

Measuring the size and structure of human activity spaces

The longitudinal perspective

Working Paper**Author(s):**

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Publication date:

2002-09

Permanent link:

<https://doi.org/10.3929/ethz-a-004444846>

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Originally published in:

Arbeitsberichte Verkehrs- und Raumplanung 135



ETC 2002 – Poster session

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Arbeitsbericht Verkehrs- und Raumplanung 135

September 02

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Measuring the size and structure of human activity spaces The longitudinal perspective

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September 2002

Abstract

The complexity of urban mobility and the failure of numerous transport strategies have shown that demand matching transport policies require a deeper analysis of the routines and dynamics of individual travel behaviour. Transportation research has so far mainly focused on the cross-sectional analysis of persons' and households' mobility patterns. In most travel behaviour studies, the main interest has been on differences between travellers or groups of travellers as travelled by easily by one-day or few-days travel diary data.

This paper addresses the long-term aspects of spatial mobility. It presents approaches to describe and measure the revealed travel patterns using the address geocodes of the six-week *Mobidrive* travel survey data. The description and measurement of the observed spatial choice is based on the *activity space* concept. The availability of the multi-week *Mobidrive* travel data makes it possible for the first time to *measure* the extent of individual activity spaces and to test hypotheses about the usage of urban space and the multi-centred structure of our daily life mobility.

Keywords

Activity space – development of measures – longitudinal travel data – *Mobidrive* – ETH Zurich – Institute for Transport Planning and Systems (IVT)

Preferred citation style

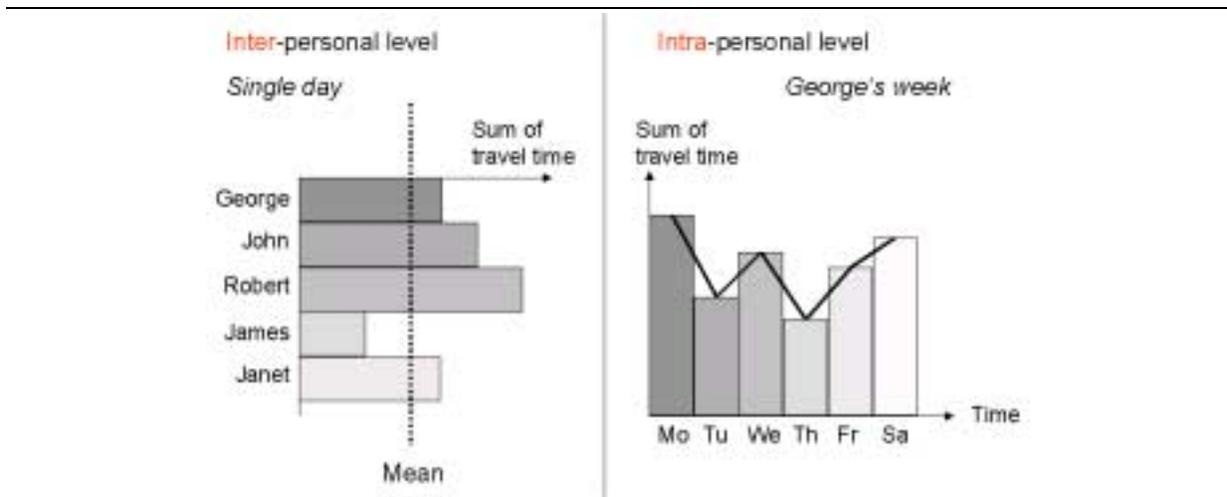
Schönfelder, S. and K.W. Axhausen (2002) Measuring the size and structure of human activity spaces – the longitudinal perspective, *Arbeitsbericht Verkehrs- und Raumplanung*, **135**, Institut für Verkehrsplanung und Transportsysteme (IVT), ETH Zürich, Zürich.

1 INVESTIGATING THE VARIABILITY AND REGULARITY IN TRAVEL BEHAVIOUR

The complexity of urban mobility and the failure of numerous transport strategies have shown that demand matching transport policies require a deeper analysis of the routines and dynamics of individual travel behaviour (see Jones and Clarck, 1988). Transportation research has so far mainly focused on the cross-sectional analysis of persons' and households' mobility patterns. In most travel behaviour studies, the main interest has been on differences between travellers or groups of travellers (*inter-personal level*, see Figure 1) which can be observed easily by one-day or few-days travel diary data (e.g. NTS/UK, NHTS/USA or KONTIV/Germany).

Mobility patterns observed on single days have been often interpreted as optimal decisions of the traveller and as a state of behavioural equilibrium – which is assumed to exist for any point of time and any situation. The investigation of the *intra-personal level* of travel which describes the variability of single persons' and households' mobility patterns over time has been restricted so far by the absence of survey data longer than one week and suitable methodology to treat such data (see Figure 1). From a scientific point of view but especially taking into account the planners' legitimate data requirements concerning the temporal aspects of travel, the available knowledge is insufficient. This has led to an incomplete explanation of travel motives and determinants.

Figure 1 Inter-personal and intra-personal level of travel behaviour



Aim of this paper

This paper addresses the long-term aspects of spatial mobility. It presents approaches to describe and measure the revealed travel patterns using the address geocodes of the six-week *Mobidrive* travel survey data (Axhausen, Zimmermann, Rindsfuser, Schönfelder and Haupt, 2002). Such description and measurement of observed spatial choice is based on an adoption of the geographic *activity space* concept (see Golledge and Stimson, 1997 for a comprehensive overview).

While the concept activity space has been put forward for about four decades, most empirical work has focussed on the structures of the mental mapping of locations (see e.g. Lynch, 1960 or Downs and Stea, 1977). The physical mapping or enumeration of the places visited has been neglected, though, due to the reasons mentioned above. The availability of the multi-week *Mobidrive* travel data makes it possible for the first time to *measure* the extent of individual activity spaces and to test hypotheses about the usage of urban space and the multi-centred structure of our daily mobility.

The analysis of individual activity spaces using longitudinal travel data is motivated by our interest in spatial behaviour from a political or planning point of view and from a methodological standpoint. The following keywords characterise these interests:

Political / planning implications of spatial behaviour:

- Distribution of activity locations in space
- Organisation of the travellers' daily life depending on that distribution
- Feedback between travel potentials and realised travel

Methodological developments:

- Exploration of long-term travel data concerning spatial variability, routines and dynamics
- Adequate representation of human behaviour in space

The remainder of the paper is organised as follows: First, the long-term oriented *Mobidrive* data source is introduced which is the base for this study. Then follows a discussion of the

concept of *activity space*. The fourth chapter presents new methodological approaches to represent and to measure individual activity spaces using (spatial)statistical methods. This is followed by exemplary calculations based on the core concepts developed and the *Mobidrive* travel data. Finally, the conceptual work and the related estimation results are evaluated from an analytical and from a planning point of view.

2 THE MOBIDRIVE TRAVEL DATA: DATA STRUCTURE AND ADDRESS GEOCODING

The collection and the exploration of longitudinal travel behaviour data was recently addressed in the German research project *Mobidrive*. The project was designed to obtain a more detailed picture of long-term mobility patterns and to develop methodological approaches to capture behavioural variability (see Zimmermann, Axhausen, Beckmann, Düsterwald, Fraschini, Haupt, König, Kübel, Rindsfuser, Schlich, Schönfelder, Simma and Wehmeier, 2001; Axhausen, Zimmermann, Schönfelder, Rindsfuser and Haupt, 2002). Based on the experiences made with a similar data collection experiment in the 1970s (Uppsala Household Travel Survey, see e.g. Marble, Hanson and Hanson, 1972), a continuous six-week travel diary survey was conducted for *Mobidrive* in the German cities of Halle/Saale and Karlsruhe in autumn 1999. A total of 317 persons over 6 years in 139 households participated in the main phase of the survey, after testing the survey instruments in a pre-test with a smaller sample in spring 1999 (44 persons). The paper-based travel-diary instrument was supplemented by further survey elements covering the socio-demographic characteristics of the households and their members, the details of the households' car fleet and transit season tickets owned and personal values as well as attitudes towards the different modes of transport. The *Mobidrive* data finally offers a unique level of detail for travel diary surveys of that type (see Axhausen *et al.*, 2002 for details of the survey characteristics).

Address geocoding

One objective of the *Mobidrive* consortium was to provide exact locational data in order to facilitate the analysis of the variability in spatial behaviour over time. One relevant analysis direction is the estimation of destination-, route- and mode-choice models which is dependent on the accurate generation of shortest origin-destination paths (see e.g. König and Axhausen, 2001; Cirillo and Axhausen, 2002).

The of precise locational data was obtained by geocoding the trip destination addresses of all main study trips (approximately 40.000 trips). The addresses – including home and workplace locations – were transformed into Gauss-Krüger coordinates in a WGS 84 (World Geodetic System) geodetic reference system. The geocoding was positive for about 95% of the reported trips.

Due to incomplete addresses and limited availability of digital address information outside the urban cores of the case study regions, the geocodes of the addresses have different degrees of resolution for the different spatial units. For the municipalities City of Karlsruhe and City of Halle, the street addresses could be geocoded on the basis of (small) building blocks (i.e. more than 90% of all geocoded trips), whereas outside the urban boundaries the addresses are available as geocodes of the centroids of the municipality, only. This has of course implications for any spatial analysis as the geocoding does not yield a 100%-exactness for the locational data – especially for non-local trips. The number of unique locations can be assumed to be slightly higher than what is revealed by the data. Furthermore, the fact that trip destinations outside the city boundaries are aggregated to one single x-y-coordinate restricts the interpretation spatial analysis results. Consistent results can be only expected for the local part of the overall mobility. As most of the ongoing investigations are of a comparative character, though, this lack of precision can be accepted.

In addition to the georeferenced trip data, there is selected digital land use and transport network information available for both case study cities. This allows to combine travel demand and supply data for the behavioural analyse (Table 1).

Table 1 Availability of additional georeferenced data

Information	City of Karlsruhe	City of Halle
Municipal organisation / structure		
Regional	✓	
City districts	✓	✓
Building blocks	✓	
Land use information		
Aggregate	✓	✓
Building block level	✓	
Structural characteristics (population, households etc.)		
Districts	✓	✓
Building block level	✓	
Road network		
Local	✓	
Regional	✓	
Public transport		
Stops, lines and schedules	✓	

3 DESCRIBING THE SPATIAL PATTERNS OF TRAVEL BEHAVIOUR: THE ACTIVITY SPACE CONCEPT

The success of transportation policy depends on an exact description and prediction of aggregate flows as well as the disaggregate travel behaviour of individuals. Measuring mobility therefore requires suitable indicators for the quantities of travel as well as the complex travel patterns combining people's movement in space and in time.

Turning to the spatial reach of mobility in particular, measures are necessary which address a range of planning and policy questions, such as

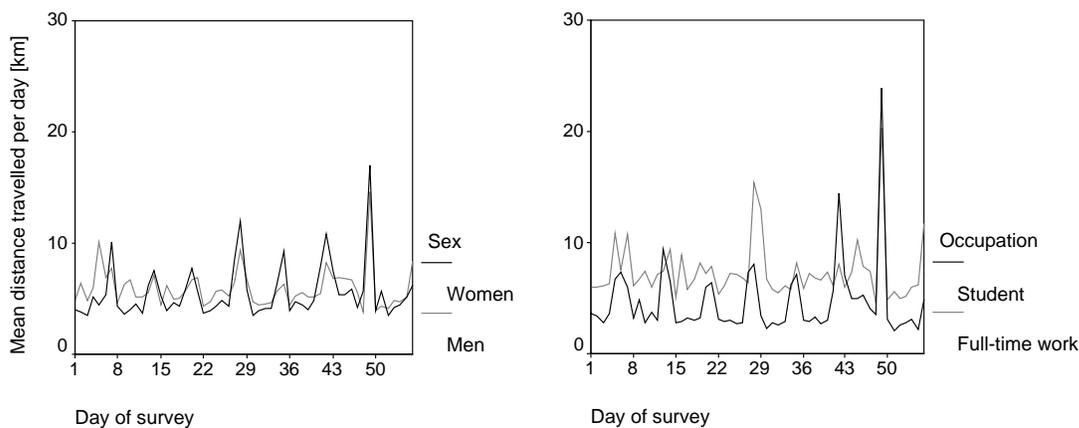
- How far are people travelling (per trip/per day)? At which speeds are people travelling?
- Which modes are used for the different classes of trip distances?
- Which destinations are chosen for the particular activities? What are the determinants for such choices?
- Which activities are combined within one chain of activities?
- Which activities are performed in vicinity of the pegs of daily travel, such as home or the work place?
- Which paths are considered for the different OD relations (route choice issue)?
- Which is the zonal or home location related accessibility for the different persons, households or travellers' sub-groups?

Some of the issues may be addressed by the calculation of simple indicators covering person as well as trip-specific characteristics (see e.g. Zahavi, 1974; Herz, 1984; Hanson and Schwab, 1995). Frequently used measures in transport planning and policy are

- Average trip distance by mode
- Total distances travelled per day (see e.g. Figure 2)
- Average speeds by time of day and mode
- Average daily traffic per network link
- Incoming and outgoing traffic per zone etc.

The following figures exemplarily gives the total daily distance travelled per day over the course of the *Mobidrive* survey period for different socio-demographic groups. It may be seen that the total amount of travel here is influenced by both, the occupational characteristics of the travellers, and the temporal (weekly) structure activity performance. The weekends (days 5/6/7, 12/13/14 etc.) show a significant increase in the average of total distance travelled for all groups presented.

Figure 2 *Mobidrive*: Mean total daily travel distances over the survey period*



* Karlsruhe sub-sample; overall survey period is 56 days due to the allocation of the sample into two waves with a two-week interval between the starts of the waves

Such travel distances as well as speeds and aggregate flows are the consequences of mainly two facts: a disperse distribution of opportunities in space and the travellers' choices of their home locations, work places and the other activity locations. From a methodological point of view, this leads to the question if both processes can be described by a joint concept representing the interactions between locational supply and individual choice.

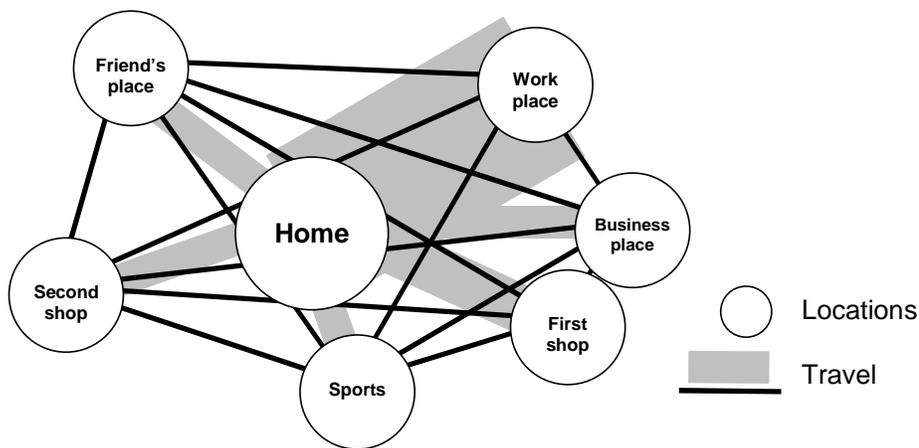
A micro-geographical approach which captures daily mobility patterns is the *activity space*. The activity space concept – which was developed in parallel with a range of related approaches to describe individual perception, knowledge and actual usage of space in the 1960s and 1970s (see Golledge and Stimson, 1997 for a discussion) – aims to represent the spatial unit which contains the places frequented by an individual over a period of time. Activity spaces are (geometric) indicators the *observed or realised* daily travel patterns (see also Axhausen, 2002). This is stressed here as related concepts such as the *action space* (e.g. Horton and Reynolds, 1971), the *awareness space* (e.g. Brown and Moore, 1970), the *perceptual*

space (e.g. Dürr, 1979), *mental maps* (e.g. Lynch, 1984) or *space-time prisms* (e.g. Lenntorp, 1976) describe the individual potentials of travel – based on spatial knowledge, mobility resources, the objective supply of opportunities etc. An activity space may therefore be defined as a two-dimensional form which is constituted by the spatial distribution of those locations a traveller has personal experience (*contact*) with (see Figure 3 for a schematic representation).

The geometry, size and inherent structure of activity spaces are determined by mainly three determinants (Golledge and Stimson, 1997, 279):

- Home: The position of the traveller's home location, the duration of residence, the supply of activity locations in the vicinity of home and the resulting neighbourhood travel
- Regular activities: Mobility to and from frequently visited activity locations such as work or school
- Travel between and around the pegs: Movements between the centres of daily life travel

Figure 3 Simplified activity space representation



Adopted from Maier, Paesler, Ruppert and Schaffer (1977) 57

In activity spaces, travellers choose routes through time and space to meet their obligations, needs and desires. The travellers will try to choose these routes optimally, but they are constrained by their knowledge (mental map), their reasoning abilities and by the time and concentration they have available to construct and select a route.

In a wider sense, the activity space comprises both those locations of which a traveller has personal experience, as well as those of which the traveller has second hand experiences through family, friends, books, films or other media (the knowledge space) (see e.g. Horton and Reynolds, 1971; Dürr 1979 or Goldenberg, Libai and Muller, 2001). In the following, though, activity space refers only to the first set of locations, those which a traveller has personally visited.

Finally, one should mention two further components of activity spaces which go beyond the actual choice processes of travellers and which will be only treated peripherally in the following: Perception and spatial learning. The frequent *usage* of networks and urban space has got implications for the way travellers define the utility, quality, or risks connected with certain areas or territories (Golledge and Stimson, 1997, 279ff.). This individual (or in many cases also group-) perception again constrains or opens up the range of potential places to go and visit. On the other hand, regular moving within and therefore frequent interaction with the built environment are key determinants for the acquisition of spatial knowledge (Golledge, 1978; Couclelis, Golledge, Gale and Tobler, 1987). Regardless of whether the information gained is modified or even lost after a while, landmarks, paths and areas of the individual activity space – used on a day-to-day basis – remain as background information. Both phenomena lead to a self-reinforcing character of activity spaces with the great importance of mobility anchors (such as home) for the individual allocation of daily activities (see also below).

4 MEASURING ACTIVITY SPACES: A CONCEPTUALISATION OF APPROACHES

As mentioned earlier, there have been only very few empirical studies on individual activity spaces (see Dijst, 1999 for a recent exception). This is due to the lack of travel data capturing longer periods of observation for single persons or households which allow to enumerate activity locations or to track people's movements in space¹. To our knowledge, this study is the only approach to analyse human activity spaces based on individual panel data.

The lack of earlier empirical research requires the development of suitable measures to operationalise the activity space concept. Describing and comparing revealed spatial activity patterns of individuals over time is therefore a challenge on a conceptual level and also for data processing. What we aim to develop are indicators which on the one hand allow to visualise spatial behaviour, and on the other hand to measure the extent of daily travel patterns of individuals over time.

The approaches presented here involve an increasing level of detail and comprehensiveness. Certainly, like all quantitative models of human behaviour, the representation of individual activity spaces is a simplification of reality, too. Nevertheless, the results help us to understand how people cluster or spread their activity demand in space.

An evolution of concepts

The methodology to describe the activity spaces basically depends on two interrelated statistical concepts: (1) Probability and (2) intensity or density estimation. The latter one may be furthermore distinguished by the intensity of actual *use* and the intensity of the *perception* of the travel environment. Transferring those concepts to activity-pattern analysis, one has to answer the following questions:

- Given the activity locations visited over time, which areas are used by a traveller with a certain *probability*?

¹ It should be noted that there is a range of studies of spatial behaviour and activity spaces on the aggregate level of sociodemographic groups or zones (see e.g. Kutter, 1973; Zahavi, 1979; Beckmann, Golob and Zahavi, 1983a,b; Holzapfel, 1980; Scheiner, 2001). Those studies use cross-sectional travel or time-use data.

- Which parts of the agglomeration are used more *intensively* than others according to activity needs, the supply of activity locations and transport infrastructure as well as the personal temporal opportunities and coupling constraints of the travellers?
- When moving through networks and visiting places, which areas adjacent to the used roads, tracks and locations do travellers perceive and memorise?

Table 2 gives an introductory overview of the approaches described in the following. As some of the sub-concepts are only slight modifications of the main approaches, the focus will be on the description of basic structures.

Table 2 Measuring activity spaces: Overview of concepts

Concepts and sub-concept	Probability	Density / Intensity	Perception
Confidence ellipses			
Arithmetic mean as centre	■		
Home location as centre	■		
Home location plus further pegs as centres	■		
Kernel densities			
Area covered (exceeding certain threshold)		■	
Volume		■	
Densities corrected for invisible areas		■	■
Minimum spanning trees (networks)			
Road network based		■	■
Specific modes considered		■	■
Shortest paths		■	■
Probabilistic		■	■
Minimum spanning tree buffered		■	■

4.1 Confidence ellipses

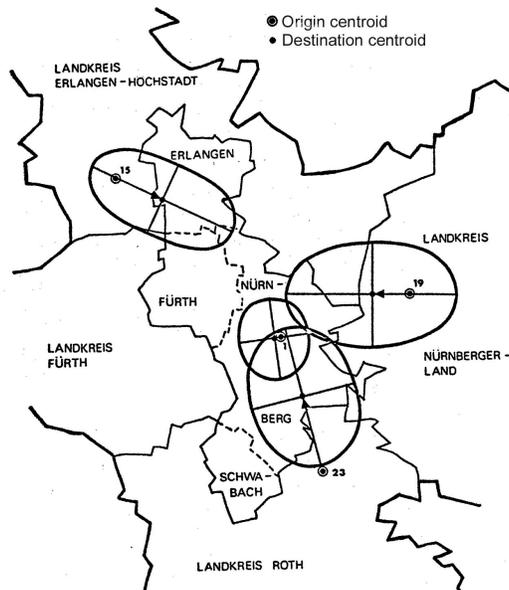
The first approach which will be presented here is the estimation of confidence ellipses to the spatial distribution of trip destinations. This approach captures the dispersion of activity locations which can be shown to correlate with a range of simpler measures, such as the standard distance (see e.g. Schönfelder, 2001; Schönfelder and Axhausen, 2001).

The confidence ellipse picks up the methodological, activity space oriented work of the 1970s UMOT project (*Unified Mechanism of Travel*) and subsequent studies (Zahavi, 1979; Beckmann, Golob and Zahavi 1983a; 1983b). One focus of the UMOT project was to analyse densities of activity locations (or trips) and to test hypotheses about the character of trip distributions at the regional level given a certain mode choice and the spatial structures of the regions studied. This work was based on one-day travel diaries.

UMOT lead to the calculation of ellipse shaped *travel probability fields* which are the geometric result of travel demand, network structure (system supply) and the supply of activity opportunities (urban form) (Figure 4). The major findings were that

- the fields' directions tend to be towards the urban cores,
- the length of the fields are proportional to the distance of the zone's centroid to the main agglomeration centre,
- there are differences of shape between the different modes of transport and
- there exists strong relations between the infrastructural supply of the region and the direction of the probability fields.

Figure 4 Travel probability fields in the of Nuremberg region



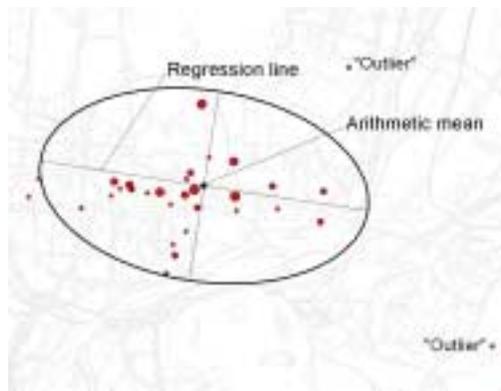
Source: Zahavi (1979) 230

The *Mobidrive* data now allows to calculate similar geometries, confidence ellipses, for each single respondent based on the travellers' trips during the six-week reporting period.

The mathematical approach of the confidence ellipses is comparable to the UMOOT calculations and was recently integrated into the common GIS software ESRI ARCVIEW[®] (see Schwarze and Schönfelder, 2001). Similar methodological techniques known as *Jennrich-Turner home ranges* have long been used in the biological habitat research to analyse competition and density effects of animals' space usage (see Jennrich and Turner, 1969; Southwood and Henderson, 2000).

Confidence ellipses – also called prediction interval ellipses – are an explorative method to investigate the relationship between two variables (bivariate analysis). They are often used for hypotheses testing and to detect outliers. Confidence ellipses are analogous to the confidence interval of univariate distributions as the smallest possible (sub-)area in which the true value of the population should be found with a certain probability (e.g. 95%).

Figure 5 Example of a confidence ellipse with outlier



Dots show location and intensity of observed activity locations of one respondent

The calculation of the ellipses is tied to the assumption that the variables are bivariate-normal. This was shown earlier for the activity locations of travellers (Moore, 1970).

The ellipses are computed with the covariance matrix of all points (activity locations) of a person

$$S = \begin{pmatrix} S_{xx} & S_{xy} \\ S_{yx} & S_{yy} \end{pmatrix}$$

where each covariance is defined as

$$s_{xx} = \frac{1}{n-2} \sum_{i=1}^n (x_i - \bar{x})^2$$

$$s_{yy} = \frac{1}{n-2} \sum_{i=1}^n (y_i - \bar{y})^2$$

$$s_{xy} = s_{yx} = \frac{1}{n-2} \sum_{i=1}^n (x_i - \bar{x})(y_i - \bar{y})$$

The determinant of the covariance matrix (generalised variance) is

$$|S| = s_{xx}s_{yy} - s_{xy}^2$$

with the ellipse size A

$$A = 6\pi |S|^{\frac{1}{2}}$$

The orientation of the ellipse is determined by the sign of the linear correlation coefficient between the coordinates x and y of the activity locations; the longer axis of the ellipse (if shown) is the regression line (Figure 5).

Modifications of the original principle and visualisation examples

In the context of spatial behaviour, confidence ellipses may be used for the description of activity location distributions in space. Furthermore, the size of the area is an indicator for the dispersion of visited locations and may be used to compare the dispersion between travellers or of one respondent on different days of the week.

As a first solution, the arithmetic mean— either of the all unique coordinates or the coordinates weighed by the frequency of visit — may be accepted as the core of the activity space. It seems nevertheless necessary to modify this analytical geometrical concept to gain a behaviourally more realistic measure.

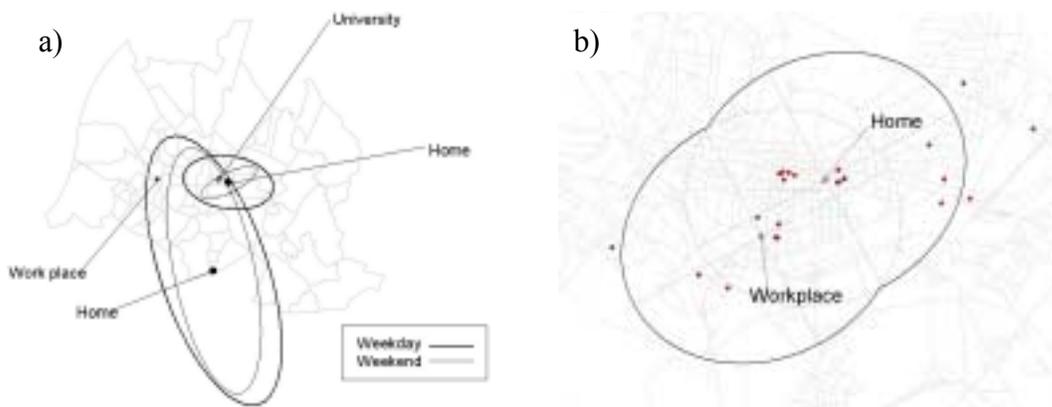
To reach this, one should consider two important characteristics of daily mobility: 1) the home location is the undoubted peg of daily mobility (see also Cullen and Godson, 1975) and 2) for most travellers it can be assumed that the geometric shape of the revealed activity patterns is ellipse-like with *two* focal points (see Dijst, 1999 for empirical findings). For the cal-

culations based on weighed frequencies, the arithmetic mean is normally close to home but this location is not a relevant real-world address, though. For a modification of the base approach, these facts are taken into account by either substituting the arithmetic mean by the coordinate of the home location (alternatively any other important activity location visited) or even by two pegs as focal points.

Figure 6 shows examples of such modifications. First, ellipses are shown where the home locations substitute the mean point in the calculation of the covariance matrix. This figure indicates significant differences between the chosen persons, but also on the intra-personal level by weekdays and weekend. This is evident for the size of the fields, the location of the action spaces within the city and the main axes of the ellipses.

The second extension (b) is the creation of two ellipses covering the activity locations related to home (such as home-based grocery shopping) plus a further peg such as work. These ellipses may be merged to visualise and measure the spatial clustering of secondary activities such as grocery shopping around the pegs (see e.g. Holzapfel, 1980) for early findings on the locational effects of the separation of home location and work place).

Figure 6 Two example local activity spaces*



* Measured as 95% confidence intervals of all locations visited during the six-week reporting period

Clearly, this adoption restricts the mathematical validity of the confidence ellipse principle, but it allows a more plausible description of the travellers' activity patterns.

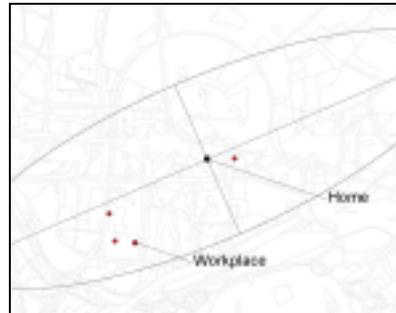
Figure 7 shows an example which reveals nicely the longitudinal character of the *Mobidrive* data. The ellipses are based on the local² activity locations visited by one respondent during the different weekdays over the six-week reporting period. What can be easily seen is the significant regularity in the activity pattern. The ellipses of the first four days of the week are relatively similar with about the same size but especially with the same main direction of travel approximately between the home location and the travellers work place. A range of secondary locations can be found around the two pegs and, furthermore, there are only few visited locations which are further away from the axis. Due to the profession of the traveller (nurse) which probably involves weekend work the Saturday pattern looks similar to the predominant weekday pattern whereas the Friday contains frequently visited locations outside the regular travel corridors which visibly shifts the main direction.

Figure 7 Activity spaces over time*

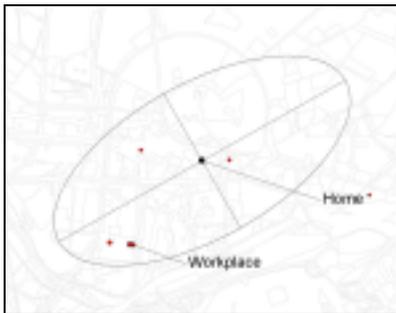
Mondays



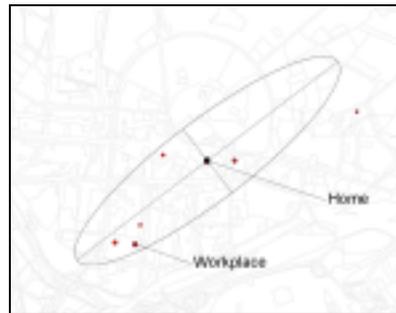
Tuesdays



Wednesdays



Thursdays



Fridays

Saturdays

² For all calculations of the paper only trips were considered which were made in a radius of approximately 25km around the city centres.



* 95% confidence ellipses; centre: household's home location) of one single Mobidrive respondent (female, 33, nurse, 2-person household); same clipping of underlying urban area

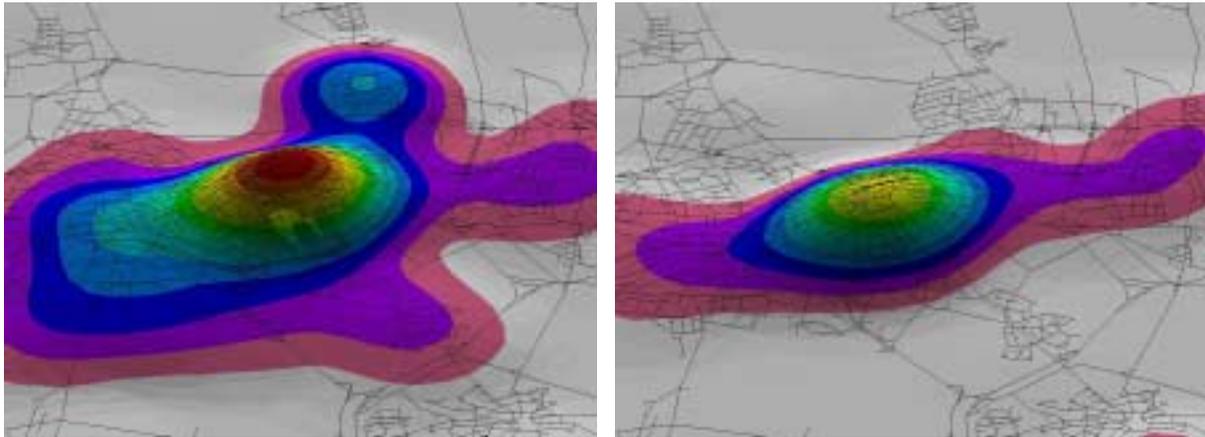
4.2 Kernel densities

As a second approach which considers activity space as distributed densities of activity performance, we propose the estimation of *Kernel densities*. Parallel to the confidence ellipses, kernel densities allow to explore the combined effects of locational choice and the frequency of visit.

The basic process behind the estimation of kernel densities is a transformation of a point pattern (such as a set of activity locations) into a continuous representation of density in a wider area. Generally spoken, the estimation is an interpolation or smoothing technique which generalises events or points to the area they are found in. The interpolation then leads to a calculation of a value for any point, cell or sub-region of the entire area which characterises the density or intensity of e.g. population or income per capita.

Kernel densities have been already applied successfully to large cross-sectional data sets (Kwan, 2000; Buliung, 2001). Modern GIS applications include tools to calculate such density measures effectively, including 3D visualisations which impressively show space-time interactions (Figure 8).

Figure 8 Aggregate activity density patterns*



* Total Karlsruhe sub-sample; Left: leisure activities, right: work

The approach applied here is related to those studies but is focusing on the personal due to the longitudinal character of the *Mobidrive* survey with numerous observations for one individual. Again, the densities and the related activity spaces of the *Mobidrive* respondents are compared quantitatively.

In this case, the intensity corresponds to the dispersion or clustering of places visited and can be complemented by the level of activity performance, i.e. the frequency of visit at the observed locations.

The technical implementation of the visualisation and the measuring of the densities is done in a Geographical Information System (GIS). GIS applications (such as ARCVIEW or ARCINFO which were both used in this study) mostly implement the density estimation by special modules. ARCINFO, for example, estimates densities within its integrated GRID module where raster grids such as shown in Figure 9 are divided into a definable amount of cells. Finally, the density values are assigned to the cells according to the kernel densities estimated for the underlying point pattern.

Figure 9 Example for a surface represented by a grid structure



Source: Fotheringham, Brunsdon and Charlton (2000) 193

For the actual density estimation, a variety of approaches exist (for an overview see Silverman, 1986) – ranging from simple histogram techniques to computational demanding maximum penalised likelihood estimators with effective smoothing. A range of density estimation techniques are frequently used in quantitative geography and other applied research areas (see Fotheringham, Brunsdon and Charlton, 2000). Again, the habitat research is one of those fields where the techniques are applied to space utilisation of animals (see Hooge, 2000; Kirkby, 2001).

Probably the most common approach, implemented in several GIS packages, is the *fixed kernel method* (also applied here). Similar to histogram techniques, a symmetrical – variably distributed – *kernel function* is placed over each data point. For all locations in the entire area (\mathcal{R}) – not only for the data points – the overlapping values are summed which yields the density or intensity estimate (Figure 10). This automatically leads to a smoothing of the surface where the level of smoothness depends on the *bandwidth* of the kernel function which is analogous to the width of ordinary histogram boxes. The bandwidths may be varied according to the necessary degree of smoothness – with greater smoothing at bigger bandwidths or values of the smoothing parameter. The GIS finally may represent the resulting estimates for all grid cells as a continuous surface.

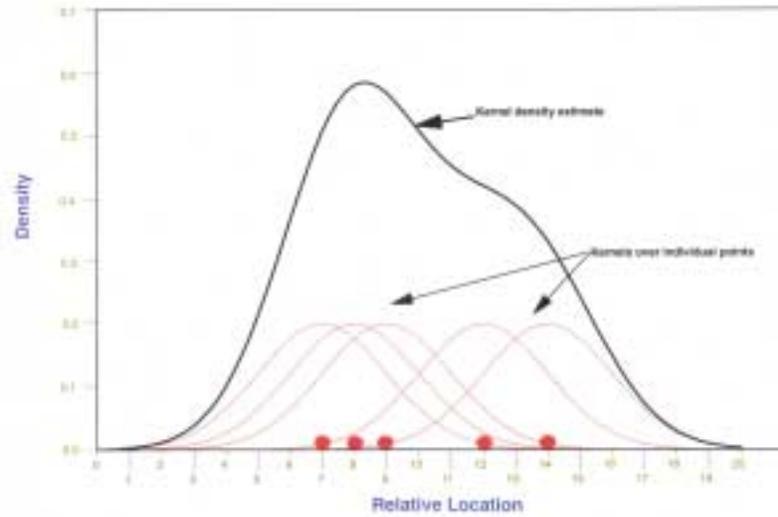
Considering a grid structure in which single points are substituted by grid cells, the base kernel density is given by the formula:

$$\lambda(s) = \sum_{d_i < \tau} K\left(\frac{d_i}{\tau}\right)$$

with

- λ density estimate at grid point s
- τ bandwidth or smoothing parameter
- K kernel function (to be further specified)
- d_i distance between grid point s and the observation of the i th event

Figure 10 Kernel density estimates



Source: adopted from Ned Levine and Associates (1999) 202

The kernel function K itself may have different forms such as normal, triangular or quartic. The results do not differ significantly as long as the distribution is symmetrical. In the following, a quartic kernel function – implemented by default in the GIS software used here (see Mitchell, 1999 for details) – is used which leads to the following kernel density

$$\lambda(s) = \sum_{d_i < \tau} K \left\{ \left[\frac{3}{\tau^2 \pi} \right] \left[1 - \frac{d_i^2}{\tau^2} \right]^2 \right\}$$

A particularity of the quartic function – e.g. compared to a normal distribution – is that outside the specified bandwidth τ , the function is per definition set to zero – with implications for the behavioural model. This means that activity locations outside a specified radius do not contribute to the density estimation of the particular point (cell) in space. In other words, a

quartic distribution of the kernel function adds weight to locations closer to the centre of the bandwidth than those further apart (see NedLevine and Associates, 1999 for characteristics of the different kernel forms).

Visualisation examples

Figure 11 shows the principle of the approach by visualising a kernel density grid around the workplace location of a *Mobidrive* Karlsruhe sub-sample respondent. The frequency of visit is considered as a (linear) weight.

It can be easily seen that – due to the quartic kernel function – the densities decrease with growing distance from the most visited location(s). The size of the dots represent the number of visits over the six-week reporting period. The visual effect of the GIS output, i.e. the gradation of colours or the visual smoothness, depends very much on the grid cell size chosen. Principally, the sum value of total densities for the entire reference area is directly related to the grid cell size – this means that the quotient of the overall density divided by number of cells is the same for every setting. Consequently, a comparison of the activity spaces (size) of one person over time or between persons should be based on the same defaults for cell size, bandwidth or scale factors³.

³ Unit scale factors are used by the GIS to convert the map units of the input point dataset (here: activity locations and the frequencies of visit) to different units. The ARCINFO default value is 1, which calculates density in units of number of points per one square map unit (e.g. m²). Considering the relatively great size of the reference areas (about 600km²) and the comparable low frequencies of visit for some of the locations, for the calculations of the next section of this study a high unit scale factor of 1.000 was chosen. This only affects the magnitude of the density results. Effectively, output grid values are multiplied by the square of the unit scale factor.

Figure 11 Out-of home activity density of one single Mobidrive respondent represented by kernel density estimates; aggregated by 6 weeks, Karlsruhe



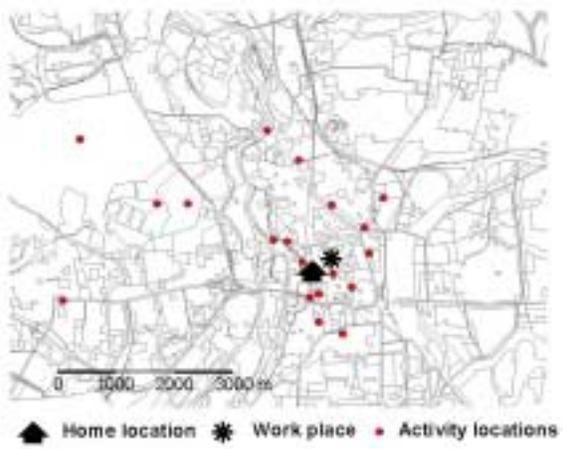
In the following figure, kernel densities are visualised for the different days of the week – illustrating the longitudinal character of the *Mobidrive* data. The kernel densities are calculated for the distribution of visited activity locations and the respective frequencies (weighed locations).

From a behavioural point of view, the selection of the bandwidth of the kernel function (search radius) is an important issue. It may be argued for the activity location data that the bandwidth reflects a maximum distance of spatial interrelationship between activity locations. One could raise the question which activity locations have a functional affiliation with each other in the understanding of people (e.g. home location and local groceries). In addition to that, what is the distance travellers accept to e.g. walk to the locations from home – indicating vicinity or familiarity with one's neighbourhood. Hence, the choice of the bandwidth should contribute to a conceptual approach of proximity and neighbourhood in daily travel. For the following example and for the calculations in the consequent chapter, a bandwidth of 1000m was chosen which can be defined as the maximum walking distance which is accepted between two places.

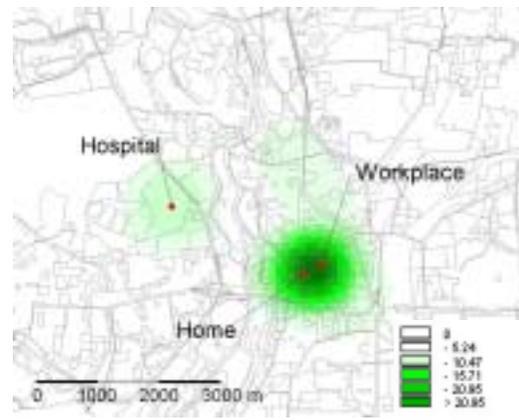
The densities show the strong regularity in the traveller's particular mobility patterns with quasi identical activity space structures and sizes from Monday to Friday and considerable changes towards the weekend. As home location and workplace are close together, high kernel densities are concentrated in the vicinity of these two mobility pegs. This is in line with an initial visual examination of the distribution of activity locations in the first sub-figure.

Figure 12 Kernel densities by day-of-week*

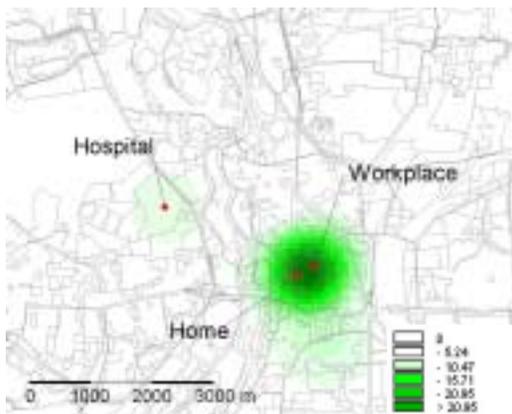
All visited locations (6 weeks)



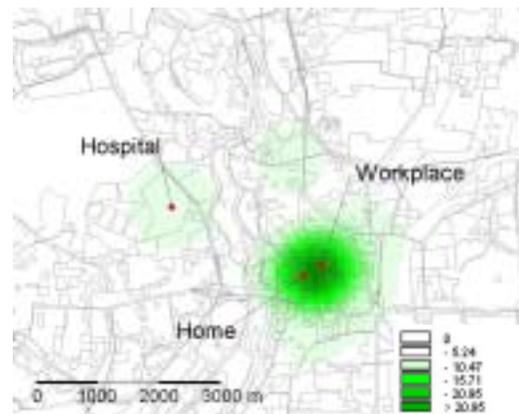
Mondays



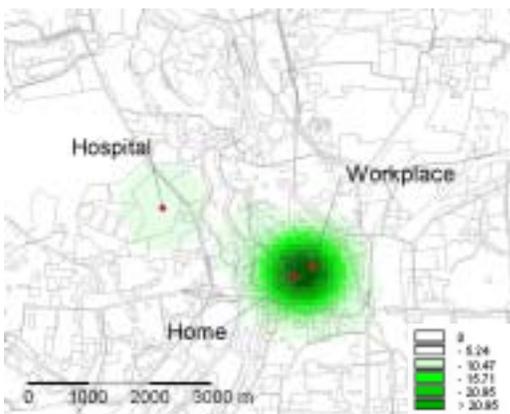
Tuesdays



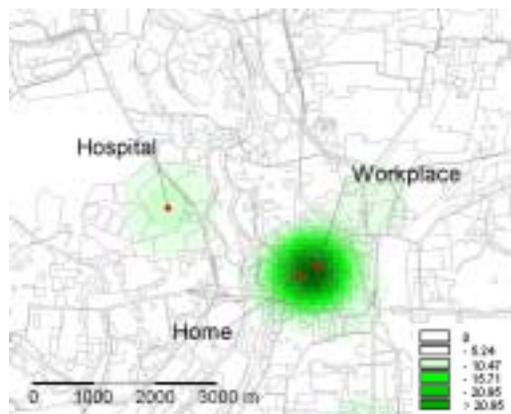
Wednesdays



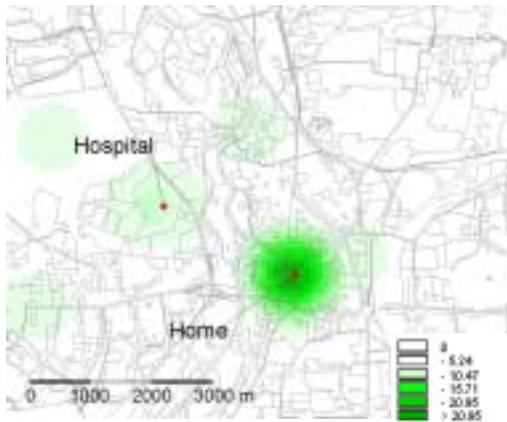
Thursdays



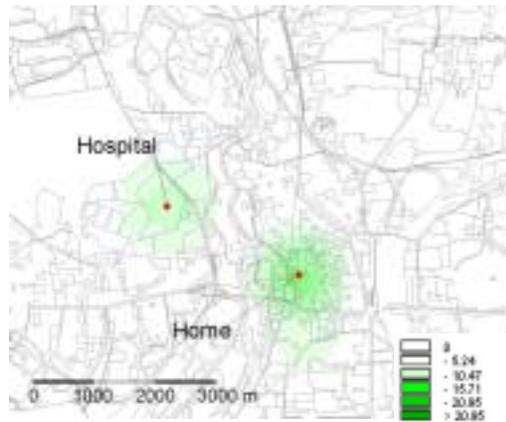
Fridays



Saturdays



Sundays



* Halle, male, 63 years; grid cell size: 100m, considered frequency for kernel estimation: frequency of visit multiplied 100, search radius/bandwidth: 1.000 m; values in 10^{-3}

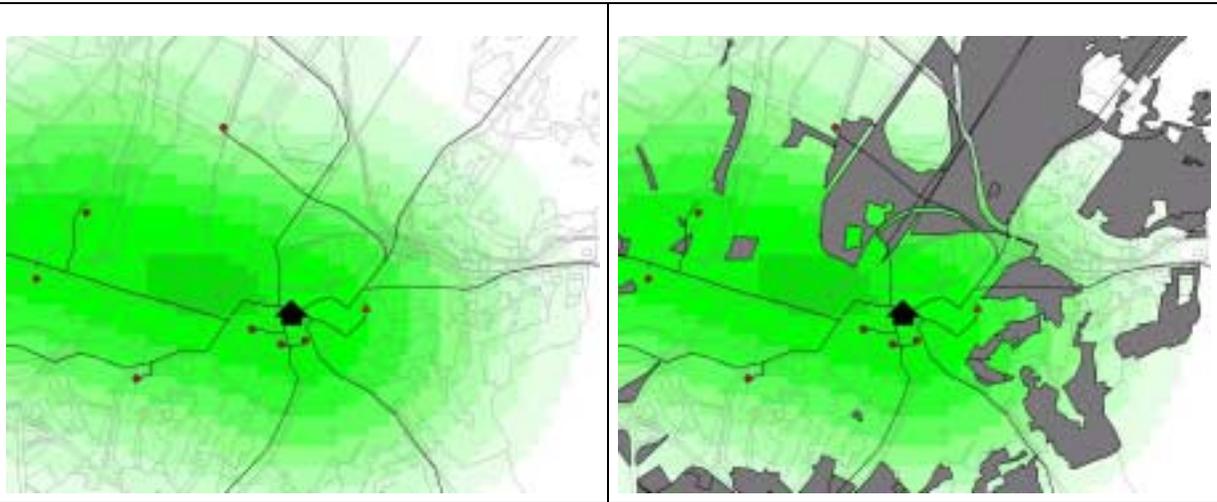
The representation of activity spaces by kernel densities is a powerful visualisation tool of spatial consumption in urban areas. From a forecasting and planning point of view, it seems useful, though, to gain quantitative results which yield possible determinants of spatial orientation and choice. Several relevant measures are considered for the comparison of densities between travellers and between the behaviour of single respondents over time (intra-personal variability):

- a) the extent of the *usage of space* is represented by the number of cells for the density value exceeds a certain threshold (i.e. > 0)
- b) the intensity of space usage given by the sum of the densities for all grid cells
- c) measure a) reduced by areas probably not open for ordinary activities, such heavy industrial or utility areas (see below).

Turning to measure (c), it can be argued the spatial supply (distribution) of activity opportunities is a further key factor for activity or trip demand and therefore for the shape of activity spaces. The availability of exact data covering the supply – such as digital point of interest data – is still limited and selective, though, which makes it difficult to relate travel supply and demand. Nevertheless, aggregate land use data which is available for both *Mobidrive* case study cities, at least yields information on areas of minimal interest for private travel such as agricultural land, industrial areas etc. Considering measure (a) or (b) as activity space indicators, one could introduce such *areas of no interest* to tailor the area to a more likely shape

(Figure 13). Sure, this is connected with a further uncertainty about the actual usage of urban space as it remains unclear if the definition of potential exclusion areas varies for the different respondents. Still, the proposed approach is a further methodological step to capture the observed activity patterns of individuals over time.

Figure 13 “No-go areas”: Agriculture, utility and disposal areas (grey shading)



4.3 Minimum spanning trees

The activity density regions presented above pretend that travellers have a spatially continuous knowledge or even make use of a continuous urban space around the activity locations visited – which is even more true for the ellipse measure introduced at the beginning. This is a simplification of human behaviour as the identified areas are certainly not *used* in a literal way. Furthermore, the potential knowledge of activity locations or landmarks is probably overestimated – depending on the chosen bandwidth of the kernel function.

By introducing a further measure for activity space characteristics, it shall be acknowledged that transport network structures shape the travellers’ perception of potential activity locations as well as the knowledge of place and the spatial orientation (Golledge, 1999). Hence, calculating the size as well as visualising the shape of human activity spaces should be oriented towards the paths chosen by the travellers.

One possibility to consider the network supply-travel interactions is to identify the part of the network which was actually used by the *Mobidrive* respondents during the six weeks of reporting. This particular portion and the roads’ adjacent built environment is supposed to be

known by the traveller dependent on the frequency of usage. The identification of the network links needs to rely initially on assumptions about the chosen routes, though, as the survey design did not capture the path choices. As an approximation of actual spatial decision making, the shortest route for each unique relation reported by the *Mobidrive* respondents was calculated – based on the individual 6-week origin-destination matrix and available road network⁴. As route choice algorithm we chose the default Dijkstra procedure implemented in the ARCINFO NETWORK module. Enhancements of this procedure are imaginable, e.g. by substituting the deterministic shortest path algorithm by a probabilistic one (see Sheffi, 1985; Bovy, 1996). Furthermore, the paths chosen can be properly assigned to the different modal networks according to the modes actually chosen for the different trips.

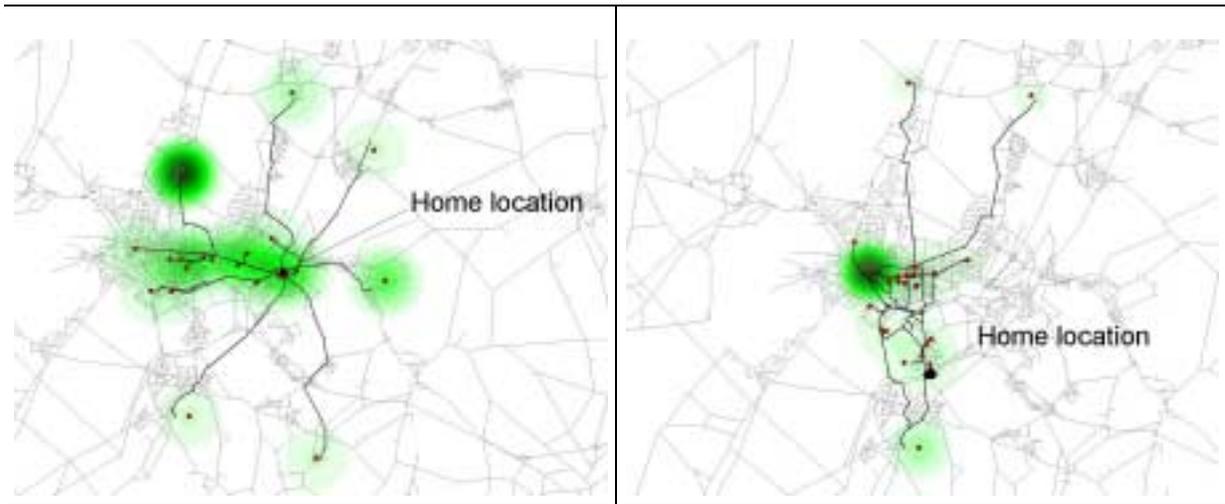
The initial application of the concept is leading to a geometry which can be compared to a *minimum spanning tree* (

Figure 14) – well known from the graph theory. The structure and size of the tree is a further quantitative indicator for the perception, knowledge and especially the usage of urban space. Considering the perception of the (built) environment, it can be assumed that there is considerable correlation between the frequency of using a network link and the knowledge of the surrounding area. It is widely agreed by psychologists and geographers that travelling through an environment is the common way of spatial learning and acquiring spatial expertise (Golledge, 1999).

What can be especially seen from the first of the two examples in

Figure 14 is that again the home location is the *major hub* for daily life travel acting as a central node in the given road network. This is what could be expected as the share of complex trip chains with diffuse travel relations is much smaller than the amount of simple home-based trips, such as home-work-home, home-shop-home or home-leisure-home. More than 70% of all *Mobidrive* home based activity chains (i.e. *tours* or *journeys*) involve only one out-of-home activity.

⁴ A digitalised road network was only available for the City Karlsruhe.

Figure 14 Two examples of *minimum spanning trees (networks)*

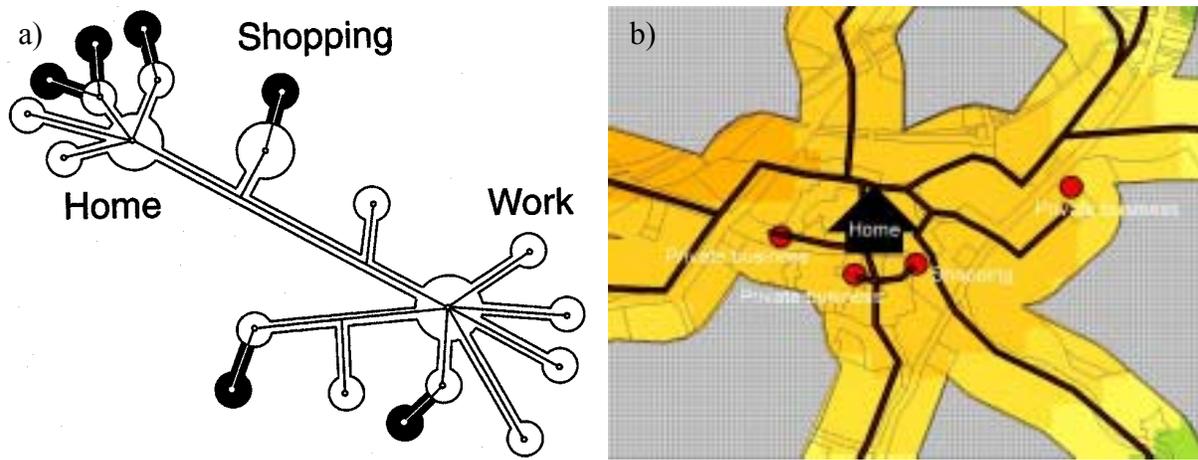
Knowing about the locations visited over a substantial period of time, the frequency of visit and the (probable) routes chosen between the places enables us to underpin spatial knowledge acquisition theories with empirical data. One such theory is Golledge's anchor point theory (Golledge, 1978) which postulates that spatial knowledge and orientation skills are acquired by linking important individual nodes and links between these locations. People build up a cognitive structure of frequently visited places which are mentally linked by hierarchical paths (Figure 15a). The knowledge of and the familiarity to particular areas are mentally organised by storing hierarchies of important pegs or landmarks in the personal action space, spread effects of minor locations in the vicinity of primary nodes and approximate distances and axes between places. Distortions in the relative location of pegs or the lack of knowledge about links between them may cause deformations in the cognitive organisation of places.

A combination of the concept with the empirical findings of *Mobidrive* may be conceptualised as follows (Figure 15b):

- 1) Taking the spanning tree geometry as the link system between the pegs of daily mobility
- 2) Creating areal buffers around the links used representing the urban environment which is recognised by the traveller
- 3) Considering the kernel densities calculated beforehand as the base for differentiating the level of knowledge or perception within the buffer areas

Using a GIS, the concept may be easily implemented by overlaying the different themes needed (spanning tree, kernel density grid, land use structure/building blocks, buffers). The exemplary visualisation nicely shows both, the *primary node effect* with a relatively large and intensively used area around the traveller's home location as well as the areas of probably less or no knowledge (grey shading). The identified area of perception widens around home with several further visited activity locations and narrows along the links to the other (main) activity centres. A calculation of the size of the known/perceived area is possible.

Figure 15 Anchor point theory revisited – Buffering the used routes system (200m)



Source for a) Golledge (1999) 17

5 SELECTED CALCULATION RESULTS

The examples above already indicated that there is behavioural variability between the days of the week of a single traveller and between respondents of certain sociodemographic groups. In the following, some selected calculation results are presented which underpin these notions and demonstrate the suitability of the developed indicators.

Summarising again the rationale of such measurement, we are expecting answers on the following questions:

- Are there differences in the size of the individual activity spaces given the different sociodemographic characteristics of the travellers?
- What are the impacts of the mobility related lifestyle decisions (household location choice, car ownership etc.) on the activity space sizes (see also Simma and Axhausen, 2001; Axhausen, Scott, König and Jürgens, 2001; Axhausen, 2002)?
- How does the extent of the activity spaces vary for the different days of the week respectively between the weekdays and the weekends?

Given the different conceptual approaches of the measures presented in the preceding chapter, the calculation yields different types of target variables. Table 3 provides an overview of variables which are described in more detail below:

Table 3 Measuring results: Target variables

Measure	Indicator
Confidence ellipses	Area of ellipse
Kernel densities	
Area covered	Share of covered area in reference area (cities' agglomerations); only cells considered which exceed certain threshold
Volume	Sum of kernel densities (all cells)
Minimum spanning tree	(Weighed) Overall length of used network

The exemplary results are given in the same order as the concepts in chapter 4.

Confidence ellipses results

The area A covered by the confidence ellipse is considered as the actual measure for the size of the activity space. As mentioned earlier, its size gives an indication for the dispersion of the locations visited over time. All results presented below are based on 95% confidence ellipse of all reported non-home activity locations weighed by the frequency of visit. The household location is considered the mean of the ellipse. Only activity locations are considered which are in a distance of about 25km from the respective city centre (see discussion above).

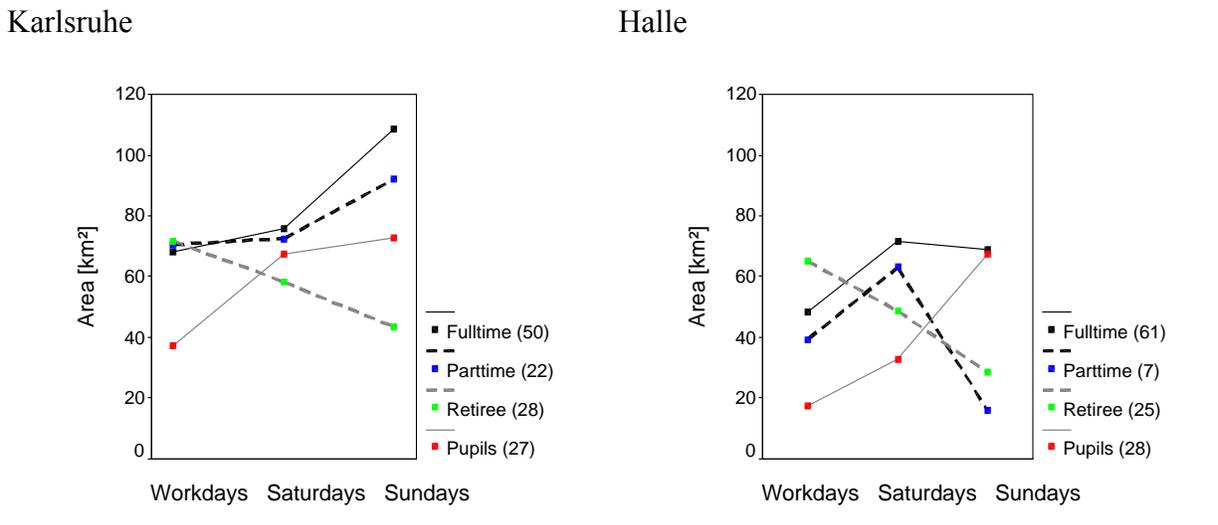
An often examined determinant for the structure of travel patterns is the occupation status of the respondents. We know from various other studies that, for example, employed people travel more than those without work or in other life-cycle stages (pupils, retirees etc.) (see Hanson, 1982 or Pas, 1984 for basics).

The results presented in the following figure imply that obligatory commitments such as work and school have a strong impact on the size of the activity space. Whereas pupils (here: only 16 years and older) have a limited activity space during the week (bound to their school's environments), the fulltime workers activity spaces are the most dispersed in both case study cities compared to the other groups. Recognising the similarities in the temporal structure of sizes for the different groups, there are differences between the case study cities concerning the level of dispersion – especially if considering the similar household and person structure of the two sub-samples. In order to avoid biases caused by different sample compositions, the Karlsruhe data was weighed by

- working status (fulltime/non-fulltime working),
- household size (1, 2, >3 persons in household)
- sex (m/f) and
- age (age groups <25, 25-<65, >65).

In parallel with the (slightly) different levels of mobility in the Western and Eastern Germany (see also basic descriptive results on *Mobidrive*: König, Schlich and Axhausen, 2000), there is a statistically significant difference in the dispersion of the activity locations, too (t-test statistics $p=0.0010$). Whereas the (weighed) mean size of activity space in Karlsruhe for all 42 days is about 78 square kilometers, it is only 56 square kilometers for Halle in Eastern Germany. This is of course partly due to the different land use patterns and infrastructure supply of the cities.

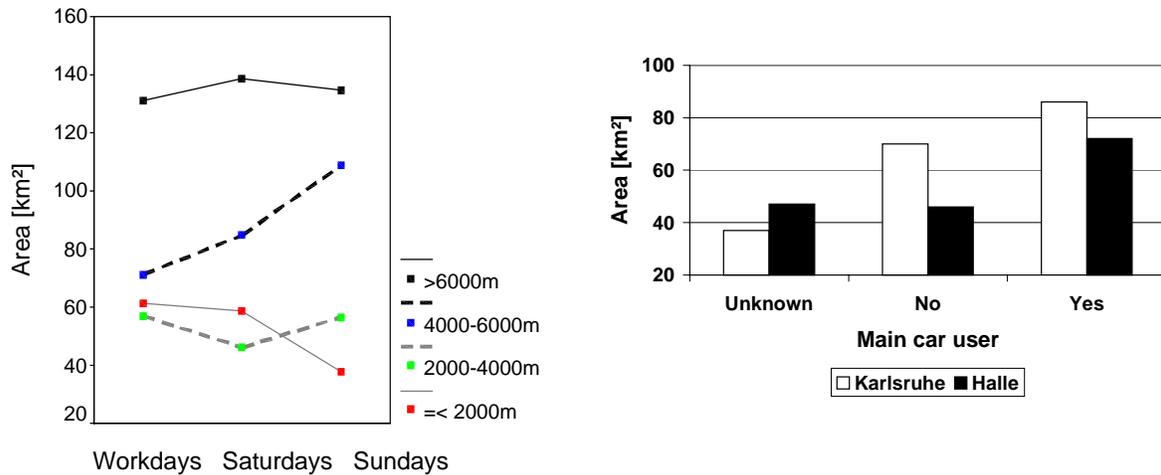
Figure 16 Mean size of confidence ellipses by city and selected socio-demographic groups



One other finding – confirming similar analysis using cross-sectional data – is that the household location and the car usage / car availability are the main factors for the size of the ellipses (Figure 17). Although both case study areas are cities only of about 200.000 – 300.000 inhabitants, a *suburbia effect* is visible. Travellers of households with locations at the edge of the cities show considerably more dispersed activity spaces than more central households – for both, weekdays and the weekend days. It is interesting, though, that the effect is not necessarily a linear one as for weekdays the sizes of ellipses for the lower categories (up to app. 6km distance from CBD) are close together. These findings are only a starting point, though, as the sub-group of the peripheral households is small for both cities (Karlsruhe: 6, Halle: 4)

Figure 17 Household location and car usage as determinants for activity space size

Karlsruhe only



Mean values; distances from city centre

An initial linear regression model is estimated to identify the directions and the strength of the relationships between the size of the activity space and the selected sociodemographic attributes (Table 4). It underlines the importance of a combined effect of the two factors shown in the last figure. Respondents who stated to be the main user of a household car and live further away from the urban core show a significant greater dispersion of activity locations compared to secondary or non-car users.

The estimates generally show that a reasonable explanation of the ellipse size determinants is possible in particular for the weekdays – the explanatory power for the weekend days is weak, though. It decreases significantly for Saturdays and Sundays (Adj R-Sq under 0.1), mainly due to the diminishing impact of the combined effect of car usage and household location.

The mentioned combined effect is represented by a variable which covers both, the (classified) distance of the household location from the city centre as well as the level of car usage (i.e. whether somebody is the *main user* of the household’s car or not). As shown above, the impact of distance does not seem to be linear as the parameter estimates in the work days model increase notably for the highest distance class (5). Other often important co-variates such as the number of working hours per week, income, school attendance or retirement do not play a clear role for the determination of the ellipse size. This is partly contradicting to the results presented in the figures above, and has to be explained by the joint effects of the se-

lected variables. It could be at least found that fulltime workers have a significantly larger activity space on weekends and low income respondents show a smaller dispersion in their activity spaces on sundays compared to other groups. Interestingly, the politically relevant *season ticket holding* is irrelevant for the activity space size in this particular model. The dispersion of individual activity spaces does not seem to be affected by the intensity of public transport – at least at this local-only level of daily mobility.

Table 4 Regression model: Size of 95% confidence ellipses⁺

	Work days (Mo-Fr)		Saturdays		Sundays	
	β	SE	β	SE	β	SE
Karlsruhe	17.1 *	8.2	23.0 *	11.2	-10.6	19.0
Pupil	-25.6 **	-1.7	1.3	19.6	13.7	35.3
Retiree	13.3	0.9	8.7	19.2	-5.2	33.6
Fulltime	4.3	0.3	28.7 **	17.1	77.7 *	31.4
Parttime	18.0	1.2	-0.1	19.2	27.8	34.2
DC3 & Main car user	40.0 *	12.1	3.3	16.4	31.6	27.7
DC4 & Main car user	59.1 *	16.7	58.2 *	22.4	48.7	38.3
DC5 & Main car user	91.9 *	41.7	25.4	54.1	-30.6	87.6
MainUser	-6.6	10.2	5.6	13.6	-29.0	23.8
SeasonTicket	-2.0	9.2	-2.4	12.1	48.5 *	20.5
Personal net income < 1000DEM/month	3.7	9.1	12.2	12.4	-53.3 *	21.6
Intercept	43.3	13.8	29.1	18.4	55.8	34.2
F-Value	5.45		2.1		2.6	
Adj R-Sq	0.16		0.05		0.07	

DCx Distance classes, distance of household location from CBD (1: 0-2000m, 2: 2000-4000m, etc.)

* Statistically significant at 95%-confidence interval

** Statistically significant at 90%-confidence interval

⁺ Karlsruhe results are weighed by working status, household size, sex and age (see above).

Kernel densities results

Figure 18 demonstrates the basic enumeration and calculation concept for the kernel density measures. For the first measure (i.e. *area covered*), the number of shaded cells which exceed a given threshold are counted and multiplied by the chosen cell size. This yields the area around the observed activity locations which can assumed to be perceived, known or even used by the traveller. For a better comparison, the ratio of this value to the overall size of the reference area (case study agglomerations) is calculated.

The selection of the threshold value play an important role for the outcome of this measure. As the fixed quartic kernel method assigns non-zero values to any grid cell found in the defined distance (bandwidth) from a data point, a measure with an insensibly chosen threshold would be biased by cells of low values. Imagine that the threshold is set to 0 which would mean that each non-zero cell counts – regardless whether the kernel density value is high or low. This of course would affect the result as sub-areas with a low usage by the traveller would have the same impact or significance as high-usage areas. In other words, isolated and low frequented activity locations would unjustifiably receive a greater importance than areas where activity locations are clustered. Following the assumption that areas of intense usage are known better and eventually receive higher utility by the traveller, a weighing in form of a suitably chosen threshold value is necessary.

The second main measure is simply the sum of all grid cell values (here: 23) which can be interpreted as the volume of the three-dimensional surface representation as in Figure 8.

Figure 18 Enumeration and calculation of activity densities

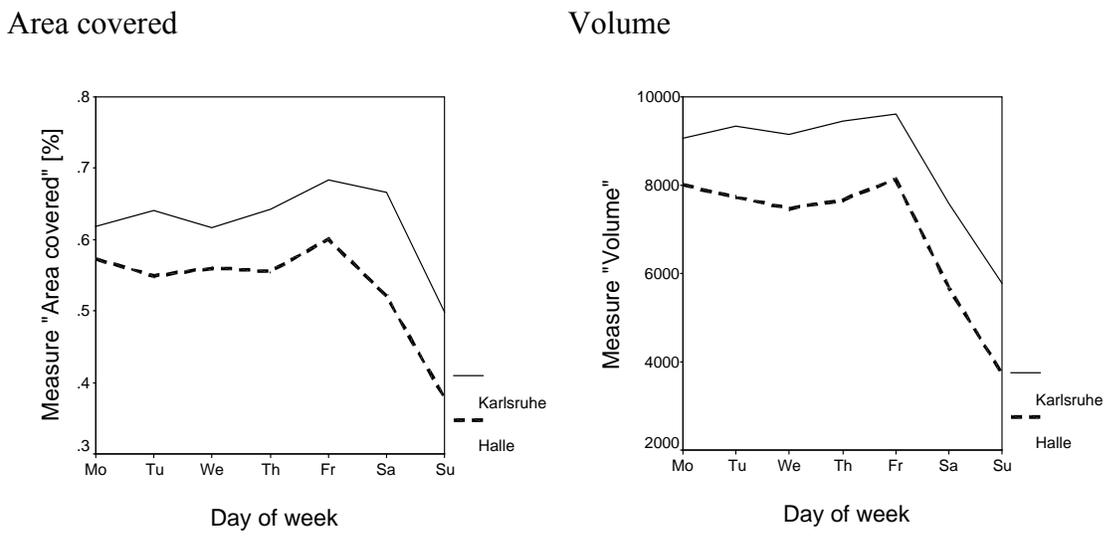
0	2	3	2
0	7	0.9	0
1	0.1	6	1

For this first examination of the density measures, we chose the following parameters for the kernel estimation and evaluation:

- Point pattern base: unique activity locations by day of week weighed by frequency of visit
- Grid cell size: 500m
- Bandwidth of kernel function (search radius): 1000m
- Threshold value for the *area covered* measure: all cells with kernel density greater than 1st quartile

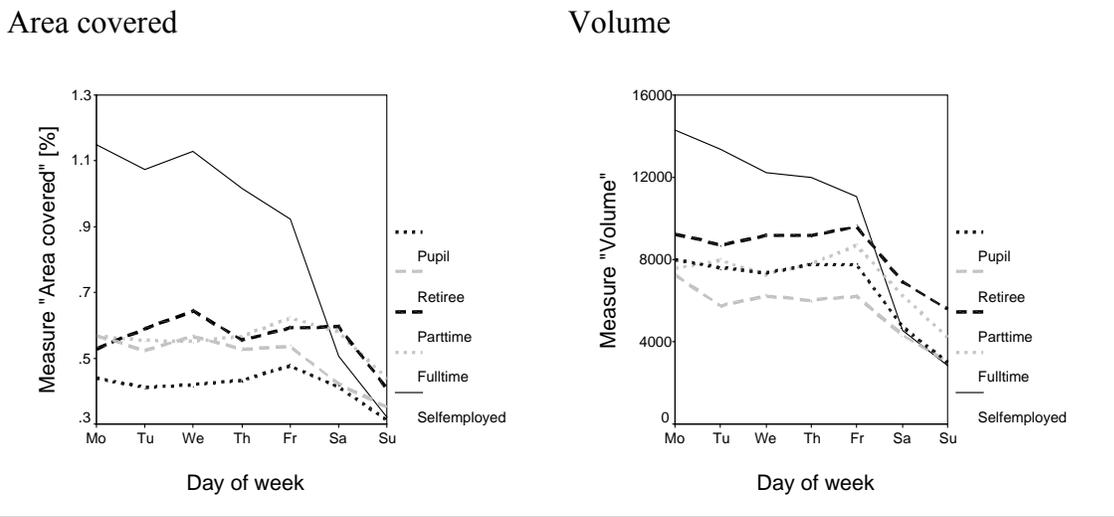
Comparing the outcome of the kernel density measures at a very aggregate level (Figure 19) already provides insight into their basic characteristics: Both measures obviously correlate with the indicators of travel demand. Similar shapes can be also shown for the number of observed trips per weekday. Nevertheless, there are differences between the measures which are especially obvious during the weekends. Where measure A (extent/size of activity space) has its peak(s) on Fridays and Saturdays, there is a considerable decrease in the value of measure B from Friday to Saturday and Sunday. This implies that the latter travel intensity indicator is highly frequency sensitive. Hence, the dispersion aspect of activity spaces (i.e. the distribution of activity locations in space) is outweighed by the level of general mobility respectively the level of activity performance at the particular destination per time unit.

Figure 19 Mean values of proposed measures by day of week and survey city



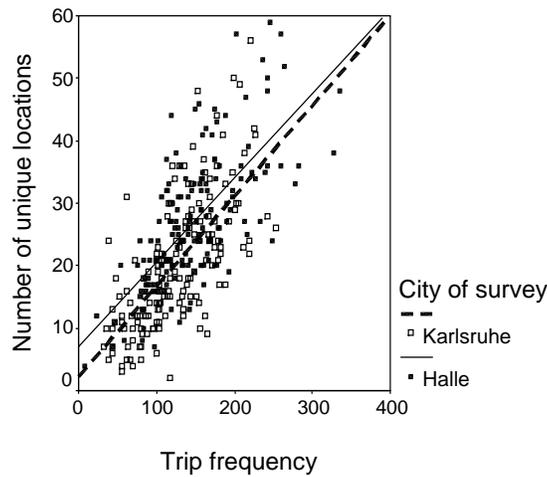
Turning to the additional factors influencing the density measures, again there are parallels to the general structures of daily mobility demand. Figure 16 makes clear that especially the occupation and lifecycle status affects the value of the activity space indicator. Employed respondents have significantly higher values during the working days of the week compared to e.g. retirees or pupils, and there is equalisation between the sociodemographic groups for the weekend days. This is especially obvious for self-employed respondents in *Mobidrive* who show 30-40% greater daily mean travel distances, durations and trip frequencies on working days than average. On weekends, though, this extra shrinks to almost zero.

Figure 20 Mean values of proposed measures by day of week and selected socio-demographic groups (Halle)



Furthermore, the frequency of travel, i.e. mean trips per day, has a strong relationship with the number of unique locations visited over the reporting period (Figure 21). This fact affects the proposed measures – especially the volume indicator. Higher travel demand can lead to a greater dispersion of activity locations which can be well observed for the self-employed subgroup with several professional or business contacts throughout the whole study area.

Figure 21 Relationship between trip frequency and number of unique locations*



* Trip frequency over the six weeks of reporting; unique locations including home location

Initial regression model estimations – equivalent to the confidence ellipses analysis above – showed that both basic kernel measures are greatly dependent on the shown relationship. The explanatory power of such models is dominated by the number or unique locations as well as by the frequency of visiting them (in particular for the *volume* measure). Other statistically significant determinants – with considerably lower importance, though – were the travellers' origin (i.e. the case study city) and the home location's distance from the city centre.

At first sight, these findings seem to be unattractive. One could ask if an indicator for the size of individual activity spaces is useful which tells us that the structures of spatial mobility are tied to the pure amount of travel? At the same time, though, the measure and the outcome of the investigation strongly confirms our expectations. It indicates that the usage as well as the up-to-date knowledge or urban space is a function of the amount of contact a traveller has. This again has strong implications for the interpretation of the analysis results – e.g. considering questions of sustainable transport or justice (see brief discussion at the end of this paper).

Minimum spanning trees

Finally turning to the *minimum spanning tree* measure, the length of the geometry as well as the differences between the sociodemographic groups are in the centre of the analysis. The

measure gives the sum of length of the used network links. At this stage of work, the measure is for Karlsruhe only and considers link lengths of the regional road network.

There are two main interrelated factors influencing the spanning tree's characteristic (Table 5). First, the size of the tree is affected by the spatial dispersion of the places visited. The measure therefore reflects the dispersion of the activity pattern – parallel to the other measures. Second, the weighed geometry (link length multiplied by frequency of usage) is directly bound to the overall group-specific travel demand. The differences of tree lengths between the sociodemographic groups confirm the common findings on the determinants of travel demand. The variation coefficient (standard deviation / mean * 100) indicates that the relative variation is high for students, whereas the group-specific distribution of the measure is in particular low for fulltime workers with potentially more similar daily activity patterns compared to the others.

Table 5 Minimum spanning trees characteristics⁺

Occupation status	N	Mean number of trips 6 weeks (Std.)	Mean number of unique locations* (Std.)	Mean unweighed** tree length [km] (Std.)	Mean ratio weighed / unweighed tree length	Std.	Var. Coeff. [%]
Pupil	27	157 (43)	23 (6)	68 (31)	2.77	0.75	27
Student	7	108 (91)	24 (15)	79 (43)	2.32	0.88	38
Apprentence	6	182 (79)	30 (12)	72 (26)	3.31	1.01	30
Housemaker	10	154 (65)	29 (11)	94 (45)	3.25	0.74	23
Retiree	28	129 (58)	25 (10)	66 (32)	3.06	0.94	29
Unemployed	1	59 (-)	8 (-)	13 (-)	1.99	-	-
Parttime	21	161 (49)	32 (12)	91 (36)	3.07	0.76	25
Fulltime	47	141 (46)	26 (10)	74 (36)	3.07	0.72	23
Self-employed	8	188 (47)	37 (10)	110 (49)	3.61	1.11	31

* Including home

** “Unweighed”: Total link length of tree, “weighed”: link lengths multiplied by frequency of usage

⁺ City of Karlsruhe only

6 CONCLUSIONS

Concluding the concepts and the initial results generated by the size-of-activity-space measures, the evaluation of approaches, the future work and some policy implications are addressed in the following.

Evaluation of the approaches

The presented approaches to describe and to measure the structure and the size of individual activity spaces are models of human behaviour and therefore simplifications of environmental perception and actual decision processes. Turning to these simplifying features of the proposed measures at first, there are some critical issues to discuss, such as

- the over-representation of actually used urban space especially with the confidence ellipse measure (“Is the area covered by the geometries actually used or perceived by the travellers?”)
- the assumption of the continuousness of space usage and knowledge pretended by the geometric shapes of the measures (“Do we really perceive, know and use urban areas in a continuous way? Should we not better represent spatial behaviour by indicators of contact with single features of the environment, such as activity locations, landmarks, network sections or important junctions?”)
- the strong impact of the frequency of travel on the measurement results, especially for the kernel densities (“If there is such a high correlation between the size of the activity space and the individual amount of travel, which is the extra gained by an investigation of activity spaces and their determinants?”)

Recognising these points, we believe that the development of the measures is a substantial contribution to the analysis of long-term travel behaviour. As for other analysis tasks based on the unique *Mobidrive* longitudinal data set, there are only few indicators for the stability and variability of travel behaviour available. The conceptualisation of the measures reflects the travel research’s intention to combine the existing theories on spatial behaviour and knowledge acquisition with empirical analysis. Based on the *Mobidrive* data which yields respondents’ information on a day-to-day basis, this is possible for the first time in this particular field of transport geography.

To sum up, the developed measures are powerful for several reasons:

- The measures are flexible and allow the researchers to choose the parameters (e.g. the choice of mean point of the confidence ellipse or the kernel bandwidths) according to the particular analysis interest.
- The implementation of the measurement is possible within common GIS software packages.
- The visualisation of the example is straightforward and enables practitioners to gain insight into the travellers' mobility routines.
- The proposed enhancements (*minimum spanning trees, no-go-areas*) nicely take into account the interaction between activity location supply and destination choice.

Future work will be focused more strongly on the implementation and the application of the proposed measures as well as on a further specification of suitable behavioural representation within the models.

Implications for planning and policy

Although this paper is more methodology oriented, the initial results yield a relevant background for a discussion on transport policy and planning issues. From our point of view, two aspects are of a particular considering potential implications of such measurement:

On the one hand, the enumeration of daily-life activity locations and the analysis of the distribution of such places reveals both, the supply structure of activity opportunities in space and the destination choice behaviour of travellers given their perceived supply. This invites transport planning and research to once more evaluate present and imaginable future urban structures from the perspective of sustainable transport policy. This includes for example measures to increase the amount of the opportunities (i.e. potential destinations) to satisfy the activity demand in the household's neighbourhood which eventually reduces travel expenses, further congestion and emissions. There is evidence that local accessibility oriented land-use planning matters (Banister, 2000). We do not neglect, though, that there are complexity and non-linearities within the interaction between locational supply and the actual choice of destinations.

On the other hand, the activity space issue has to be put on the agenda when discussing the relationship between poverty, the deprivation of urban areas and transport. Kenyon, Lyons and Rafferty (2002) argue that important determinants of the activity space such as poor or unavailable transport (e.g. car ownership) as well as reduced accessibility to facilities, goods

and services are dimensions and factors of social exclusion. The size and structure of the activity space therefore may act as a – highly political – indicator of social justice and the efficiency of a infrastructure supply policy matching societal needs.

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