EXPLORING ACTIVITY SPACE METRICS ALONG A NEW TRANSIT ORIENTED DEVELOPMENT RAILWAY CORRIDOR

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ABSTRACT

This paper reports on the relationships between the size of activity spaces (measured by a vector of parametric and non-parametric indicators) and transit-oriented developments (TOD), considered before and after the opening of a new 72km railway corridor in Perth, Western Australia, in December 2007.

We examine new geometries of activity spaces (ellipses, super ellipses, Cassini ovals, and bean curves) as well as kernel densities, representing activity spaces of households residing within three unique TOD precincts along the railway corridor. These precincts cover a wide spectrum of TOD features, ranging from mixed land use, with good feeder-bus connections and encouraging pedestrian as well as cycling movements, to transit interchanges, or retrofitted residential areas.

After accounting for socio-demographic elements, we noticed a significant difference in the size of the activity spaces by precinct, decreasing with higher citywide accessibility. This was observed in both occasions, before and after the railway opening. The finding holds for most of the metrics used to quantify the activity spaces. Increased access provided by the TOD corridor is reflected in a greater use of the corridor and the city, resulting in larger activity spaces for the precincts further away from the city. It remains to further ascertain whether changes in the activity spaces are due to primarily residential sorting and/or are associated with enhanced access to urban facilities as result of the new developments.

With respect to the metrics used for activity spaces, the parametric indicators are highly correlated with each other, but bean curves and kernel densities display the smallest areas. Due to their flexibility and visual capabilities kernel densities have the potential to become preferred tools for activity space estimation, however further investigation is required in other settings.

Keywords: activity space, TOD, kernel density, confidence ellipse, hyperellipse, Cassini oval, bean curve

1. INTRODUCTION

People travel between places in order to perform activities necessary to their daily living. In general travel is associated with a cost/disutility (except some trips – e.g. discretionary – enabling individuals to obtain benefits from the activities performed during travel). Typically a trip is made if the gain/satisfaction achieved at the destination is higher than the cost of reaching that destination (Ortúzar and Willumsen, 2001). However, places with certain appealing attributes are likely to attract more trips, and routes perceived to be shorter, easier, more pleasing are likely to be chosen more often. This simply shows that relationships underlying travel behaviour are not "global", but localised and varying across space.
The set of these locations visited form a space for which the individuals are likely to be more aware/informed, as they have more direct contact with those locations in their daily routines and visit them more frequently (the relation is reciprocal – through travel people build their mental maps of places and later this map, reflecting the individual's specific knowledge of the space, is an ingredient in the choice for location and travel – Hannes et al., 2008). The activity space reflects not only the demand for activities, but also the supply of facilities supporting those activities. The extent of it depends on how far the individual can and has the willingness to travel in order to reach those locations given her/his budgetary and time restrictions, as well as institutional constraints.

Access to opportunities is a key measure to participation in activities (Church et al., 2000; Hine and Mitchell, 2003; Currie et al., 2009). If urban planning and infrastructure network development account for the individual diverse needs and offer places (functional and pleasant) with a suite of services closer to individuals' residences, it is possible that activity spaces reflect the conditions inherent to the underlying urban framework. Within this research we examine whether a difference in transit-oriented development (TOD) conditions may be associated with modifications of the individual/household activity spaces (i.e., less spatially dispersed). Careful planning of a TOD around a major transport corridor, with concerted efforts to promote mixed land use and multi-purpose activity centres at acceptable densities, whilst paying attention to achieve job-housing balance (so that travellers are able to fulfil a variety of activity needs at a single location, Cervero and Duncan, 2006), holds a promise for desired travel behaviour changes (Smart Growth Network, 2003; Cervero, 2005).

The aim of this research is twofold: a) to critically assess a variety of metrics for assessing household activity spaces within a TOD setting, and b) to explore changes in activity spaces across three TODs, pre and post-opening of the railway corridor connecting them to the city. The paper is divided into five sections, including this introduction. The remainder of the introduction presents the main concepts of TOD and activity space (AS). Section 2 reviews the past research that developed and applied activity spaces with various formulations and in different urban environments. It indicates the main benefits and limitations of the most widely used metrics. In Section 3 we present the geographical setting and provide a description of the models used in this paper. Section 4 discusses the results, comparing the vector of metrics across three railway precincts as well as before and after the opening of the railway line. The final section presents implications for policymaking and addresses some of the limitations of the analysis.

1.1 Built Environment (BE) and Transit Oriented Development

The complex relationships between BE and travel are due to their multidimensional nature. Although transport modellers have a good handle of the multiple dimensions of travel, numerous aspects of the built environment need to be addressed in relation to these dimensions. Consequently, a fundamental question arises. What aspects associated with the BE may be influencing a certain dimension of travel? Cross-sectional studies suggest that mixed land uses, improved street connectivity, and higher densities support non-motorised travel modes and shorter trip making. By contrast, the evidence is equivocal once other BE characteristics are included in the analysis at the local level (e.g. footpaths' conditions) (Khattak and Rodriguez, 2005: 484; Schwanen and Moktharian, 2005a and b). In addition, the neighbourhood shape and scale parameters, used to measure and/or describe the urban form may differ between planners and users. Numerous studies consider pre-defined spatial units (census districts, postal codes, traffic analysis zones) as operational substitutes for neighbourhoods, simply because data is readily available and easy to match to travel information. However, it is not clear how individuals perceive space and scale of their surroundings, nor how they filter spatial information when making spatial choice decisions (Golledge and Gärling, 2003; Krizek, 2003; Guo and Bhat, 2004; Bhat and Guo, 2007;).

1.1.1 TOD Characteristics

TOD has been flagged as a model that integrates LU and transport, promotes smart growth, injects vitality and expands lifestyle choices, whilst reducing urban sprawl (Newman and Kenworthy, 1999; Cervero et al, 2004; Dittmar and Ohland, 2004; Renne and Wells, 2004; Newman, 2005; Renne et al, 2005). Varying definitions of TOD exist. Many are given in *TCRP Report 102: Transit-Oriented Development in the United States: Experiences, Challenges, and Prospects* (Cervero et al., 2004).

TOD is associated with moderate to higher density development, located within an easy walk (approximately 800 m) of a major public transport stop (operating on highly synchronised and reliable timetables, 5-15 min servicing intervals and with extended operating hours), generally with a mix of residential, employment, and shopping opportunities, designed for pedestrians and cyclists, without excluding the automobile (TRB - TCRP Report 95, 2007; Centre for Transit Oriented Development, 2006). TOD can be delivered as "green-field" construction or redevelopment of existing built-up areas, with the design aim and orientation to facilitate transit use (California Department of Transportation, 2002: 3). TOD creates the conditions for a better coordination of services in space and a greater possibility for combining various activities/tasks.

If done well, TOD has a myriad of beneficial impacts such as on real estate market conditions, safety and visual amenity of the urban environment, overall physical activity levels of residents and air quality. But the task is not trivial and the integration of services is challenging in many cases. As the TRB - TCRP Report 95 (2007) states, "*It takes more than good transportation policy alone (land use and self-selection) to develop high-quality and effective TOD*" – p.17-6.

1.1.2 TOD and Travel Behaviour

TOD is meant to encourage a higher uptake of cycling and walking and the use of public transport services while diminishing the reliance on car driving. Reporting on a detailed analysis of 12 housing projects near BART stations in San Francisco, Cervero et al. (2004) established an average household size of 1.66 people per household (hh), with car ownership levels of 1.26 vehicles per hh within the TODs (70% of hh with < 2 vehicles), compared to 2.4 people and 1.64 vehicles for all households located in the census districts considered by the study, but not located within the TOD (48% of hh with < 2 vehicles). Given Cervero's findings, the Californian Department of Transportation (2002) concluded on TOD's potential in reducing households' parking needs (by 23%); however, the cause for this remains unclear. Further it is noted that Cervero factored out the statistical analysis of the causality (i.e. TODs impact on car ownership, or TODs attractiveness for "car-less" households). From the review of Cervero's other studies in relation to rail accessibility, the Californian Department of Transportation derived a preference in residential location choice linked to TODs offering good transit accessibility to employment opportunities. Khattak and Rodriguez (2005) established that single-family households in "neo-traditional" neighbourhoods substitute car trips with walking trips and reduce travel distances, compared to households in conventional neighbourhoods; this is the case even after controlling for demographic characteristics and for residential self-selection. In a review of many empirical studies, Kim et al. (2007) established that the association between transit availability/accessibility and car ownership was statistically significant, although minor in comparison to household characteristics.

Cervero (2001) reported on accessibility and mode choice, and identified the prevailing mode chosen for commuting by the access mode distance from the home location (walking - 1 km or less; bus transit – 1 to 1.6 km, park-and-ride - beyond 1.6 km). Similar results are found in TRB – TCRP (2007), where public transport mode shares decrease with the distance from the railway station (e.g., Washington and California BART).

Kim et al. (2007) stressed the importance of population density in operating successful public transport. Linked to population density, Perth's Public Transport Authority consider approx. 2,500 to 3,000 boardings per day as a trigger value for initiating the development of a new railway station; for a successful bus service the requirement is approx. 300 dwellings per network kilometre within walking range. This confirms the general understanding that density is often correlated to ridership. Cervero et al. (2004) reported that doubling of mean residential densities from 25 to 40 dwellings per hectare resulted in almost 4% increase in commuter mode share for a typical railway in the San Francisco Bay Area. Also analysing transit ridership for the MetroRail in Arlington County, Virginia, Cervero et al. identified a strong positive relationship between additional office/retail floor space near the station and a public transit passenger increase (approximately every additional 9,000 m^2 floor area resulted in a 50 person share increase in ridership).
Chen and McKnight (2007) reviewed the role of density as to explain activity-related time-use behaviour; on the one hand a proximity based theory was revealed, where due to "closeness" of various activity opportunities in high density areas a positive association

between activity-related time-use behaviour and density existed (Goulias, 2002; Levinson, 1999), on the other hand various studies found different relationships based on density levels. At very low densities (< 200 person/m^2) people spent significantly more time on travelling and less time on shopping; between 200 person/ m^2 to 8,000 person/ m^2 constant relationships were revealed; finally, at densities above 10,000 person/ m^2 people spent less time at home, on shopping and other activities, but more time at work and travelling. Chen and McKnight (2007) therefore concluded a possible U-shaped relationship between activity related time-use behaviour and density; however, this relationship requires further examination in terms of its validity in relation to TOD.

This brief presentation of TOD attributes and behavioural links indicates that TOD is likely to affect residential choice decisions as well as car ownership decisions, with further impact on activity-travel patterns. But this positive association of TOD with more environmentally friendly travel and reduced congestion, may be a result of self-selection (Guo and Bhat, 2004; Handy et al., 2005; Schwanen and Mokhtarian, 2005 a and b). Hence, for an accurate and complete assessment of potential travel related changes accountable to TOD, we need to control for household and individual demographics and attitudes (unobserved factors).

1.1.3 Spatial Cognition and Activity Spaces

The theory of activity spaces stems from biological research undertaken on habitat use, territoriality behaviour, and mammals' home range studies (Burt, 1943; Jennrich and Turner, 1969, Mazurkiewicz, 1969; Worton, 1989; Seaman and Powell, 1996; Simcharoen et al., 2008) and has been applied in other areas such as the analysis of crime incident locations (Levine, 2002) or accessibility to health care services (Guagliardo, 2004). Concepts such as the micro-geographical activity space were initially developed during the 1970s as one suitable method in a wider approach to describe *spatial perception, spatial awareness and spatial usage (activity)* of travellers (Horton and Reynolds, 1971). The concept is related to the space-time path and prism demarcating possible locations for conducting activities during a certain timeframe, given a time "budget" for travel and the speed of the transport services as well as an array of potential constraints (Burns, 1979, based on Hägerstrand, 1970). A significant improvement in the quality of services, resulting in greater potential to reach further destinations, may be either reflected in larger activity space-time prisms or in time savings that can be added to stationary activity times.

The activity spaces are geospatial, statistical measures. Following basic work that applied simple elliptical measures (Zahavi, 1979; Holzapfel, 1980; Beckmann et al., 1983a and b), initial steps to apply the activity spaces more frequently in transport research have only commenced recently. This "delay" is primarily due to the data-hungry requirements of activity spaces (longitudinal, geo-coded travel data, GIS-based, with time stamp for advanced representation, or at least sets of visited locations with frequency and duration of visit) and their "fuzzy" nature and measurement, with a lack of standard tools and software applications for easy calculation. A range of studies have been undertaken at the aggregate level (using cross-sectional travel or time-activity data) to investigate the spatial behaviour and activity spaces of particular socio-demographic population clusters. Empirical studies have been conducted either on revealed activity spaces (Botte, 2003, Axhausen et al., 2004a, b; Olaru et al., 2005; Buliung and Kanaroglu, 2006; Kamruzzaman et al., 2009) or focused on travel potentials or opportunities (Brown and Moore, 1970; Horton and Reynolds, 1971; Burns, 1979; Casas, 2007) based on influential work by Hägerstrand's (1970) space-time geography, linking spatial mobility to temporal aspects as well as individual and collective constraints.

Activity spaces can be used to analyse the spatial arrangement of travel (realised – *activity space* or potential – *action space* – Horton and Reynolds, 1971) in context with the underpinning household and individual travel choices (see Golledge and Gärling, 2003 for a background summary on the emergence of the concept of activity spaces, knowledge space, mental/cognitive maps, etc.).
Dijst (1999) analysed individual activity spaces in a case study of two Dutch communities. Axhausen and colleagues reported on activity spaces from Mobidrive and Borlänge, evaluating and visualising variation of activity spaces for individual travellers and testing suitability of activity spaces for identifying social exclusion (Schönfelder und Axhausen, 2002, 2003a and b). Transferring those measurement approaches for human activity spaces, Axhausen et al. (2004a and b) applied the underlying methods to the analysis of commuter movements in Switzerland over three decades. Olaru et al. (2005) investigated activity spaces in Sydney, by day of week and type of household, in a structural equation modelling framework. Buliung and Kanaroglou (2006) applied activity space measures and space–time trajectories for Portland. Chapleau and Morency (2007) reported on commuter travel behaviour at individual level for 40,000 households in Toronto. Casas (2007) examined jointly activity spaces and potential access (cumulative opportunities) for activity participation in Western New York. Recently, Kamruzzaman et al. (2009) used activity spaces to assess the participation in activities by students in Northern Ireland.

In summary, activity spaces are dynamic measures, based on the individual/household travel (to this effect they can be considered "people-based" accessibility measures as described by Miller, 2005) that have been frequently used to identify differences between socio-demographic groups (Schönfelder and Axhausen, 2003a and b; Olaru et al., 2005; Casas, 2007) and in this research we aim to perform the same type of analysis; however, we now assess various metrics for their suitability to explore the association between TOD, socio-demographics and activity spaces, ultimately with the aim to derive an easily comprehensible indicator (degree of "TODness") as a tool to assist practitioners in the comparison and analysis of TOD effectiveness.

2 CONCEPTS AND MODELLING APPROACH

2.1 Parametric and Non-Parametric Formulations for Activity Spaces

The activity space encompasses the location of daily activities that ensure the activity-travel needs and desires are achieved within an acceptable time and cost constraint. *It reflects spatial processes that cannot be captured in classical demand models, and takes account of* *time limitations (generalised costs)* and it can be built at the individual or household level. Its geometry, size, and inherent structure is believed to be strongly conditioned by the determinants of the household basic places (home and work or other frequently visited activity centres are usually the pegs for scheduling daily activities), and further, by the accessibility provided by the transport network and the time constraints (institutional or personal) (Golledge and Stimson, 1997). It endeavours to symbolise observed or realised time-travel patterns using one easily comprehensible geometric indicator (observed or realised distribution of places visited within a certain space and frequented over a period of time within a given time and cost "budget").

A variety of methods has been established, usually defined in a two-dimensional form, in particular standard distance, confidence ellipse, polygon, kernel density (Silverman, 1986; Worton, 1989; Fotheringham et al., 2000; Buliung and Kanaroglu, 2006; Fan and Khattak, 2009), minimum spanning tree, buffer (Schönfelder and Axhausen 2002, 2003a and b; Chapleau and Morency, 2007), but also three-dimensional (e.g. space-time prism – Burns, 1979, Lenntorp, 1976; fishtank/aquarium – Kwan, 2000). Different formulations have aimed to accentuate the various dimensions of travel related choice decisions or potentials to reach opportunities, whilst providing the connection to spatial information (distribution/ concentration/ spread) and temporal dimensions (e.g. time spent on both activity and travel) (Chapleau et al., 2008). More recently, Rai et al. (2007) compared new geometries such as superellipses, Cassini ovals and bean curves with confidence ellipses, providing insights and recommendations on appropriateness of various shapes for certain conditions.

Previous research has identified limitations of some measures which are not "detailed" enough to accurately represent activity spaces and suggested that there is no single measure for activity spaces, but rather a set/vector of measures highlighting various aspects of the activity space (Schönfelder and Axhausen 2002, 2003a and b, 2004; Buliung and Kanaroglu, 2006; Rai et al., 2007). For example, standard distances, that impose symmetry around the home, tend to exacerbate the effect of spatial outliers and do not account for weighting of activity locations; confidence ellipses are less sensitive to outliers, as confidence intervals can be specified and weighting of activity locations is possible, but they are likely to overestimate the size of activity spaces; polygons represent the maximum geographical extent of the activity space, considering all locations as equally important, and they cannot be estimated for commuter ('pendulum') home-work travel activity patterns; buffers and spanning trees assume that narrow bands of space around a road or track network are known to the user (which may not be true in reflecting the real cognitive extent of space or the individual behaviour), they are data intensive and do not incorporate importance of locations in their definition. In the same line of thought, some measures such as space-time prisms are difficult to analyse quantitatively and with the intent of identifying temporal dynamics in accessibility.

In the following we will be discussing only kernel density (non-parametric), confidence ellipse, superellipse, Cassini oval and bean curve (parametric) formulations for representing activity spaces.

2.1.1 Kernel Density

The kernel density bivariate estimator describes the activity spaces by calculating densities based on the locations visited by individuals and assumes no barriers in reaching those locations in any direction and within a predetermined bandwidth. The output densities are obtained by initially "placing" kernel density distributions (kernels) over the spatially distributed data points and in a second step overlapping those kernels to derive a more continuous density surface and to reflect clustering as well as the higher probability for visiting or knowledge of certain locations. This information is then reflected in a raster data set. Each cell in the raster data set is assigned a value calculated according to the distance from the starting feature (activity location) and the proximity to the other features in the data set. Kernels can also incorporate other variables associated with travel behaviour, such as the frequency or duration of activity in a particular location. Output areas can be considered at 100% (all inclusive non-zero activity density area) or any other specified level (e.g. 95% interval, as such allowing the analyst to discard parts of the activity space that may consist of infrequent, non-typical activities in the life of the individuals, determined by some special conditions or events) or even density band. Further, the bandwidths (search radius) and kernel function can be specified by the analyst.

As highlighted in previous work, the results are sensitive to the choice of the bandwidth for the kernel function and derivation of an appropriate value, context-selected based on the specificity of the problem to be analysed, is recommended (Gibin et al, 2007). O'Sullivan and Unwin (2003) explored bandwidths between 100 m and 1,000 m, consistent with the average distances between locations. In our application we used a bandwidth of 3 km, based on the average distance of trips within precincts and within the accepted maximum walking and average cycling distance to the railway station (therefore using a context based approach). It has to be noted that the TOD precincts analysed are still atypical when compared to European or many American counterparts: our local TOD precincts are still to achieve the higher densities observed overseas.

2.1.2 Confidence Ellipse

Similar to the activity space based on kernel density estimation, the bivariate confidence ellipse (CE) can be seen as an indicator of the activity space area in which the household conducts its daily activities with a certain probability (e.g. 95%). The size and the orientation of the confidence ellipse can be easily determined incorporating the importance of activities (the reader can find the mathematical definition of CE presented in Schönfelder and Axhausen 2002; Olaru et al., 2005; Rai et al., 2007). The CE can be established by mode of transport or by purpose and the longitudinal studies (or at least week diaries rather than one day diary) are more appropriate for CE estimation. In general CE are better suited for activity spaces with one or two clusters of locations visited during the analysis timeframe (Rai et al., 2007).

2.1.3 Super-Ellipse

The super-ellipse is a "generalisation" of the CE (when r=2), which can also address a situation with four clusters of activities by including a diamond-like form of the activity space. The parametric equations are provided in Rai et al. (2007):74.

2.1.4 Cassini Oval

While an ellipse is the locus of points so that the sum of its distances to two fixed points (foci) is constant, the Cassini oval is the locus of points based on a constant product of its distances to two fixed points. The shape of the curve depends on the ratio between b (square root of the constant) and a (distance between the two fixed points). When the two values b and a are equal, the oval becomes a lemniscate (see Rai et al., 2007:75 for the parametric form of the curve).
This curve is able to capture two clusters of activities, but unlike a confidence ellipse does not impose that the area between clusters is known and frequently used by the individual or household. Thus the area of a Cassini oval is smaller, as it does not include the intermediate area between clusters of locations.

2.1.5 Bean Curve

The bean curve can accommodate three clusters of activities; it is in fact a rounded triangle and its parametric form is given in Rai et al. (2007):75.

3 DATA AND METHODOLOGY

3.1 Data collection

Data was collected in Perth, Western Australia in three waves, as follows: Wave 1 – November-December 2006, before the opening of the new railway corridor; Wave 2 – July-August 2008, after the opening of the corridor; Wave 3 – July-August 2009, settle-in behaviour (not yet available for analysis).
Our surveys have had the objective to assess the behavioural responses to emerging TOD precincts and the instruments varied between waves according to the research questions. In the following we will focus on the trip diaries (2006 and 2008), as they provided the data required for this analysis. For detailed information on the data collection the reader is recommended Curtis and Olaru (2007, 2010).
Twenty-four hour trip diaries were completed by every household member travelling independently (memory joggers were provided before the travel day in order to aid the completion of the trip diaries). Trip diaries included all their travel on a specified Wednesday (origin, destination, departure and arrival time, purpose/activity, mode of travel, route, party size, out-of-pocket cost, parking, transfers). The activities were aggregated into five main categories: work or education, shopping (for grocery and for other), recreational activities

(spectating or participating in a cultural event, spectating a sporting event, eating out, physical activities, visiting friends or receiving visitors), pick-up/drop-off, personal business.

The trip diaries were geo-coded manually after the data was checked for accuracy and consistency. As the activity spaces need to rely on very detailed and accurate data of the activities locations and times, incomplete data, where the specific address could not be exactly established, was not considered in the analysis.
The analysis was performed at the household level and excluded cases where the household members worked from home or did not travel during the allocated day for various reasons (e.g. illness).

3.3 Geographical setting

The railway corridor was built through both established areas and green fields, offering various opportunities to implement transit-oriented development features at some of the railway stations. We selected for research three precinct stations, which represent different TOD environments (Table 1) to assess potential differences in activity spaces. More details on the precincts can be found in Curtis and Olaru (2007, 2010).

Table I – Profile of the three precincts

Bull Creek	Cockburn Central	Wellard
o 12 km from CBD, highest population density and accessibility. o Well-defined public transport network in area. o In established urban area, primarily a generation point and interchange, with no mix of land use. Comparing the precincts, residents have highest education and income. Highest real estate values.	o 21km from CBD, lowest population density. o Considerable transit interchange and park-and-ride facilities. o Introduces mix of TOD features (multifunctional Town Centre, residential, commercial, cultural use). o Residents have largest families, highest employment rate, and the largest % of Australian born residents.	o 39km from CBD, highest % of car trips, lowest % of walking and cycling. o Introduces the most TOD design features (mixed use Main street combined with residential), but not yet fully implemented. o Residents have lowest employment rate, income, car ownership. Lowest real estate values (REIWA, 2006-2008).

3.4 Methodology

This research evaluates the association between different TOD opportunities and household travel behaviour via activity spaces. It applies activity spaces at the household and precinct level to investigate whether and to what extent TODs reduce the activity spaces. We hypothesize that by providing manifold (non-work) opportunities in the near vicinity of the TOD precinct, the need to travel further is reduced and the activity spaces may shrink. As changes are not uniform for all residents in the TOD precincts, the modifications are assessed in relation to the daily routine needs for various categories of population with different socio-economic characteristics. An innovation of the approach is its use at the household level and not only individual level; when household is the core of attention, the measure is then incorporating the space-time negotiation that occurs within families and therefore is a more reliable measure to illustrate decisions on activities and travel (location, destination, mode and route choice, trip chaining). To the best of our knowledge the activity space concept has not been applied to analyse potential BE-induced changes in travel behaviour.

The before and after railway opening data enable an improved analysis of BE changes in relation to behavioural modifications induced by TOD (dynamic aspects of travel) and future research of self-selection. This approach provides more "*statistical leverage in sorting out causal patterns because they enable the analyst to separate effects of persistent interpersonal differences from real inter-temporal relationships*" (Duncan et al., 1987 cited by Kitamura et al., 2003: 192). Therefore it has powerful implications for urban land-use policies aspiring to boost density or land-use mix and lower levels of car use.
Our current comparison is made using MANCOVA analysis to model the differences between activity spaces of households in the three precincts and between waves 1 and 2, accounting for several socio-demographics.

Trip diaries data for all residents who travelled during the allocated day were geocoded for analysis. We excluded from our analysis extra-urban long-distance trips (air-travel work trips).

We used the Palisade Decision Tools - Evolver and Microsoft Excel to calculate (minimise) the parametric curves. The optimisation for the four geometries of activity spaces was performed using genetic algorithms. This is different from Rai et al. (2007) who used a simplex algorithm modifying the orientation of the curves at steps of 22.5^{o}. The genetic algorithms have the benefit of a quick and efficient computation, without the need of a step variation of the orientation (this has become part of the decision variables for optimisation). In addition, other variables can also be easily introduced into the analysis.

In order to calculate the fixed kernel density areas[1] we used ArcGIS Spatial Analyst with a looping routine, written in Python, to determine the areas of the kernel. The selection of the bandwidth allowed for inclusion of all intra-urban trips and to those locations outside of the TOD precinct.

In this research, we considered for all parametric indicators and for kernel density 95% coverage of the activity locations (examples provided in Appendix A6 – Figures A1 and A5). The measures were determined at both household level and precinct level.

[1] Although there is no standard software for calculating activity spaces, Buliung and Remmel (2008) recently developed *aspace* – an open source library in R program to visualise and measure several spatial properties, Beyer (2002) provided in the SpatialEcology website his Hawth's Analysis Toolkit for ArcGIS, now developing into a Geospatial Modelling Environment. Levine and Associates offer CrimStat III for kernel density estimation.

4 EMPIRICAL RESULTS

Below we present the results our analysis of activity spaces for all three precincts before and after the opening of the railway at two levels: precinct and household (Tables 2 and 3). The samples are representative for the three precincts (comparison was done with Census 2006 data from Australian Bureau of Statistics, 2006).

Table 2 shows the results of optimised activity spaces including 95% of the locations for households in the three precincts. The smallest activity spaces are derived from kernel densities (Figures A2-A4), followed by super-ellipse and bean curves. The parameters of the ellipses, Cassini oval, and bean curves vary across optimisations. Comparing the parametric formulations, consistent with previous research, our results indicate that the confidence ellipses overestimate the activity spaces and that more research should examine alternative shapes, which provide greater flexibility. We found that the bean curve and the super-ellipse were better suited for estimation at the precinct level with ‘richer’ data (more frequent locations). Cassini oval measures have higher values than the confidence ellipses, but this is can be explained by the fact that the Cassini oval is best tailored for activity spaces with two clear clusters of activities. In our research, we identified small multiple clusters of activities for each precinct, outside the precinct or the city.

When analysing the activity spaces across precincts, we found an increase in the size of activity spaces with the distance from the city. The findings are similar for both waves, the smallest activity space corresponds to Bull Creek and the largest to Wellard.

Table 2 – Activity space metrics for the three precincts (precinct level)

Measures	Bull Creek		Cockburn Central		Wellard	
	Before	After	Before	After	Before	After
Confidence ellipse, CE (km^2)	1,060.38	981.54	1,472.95	1,802.69	2,416.67	2,268.24
Super-ellipse (km^2)	521.04	549.14	837.66	1,019.91	1,379.35	1,653.12
Cassini oval (km^2)	1,669.86	1,421.74	2,670.02	3,058.61	2,726.48	4,485.02
Bean curve (km^2)	1,222.47	637.51	1,183.24	1,281.47	1,560.36	1,341.96
Kernel density (km^2) - bandwidth 10 km	465.60	425.72	559.61	538.86	731.21	747.64

When comparing the activity spaces between waves, we noticed a slight reduction in the activity space for Bull Creek precinct, but not so for Cockburn Central and Wellard. The analysis of the destinations revealed that households in Cockburn and Wellard seem to enjoy their greater access to the city and the opportunities provided within the corridor and they shop more often in the CBD and at Gateways (Cockburn Central).

Table 3 presents the optimal activity space areas at the household level. The large variability indicates the dependency of the areas on the shape and spatial distribution, indicating there is no single best approach to define all activity spaces.

Similar to the results at the precinct level, kernel densities show the smallest areas and Cassini ovals the largest. This suggests that Cassini oval should be applied only for activity spaces with two clusters of activities, in order to avoid overestimation of the activity space. Considering the importance of home and other pegs in the daily activities, in this research we derived curves centred in the centre of gravity (weighted) of the activity space. Clearly, the optimised areas may vary if we relax this constraint. It is also important to note that our curve areas are minimised to include a min 95% of the activities, but the excluded locations may differ across formulations (i.e., the number and locations excluded when minimising the confidence ellipse may be different from the excluded locations when minimising the hyperellipse).

Table 3 – Household activity space metrics for the three precincts (averages and standard deviations)

Measures	**Bull Creek**		**Cockburn Central**		**Wellard**	
	Before opening	**After opening**	**Before opening**	**After opening**	**Before opening**	**After opening**
Confidence ellipse, CE (km^2)	149.42 (105.68)	136.95 (191.91)	256.06 (271.09)	186.85 (209.82)	178.84 (182.95)	211.63 (254.49)
Confidence ellipse – GA optimised (km^2)	246.83 (316.67)	192.99 (146.13)	292.11 (200.09)	263.70 (186.04)	338.05 (440.88)	365.42 (396.85)
Hyper-ellipse (km^2)	302.24 (315.48)	293.82 (316.16)	308.47 (316.70)	279.61 (198.94)	458.43 (490.10)	458.66 (536.51)
Cassini oval (km^2)	298.68 (184.41)	278.78 (210.22)	428.94 (314.49)	355.87 (271.50)	579.80 (449.00)	537.83 (751.73)
Bean curve (km^2)	240.12 (191.56)	164.31 (159.54)	328.25 (256.89)	259.22 (180.92)	232.33 (246.34)	341.58 (389.51)
Kernel density (km^2) - bandwidth 3 km	43.70 (16.08)	44.04 (15.56)	41.03 (13.47)	38.58 (14.27)	39.27 (15.25)	44.64 (15.91)
Kernel density (km^2) - bandwidth 6 km	138.80 (49.24)	128.42 (49.37)	114.27 (47.71)	131.81 (45.65)	138.78 (51.49)	155.26 (54.38)

There are statistically significant correlations (<0.001) among four geometries (above 0.82), but not with the kernel density estimates. This is an artefact of the derivation of kernel density, which regards only the spatial distribution of activities without including the routes. Depending on the bandwidth, the kernels may not always form continuous shapes due to the underlying spatial distribution and frequency/duration of activities at the visited locations. The geometries (albeit indirectly and partially) incorporate the area between the spatially distributed activity locations.

The analysis of the univariate distributions of activity spaces has shown that all geometries display a greater variability compared to the kernel densities, and have higher skewness.

To compare the size of the activity spaces in time and space we used MANCOVA analysis with two factors and five household covariates. The results provide evidence that the vectors of activity space metrics do vary across precincts and between 2006 and 2008 (multivariate tests significant at 0.028), whilst accounting for the covariates (household size, number of children and of vehicles, household income, and the level of “busyness” (number of paid and unpaid working/studying hours)[2]. More detailed tests indicate that differences are more prominent among precincts, but only marginally between wave 1 and wave 2 (0.076). The number of residents is the most significant covariate (<0.001) and kernel density the most significant activity space metric in discriminating between precincts and waves.

The activity spaces increase with the distance from the city, with the households residing in Bull Creek displaying the smaller activity spaces. The largest activity spaces are recorded for the residents of Wellard. After the opening of the railway corridor, the activity spaces may have decreased in Bull Creek, but they increased in Wellard. Therefore, the hypothesised shrinkage in the household activity spaces as result of TOD developments is not currently confirmed. Still to be found are separate contributions (if any) of the presence of the railway and of the socio-demographic fabric and self-selection to this change. In addition, the activity spaces include both work and non-work activities. As TOD benefits are expected to be prevalent at a local level, further research would require removing work and study from the activity spaces, and assessing the modifications.

With respect to socio-demographics, the activity spaces also seem to increase with the number of vehicles, level of busyness (number of weekly working hours – paid and unpaid), as well as income.

5 DISCUSSION, CONCLUSIONS, AND IMPLICATIONS

Activity spaces are rich tools for capturing individual and environmental differences. We explored a vector of geometries for households and precincts and found that various metrics are correlated to each other and that each has its own benefits as a result of the inherent conceptualisation and derivation. We noticed that the frequency of locations and their distribution affect the metrics and we suggest that kernel densities and bean curves may be further used, in particular for their flexibility and visualisation capabilities.

Kernel densities have the smallest area values, and Cassini ovals the largest. The statistical analysis of various shapes shows that the four parametric measures are highly correlated with each other, but the bean and super-ellipse curves are likely to represent more accurately the area of activities. The kernel density areas were not correlated to the other geometries. We need to emphasize that the optimisation of the four geometries was done separately for each curve and that we constrained the centre of the shape to the centre of gravity of the household activities (this restriction can be easily relaxed if justified).

Additional analysis was carried out to assess the impact of activity durations on the size of the activity spaces (modifying the centre of gravity). We found no significant changes compared to the findings based on frequency of activities. Similar to Kamruzzaman et al. (2009), we have used activity duration as indicator for the kernel density activity space, but

[2] For details on the questionnaire and the socio-demographic profiles of the precincts, please refer to Curtis and Olaru, 2007 and 2010.

again, under our current analysis settings the duration has not altered significantly the kernel density areas.

Nonetheless, it is relevant to indicate that when kernel density estimators were applied considering information on the routes, their area values became closer to the other geometries and particularly to the bean curve[3]. The lack of information on the routes is considered a limitation of the approach and we are currently working on including this data, with the intention to test the contribution of the routes on the activity spaces.

Although premature to draw conclusions that TOD changes behaviour and modifies activity spaces, our findings suggest associations between TOD features and trip making and destination choices, as reflected in the activity spaces. The activity spaces are smaller in precincts with higher access (Bull Creek) and this pattern is maintained after the opening of the railway corridor. However, not all precincts experience reductions in the activity spaces after the railway opening. The increased time accessibility brought about by the railway corridor facilitates residents from Wellard to expand their range of activities towards the city. For residents of Bull Creek and Cockburn Central, the railway opening coincided with new opportunities of walking and cycling (Bull Creek) or presented by mixed land use around the railway precinct (Cockburn Central).

As demonstrated in previous research, the relationship between BE and travel behaviour may be overestimated if we neglect to account for residential sorting and neighbourhood preferences. Our modelling has shown positive associations between the number of household members, children, as well as the number of working and studying hours with the activity spaces. This is expected, as the number and variety of daily commitments create the demand for activities in various locations, which is likely to expand activity spaces.
This is essential information for our planners, and the results are encouraging for further exploring activity space changes following changes in BE. In our future research, incorporating the 2009 trip diaries (once verified and geocoded) in the analysis, we may be able to further validate these preliminary results.

Despite promising results, more advanced research is now required to model simultaneously built environment characteristics, socio-demographics, and attitudes with travel behaviour in a longitudinal approach. This would assist urban planners and transport practitioners to ascertain the separate contribution of built environment features and transport services to achieving successful TODs.

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[3] A test has considered a small number of households with trip diaries including geocoding of the routes.

Redevelopment Authority, City of Cockburn, Midland Redevelopment Authority, Town of Kwinana, City of Rockingham.

REFERENCES

Australian Bureau of Statistics (2006). Census 2006 CDATA, Canberra, http://www.abs.gov.au.

Axhausen, K.W., Botte, M. and Schönfelder, S. (2004a). Systematic Measurement of Catchment Areas. CTPP 2000 Status Report, U.S. Department of Transportation in cooperation with the TRB Census Subcommittee, available at http://www.fhwa.dot.gov/ctpp/sr0804.pdf, accessed February 2010.

Axhausen, K.W., Botte, M. and Schönfelder, S. (2004b). Measuring the spatial reach of persons, cities or organisations. STELLA Group 3 meeting, Arlington, available at http://www.ivt.ethz.ch/vpl/publications/presentations/v82.pdf, accessed February 2010.

Beckmann, M.J., T.F. Golob and Y. Zahavi (1983a). Travel probability fields and urban spatial structure: 1. Theory. Environment and Planning A, 15 (5), 593-606.

Beckmann, M.J., T.F. Golob and Y. Zahavi (1983b). Travel probability fields and urban spatial structure: 2. Empirical tests. Environment and Planning A, 15 (6), 727-738.

Beyer, H.L. (2002). Hawth's Analysis Tools, available at http://www.spatialecology.com, accessed February 2010.

Bhat, C.R. and Guo, J.Y. (2007). A comprehensive analysis of built environment characteristics on household residential choice and auto ownership levels, Transportation Research Part B: Methodological, 41 (5), 506–526.

Botte, M. (2003). Strukturen des Pendelns in der Schweiz 1970 – 2000 (Commuting in Switzerland 1970- 2000), MSc Thesis, Institute for Transport Planning and Systems (IVT), Swiss Federal Institute of Technology (ETHZ), Zurich, Switzerland, available at at http://www.ivt.ethz.ch/docs/students/dip36.pdf, accessed February 2010.

Brown, L.A. and E.G. Moore (1970). The intra-urban migration process: a perspective. GeografiskaAnnaler, 52(B), 1-13.

Buliung, R.N. and Kanaroglou, P.S. (2006). A GIS toolkit for exploring geographies of household activity/travel behavior. Journal of Transport Geography, 14 (1), 35–51.

Burns, L.D. (1979). Transportation, temporal and spatial components of accessibility. Lexington, MA: Lexington Books.

Burt, W.H. (1943). Territoriality and home range concepts as applied to mammals. Journal of Mammology, 24, 346–252.

California Department of Transportation (2002). Parking and TOD: Challenges and Opportunities, Statewide Transit-Oriented Development (TOD) Study - Factors for Success in California. Special Report, 2002, available at http://transitorienteddevelopment.dot.ca.gov/PDFs/Parking%20and%20TOD%20Report.pdf, accessed February 2010.

Casas, I. (2007). Social exclusion and the disabled: an accessibility approach. The Professional Geographer 59 (4), 463-477.

Center for Transit Oriented Development (2006). Preserving and Promoting Diverse Transit-Oriented Neighborhoods. A collaboration of the Center for Neighborhood Technology, Reconnecting America, and Strategic Economics, 2006, available at http://www.cnt.org/repository/diverseTOD_FullReport.pdf, accessed February 2010.

Cervero, R. (2005). Transit-Oriented Development in America: Strategies, Issues, Policy Directions. Paper presented at the Transit Oriented Development-Making it Happen Conference, Fremantle, Australia.

Cervero, R. and Duncan, M. (2006). Which reduces vehicle travel more: jobs-housing balance or retail-housing mixing. Journal of the American Planning Association, 72 (4), 475–490.

Cervero, R., Murphy, S., Ferrel, C., Goguts, N., Tsai, Y., Arrington, G.B., Boroski, J., Smith-Heimer, J., Golem, R., Peninger, P., Nakajima, E., Chui, E., Dunphy, R., Myers, M., McKay, S. and Witenstein, N., (2004). Transit-Oriented Development in the United States: Experiences, Challenges, and Prospects. TCRP Report 102, Transportation Research Board, National Academy Press, Washington, USA.

Chapleau , R. and Morency, C. (2007). Pseudo Panel Study Derived from Three Consecutive 5-Year Interval Household Travel Surveys. in the Proceedings of the 11th World Conference on Transportation Research WCTR, Berkeley, USA, June 24–28.

Chen, C. and McKnight, C.E. (2007). Does the built environment make a difference? Additional evidence from the daily activity and travel behavior of homemakers living in New York City and suburbs. Journal of Transport Geography, 15 (5), 380–395.

Church, A., Frost, M., Sullivan, K. (2000). Transport and social exclusion in London. Transport Policy, 7 (3), 195–205.

Currie, G., Richardson, T., Smyth, P., Vella-Brodick, D., Hine, J., Lucas, K., Stanley, J., Morris, J., and Kinnear, R. (2009). Investigating links between transport disadvantage, social exclusion and well-being in Melbourne – preliminary results. Transport Policy, 16 (3), 97–105.

Curtis, C. and Olaru, D. (2007) Travel 'minimisation' and the neighbourhood, in the Proceedings of the European Transport Conference, Noordwijkerhout, The Netherlands, October 17-19.

Curtis, C. and Olaru, D. (2010) The Impacts of a New Railway Corridor: Travel Behaviour Change of Residents in New Station Precincts, paper reviewed for the 12th World Conference in Transportation Research, Lisbon, Portugal, July 11-15.

Dijst, M. (1999). Two-earner families and their action spaces: a case study of two Dutch communities. GeoJournal, 48 (3), 195–206.

Dittmar, H. and Ohland, G. (2004). The new transit town: best practices in transit-oriented development. Island Press, Washington DC.

Duncan, G.J., Juster, F.T. and Morgan, J.N. (1987). The role of panel studies in research on economic behaviour. Transportation Research Part A: Policy and Practice, 21 (4–5), 249–263.

Fan, Y. and Khattak, A.J. (2009). Urban form, individual spatial footprints, and travel: An examination of space-use behaviour. Travel Behaviour Analysis TRB 2082, ISSN: 0361-1981, 98–106.

Fotheringham, A. S., Brunsdon, C. and Charlton, M. (2000). Quantitative Geography: Perspectives on Spatial Data Analysis. Sage Publications, London.

Gibin, M., Longley, P., and Atkinson, P. (2007). Kernel Density Estimation and Percent Volume Contours in General Practice Catchment Area Analysis in Urban Areas. in the Proceedings of GISRUK 2007, Nui Maynooth, Ireland, April 11-13.

Golledge, R.G. and Gärling, T. (2003). Cognitive maps and urban travel. Research Paper, 601, Transportation Center, University of California.

Gollege, R.G. and Stimson, R.J. (1997). Spatial Behaviour: A Geographic Perspective, Guilford Press, New York.

Greenwald, M.J. (2006). The relationship between land use and intrazonal trip making behaviors: Evidence and implications. Transportation Research Part D: Transport and Environment, 11 (6), 432–446.

Goulias, K.G. (2002). Multilevel analysis of daily time use and time allocation to activity types accounting for complex covariance structures using correlated random effects. Transportation 29 (1), 31–48.

Guagliardo, M.F. (2004). Spatial accessibility of primary care: concepts, methods, and challenges. International Journal of Health Geographics, 26 (3), 1–13.

Guo, J.Y. and Bhat, C.R. (2004). Modifiable areal units: problem or perception in modeling of residential location choice?. Transportation Research Record, 1898, 138–147.

Hägerstrand, T. (1970). What about people in regional science?. Papers of the Regional Science Association, 24 (1), 7–21.

Handy, S., Cao, X. and Mokhtarian, P.L. (2006). Self-Selection in the Relationship between the Built Environment and Walking. Journal of the American Planning Association, 72 (1), 55–74.

Handy, S.L, Cao, X., and Mokhtarian, P.L. (2005). Correlation or causality between the built environment and travel behavior? Evidence from Northern California. Transportation Research Part D: Transport and Environment, 10 (6), 427–444.

Hannes, E., Jenssens, D., and Wets, G. (2008). Destination Choice in Daily Activity Travel.Mental Map's Repertoire. Transportation Research Record TRR 2054, 20-27.

Hine, J. and Mitchell, F. (2003). Transport disadvantage and social exclusion: exclusionary mechanisms in transport in urban Scotland. Ashgate, Hampshire.

Holzapfel, H. (1980). Verkehrsbeziehungen in Städten. Schriftenreihe des Instituts für Verkehrsplanung und Verkehrswegebau, 5, University of Technology, Berlin.

Horton, F. and D.R. Reynolds (1971).Effects of Urban Spatial Structure on Individual Behaviour.Economic Geography, 47, 36-48.

Jennrich, R.I. und F.B. Turner (1969). Measurement of non-circular home range. Journal of Theoretical Biology, 22, 227–237.

Kamruzzaman, Md, Hine, J., Gunay, B., and Blair, N. (2009). Using GIS to visualise and evaluate student travel behaviour. Journal of Transport Geography, in press, doi:10.1016/j.trangeo.2009.09.004.

Khattak, A.J. and Rodriguez, D. (2005). Travel behaviour in neo-traditional neighborhood developments: A case study in USA. Transportation Research Part A: Policy and Practice, 39 (6), 481–500.

Kim, S., Ulfarsson, G.F. and Hennessy, J.T. (2007). Analysis of light rail rider travel behavior: Impacts of individual, built environment and crime characteristics on transit access. Transportation Research Part A: Policy and Practice, 41 (6), 511–522.

Kitamura, R., Yamamoto, T., and Fujii, S. (2003).The effectiveness of panels in detecting changes in discrete travel behaviour. Transportation Research Part B: Methodological, 37 (2), 191–206.

Krizek, K. (2003). Residential relocation and changes in urban travel. Does Neighborhood-Scale Urban Form Matter?. Journal of The American Planning Association, 69 (3) 265–281.

Kwan, M.-P. (2000). Interactive geovizualization of activity-travel patterns using three-dimensional geographical information systems: a methodological exploration with a large data set. Transportation Research C 8, 185-203.

Lenntorp, B. (1976). Paths in space-time environments: A time geographic study of movement, possibilities of individuals. In Lund Studies in Geography, 44, Lund, Sweden.

Levine, N. (2002). CrimeStat (Version 2.0): A spatial statistics program for the analysis of crime incident locations. Ned Levine & Associates, Houston, TX, and the National Institute of Justice, Washington, DC.

Levinson, D. (1999). Space, money, life-stage, and the allocation of time. Transportation, 26 (2) 141–171.

Mazurkiewicz, M. (1969) Elliptical modification of home range pattern. Bulletin of the Academy of Policy and Science, 1 (2), 427–431.

Meurs, H. and Haaijer, R. (2001). Spatial structure and mobility. Transportation Research Part D: Transport and Environment, 6 (6) 429–446.

Miller, H.J. (2005). Placed-base versus people-based accessibility. in Levinson, D. and Krizek, K.J. (eds.) Access to Destinations, London, Elsevier, 63-89, ISBN 0080446787.

Newman, P. (2005). Transit Oriented Development: An Australian Overview. Presentation Paper, Transit Oriented Development-Making it Happen Conference, Fremantle, Australia, July 2005.

Newman, P. and Kenworthy, J. (1999). Sustainability and Cities: Overcoming Automobile Dependence, Island Press, Washington, DC.

Newman, P. and Kenworthy, J. (2006). Urban design to reduce automobile dependence. Opolis 2 (1), 35-52, available at www.escholarship.org/uc/item/2b76f089, accessed February 2010.

O'Sullivan, D. and Unwin, D.J. (2003) Geographic information analysis. John Wiley and Sons. New Jersey.

Olaru, D., Smith, N., and Peachman, J. (2005). Whereabouts from Monday to Sunday?. In the Proceedings of the Australasian Transport Research Forum 2005 – Transporting the Future: Transport in a Changing Environment, Sydney, Australia, September 28-30, ISBN 1 877040 428, available at http://www.patrec.org/web_docs/atrf/papers/2005/Olaru,%20Smith%20N%20&%20Peachman%20(2005).pdf, accessed February 2010.

Ortúzar, J. de D. and Willumsen, L.G. (2001). Modelling Transport (2nd ed.), John Wiley and Sons, Chichester.

Rai, R.K., Balmer, M., Rieser, M., Vaze, V.S., Schönfelder, S., and Axhausen, K.W. (2007). Capturing Human Activity Spaces. New Geometries, Transportation Research Record TRR 2021, 70-80.

Real Estate Institute WA REIWA (2006-2008) Long Term Growth Rates, available at http://www.reiwa.com.au/research, accessed February 2010.

Renne, J.L. and Wells, J.S. (2004). Emerging European style planning in the USA: transit-oriented development. World Transport Policy & Practice, 10 (2), 12–24.

Renne, J.L., Wells, J.S. and Voorhees, A.M. (2005). Transit-Oriented Development: Developing a Strategy to Measure Success. Research Results Digest, 294, National Cooperative Highway Research Program (NCHRP), Transportation Research Board, National Academy Press, Washington, DC.

Rodriguez, D.A. and Joo, J. (2004). The relationship between non-motorized mode choice and the local physical environment. Transportation Research Part D: Transport and Environment, 9 (2), 151–173.

Rushton, G. (1971). Behavior correlates of urban spatial structure. Economic Geography, 47 (1), 49–58.

Schönfelder, S. and Axhausen,K.W. (2002). Measuring the size and structure of human activity spaces: The longitudinal perspective. Working Paper 135, Institute for Transport Planning and Systems (IVT), Swiss Federal Institute of Technology (ETHZ), Zurich, Switzerland.

Schönfelder S. and Axhausen, K. W. (2003a). Activity spaces: Measures of social exclusion?.Transportation Policy, 10 (4), 273-286.

Schönfelder, S. and Axhausen,K.W. (2003b). On the variability of human activity spaces. in M. Koll-Schretzenmayr, M. Keiner and G. Nussbaumer (eds.), The Real and Virtual Worlds of Spatial Planning, 237-262, Springer, Heidelberg.

Schönfelder, S. and Axhausen,K.W. (2004). Structure and innovation of human activity spaces, Arbeitsberichte Verkehrs- und Raumplanung. 258, IVT, ETH Zürich, Zürich, available at http://www.ivt.ethz.ch/vpl/publications/reports/ab258.pdf, accessed February 2010.

Schwanen, T. and Mokhtarian, P.L. (2005a). What affects commute mode choice: neighborhood physical structure or preferences toward neighborhoods?. Journal of Transport Geography, 13 (1), 83–99.

Schwanen, T. and Mokhtarian, P.L. (2005b). What if you live in the wrong neighborhood? The impact of residential neighborhood type dissonance on distance travelled. Transportation Research Part D: Transport and Environment, 10 (2), 127–151.

Seaman, D.E. and Powell, R.F. (1996). An evaluation of the accuracy of kernel estimators for home range analysis. Ecology, 77, 2075-2085.

Silverman, B.W. (1986). Density Estimation. London: Chapman and Hall, UK.

Simcharoen, S., Barlow, A.C.D., Simcharoen, A., and Smith, J.L.D. (2008). Home range size and daytime habitat selection of leopards in HuaiKhaKhaeng Wildlife Sanctuary, Thailand. Biological Conservation 141, 2242-2250.

Smart Growth Network (2003). Getting to smart growth II: 100 more policies for implementation, available at http://www.smartgrowth.org/pdf/gettosg2.pdf, accessed February 2010.

Transportation Research Board (2007) Traveler Response to Transportation System Changes, *Transit Cooperative Research Program (TCRP) Report*, **95**, Washington, DC.

Weber, J. (2003). Individual accessibility and distance from major employment centres: An examination using space-time measures. Journal of Geographical Systems, 5 (1), 51–70.

Weber, J. and Kwan, M. (2003). Evaluating the effects of geographic contexts in individual accessibility: a multilevel approach. Urban Geography, 24 (8), 647–671.

Worton, B.J. (1989). Kernel methods for estimating the utilization distribution in home range studies. Ecology, 70, 164-168.

Zahavi, Y. (1979). The "UMOT" Project, U.S. Department of Transportation, Research and Special Programs Administration.DPB-10/79/3, U.S. Department of Transportation, Washington, D.C.

Zhang, M. (2005). Intercity Variations in the Relationship between Urban Form and Automobile Dependence. Transportation Research Record, 1902, 55–62.

APPENDIX

A1 Kernel density

Kernel estimation transforms a set of point activities into a continuous surface of potential activities, where the values reflect the intensity of using a particular location:

$$\hat{\lambda} = \frac{3}{\pi\tau^2}\left[1 - \left(\frac{s_i}{\tau}\right)^2\right]^2$$

, where s_i is the distance of a spatial event i from the estimation point and τ the bandwidth (this affects the smoothness of the surface).

A2 Confidence ellipse

The ellipse is defined by:

$$\left(\frac{x - \bar{x}}{a}\right)^2 + \left(\frac{y - \bar{y}}{b}\right)^2 = 1$$

, where $\bar{x}, \bar{y}$ represent the centre of gravity of the set of activity locations weighted or not; a and b are the lengths of the major and minor elliptical axes.

The parametric form of the ellipse rotated by angle θ is:

$$\begin{cases} x = a\cos t\cos\theta - b\sin t\sin\theta + \bar{x} \\ y = a\cos t\sin\theta + b\sin t\cos\theta + \bar{y} \end{cases}.$$

The area of the ellipse is given by A= π*a*b.

A3 Super ellipse

The superellipse is defined by the curve: $\left|\frac{x-\bar{x}}{a}\right|^{r}+\left|\frac{y-\bar{y}}{b}\right|^{r}=1$

with the parametric equations:

$$\begin{cases} x = a(\cos t)^{2/r}\cos\theta - b(\sin t)^{2/r}\sin\theta + \bar{x} \\ y = a(\cos t)^{2/r}\sin\theta + b(\sin t)^{2/r}\cos\theta + \bar{y} \end{cases},$$

where $\bar{x}, \bar{y}$ represent the centre of gravity of the set of activity locations, weighted or not; r is the parameter of the superellipse (r=2 is the normal ellipse); a and b are the lengths of the major and minor elliptical axes, and θ the angle of rotation of the shape.

If r>2, the hyperellipse resembles a rectangle, if r<2 we obtain a hypoellipse with a shape of a diamond or even a cross (as the aim here is to obtain the minimum activity spaces, of interest is only r<1).

The area of the super-ellipse is equal to:

$A = 4ab\frac{[\Gamma(1+1/r)]^2}{\Gamma(1+2/r)}$, where Γ is the Gamma function.

A4 Cassini oval

Cassini oval is the locus of points for which: $(\bar{x}^2 + \bar{y}^2 + a^2)^2 - 4a^2\bar{x}^2 = b^4$
where b>a and the parametric equations are:

$$x = a\cos(\theta + t)\sqrt{\cos(2t) + \sqrt{\left(\frac{b}{a}\right)^4 - \sin^2(2t)}} + \bar{x}$$

$$y = a\sin(\theta + t)\sqrt{\cos(2t) + \sqrt{\left(\frac{b}{a}\right)^4 - \sin^2(2t)}} + \bar{y}$$

The area of the oval can be calculated as: $A = \int_{-\pi/4}^{\pi/4} a^2\left[\cos(2\theta) \pm \sqrt{\left(\frac{b}{a}\right)^4 - \sin(2\theta)^2}\right]d\theta$.

Note: If b>a, then the curve is a single connected loop, for b=a the curve is a lemniscates, and for b<a, the locus includes two separate parts.

A5 Bean curve

The bean curve is defined by $(x^4 + x^2y^2 + y^4) = x(x^2 + y^2)$ with the parametric form:

$x = a\sin^2(\theta)$,

$y = b\sin(\theta)\sqrt{\dfrac{\cos^2(\theta) + \cos(\theta)\sqrt{1+3\sin^2(\theta)}}{2}}$.

The area of the bean curve is: $A = \sqrt{2}ab\int_0^1 \sqrt{x(1-x+\sqrt{1+(2-3x)x})}dx \approx 1.058049ab$

A6 Maps

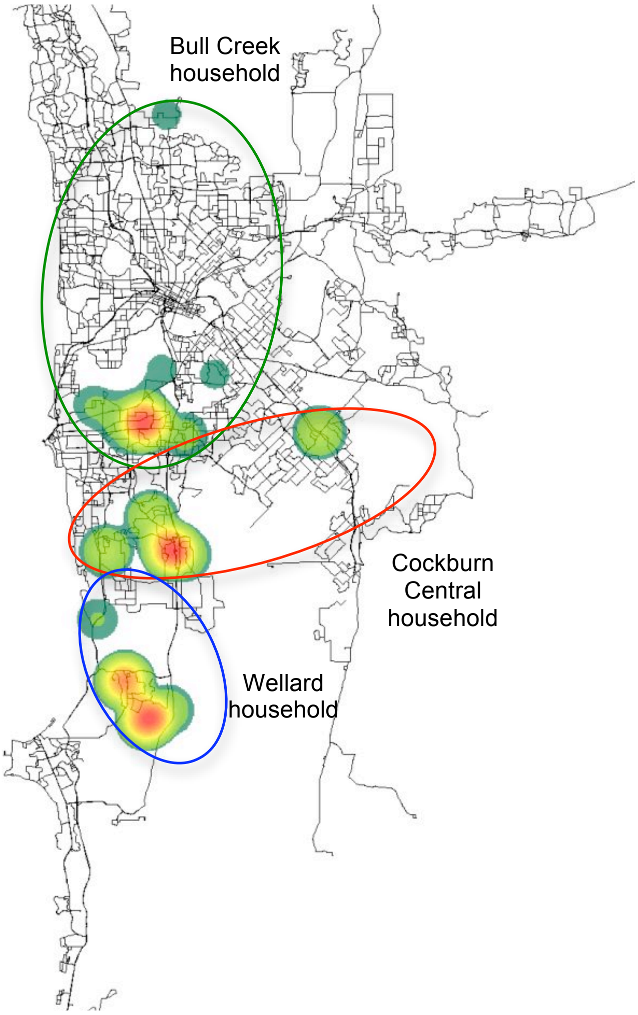

Figure A1 Example of kernel densities and confidence ellipses for three households residing in the three precincts

Figure A2 2006 and 2008 Kernel densities for all activities performed by Bull Creek residents

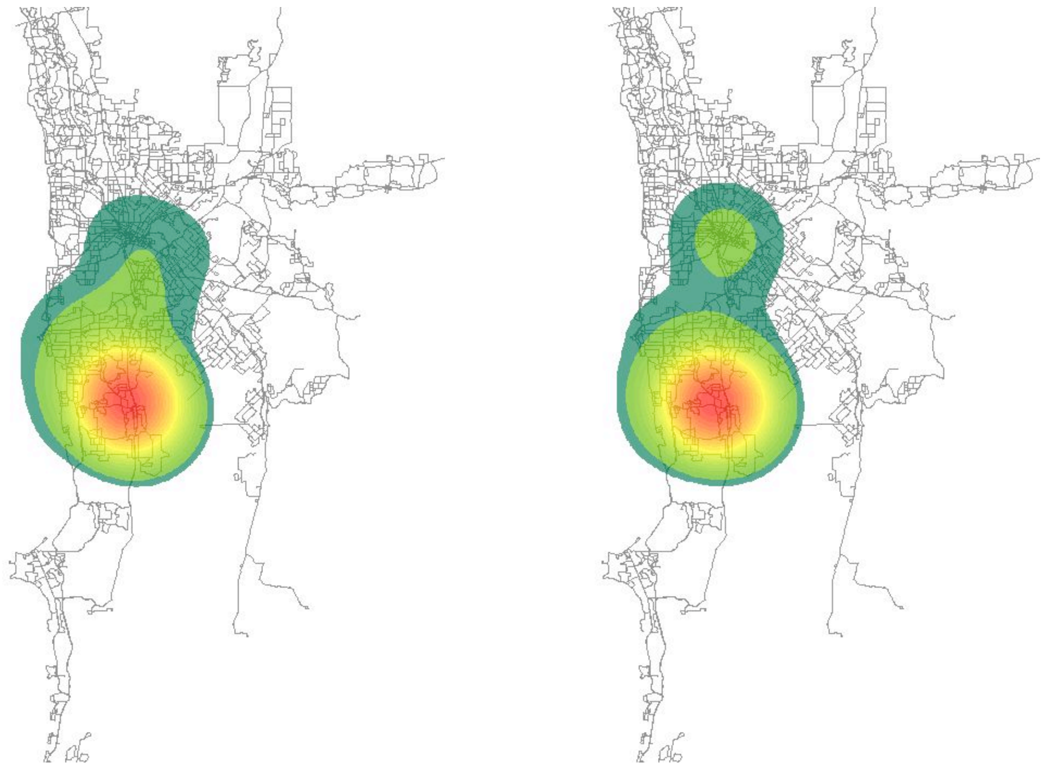

Figure A3 2006 and 2008 Kernel densities for all activities performed by Cockburn Central residents

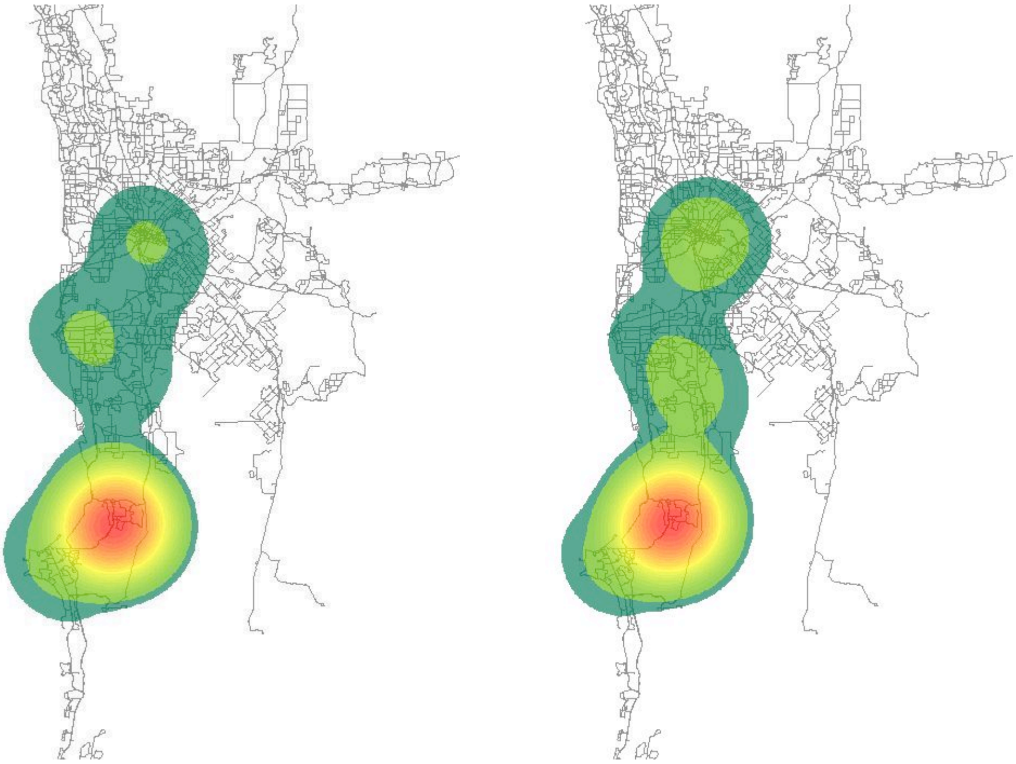

Figure A4 2006 and 2008 Kernel densities for all activities performed by Wellard residents

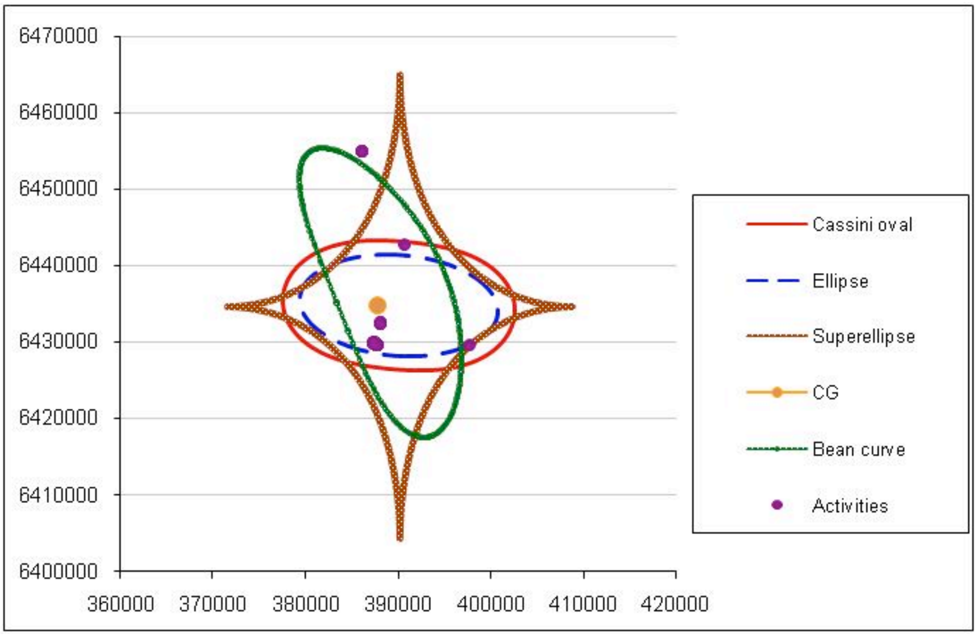

Figure A5 Example ellipse, hyperellipse, Cassini oval, and bean curves