed ning selgitada välja inimeste koosseis nende tunnuste ja liikumiste geograafia põhjal (Artikkel III). Traditsiooniliste liiklusloenduritega on väga keeruline tuvastada konkreetse maantee kasutajad ja nende liikumised. Tallinn-Tartu maantee lennujaama piirkonna näitel selgitati doktoritöös arendatud metoodika põhjal välja, et hoolimata õhtusel tipptunnil eeslinlaste ja teiste töölt koju liikujate osakaalu suurenemisest, moodustavad nad vaid umbes kolmandiku (31%) kõigist teelõigul liiklejatest. Kolmandaks saab metoodikat rakendada segregatsiooni uurimisel, võimaldades segregatsiooni uurida uudsel, inimese tegevusruumi põhisel lähenemisel (Artikkel V). Nii selgitati eestikeelsete ja venekeelsete tallinlaste selged erisused reisikäitumise ruumilises mõõtmes ning seda nii abstraktses kui ka geograafilises ruumis.

Kokkuvõttes väidab autor käesoleva doktoritöö tulemuste põhjal, et (i) mobiiltelefonide kõnelogiandmed on väärtuslik täiendus traditsioonilisele inimese reisikäitumise ruumilise mõõtme uurimisele indiviidi tasandil, võimaldades anda märkimisväärse panuse tuleviku „tarkade“ linnade planeerimisele; (ii) väljatöötatud metoodika tuvastab ja pakub uusi teadmisi inimese reisikäitumise kohta, kuna selle eriline väärtus on võimalus kasutada senisest pikemaid vaatlusperioode ja hinnata ruumikasutuse varieeruvust; (iii) väljatöötatud metodoloogia võimaldab saada täiendavaid teadmisi ühiskonnaprotsessidest.

Doktoritöö tulemused on heaks aluseks edasistele mobiiltelefonide kõnelogiandmetel põhinevatele uuringutele ja metoodika arendamisele. Tulevikus on oluline kasutada täiendavaid isikuandmeid, kaasata maakasutuse andmebaase ning ühildada mobiiltelefonide kõnelogiandmed küsitlusuuringutega. Väljatöötatud metoodika täiendamisel tuleks keskenduda lisaks ühiskonnanähtuse kirjeldamisele ka nende põhjuste täpsemale selgitamisele.

PUBLICATIONS

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