The Connection of Urban Form and Travel Behaviour:
A Geo-Spatial Approach to Measuring Success of Transit Oriented
Developments Using Activity Spaces

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Abstract

A renewed interest in public transport, and particularly rail, has sparked a renaissance of Transit Oriented Development (TOD), with the aim of creating more liveable urban environments and fostering more sustainable travel behaviour. But without in-depth knowledge of the complex interactions between urban form, human activities and travel behaviour, the risk of mismatched urban planning outcomes, failing to adequately address human needs and desires, appears obvious. Hence, a debate on the relative roles of built environment and personal preferences and attitudes in shaping travel behaviour has been ongoing; however, the related empirical and theoretical research has often remained inconclusive in its findings. This research further adds to the discourse on the associations between different TOD opportunities and households’ travel behaviour. There are a number of contributions that this research is making: 1) it compares various geometries and highlights the benefits of kernel density as the most appropriate spatial tool for Activity Spaces for a one-day travel diary; 2) through a data enrichment methodology, it reveals the potential for GPS methods to enhance the Activity Space measures; 3) it analyses changes in Activity Spaces as a result of changes in urban form and development of TODs; 4) it evaluates in a structural equation model the connections between TODs and travel behaviour after accounting for household preferences and self-selection; and 5) it validates findings of the multivariate model with an Artificial Neural Network for enhanced credibility and confidence in the findings. These contributions are explained briefly in the following paragraphs.

After investigating the potential of Activity Space Analysis and adopting the concept as a central research element for the behavioural analysis of activity-travel patterns, Activity Space analysis was systematically examined in terms of methodology, visualisation, and practical application and subsequently deployed to evaluate urban form implications on household travel behaviour, with the aim to measure TOD success. The examination of a new public transport railway line, crossing the southern suburbs of Perth, Western Australia (WA), along a 72km long network spine, provided a real world scenario for measuring realised Activity Spaces and validation of the holistic modelling approach developed for this research.

From a methodological perspective, this dissertation then further expands the modelling approach through hybridisation of geographical, transport research techniques with data mining, i.e. combining geospatial analysis and Structural Equation Modelling with Artificial Neural Networks. This approach created the basis for several significant research innovations and increased the reliability of the results. The research shows the benefits of a hybrid analysis, applying a mix of modelling techniques, both spatial and a-spatial, for examining the complex relationships in a combined consideration of multiple sources of data. The empirical analysis confirmed the superior ability of kernel density to measure realised Activity Spaces with limited
travel data (one-day trip diary) and showed how route data influences its size. The Activity Spaces varied across various TODs and before and after the new TOD-related transport infrastructure came into service.

Overall, the approach to measuring success of TOD gave positive results. TOD policies and implementations were effective when they accounted for what residents value, i.e. well-designed urban environments can succeed in changing household travel behaviour, even after accounting for socio-demographics, personal preferences and circumstances (self-selection). By mixing and co-locating urban facilities in a carefully balanced way, at the right densities and service levels, improved efficacy of the urban system can be achieved. In this instance, travel has become to a greater extent multi-modal and less reliant on car. Signs of an intensified urban life have emerged, showing more environmentally friendly patterns of transport use and providing valuable (life-) opportunities for increased engagement in other activities. The results confirmed that TOD, and hence the built environment, matters.

These research findings have important implications for planners, public transport service providers, and communities, beyond WA borders. By offering insights into a web of complex relationships within the TOD sphere, this dissertation provides essential knowledge, methodological advancements and measurement tools that could be included in the standard TOD planning toolkit to assist in delivering more sustainable and liveable cities.

*Keywords: activity space, built environment/ urban form, transit-oriented development (TOD), travel behaviour, spatial analysis, confidence ellipse, kernel density, structural equation modelling, artificial neural networks.*
# Table of Contents

Acknowledgements .......................................................................................................................... 9  
Statement of Candidate Contribution ............................................................................................ 11  
1. Introduction.................................................................................................................................. 13  
   1.1 Specific Urban Challenges ........................................................................................................ 16  
2. Literature Review.......................................................................................................................... 23  
   2.1 Transport and Geography ........................................................................................................ 23  
   2.2 Connecting Land Use and Travel Behaviour ....................................................................... 29  
   2.3 Urban Growth and Urban Sprawl ......................................................................................... 32  
   2.4 TOD and Travel Behaviour .................................................................................................... 40  
   2.5 Self-selection or Residential Sorting .................................................................................... 42  
   2.6 Impacts/Benefits of TOD ....................................................................................................... 43  
   2.7 Measuring Success of an Urban Planning Intervention ...................................................... 48  
3. TOD in Western Australia ........................................................................................................... 51  
   3.1 TOD in Australia ..................................................................................................................... 51  
   3.2 Strategic Planning and Policy, Western Australia – State and Local Level ..................... 52  
   3.3 A Practitioner’s View – Understanding Implications .......................................................... 56  
4. Activity Space – Importance Definition, and Measurement ..................................................... 59  
   4.1 Human Activities in Space and Time .................................................................................... 59  
   4.2 Spatial Cognition and Activity Spaces .................................................................................. 60  
   4.3 Definitions, Metrics for Realised Activity Spaces (RAS) ...................................................... 67  
   4.4 Confidence Ellipse ................................................................................................................ 68  
   4.5 Super-Ellipse ........................................................................................................................ 69  
   4.6 Cassini Oval .......................................................................................................................... 70  
   4.7 Bean Curve ............................................................................................................................ 71  
   4.8 Kernel Density ....................................................................................................................... 72  
5. Research Methodology .............................................................................................................. 75  
   5.1 Research Objective and Questions ......................................................................................... 75
5.2 Methodology ................................................................................................................ 75
5.3 GIS-based modelling ................................................................................................... 77
5.4 Multivariate Data Analysis Models .......................................................................... 78
5.5 Structural Equation Modelling (SEM) ..................................................................... 79
5.6 Artificial Neural Networks ....................................................................................... 81
6. Empirical Data .................................................................................................................. 83
6.1 Survey Data .................................................................................................................. 83
6.2 GIS Data ...................................................................................................................... 85
6.3 TOD Precincts ............................................................................................................. 87
7. Data Analysis and Results ............................................................................................. 95
7.1 Data Visualisation ....................................................................................................... 96
7.2 Numerical Results at the Household Level ............................................................... 114
7.3 Numerical Results at the Precinct Level ................................................................. 120
7.4 Activity Spaces Embedding Trips –Benefits to Modelling ...................................... 123
7.5 Structural Equation Modelling (SEM) ...................................................................... 129
7.6 Artificial Neural Networks (NN) Results ................................................................. 145
8. Conclusions and Limitations ....................................................................................... 151
8.1 Conclusions ................................................................................................................ 151
8.2 Limitations .................................................................................................................. 161
8.3 Further research ........................................................................................................ 163
8.4 Final words ............................................................................................................... 164
9. Bibliography .................................................................................................................. 167
10. Appendices ................................................................................................................. 199
Tables ........................................................................................................................................ 201
A.1 SEM Results - Direct Effects (BC - Default model) .................................................. 201
A.2 SEM Results - Total Effects (BC - Default model) .................................................... 202
A.3 SEM Results - Direct Effects (CC - Default model) .................................................... 203
A.4 SEM Results - Total Effects (CC - Default model) .................................................... 204
A.5 SEM Results - Direct Effects (W - Default model) ..................................................... 205
A.6 SEM Results - Total Effects (W - Default model) ................................................................. 206
A.7 SEM for Realised Activity Space - Whole Sample with KD & CE indicators .............. 207
A.8 Correlations Variables Included in the SEM for Realised Activity Spaces .............. 209
A.9 Additional Resources on Artificial Neural Network Modelling ................................. 210
Figures ....................................................................................................................................... 211
F.1 Artist’s Impression – Wellard TOD (Landcorp) ............................................................. 211
F.2 Structure Plan Cockburn Central ................................................................................... 211
F.3 Metropolitan station precincts: Actual land uses at 2007 (net density shown) .......... 212
F.4 Directions 2013 – Indicative Policy Application Area ................................................ 213
F.5 Standardised SEM Results – Bull Creek precinct ....................................................... 214
F.6 Standardised SEM Results – Cockburn Central precinct ........................................ 214
F.7 Standardised SEM Results – Wellard precinct ......................................................... 215
F.8 Map of Perth’s Rail Network and Study Area ............................................................ 216
Program Source Codes ........................................................................................................ 217
P.1 Program Source Code – Calculate Kernel Density Loop Tool ..................................... 217
P.2 Program Source Code – Slice Grid Tool ..................................................................... 221
P.3 Program Source Code – Calculate Kernel Density Areas ....................................... 223
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This dissertation has filled me with optimism. I have realised if we pay attention to different settings of our daily surroundings and learn from the past experiences and present behaviours, we can better plan for and more successfully accommodate urban growth in a manner that is not just about the now and then, but delivers sustainable and liveable urban environments for coming generations, without creating new Brownfield’s for the future. I have hope embedded in this dissertation: guided by contemporary research and knowledge, functional places can be developed that are flexible to remain liveable and attractive for people in perpetuity. We need to act responsibly to ensure genuine collaboration between policy makers, statutory authorities as well as industry practitioners involved in design, implementation and ongoing management of our built environment, urban systems and networks, in order to strengthen diversity by creating a healthy mix of places and opportunities for people to live.
Statement of Candidate Contribution

The thesis has been substantially completed during the course of enrolment in this degree at The University of Western Australia and has not previously been submitted for a degree at this or another institution, and to the best of my knowledge and belief, this thesis contains no material previously published or written by another person, except where due reference is made in the text of the thesis.

The thesis is my own composition and it acknowledges literature and other sources. No identical work presented within this thesis has been co-published with other authors.

Collaborative research preceding this thesis has been appropriately cited to the co-authors. This is a declaration to this effect, signed by me and also by my principal supervisor.

Markus Botte 11 April 2014
Associate Professor Doina Olaru 11 April 2014

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1. Introduction

The relationships between form, use and density of urban development and their influence on human behaviour and travel have been widely discussed in the literature (see e.g. Mitchell and Rapkin, 1954; Wingo, 1961; Chapin, 1968; Rushton, 1971; Horton and Reynolds, 1971a; Pushkarev and Zupan, 1977, Cervero, 1988, 1991, 1996; Giuliano and Small, 1993; Ewing et al., 1996; Cervero and Kockelman, 1997; Boarnet and Sarmiento, 1998; Crane and Crepeau, 1998; Miller and Ibrahim, 1998; Boarnet and Greenwald, 2000; Newman and Kenworthy, 1989; Badoe and Miller, 2000; Crane, 2000; Schwanen, 2002; Bagley and Mokhtarian, 2002; Ewing et al., 2003; Zhang, 2004; Forsyth et al., 2007; Ewing and Cervero, 2010). Together with a call for more sustainable urban design and transport alternatives, strategies that rely on these relationships have formed key elements of many land use and transport policies (e.g. as part of the six liveability principles of the Partnership for Sustainable Communities, U.S. Government, 2009) or even influenced legislative frameworks around the world (e.g., for an early statutory attempt to create more liveable cities, the United Kingdom and the Greater London Regional Planning Committee’s Green Belt (London and Home Counties) Act, 1938. For more recent examples, see federal legislation in the US: The Transportation Equity Act for the 21st Century published by the Federal Highway Administration, 1998; or the Safe, Accountable, Flexible, Efficient Transportation Equity Act: A Legacy for Users, US Government, 2005a; and at the state legislative level, the Massachusetts General Laws, Massachusetts Government, 2008, or in Australia: State of Western Australia, 2006; Department of Infrastructure and Transport, 2011; New South Wales Government, 2011).

The recognition and adaptation of the original ideas of land use-travel behaviour in the policy context are driven mainly by concerns about traffic congestion, cost-effectiveness of public transport, sustainability of transport patterns, population health, segregation and social exclusion, and road safety, prevailing in many major cities around the world. In the last decade, the adverse effects on the planet’s climate, as well as predictions of dwindling fossil fuel resources have added to the debate on how urban planning should change (e.g. for some Australian examples refer to Garnaut, 2008a, 2008b; Department of Infrastructure, 2010; Department of Infrastructure and Transport, 2011).

More specifically, urban design movements and models such as “New Urbanism”, “Smart Growth”, “Urban Containment”, “Compact City”, “Urban Village” and “Urban Intensification” have emerged on the research agenda, encompassing many of the basic principles that are at the heart of Transit Oriented Development (TOD). With some differentiation, they all have in common the aim to curb reliance on car travel, by offering more sustainable travel alternatives and urban environments (Duany et al., 2000; Brown and Southworth, 2008; Institute of
Transportation and Development Policy, 2014; Kamruzzaman et al., 2014). Although the conventional idea that a high-density urban land-use mix is leading to decreased automobile-based travel, reduced transport energy needs and emissions - hence fostering sustainable mobility - is plausible (Newman and Kenworthy, 1989, 1999; Cervero, 2001a; Boussauw et al., 2012, Topalovic et al., 2012), the development, planning and modelling of integrated land-use and transport systems, are much more complex. An any early discussion and conceptualisation of an integrated land use and transport model is presented by Waddell et al. (2001); for a comprehensive overview of methodological and organisational challenges in implementing an integrated transport and land use model across various organisations in Northern America, see Waddell (2011). The complexity stems from ambiguities within the aims of the strategic tasks and the failure to fully incorporate real behaviour into planning and modelling. The reluctance of urban people to accept policy directions, the non-receptivity or resistance to fulfilling the desired objectives, or the departure from what was believed or planned, have been subject to lively discussion in the research community.

Hence, over the last decades considerable research efforts have aimed to explore and affirm relationships between urban form and activity-travel patterns (Kitamura et al., 1997; Zhang, 2005; Cervero and Murakami, 2010; Ewing and Cervero, 2010), often with the idea to identify measurable associations, such as the interconnectedness between travel behaviour and urban environment (Rushton, 1971; Handy, 2006) as well as implications for quality-of-life (Türksever and Atalik, 2001). Efficacy of urban development, via provision of mixed land-use and multi-purpose activity centres, with increased densities, accounting for carefully balanced job-housing ratios (Cervero and Duncan, 2006) and serviced by high-quality public transport, are commonly signalled as the 'holy grail' in developing sustainable, liveable urban environments. In Australia, Newman and Kenworthy’s (1989) work on multi-city comparisons, attempting to draw the density-transport connection, significantly influenced the local debate. The “urban renewal” concept, which has been embraced and adapted to local conditions in all Australian State Capital, Cities takes its basic principles from the original transport-oriented development (TOD) notion (Department of Planning and Development, 1995; Melbourne City Council, 2010; Department of Planning and Local Government, 2010; NSW Government, 2011; Metropolitan Redevelopment Authority, 2012). TOD evolved mainly in Northern America and Europe (e.g. Owens, 1992; Breheny and Rookwood, 1993; Calthorpe, 1993; Hall and Ward, 1998; Smart Growth Network, 2003), but was adopted in other countries around the world over the last decades (Wilkinson, 2006; Zhang and Lin, 2011).

In Western Australia and interstate, TOD has seen various implementation attempts (e.g., in Perth: East Perth and Subiaco; in Melbourne: Camberwell, Docklands; in Brisbane: Southbank; in Adelaide: Bowden; in Sydney: Chatswood, Bondi Junction, Edgecliffè, Kogarah Centre,
Parramatta, Pyrmont, Strathfield) and has influenced strategic planning and policy making to varying degrees. The aim has been setting directions to achieve the desired efficacy of the cities in the near future (Austroads, 1998; State of Western Australia, 2006, 2010a, 2010b; 2011, Victoria Transport Policy Institute, 2013). Over recent years the Australian federal government has shown a renewed interest in the “Building Better Cities” program of the early 1990s (Department of Health, Housing and Community Services, 1992). To date, this has mainly resulted in major urban infrastructure delivery through the Infrastructure Australia fund. Pending further development of a comprehensive urban policy at Commonwealth level, opportunities to encourage more TODs in Australia remain largely unexplored or in the hands of State and Local Government as well as private investors.

While there are signs that state governments in Australia are planning to use transit oriented development strategies in the future, there are still very few real examples of TOD in practice in our cities. They have been the exceptions rather than the rule and where they have occurred, have not always been part of a comprehensive, city-wide strategy.

The “Compact City” and “Urban Containment” concepts have since received some criticism in terms of their role in addressing car dependence; this just means they may not be best suited to fully resolve all urban transport issues (Bertolini, 1999; Angel et al., 2011; Mees, 2011). Given the continuing decentralisation of cities around the world (Angel et al., 2011), “deconcentrated clustering”, which Bertolini (1999: 209) describes as an “urban development strategy, geared to the accessibility of urban-regional networks of transportation nodes and activity places”, it is believed that these ideas still hold promise for stimulating desired travel behaviour changes. These changes are expected to reduce congestion and other negative externalities of travel (Smart Growth Network, 2003; Transportation Research Board, 2004), thus directly supporting the idea of TOD planning and careful development of activity centres around key public transport nodes.

Despite a glut of policy-based discourse and urban planning research on links between urban form and behaviour over recent years (e.g., Transportation Research Board, 2004; Badland et al., 2008; Bhat and Guo, 2007; Center for Transit Oriented Development, 2006; Coalition for Smart Growth, 2006; Khattak and Rodriguez, 2005; Mokhtarian and Cao, 2008; Ewing and Cervero, 2010; Zhang, 2010; Mees, 2011), so far no congruent positions have arisen. The uncertainty is twofold. On the one hand, the conventional wisdom of “offering the right mix” to modify established behavioural patterns appears logical, but on the other hand personal attitudes and attributes could outweigh any mobility effects associated with characteristics of the urban form (Kitamura et al., 1997; McQuaid et al., 2001; Ewing and Cervero, 2001; Schwanen and Mokhtarian, 2005a; Zolnik, 2009). In other words, the particular lifestyles of individuals and households (e.g., “extremely mobiles”) or economic considerations (e.g., where travelling a
greater distance gives access to a better paid job) could foster transformation of accessibility benefits (e.g., from a faster transport mode) into an increase in the activity portfolio and associated increase in travel and/or further distances travelled by car, rather than reducing car travel or switching to environmentally friendlier modes of mobility (EFM’s) (Cao and Mokhtarian, 2005). This even leads to the question of whether effective policies alone can significantly contribute to addressing the urban transport dilemma and whether the idea of the built environment influencing behaviour may have been somewhat overrated (Mees, 2010, 2011).

In this context, the study of activity related travel patterns plays an important role and has been long recognised as “indispensable to guide the formulation and implementation of the policies” aimed at resolving urban growth challenges, along with the call for scientifically sound conceptualisations (Axhausen and Gärling, 1992: 337). Consequently, the interest in the study of activity and travel over the years has remained strong and led to a variety of frameworks and models. However, the complex nature of activities and the need to include the various aspects in the modelling of travel behaviour has challenged researchers with a multitude of questions. A pressing one is the rise in individual mobility: Khisty and Zeitler (2001) drew attention to the “hypermobility” (or imbalanced mobility) phenomenon of 21st Century society around the world (“the new mobilities paradigm”, discussed by Sheller and Urry, 2006) to a point where “movement has become a phenomenon in its own right” (Ahas et al., 2010: 3).

1.1 Specific Urban Challenges

The intricacies of travel behaviour and their manifold relationships with various aspects of urban spatial structure, the socio-economic environment and individual preferences have imbued research and practice in urban planning with many difficulties. Understanding effects of urban sprawl and congestion, the associated—environmental degradation and competition between and within expanding economic opportunities adds further to the task. An overview of the common causes and consequences of urban sprawl and a discussion of its efficiency and equity implications as well as potential corrective actions are presented by Nechyba and Walsh (2004).

Chen and McKnight (2007) considered that striking changes in society during the past decades (e.g. vanishing gender-based household settings), combined with increased car ownership and technological progress (e.g. information and communication technologies), required a shift in the thinking that has dominated urban planning and transport modelling. They acknowledged the role played by to the traditionally powerful Alonso model (Alonso, 1964, 1971), which
assumes an optimal city size based on cost-benefit considerations, and its role in urban spatial
planning, but emphasised the need re-focus research priorities on a more flexible modelling
framework, i.e. one where the traditional influence of workplace on residential location is
expanded to include other activities and factors that can strongly influence the location choice
and subsequent travel decisions. Based on empirical studies examining six-week continuous
travel diaries of German households (Mobidrive), Frusti et al. (2002) underlined the importance
of considering fixed commitments and daily routines when studying daily activity travel
patterns, in order to improve the assessment of urban policy impacts on travel behaviour.

A similar view is expressed by Zolnik (2009), who investigated the influence of personal and
gender-based constraints on commuter travel, such as negotiation between family members
sharing household responsibilities. He analysed journey-to-work times in relation to various
land uses, socio-economic factors and transport network performance factors. In his findings,
Zolnik (2009) could not confirm the influence of gender specific responsibility constraints;
interestingly, results did not support the view that development intensity and the mixing of land-
use have notable influences on travel differences; nevertheless, income and occupation, as well
as vehicle ownership, had a very important role in commuter travel decisions (Jones and Clark,
1988).

Related to personal characteristics and circumstances, self-selection is a crucial area of research,
especially the degree to which travellers match their preferred and actual type of residential
location (Schwanen and Mokhtarian, 2005a, 2005b), considering the relation between individual
characteristics and the physical and artificial environment, including transport.

Consequently, this PhD research was stimulated by the indeterminacy and conflicting
arguments presented in both the literature and policy discussion in respect to the complex
connections between urban form and travel behaviour, and has been further inspired by the
paucity of understanding of the strengths and challenges of time-space and context constraints
on daily travel behaviour. Its aim is to contribute to a better comprehension of the milieu of
relationships and to propose a methodology suitable to measure potential modifications in travel
behaviour resulting from TOD, using Activity Space analysis.

The Activity Space concept forms the main analytical tool of this research. Activity Spaces are
representations of the use of space by individuals, as revealed by participants in travel surveys.
They can grossly be thought of as the “home range” of individuals (expanding on the work
originally proposed in the field of ecology to understand territorial and ranging behaviour of
animals) and provide an estimate of the spatial usage for fulfilling daily activities. This research
is geared to apply Activity Space analysis in combination with other contemporary research
approaches to form a novel tool set that can assist in land use planning, analysis and policy making, thereby enriching the understanding of TOD effects on travel patterns and location.

By examining Activity Spaces (including all work and non-work activities) in relation to socio-demographic characteristics, the urban fabric and the transport services provision, this research provides insights on what combination of urban facilities is conducive to environmentally friendlier modes of transport and reduces Activity Spaces. Thus, the Activity Space may assist in resolving key aspects of urban planning, as it not only accounts for individual characteristics, but also embeds spatial and temporal elements of travel behaviour along with infrastructure and institutional constraints (Church et al., 2000; Harvey and Taylor, 2000).

This research follows on the stream of activity-based models and investigates changes in household Activity Spaces resulting from modifications of the urban form and transport network. The need for richer spatial metrics that embed travel and activities, and assessing their relationships with planning policies, have been recognised as areas that deserve high priority on the research agenda. The research is distinguished from previous scholarly work by its unifying view of the relationships between urban form, spatial use, spatial choice (residential location) and travel patterns, in a multi-level analysis of quasi-longitudinal data.

To analyse the spatio-temporal transport and land-use interactions and to evaluate the impact of different development opportunities on household travel behaviour, a combination of geographic and transport research methods is used. Multivariate data techniques are combined with geo-spatial data analysis and graphical visualisation tools and embed a complex disaggregated metric of travel behaviour – the Activity Space (AS)\(^1\).

The topic and findings are extremely timely, considering the widespread trend of the contemporary urban policy agenda towards delivery of high density, integrated, multi-purpose activity centres, developed around major public transport railway hubs. Especially relevant in this context is the need to resolve the multiple challenges currently faced by decision makers (such as government agencies, land developers, urban designers and transport planners) in delivering better and more sustainable urban environments around the globe, for an ever-

\(^1\) Due to the nature of the data available for this research (24 hour trip diaries), the analysis focuses in particular on spatial aspects, with only limited consideration of temporal dimensions. A natural extension of this research would incorporate further temporal pattern analysis based on longitudinal data (preferably multi-week trip diaries).
increasing urban population. Moreover, the fast pace and critical nature of socio-demographic, economic and environmental changes in Australia, demonstrate the local need for research on effective ways to contain travel demand and diminish transport externalities. While measuring transport policy impacts, this research also develops important ideas on how planning can better respond to urban expansion. More specifically, it provides empirical evidence on the role of the urban form in shaping activity-travel behaviour, using Transit Oriented Development (TOD) as an example of managing growth in metropolitan areas.

The central aim is to add to the body of knowledge on the connection of urban form and travel by combining statistical and geo-spatial analysis methods. The research pursues two lines of inquiry: 1) to investigate the potential of Activity Space measures for understanding complex human activity-travel behaviour and; 2) to systematically relate Activity Spaces to urban form and measure the success of emerging TOD areas in changing the way their residents behave. Using Activity Space Analysis, a concept with basic origins dating back to the days of early social sciences (Lefever, 1926), this research examines interrelated issues of methodology, visualisation, and practical application, and confirms that the urban form, and hence TOD, is associated with changes in travel behaviour as captured through household Activity Spaces.

The research has conceptual, methodological, as well as practical implications. From a conceptual and methodological perspective, it is the “holistic” modelling approach that deserves recognition, with this study successfully linking advanced geo-spatial analysis (i.e. GIS-based analysis of both traditional measures and contemporary methodological variations of the theoretical Activity Space construct), with multivariate statistical investigation (i.e. embedding the Activity Space measure as a latent construct into Structural Equation Modelling – SEM), and subsequent validation of the results (i.e. via Artificial Neural Network analysis). The critical comparison of numerous geometries for Activity Spaces shows the benefits of using kernel density estimation for capturing spatial use of the urban environment, whilst accounting for frequency and duration of activities, over other proposed metrics (convex polygon, confidence ellipse, network buffer, Cassini ovals, etc.).

The Structural Equation Model and its validation through Artificial Neural Networks provide insights into how transport and urban policies affect various segments of the population. This is a crucial step for any professional who endeavours to confirm the robustness of a chosen approach and support the credibility of her/his findings. Likewise, this is particularly important for me, as a practitioner often hearing the criticism of research as being directed to some scientific elite, without full regard to real world problems. Having said that, the differential relationships identified for three distinctive TODs and the changes in travel behaviour that have occurred since the opening of the rail corridor in travel behaviour, call for even more sophisticated ways of embedding modelling developments into praxis.
This research also includes a specific investigation of Activity Spaces for a sub-sample of households, where route information was inferred, similar to data provided by GPS-tracking. The results reveal the potential of a cost-effective and non-intrusive data enrichment methodology that allows for additional insights into expected travel behaviour, whilst addressing the privacy concerns typically posed by GPS-based collection methods.

Overall, the modelling strategy adopted in this research endorses the emerging research interest in integrated modelling techniques (Kamruzzaman and Hine, 2012), with combining both qualitative and quantitative methods “in responding to the complex mobility needs of today...” and thus offering “…a wider-angle lens of measuring...Activity Space” (McCray and Brais, 2007:411).

In terms of its practical implications, this study presents positive results on the ability of a TOD to change household travel behaviour, after accounting for socio-demographics, personal preferences and circumstances. The examination of a new public transport railway line (“Mandurah Line”), crossing the southern suburbs of Perth, Western Australia (WA), along a 72km long network spine, facilitated a real world validation of the holistic modelling developed for this research in a TOD context, incorporating Activity Spaces as a central element of the analysis.

A variety of configurations of railway station precincts, ranging from a congenial TOD (with a variety of shops, services, and other attractions) to precincts acting primarily as origin stations or public transport interchanges have been evaluated. Three broad types of TODs were investigated along the new railway corridor: Greenfield (Wellard), Brownfield (Bull Creek, residential), as well as one centred around a transit interchange/shopping precinct (Cockburn Central - Gateway), along with their diverse impacts on the Activity Spaces of the residents living in those areas. Figure F.8 (see Appendix) provides an overview of the study area and location of the new railway line.

The results of this investigation, which are discussed in detail in Section 7, confirmed the impact of TOD-based urban landscapes, even during the establishment phase (when the TODs are still emerging), outlining distinctive differences alongside the corridor between the newly planned precincts and TODs retrofitted and transformed from the existing land use. Here, the TOD success was reflected by a reduction of Activity Spaces and concentration of observed daily activity schedules along the corridor (especially by households in Wellard, which had the highest car use prior to the TOD intervention) and at the local scale. This impact can be directly attributed to the new rail connection, given the still deficient TOD-idiosyncratic land use at this location. In Bull Creek the TOD impact was clearly reflected in increased neighbourhood recreational walking. Likewise, in Cockburn Central, the results confirmed that by mixing and
co-locating urban facilities in a carefully balanced way, at the right densities and service levels, improved efficacy of the urban system has been achieved. Signs of an intensified urban life have emerged, with reduced daily travel and lower car use observed in this precinct, showing a substitution of environmentally friendlier patterns of transport usage and providing valuable (life-) opportunities for increased engagement in other activities. This more sustainable activity travel behaviour suggests that infrastructure changes and services provision are valued by residents and have most likely induced changes in travel.

These findings have important implications for planners, public transport providers, and communities, beyond WA borders. By offering insights into a web of complex relationships within the TOD sphere, this research provides essential knowledge for the planning of a more sustainable and liveable development of cities.

Ultimately, it is the planning that matters, and in a TOD sense this requires decision makers to design urban form in an integrated way that accounts for what (sub-)urbanites value most. The results of this research clearly draw a strong link between the households’ value system and the access to transport and urban facilities. If transport and urban planning provide adequate services and match household demands, by improving amenities and travel services, and by catering for multi-stop space and time-oriented household activity agendas, such TODs can successfully deliver their intended benefits.

However, based on the findings presented here, this achievement clearly depends on the degree of consonance between households’ needs and desires, for each TOD design and implementation. This was expressed in the households’ willingness to pay for certain urban features. For example, from the findings it is evident that synchronisation between provision of TOD services and household preferences (a prerequisite for a TOD to have an impact), is currently met more often for residents residing in Bull Creek than in Wellard, where the full suite of TOD facilities are yet to emerge. By comparing household preferences and willingness-to-pay for urban features within various study precincts, an element of value uplift associated with TOD has become evident, and this result should also be of particular interest to developers and real estate agents.

In summary, the study and its findings directly support the research goals of offering consolidated measures to capture the complex household activities and travel and relating them to urban form changes, whilst considering preferences and self-selection issues:

- By comparing six geometries it provides evidence for using Kernel Density as the most reliable metric for measuring Activity Spaces when one-day trip diary data is used;
• It applies a mix of modelling techniques, both spatial and a-spatial, for examining the complex relationships between the built environment, urban form and travel behaviour; and combines multiple sources of data;
• Cross-validation of multivariate and Artificial Neural Network models offers credibility and confidence in the findings, showing that TOD matters and is effective where it accounts for what residents value (policies have an impact);
• It reveals the potential for GPS methods to enhance the Activity Space measures.

The structure of the remainder of this thesis is as follows: Chapter 2 presents a review of planning, transport, and behavioural aspects related to transit oriented development, relocation decision drivers, and characteristics of TODs, followed by a description of the current indicators used in practice. Chapter 3 sets the empirical case (Perth, Western Australia) and offers a practitioner perspective on the benefits and barriers of implementing TOD. Chapter 4 is dedicated to Activity Spaces, as a key multidimensional indicator of household activity and travel needs and how well the urban infrastructure supports them. The adopted methodology is described in Chapter 5 and the sources of data in Chapter 6. They are followed by results of the data analysis (Chapter 7) and findings and concluding implications for researchers and practitioners (Chapter 8).

The thesis also includes a number of Appendices, supporting the presentation of the case study, presenting detailed results, and offering the program source code for replication in other contexts.
2. Literature Review

2.1 Transport and Geography

“Transport is customarily regarded as a derived demand, an activity which is undertaken or endured in order ultimately to do something else more important, engaging or fun... it is an expression of the desire to realize a particular ambition... it helps to tell us something about something else.” (Shaw and Sidaway, 2010: 515)

Abundant scholarly literature addresses linkages between transport and geographical analysis used in planning (see Ortúzar and Willumsen, 2001, for a comprehensive overview) and this section does not re-iterate the four/five-step modelling approaches (Wachs et al., 2007). It rather presents new perspectives on the analysis of human spatial behavioural geography, focusing on visions and ideas that sparked interest in a multitude of disciplines (transportation modelling, ecology, economics, urban planning, decision science, cognitive and behavioural sciences, archaeology, computer sciences, etc.). Over the years, a wide array of geographical approaches and concepts has evolved to enhance knowledge and understanding of spatial processes and relationships. The development of those spatial theories and models can be seen as some of the fundamental achievements in the history of geography, giving it purpose and structure (Rushton, 1971; Golledge 1976, 1978, Hubert et al., 1981; Timmermans, 1981; Golledge and Stimson, 1987; Golledge and Timmermans, 1988; Egenhofer and Golledge, 1998; Amedeo et al., 2009).

About a decade ago, Golledge (2002), raised questions on how geography in the 21st century can play a role in solving some of the more imminent problems that face modern world society. He enumerated several areas which can benefit from geographical expertise: assistance in creating and maintaining sustainable urban environments, addressing climate change and dwindling (fossil) fuel resources, resolving challenges in regional development, all valid questions which have since ignited a new flurry of interest in the geographic research community.

To date, innovative methods of spatial analysis and modes of representation continue to develop (Miller and Shaw, 2001; Steinberg and Steinberg, 2006; Farber and Páez, 2007; Páez et al., 2009), exploring the complex interaction of the physical environment with human behaviour, in particular the spatial relations of urban form, travel behaviour and quality of life. Whilst mainstream research was focused on elements of distance and travel time, hence a-spatial (Páez et al., 2009), more sophisticated research efforts, that consider a richer spatial view (accounting for aspects such as orientation, concentration or varying distribution of the matters of interest within a spatial fabric) and even undertake to include underlying motivational factors of human
behaviour within the analysis, have since increasingly gained momentum (Buliung and Kanaroglou, 2007; Harvey, 2008; Páez et al., 2009).

This research endeavours to contribute another element in the vast and constantly evolving field of research by addressing the fundamental research question: *How does one best attempt to measure travel behaviour changes over time, within a spatial context and reflecting the complex and multi-dimensional nature of various relationships?*

### 2.1.1 What is Special about Spatial?

It may not be obvious why spatial data requires special treatment and why substantial research in transport planning still applies non-GIS based data analysis, despite acknowledging that it is addressing inherently spatial processes. Given the relatively recent diffusion of GIS technologies and analytical tools, research has relied on concepts of distance, adjacency, neighbourhood, and network (Figure 1), without questioning the relationships between attributes and the spatial location. As described by Harvey (2008: 629), it is the “mechanistic approach that ignored the spatial, temporal, and individual interdependencies among transportation, land use and population”, which “has left a legacy of urban areas with seriously inappropriate land use and transportation systems.”

Nevertheless, the non-random distribution of phenomena and their non-uniformity in space remain a major interest, along with the various scales characterising spatial processes.

<table>
<thead>
<tr>
<th>Proximity, Distance</th>
<th>Adjacency, Linkage</th>
<th>Density, Neighbourhood</th>
<th>Connectivity, Network</th>
</tr>
</thead>
<tbody>
<tr>
<td><img src="image1" alt="Proximity Diagram" /></td>
<td><img src="image2" alt="Adjacency Diagram" /></td>
<td><img src="image3" alt="Density Diagram" /></td>
<td><img src="image4" alt="Connectivity Diagram" /></td>
</tr>
</tbody>
</table>

*Figure 1: Basic Spatial Concepts*

Figure 1 presents a number of localities (A-F) on a local road network that is not fully connected. Although distances might have been used in a spatial analysis, they conceal the fact
that localities A and D are not linked directly (they are not “adjacent”). In terms of density and locality, only four locations are included in the area of interest, leaving A and F outside. Consequently, aggregated descriptors of the “area” would not only ignore the spatial variability within the area, but also alter its relationships with other areas in its proximity. From this simple representation of basic spatial concepts it is clear that without proper description and initial definition of the spatial characteristics, any analysis runs at risk of being weak or even erroneous.

Likewise, the signals of the built environment are not separable from self-selection and travel behaviour. Spatial factors exert influences on many levels at varying time-scales. Urban land use and urban form (Verburg et al., 2004) present only two of the many influences on human behaviour; however, both do have major implications for most of us in daily life, often with lasting effects.

An and Brown’s (2008) investigation of land-change dynamics, integrating survival analysis with GIS, presents urbanisation as a unidirectional land-use transformation process, driven by a complex array of factors (Zhang, 2001). Once the land has been developed, the infrastructure is expected to last for decades (at least) and land-use changes may result in rigid, highly inflexible frameworks that are constraining opportunities for future modifications. The minute human actions have sculptured a new urbanised face of the earth, the resultant transformations, such as the core settlement and economic fabric and intertwined transport network, continue to dominate human life in perpetuity and represent nearly irreversible influences. This is referred to by Munroe (2009) as a “spatiotemporal path dependence” of development patterns (p.154). Unless extreme events, such as natural disasters (the 1755 Lisbon earthquake, more recently the 2010 and 2011 Canterbury earthquakes in New Zealand or earthquake related events, such as the Tsunami impacting the east coast of Japan in 2011; the emerging response to sea level rise triggered by climate change for many low lying cities around the world) or human destruction (warfare, fire, other catastrophic events) occur and alter the urbanised area, future modifications are often limited and urban regeneration potentials are “constrained” by their historic core (e.g., Rome, Paris, London) (Tacitus, in Church et al., 1876; Laurian, 2012; Ween, 2012). Extreme economic conditions (deindustrialisation, outmigration) may also have severe impacts on the urban form. The effects of Detroit’s fall in the 1950’s made it an example of a disarticulated planning process, with disruptive effects on the functioning of the city until the present day.

Given the reduced incidence of these events, examples from around the globe demonstrate “cities can exist through long stretches of history without significant renewals” (Anas, 1978: 83) and once the “arteries” of a new layer are added to the city (sometimes with detrimental effects on the historical/cultural heritage), it is improbable that major changes will be made to that urban infrastructure in the short to medium term. Thus, city dwellers will need to adjust
their behaviour to the governing framework, or in other words, their “resilience” is sought. Within a somewhat predefined and rigid spatial urban framework and underlying immobile land resources, urban lives go on. People change residences, travel between places, and perform activities necessary to their daily living, thereby adapting and adjusting to the urban structure.

This premise is used even for shorter-term trends and urban planners expect that population will follow the built environment and act accordingly, i.e. to uphold the values promoted by new developments.

Travel is generally associated with a disutility (except for some discretionary trips that enable individuals to obtain benefits from the activities performed during travel and where travel is seen as a valuable activity in its own right, see Mokhtarian et al., 2001; Ory et al., 2004; Páez and Whalen, 2010; Redmond and Moktharian, 2001; Whalen et al., 2013) and this has major implications for travel behaviour. Typically, and unless superior motives or constraints dictate it, a trip is only made if the gain or satisfaction achieved at the destination is higher than the cost of reaching that destination (Stutz, 1973; Ortúzar and Willumsen, 2001). Therefore, 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.

The functioning of urban areas in space and time is based on multiple processes of spatial choice. Space provides a medium for connecting the individual, subjective and social measures with the objective, physical elements of the real world, including their spatial arrangement within the surroundings (Figure 2).

Space has a variety of connotations and presents itself at different scales, depending on the aspect in which it is considered. From personal to public or from individual space to real-world geographical space, spatial elements are experienced/perceived differently by individuals. Planning and performing activities (e.g., travel behaviour) within space have to account for the links between various spheres and the permeability of one space leading into another. Here the subjective perceptions may affect the use of space to a large extent; hence “space” is relative.

Figure 2 also shows that relationships underlying spatial behaviour and spatial decisions are not “global”, but depend on the local and individual circumstances, and on the types of forces acting on the urban environment; hence circumstances vary across space. The four quadrants present two clusters: objective measures, regarding primarily supply (quadrants 2 and 3) and demand characteristics and perceptions (quadrants 1 and 4). The concentric areas display core concepts and provide descriptors that illustrate the themes and their scale, for example “safe”, “green”, “attractive” urban areas represent signifiers of intangible qualities for comfort and image (quadrant 4), whereas “close” and “walkable” refer to accessibility (quadrant 3) or “vital” and
“sustainable” to the overall functionality of urban areas (quadrant 2). The outer area represents the objective and measurable data.

Given the non-reversibility of spatial planning decisions, it is therefore extremely important not only to consider objective and aggregate measures of space, but also to include in the assessment the variety of subjective measures and the multiple interrelationships affecting spatial processes and travel.

Figure 2: Aspects and Scales of Space – Objective and Subjective Measures

Note: This figure has been based on Hall (1966) - graphical depiction adapted from en.wikipedia.org/wiki/File:Personal_Space.svg and pps.org/reference/what_is_placemaking/, both accessed in November 2013.

In addition, the neighbourhood shape and scale parameters, their appreciation and manner in which they are 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. But this may not be the right scale to assist in gaining a better understanding of localised interactions and how decisions are made. With this level of granularity, it is unclear how individuals perceive space and the scale of their
surroundings, or how they filter spatial information when making spatial choice decisions (Golledge and Gärling, 2002; Krizek, 2003; Guo and Bhat, 2004; Bhat and Guo, 2007).

Most of the geographical analysis is based on the assumption that “likes attract each other”. In other words, entities located spatially close to each other seem to be more similar than entities further away. This spatial dependence represents one of the main characteristics of geographical phenomena (Miller, 1999b; Miller and Shaw, 2001) and it is in general measured by spatial autocorrelation (see Cliff and Ord, 1973, for a seminal work describing the phenomena; or Hubert et al., 1981, 1985 for classical papers on assessing spatial autocorrelation effects). The adjacency and tendency to homogeneity in a small “neighbourhood” leads to clusters/pockets of locations with high correlation along one or more attribute dimensions (O’Sullivan and Unwin, 2003). These dimensions may be socio-economic characteristics, infrastructure (transport) features, pollution concentrations or exposure, travel patterns, etc. Another special feature of space is the degree of uniqueness of each location with respect to the overall spatial system – called spatial heterogeneity (Miller, 1999b; Fotheringham et al., 2000; O’Sullivan and Unwin, 2003; Páez and Scott, 2004). This means, although a neighbourhood may be homogenous in housing stock, each property is unique and has features making it distinguishable from others. Because of this, a spatial gradient exists in most spatially associated behavioural systems, i.e. where general behavioural processes become the result of locally contingent interactions. In modelling terms, spatial structure affects both the estimation of the model parameters and the residuals, and consequently, analyses that do not capture spatial dependency and heterogeneity could be invalid and unreliable (drifts of the parameters, underestimated parameter errors).

Geo-technologies (GIS, GPS, remote sensing) and modelling techniques – parametric or non-parametric – provide a vehicle for disseminating spatial analysis to transport researchers and practitioners. Various technologies have been developed (geographically weighted regression, multilevel analysis for separation of individual vs. place heterogeneity), but little has been applied to travel behaviour (notable exceptions: Páez, 2006; Farber and Páez, 2007; Páez et al., 2009). This research seeks a re-consideration of these approaches (adopted by a rather limited scientific community of geospatial scientists) as the state-of-the-art path for advancing the geospatial understanding of urban travel behaviour, whilst eliminating the artificial division between geography and travel.
2.2 Connecting Land Use and Travel Behaviour

As outlined earlier, there is reasonable agreement in the transport academic community that, despite the explosion of empirical studies over the past two decades, it is still premature to draw any conclusions from the evidence regarding the impacts of the urban form on activity-travel behaviour.

More specifically, two main streams are identified:

- research stressing the importance of spatial structure in adequately describing residential location choice, accessibility, and travel behaviour (e.g., Gordon et al., 1989; Salomon and Mokhtarian, 1998; Prud’Homme and Lee, 1999; Schwanen, 2002; Pozsgay and Bhat, 2001; Schwanen and Mokhtarian, 2005a, 2005b; Cervero, 2005; Hanson et al., 2005; Khattak and Rodriguez, 2005; Naess, 2005; Handy et al., 2005; Chen and McKnight, 2007; Weis and Axhausen, 2009);

- research questioning the role that spatial context plays in travel behaviour (or its magnitude) and supporting individual characteristics as the main factor in explaining observed behaviour (e.g., Meurs and Haaijer, 2001; Timmermans et al., 2002; Scheiner and Kasper, 2003; Weber and Kwan, 2003; Bhat and Guo, 2007; Fan and Khattak, 2008; Kim et al., 2007; Cao et al., 2009; Zolnik, 2009; Ewing and Cervero, 2010).

Prior to probing the detailed evidence and investigating motivations and reasons behind this apparent dichotomy, it should be noted that a multiplicity of terms and expressions are used within the research community to describe essentially identical aspects. It is the author’s view that this lack of an agreed common language does not necessarily represent a lack of rigour within this research field, best described as an evolving area of investigation; yet, to integrate a discipline requires specific denominations. Many terms are used freely, often mutually interchangeable, for example “spatial structure”, “spatial context” or “built environment”, “urban fabric”, “urban form” etc. Depending on the context of the application, or on the user’s preference for a certain term (also a reflection of their professional background), a rich discourse and blend of concepts is apparent. For example, where urban planners would possibly refer to “urban regeneration” or “smart growth”, geographers or engineers are more inclined to use technical terms, such as “a master-planned city”, whereas architects may have a preference for more creative expressions, such as “new urbanism”. Ultimately these are all generic terms describing an approach to delivering efficient, inclusive, vibrant, safe and sustainable urbanisation.

Returning to the two opposing views on urban form and travel decisions, some evidence in favour of one or the other assertion is presented in the following.
In explaining an individual’s travel decision making, Gordon *et al.* (1989) argued that it is the spatial context of urban form, unrelated to population density, which determines travel behaviour and accessibility. Salomon and Mokhtarian (1998) had similar views; they suggested two main related advantages in developing “smarter communities” with high levels of access: short distance between activity locations and a potential for increased use of public transport alternatives. Considering overall benefits, Prud’Homme and Lee (1999) claimed a relationship between productivity of a city and its efficient transport and land use planning (so-called “urban management”). Cervero *et al.* (2002) found real benefits of TOD in terms of more environmentally friendly travel behaviour.

At the individual level, Chen and McKnight (2007) found a significant impact of the spatial context on travel and even suggested that a reduced level of trip chaining (reflecting an increased opportunities space to match demand within an accessible environment) could be seen as a “success measure” for accessibility. The reasoning provided is that an individual’s activity sequencing behaviour may be deterred or fostered by the provision of transport and other urban amenities. This seems plausible; where the underlying activity opportunity densities are high, visits to fewer locations are needed to fulfil the daily activity needs. Increased land-use may come with the additional bonus of improved accessibility to public transport or other non-motorised transport alternatives, better quality of environment and health. Chen and McKnight (2007) also noted that a smart urban form could even increase the mobility of its population, as a lot more activities could be realised within given time constraints.

Moving to a different spatial scale, Greenwald (2006) focused on intra-zonal trips to discuss the urban form influence on destination selection by individual travellers. Because intra-zonal trips are shorter in distance and many associated activities are shorter in their duration, they are more likely to be candidates for mode and destination changes as result of modifications in the urban form. Both the variety and scale of economic activity plays a significant role in choosing intra-zonal destinations, but a small influence of street design and housing concentration is evident as well. Greenwald (2006) also suggested the existence of threshold effects for size of economic activity (5-10 employees/business) in the ability to alter travel behaviour. Related to local travel, Loukaitou-Sideris *et al.* (2002: 146) obtained “subtle” relationships between the physical as well as social station characteristics and the urban surroundings and crime levels around rail stations when testing correlations between urban form and human behaviour.

On the other side, in the camp of researchers advocating the prevalence of individual effects on travel behaviour, the findings are more contrasting. Bhat and Guo (2007) recognised the complexity in describing and measuring the interrelationships between urban form and travel behaviour, and the role that individual characteristics, such as self-selection (residential sorting) and demographics, as well as income categories, may play. However, Bhat and Guo (2007) did
not exclude or question the importance of spatial context in their research. Similarly, Eluru et al. (2009) treated individual preferences as determining factors in the choice of an urban form conducive to a favoured lifestyle. Kim et al. (2007) made some progress by showing that individual characteristics (socio-demographics) and attitudes (preferences, concerns, and perceptions) played moderator roles in the link between urban form and travel. In Australia, Curtis and Olaru (2010a, 2010b) highlighted significant relations between personal preferences and circumstances with location choices, connecting a lack of car ownership with a clear preference for residential proximity to public transport services.

In an attempt to resolve the disagreements in the research community, Leck (2006) undertook a statistical meta-analysis of the impact of urban form on travel behaviour. The results appeared even more ambiguous. In support of the role attributed to the spatial structure, he concluded that residential density is “the most important built environment element influencing travel choice” (p.37). His findings therefore affirmed the strong predictive nature of a carefully selected, mixed and scaled land use (as described by density and diversity) on travel behaviour, and in particular mode share, whilst further softening the role of socio-economic parameters. He also concluded that “the claim of many New Urbanists and Neo-Traditional planners concerning the advantages of a grid layout and continuous sidewalks design does not seem to have merit” (p.54), an argument that calls for caution when hypothesising travel behaviour changes as a direct result of certain urban form characteristics. In essence, he could not endorse a positive shift toward public transport based on improvements in neighbourhood walkability alone. This concurs with similar evidence obtained by Khattak and Rodriguez (2005: 484) and Schwanen and Mokhtarian (2005a and b), re-affirming the equivocal nature of findings on the influence of urban form characteristics (e.g., footpath conditions) on travel behaviour at the neighbourhood level.

Given these conflicting results in the literature, the call for a more comprehensive consideration of the connection between urban form and travel behaviour, accounting for the intricate interrelationships and decision-making processes involved, is warranted. Chen and McKnight (2007) recommended more research to explore the relationship between spatial context, specific characteristics of the urban form and human behaviour, and stressed the importance of research associating the spatial context with accessibility measures, activity and travel patterns. On a similar note, Bhat and Guo (2007) highlighted two major inter-related problems that need to be carefully addressed by scholars: (1) complexity and multi-dimensionality of the relationships, and (2) control for any spurious association due to residential sorting, a prerequisite to obtain insights about the “true” causal impact of the urban form on travel behaviour.

Consequently, any effort to further resolve this research dichotomy, ultimately leads back to a fundamental question formulated in this research: How does one best attempt to measure travel
behaviour changes over time, within a spatial context and reflecting the complex and multi-dimensional nature of various relationships?

While many prior studies approached this question with a somewhat sectoral and/or myopic view, considering in isolation or explicitly only aspects such as mode share, ridership, travel distances and times, trip frequencies and trip chaining, Section 4 of this research introduces a geo-spatial approach using Activity Spaces. Given their nature, Activity Spaces allow for integration of multiple elements into one construct, reflecting both demand and supply. In response to the research question above, the Activity Space analysis provides a “vehicle” for researchers to capture and reflect underlying complex relationships in urban processes in a single measure.

2.3 Urban Growth and Urban Sprawl

In history, often once a relatively stable socio-political environment had been achieved within a society, residential clustering, closeness and intra-urban proximity within traditional, compact cities often became more or less redundant. This is because the physical shelter provided by the city’s protective, often fortified environment, no longer served a purpose or even posed a risk to its inhabitants such as to health and safety (e.g., The Great Fire of London in 1666, or The Great Plague 1665-1666 in the Kingdom of England). What took priority later in the 19 and 20th century was access to employment and urban facilities via transport (Grübler, 1990; Anas et al., 1998; Ingram, 1998; Angel et al., 2011; Ween, 2012). Driven by strong population growth and expanding economic activity, together with the longing for a more liveable, village like environment, the footprint of urban areas has since been enlarged. The range of opportunities increased and transport services dictated the conditions for reaching various destinations. The time-space accessibility improvement that allowed modern city dwellers to perform their daily activities, to satisfy essential and supplementary needs, is the basic premise underlying classical economic theory of urban spatial structure (Alonso, 1964; Mills, 1967; Muth, 1969; Wheaton, 1976; Anas, 1978; Brueckner, 1987). This theory posits that urban areas expand in line with increases of population and income, but also with a reduction in transport (generalised) costs. Levinson (2008), who analysed the effects of suburban expansion in London found feedback mechanisms between rail investments and population movements, confirming the strong spatial relationships between co-development of transport infrastructure and population growth. He stated that transformation processes of traditional urban areas are aligned with the increasing availability, speed and efficiency of the transport systems. New and fast transport systems emerge, grow, reach maturity, then saturation, and subsequently decline, as they are replaced with even faster alternatives (Cervero, 1985; Grübler, 1990), enabling a continuing
metamorphosis of urban structure ("the persistent S-shaped life cycle model", Grübler, 2003: 353). With new transport technologies and transport infrastructure network expansion as catalysts, this morphological change led to vastly spread-out and functionally diffused urban areas, absorbing land on the fringe, where it was more readily available and affordable (Heimlich and Anderson, 2001).

Hence, within the last century, the world has seen many “modernised” Western cities reaching far out into their surroundings. Multiple terms have been developed to refer to this process: conurbation, subtopia, sprawl, sub- and peri-urbanisation, describing a transformation that was driven by the “accelerated shrinking of distance” (Axhausen, 2007: 16) and fostered by urban planning and transport decisions aimed at increasing the liveability and productivity of the city (for a detailed explanation of the processes, e.g. see Friedrichs, 1977).

In the evolution of many North American and Australian cities, the increasingly rapid and seemingly uncontrolled expansion or “sprawl” of urban development substantially relied on the ubiquitous nature and availability of the car. Interestingly, in Australia, this “love affair with the automobile” has driven car ownership levels to the height of 2.1 cars per household, which represents the fourth highest level of car-use by world standards (Weller, 2009: 83). In the case of Perth the trend is continuing, as “currently 70 % of new residential development still occurs at or beyond the boundaries of developed areas” (Weller, 2009: 81), with little employment and access. This seems to further exacerbate the city’s already high level of car dependence, even though observations in many countries of the developed world seem to suggest that car ownership may have reached a maximum, the “peak car” phenomenon (Newman, 2012).

Notwithstanding, the trend of dispersion and decentralisation has remained largely uncurbed and is predicted to continue, especially in developing countries (Angel et al., 2011). In many of these countries, new urban growth means developing into peri-urban areas, beyond the suburban fringe, or even farther afield into the rural hinterland. Often, cities are growing by converting otherwise undeveloped natural areas, reshaping natural habitat with mono-zoned, repetitive dwelling patterns of low residential density. Frequently, this process has threatened wildlife and caused destruction of productive agricultural areas, that historically provided valuable resources to sustain the daily life in the cities (Heimlich and Anderson, 2001; Ewing et al., 2005; Irwin; 2004). It appears that, supported by modern transport, processing and handling technologies, a spatio-temporal and low-cost omni-presence of most staple and even perishable food products has gained momentum in recent times. This has made low-value farm production on the urban fringe highly unattractive from an economic viewpoint, in comparison to more immediate and high monetary gains achieved by a shift of agricultural land to urban use - Ewing et al., 2005; Chen, 2000; An et al., 2011. At the same time, higher household incomes, an intrinsic and evolving human desire to secure and occupy space, and a favourable market fostering
affordability of (larger) land parcels on the urban fringe have made the urban expansion and dispersion possible. This was seen as an inevitable and natural process (Mieszkowski and Mills, 1993), which urban planners and transport professionals are now “mandated” to contain and, if possible, to reverse.

2.3.1 Positive and Negative Effects of Urban Growth

Growth has multiple effects. Economies of scale and increased standards of living through enhanced accessibility to a variety of opportunities via infrastructure provision represent obvious factors favouring urban development (Hansen, 1959; Anas et al., 1998, Ingram, 1998; UN Human Settlement Programme; 2009). Additional reasons for sparse, scattered peri-urban development patterns and polycentric cities, or, in some cases, "leapfrog" patterns of lower density development, include: more affordable housing and the lowering of congestion without significant increases in commuting times (Irwin, 2002, 2004); a more flexible and accommodating planning framework (Carruthers and Ulfarson, 2002); more cooperative relationships in both the development industry and local authorities or lack of otherwise competing players (Byun and Esparza, 2005); increased housing affordability; social stability; reduced crime rates and better child education opportunities (Mieskowski and Mills, 1993; Downs, 1999).

However, growth is also associated with adverse impacts on inhabitants and the local environment, both during and after post-urban transformation. Overall, the land-use transformations can: a) cause damage to ecological communities (both flora and fauna), potentially pose threats to rare species, or cause dramatic reductions in unique local habitat and arable land (Vitousek et al., 1997; Irwin, 2004; Chen, 2000, Weller, 2009); b) alter geo-hydrological and geo-chemical processes (Barron and Barr, 2009), with the result of subsequent adverse and often lasting environmental consequences of reduced waterway health or major changes in local micro-climate (Wong and Brown, 2011); c) increase air pollution (Newman and Kenworthy, 1999) and obesity (World Health Organisation, 2004) due to heavy car reliance and limited opportunities for trip substitution with healthier alternatives of walking or cycling, especially for commuting (Handy et al., 2002; Weller, 2009). These consequences intensify if the development pattern becomes more dispersed (Theobald, 2004). A concerning statistic was presented by Angel et al. (2011), who examined 3,646 metropolitan agglomerations and cities with populations in excess of 100,000 in the year 2000. They generalised the average global expansion rates of urban land at a rate that was more than double the growth rate of urban inhabitants. It is worth noting that congestion is often cited as a factor limiting growth, despite the fact there may be an increase in underlying demand. This is because congestion 'chokes off' demand, so the underlying trends are not always expressed (Graham and Glaister, 186:2006).
In 2013 Western Australia continued to record the fastest population growth rate of all Australian states and territories at 3.4% (Australian Bureau of Statistics, 2013). In Perth, the urban growth has seen the city expanding from north to south, down a coastal strip that now covers more than 100,000 ha of land, with 900 ha of native vegetation cleared each year between 1998 and 2004 (Weller, 2009: 125). This expansion is equivalent to an individual (ecological) footprint of 14.5 ha, required to sustain the life of an urbanite within the metropolitan area (Weller, 2009: 30). If Perth’s growth (Figure 3) is to continue in a business-as-usual manner (Weller’s so-called BAU-City), we will witness in the next few decades a doubling in its size, with 200,000 ha of low-density suburbia (12 dwellings/ha) stretched along 170km of coast (N-S).

Figure 3: Perth’s Spatial Footprint, incl. Forecast – Business As Usual (Weller, 2009: 26)

The decentralisation of cities and population and industry dispersion into the urban surroundings has differential impacts on a city’s social and environmental sustainability (Ewing, 1997). Sometimes, urban growth provides benefits to the outer municipalities, to the detriment of the inner urban core (Downs, 1999). However, the initial economic advantage offered to suburbanites and new businesses on the urban fringes may quickly be eroded by a range of adverse impacts (Boussauw et al., 2012). If low-density suburban developments insufficiently cater for essential facilities: transport, schooling, services, and even affordable housing alternatives, the effects go in the opposite direction; the structural separation city-suburbia and outward migration of employment options in newly developed suburban areas has frequently stranded many socio-economically disadvantaged, low-skilled and low-income households in areas close to the urban core, a phenomenon termed the “spatial mismatch”. Related to this, the “reverse commute” has become a common sight, with urban workforce travelling outwards, mostly by car, to access employment in peripheries with poor public transport. Observed mainly in Northern America, this phenomenon has resulted in job-housing imbalance and social and residential segregation following on from residential and employment suburbanising processes (Downs, 1999).
Obviously, the effects combine and propagate across the city and, these distinct spatial effects
and the time scales require specific examinations and recognition. For example, the
counterproductive impact of public transport fare capping (for socio-economic reasons) it worth
noting here, since it disproportionately favours longer distance travel and thereby reinforces
space versus transport decisions of households.

In terms of bearers of the effects, local communities ultimately feel the burden of retrofitting
costs for missing or inadequate infrastructure and facilities. This is particularly the case where
projects commenced without adequate developer contribution to the provision of community
services in newly developed areas, all with the idea of gaining initial economic momentum. The
rather “unfair” advantage given to the expansion of a dispersed development pattern (yet to
include essential urban services) over urban densification is an outcome that should be
eliminated from practice (Anas et al., 1998).

2.3.2 Inescapable Urban Growth

Notwithstanding its negative consequences, there are lasting positive aspects of urban growth,
leading to long-term economic growth of whole regions. This is especially relevant if the
expansion continues in areas where spatial growth is bound by natural or administrative
boundaries (which changes the direction of development from horizontal to vertical) or if it
occurs at a geographical scale and density that enables an ultimate agglomeration of individual
sprawled cities to begin, forming an inter-connected “mega” city (e.g., New York, Boston-
Washington Area, Tokyo, European Backbone). Cities that have merged with each other in this
manner can better exploit hidden or otherwise inaccessible opportunities, which, together with
an interchange of labour, resources and other economic synergies, can reduce the need for
further expansion (for example there are well documented accessibility benefits in regions such
as around Zürich, Switzerland, the Boston/Washington area (BosWash) in the USA and even in
Tokyo, Japan, where agglomerations that have evolved near major rail stations and begun to
foster more uniform trip distributions and mode shares across the metropolitan area (Alpkokin
et al., 2007). Both types of development, vertical and megacities, are supported by high
population and employment densities. Given the vastness of the territories, and the sparse
distribution of cities across geographical space in North America, and especially in Australia,
the likelihood of efficient agglomeration cities emerging is immensely reduced.

2.3.3 Solutions - Urban Development “in an Opposing Direction”

“To a large extent, the suburbanization of population is a short run dynamic response to the
failure of inner city densities to adjust upward” (Anas, 1978: 84).
Contemporary planning seeks to address the expansion pressures of cities by fostering development “in the opposite direction”, i.e. by devising policies and development strategies intended to contain urban sprawl. One building block to promote more compact urban solutions has been seen in the implementation of Transit Oriented Developments. Compactness (high residential density and land use mix) combined with good public transport services can be seen as the first form of Transit Oriented Development (TOD) – with similar historic precedents for TOD going back as far as the early master-planned worker’s estates established near London during the 18th Century (Carlton, 2009), built around the principle of proximity to employment, access to facilities and available transport systems. In the modern context, this simplistic form of TOD has been expected to encourage a reduction of car travel and substitution of public transport and/or other environmentally friendly travel modes (Cervero, 2001a,b; Cervero and Duncan, 2003; Transportation Research Board, 2004; Center for TOD, 2006; Curtis et al., 2009; Dittmar and Ohland, 2004; Wilkinson, 2006; Spielman and Yoo, 2009; Ewing and Cervero, 2010; Kamruzzaman et al., 2014; Institute for Transportation and Development Policy, 2014).

By increasing the accessibility to local activities and promoting alternative transport modes, as well as creating environments conducive to walking and cycling, it is believed that individuals/households will take advantage of these opportunities and decrease their overall demand and distance to travel (Boarnet and Crane, 2001; Buliung and Kanaroglou, 2006b; Cervero and Kockelman, 1997; Handy et al., 2005; Crane, 2000; Ewing and Cervero, 2001; Kamruzzaman and Hine, 2012; Aditjandra et al., 2013).

Analysis by Bertolini (1999) starts to unpack the potential solutions for managing the urban growth. One is distributing hubs of activities across the city from a polarised monocentric development scheme toward a poly-centric city (“deconcentrated clustering”, see Bertolini, 1999: 209). In fact, empirical evidence suggests that most urban systems experience a transition from a monocentric to a polycentric organization as they grow and expand (Louf and Barthelemy, 2013:198702-1). The “network city” or a city based on strategically placed activity centres, developed around public transport nodes, ensures compactness and accessibility, whilst accommodating growth. The “network city” philosophy has been embraced in Perth, Western Australia in the past years (State of Western Australia, 2010a, b, 2011) and will be described in greater detail in Section 5.2. Similarly, poly-centric city models have been pursued in cities elsewhere around the world (e.g. Sydney, New South Wales).

A hybrid solution (a network of urban developments with mixed land use and oriented towards public transport) was further discussed recently by Weller (2009: 264-274), who referred to a late 19th century planning idea (the Garden City concept, developed by Ebenezer Howard) as an answer for urban sprawl. Weller (2009) proposed the Garden City, “one of the most influential planning forms of the time” (United Nations Human Settlements Programme, 2009: 49), “as a
new kind of 21st Century village, a POD” (Weller, 2009: 268). A POD (which is a Performance Oriented Development) is an expansion of TOD that incorporates ecological performance measures related to urban form. Weller (2009) even recommended 48 Garden City style development nodes in Perth, with 40 dwellings/ha, to adequately accommodate the projected urban growth. Although Western Australia is far from the POD planning form, there are directions in place to suppress a further urban spread through TODs.

The next section presents the characteristics of TOD, which made it a fundamental contemporary planning paradigm.

2.3.4 TOD, Smart Growth and New Urbanism - Definitions and Characteristics

TOD is related to concepts of “Smart growth” and “New Urbanism” (Congress for the New Urbanism; 1996; Smart Growth Network, 2003; Curtis et al., 2009; Ewing and Cervero, 2010) and embeds the principles of “D variables” – density, diversity, design (Cervero and Kockelman, 1997) enriched with destination accessibility and distance to public transport (Ewing and Cervero, 2001; Ewing and Dumbaugh, 2009). Demand management and demographics (the latest additions to the “D” list) are included in a few studies, mainly to control for confounding effects (Ewing and Cervero, 2010). Over the last decade, planners and politicians, who have realised the multiple benefits of TOD, reaching far beyond the originally anticipated potential, have internationally adopted the TOD concept. Under the term “Green TODs” (Cervero and Murakami, 2010), next-generation transit-oriented developments are currently taking shape in many places around the world, aiming to create ultra-sustainable, self-sufficient urban environments. While the core planning tasks remain focused on spatial integration of transport and land use planning, consideration of environmental and community planning aspects are becoming increasingly interlinked with the traditional TOD model (Cervero and Ewing, 2010; Cervero and Murakami, 2010).

TOD has originally been flagged as a model of joint land-use and transport development, promoting smart growth (as opposite to urban sprawl), injecting vitality and expanding lifestyle choices (Newman and Kenworthy, 1998, 1999; Transportation Research Board, 2004; Dittmar and Ohland, 2004; Renne and Wells, 2004; Renne et al., 2005). Varying definitions of TOD exist. Many are given in the Transit Cooperative Research Program (TCRP) Report 102 on Transit-Oriented Development in the United States: Experiences, Challenges, and Prospects (Transportation Research Board, 2004) and they are summarised next.

Essentially, TOD is associated with moderate to high-density development, located within an easy walk (approximately 800m) of a major public transport stop (operating on highly synchronised and reliable timetables, at high frequency (5-15 min) and with extended operating
hours), generally with a mix of residential, employment, and shopping opportunities, designed for pedestrians and cyclists, without excluding the automobile (Transportation Research Board, 2007b; Centre for Transit Oriented Development, 2006). This definition was recently revised by the Institute for Transportation and Development Policy (2014), which proposed a new standard of TOD with 21 metrics, based on eight principles: walk, cycle, connect, transit, mix, densify, compact and shift. TOD creates conditions for better coordination of services in space and time due to a greater possibility for combining various activities. TOD can be delivered as a new “green-field” development or as a re-development or retrofitting of existing built-up areas, both with the design aim and planning orientation geared to facilitate public transport use (California Department of Transportation, 2002: 3). A well-designed TOD is expected to enhance access to opportunities both at the city level as well as the local level. This means that TODs are likely to better account for the individual and diverse activity needs, which has positive impacts on realised travel patterns (Curtis et al., 2009).

In terms of residential and commercial density, various guidelines have been proposed. Based on early TOD research, Calthorpe (1993) recommended that TODs allocate a minimum of 20% of their land area to housing, with an average minimum residential density of 10-15 dwelling units per acre, depending on the location of TOD. Calthorpe (1993) also suggested minimum floor area ratios of 30% for retail with surface parking and 35% for offices without structured parking. These values are not achieved in numerous TODs in Australia (see Australian Bureau of Statistics, 2011 for further information), and different criteria had to be set. Newman (2005) proposed a minimum of 35 people and jobs per ha for a decent public transport system to be built (with this kind of density also being associated with a minimum array of urban services and amenities). They added that a local centre can be created with 10,000 people and jobs (1 km radius area), or a town centre can be created with a population of 50,000 people and jobs (3 km radius area).

With respect to the distance from the public transport station, there is a wide variety of walking distance guidelines, generally between 400 and 800 m (Dittmar and Ohland, 2004; O’Sullivan and Morrall, 1996). O’Sullivan and Morrall (1996) reported in Calgary, Canada average walking distances to the suburban light rail transit (LRT) stations of 649 m and to the CBD stations of 326 m. They found that people tend to walk further to reach an LRT station than a bus stop and raised a concern regarding a likely underestimation of LRT walking distances. Similar findings were presented by Daniels and Mulley (2013), based on HTS data in Sydney. Cervero (2001a) found up to 1 km walking distance in the Bay Area Rapid Transit (BART) system in California, but this is still low compared to the distances advocated by the World Health Organization (WHO) as acceptable and realistic for an adult (based on European studies, WHO suggests policies promoting a shift towards more walking and cycling as transport modes...
should concentrate on the trips for which motorized modes are often used but whose length easily permits their completion on foot or by bicycle; this applies to many trips shorter than 5 km) – (World Health Organization, 2004: 32).

An important distinction needs to be made between TOD and its “evil brother”, the “transit-adjacent development” (TAD – see Arrington, 2003; Cervero et al., 2002). TAD can be defined broadly as development in close proximity to public transport, generally within one-quarter mile (400 m). Whilst the development is close to public transport, it is not specifically oriented to public transport, and this is reflected in the travel behaviour of people around it.

2.4 TOD and Travel Behaviour

In Section 2.2 generic relationships between urban form and travel have been discussed. This section will explore further the details of this relationship, specifically under the notion of Transit Oriented Development. It is mainly focussed on associations, not causality. For further reading on the latter, the reader is referred to Cao et al. (2009) whom undertook an extensive literature review and analysis of empirical evidence on association and causality, including residential self-selection. Four criteria must be met in order to infer that TOD causes travel behavioural change, including: a) associations – a statistically significant relationship between the cause (e.g. TOD) and effect (e.g. travel behaviour); b) non-spuriousness – a relationship that cannot be attributed to another variable; c) time precedence/order – the cause precedes the effect; and d) causal mechanisms – a logical explanation for why the alleged cause should produce the observed effect. Much of the prior research in the context of TOD has satisfied only the first two criteria because it has been based on cross-sectional research design – testing relations between built environment and travel, accounting for residential self-selection and attitudes. Section 2.5 will then further clarify and elaborate on the difference between causality and associations as part of this research.

TOD is meant to encourage a higher uptake of cycling and walking and the use of public transport services, whilst diminishing the reliance on car driving (Cervero and Duncan, 2003; Handy, 2006; Badland et al., 2008; Zhang, 2005; Villanueva et al., 2012; Kamruzzaman et al., 2014). Reporting on a detailed analysis of 12 housing projects near BART stations in San Francisco, the Cervero et al. (2004) established that TOD areas recorded an average 1.66 persons and 1.26 vehicles per household, compared to 2.4 persons and 1.64 vehicles for all households located in the census districts considered by the study, outside TODs. Whereas only 48% of all households in the whole area had fewer than two vehicles, in the TOD districts 70% of households owned less than two vehicles; the finding was linked to the good accessibility of
public transport, which enabled households to reduce their car dependence. In consequence, TODs also offer the potential to reduce the demand for parking per household (by 23%).

While Cervero (2001a, b) did not statistically test the direction of causality in those studies (i.e. do TODs cause people to own fewer cars, or are people with fewer cars attracted to TODs?), he cited other empirical work supporting the assertion that residents are choosing to live in TOD locations that offer good public transport accessibility (particularly to job sites) and hence enable reduction of car use. Cervero (2001a, b) also reported on accessibility and mode choice, and identified the prevailing mode chosen for commuting in relation to the access mode distance (walking - 1 km or less; bus public transport – 1 to 1.6 km, park-and-ride - beyond 1.6 km). Similar results were found by Wachs et al. (2007), where public transport mode decreased with the distance from the railway station (e.g., Washington and California BART).

When comparing conventional and “neo-traditional” neighbourhoods, Khattak and Rodriguez (2005) found that single-family households in “neo-traditional” neighbourhoods replace car trips with walking trips and reduce travel distances much more than households in other areas; this was the case even after controlling for demographic characteristics and for residential self-selection. Later, in a review of many empirical studies, Kim et al. (2007) established that the association between public transport availability/accessibility and car ownership was statistically significant, although minor in comparison to household characteristics and car ownership.

Population density is another key factor that matters in developing a wide range of services and amenities and operating successful public transport, and density is often correlated to ridership. Pushkarev et al. (1976) suggested a critical threshold of at least 30 persons per hectare within walking distance of stations for sustaining public transport. 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. When analysing public transport ridership for the MetroRail in Arlington County, Virginia, Cervero et al. (2004) identified a strong positive relationship between additional office/retail floor space near the station and a public transport passenger increase (approximately every additional 9,000 m$^2$ floor area resulted in a 50 person share increase in ridership).

Likewise, Chen and McKnight (2007) reviewed the role of density as a measure to explain activity-related time-use behaviour. On the one hand a proximity-based theory was reinforced, where due to “closeness” of various activity opportunities in high density areas a positive association between activity-related time-use behaviour and density exists (Levinson, 1999; Goulias, 2002); on the other hand, this relationship changes, depending on the density levels: at very low densities (less than 200 persons/m$^2$) people spent significantly more time on travelling

41
and less time on shopping; between 200 persons/m² and 8,000 persons/m² constant relationships were revealed; finally, at densities above 10,000 persons/m² 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.

On the topic of 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 essential to ridership of public transport (Kim et al., 2007).

This short presentation of the behavioural links between TOD and travel behaviour indicates that TOD is likely to affect residential choice as well as car ownership decisions, with further impact on activity-travel patterns. But the 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, b; Kamruzzaman et al., 2014). 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).

2.5 Self-selection or Residential Sorting

Residential self-selection or sorting indicates a preference of households to locate according to their travel preferences (Bhat and Guo, 2007). This proclivity has been frequently cited as one of main difficulties in assessing the strength of relationships between urban form and travel behaviour. For instance, Bagley and Moktharian (2002) could not confirm a significant role of the built environment in influencing travel behaviour, once self-selection had been accounted for within the analysis.

This phenomenon simply shows that residential relocation/mobility behaviour, driven by underlying complex determinants of personal characteristics, preferences and attitudes, together with manifold attributes of the urban form, represent a critical aspect in gaining a better understanding of land use-travel dynamics. Long-term comparison of activity travel choices and patterns, the assessment of LUTE (Land Use Transport Environment) policy implications, or the predictive power of land-use planning and transportation models (Eluru et al., 2009) are all subject to residential self-selection. The assumption that households locate themselves in
neighbourhoods and then, based on neighbourhood attributes, choose how they travel, may lead to spurious causal effects of urban form on travel (and potentially lead to misinformed design policies) (Boarnet and Crane, 2001; Cervero and Duncan, 2003; Krizek, 2003; Kamruzzaman et al., 2014). For example, when good land-use mix is associated with decreased car trips in the population, rushing into the conclusion that land-use has caused the reduction of car travel (and ignoring the reasons behind the residential and travel choices) is a serious mistake. Households and individuals who are auto-disinclined, because of their demographics (e.g., lower income), attitudes (e.g., more active), or other characteristics, may search for locations with high residential densities, good land-use mix, and high public transport service levels, so they can pursue their activities using non-motorised travel modes (Kitamura et al., 1997; Kitamura et al., 2003; Handy, 2006; Bhat and Guo, 2007; Chen and McKnight, 2007). If this were to be true in a particular city, urban land-use policies aimed at, for example, increasing density or improving the land-use mix, would not necessarily stimulate lower levels of car use in the overall population, but would rather alter the spatial residence patterns of the population based on their desire for car trips.

In addition, it appears that the urban form can constrain underlying individual preferences with asymmetrical effects, i.e. suburban dwellers with a preference for non-car travel are struggling to fulfil this desire in areas devoid of a traditional urban fabric, whereas suburban individuals who reside in surroundings that are more suited to non-car travel, by providing a range of typical urban facilities and services in close proximity, in most cases are still able to realise their preferences for car travel (Cao and Mokhtarian, 2005).

Overall, evidence shows that urban design and integrated land use and transport planning alone will not necessarily bring about changes in travel behaviour that, in turn, lead to less congestion and other social, environmental, and economic benefits. Rather, an ensemble of solutions is required to achieve all-embracing satisfactory outcomes. Public policy tools such as growth management and transport demand management (e.g. congestion pricing) are also needed for truly effective changes in travel behaviour (Srinivasan and Bhat, 2006).

### 2.6 Impacts/Benefits of TOD

Effects of public transport and associated TOD investments include reduced car dependence and increased public transport ridership, along with more walking and cycling (Cervero, 2005; Chen and McKnight, 2007), increases in property values (Transportation Research Board, 2004; Hess, 2007; Pagliara and Papa, 2011), as well as stimulation of economic development at the local level. They were clearly articulated and summarised in the report of the Center for Transit
Oriented Development, CTOD (2006), which contended that creating and preserving diverse TODs has a multiple positive impact on households and regions: greater housing and transport opportunities, better environmental outcomes and stronger family and neighbourhood economies.

Notwithstanding their obvious benefits, there seem to be problems with the broader acceptance, adoption and implementation of TOD, Smart Growth or New Urbanism principles. Sometimes, only one outcome is considered, at other times the combined benefits are yet to be evaluated. From a national survey of US public transport agencies, Cervero et al. (2004) realised that professionals see TOD as a way to increase public transport ridership, with promotion of smart-growth and community economic development remaining as secondary goals. As stated in Cervero et al. (2004): “Relatively little empirical research has been conducted documenting the economic benefits of TOD beyond studies showing developments near rail stations boost ridership and increased land values” (p. 453). However, more recently, mitigating urban sprawl and promoting healthy environment and community (health and safety) have been highlighted in the list of TOD benefits, along with increased use of public and non-motorised transport modes (Transportation Research Board, 2007b).

These gains trace back to accessibility effects provided by public transport, both at citywide and local levels (Hsu and Hsieh, 2004). Nevertheless, the TOD benefits are much more than that. They increase the benefits of developing urban public transport systems through their amenity components. By adding the right mix of land use in proximity to the public transport stations and by providing walking and cycling friendly areas, TODs have a positive effect in urban land markets, in revitalisation of the urban areas, and in the quality of life of the community (Türksever and Atalik, 2001; Litman, 2011; Topalovic et al., 2012). These aspects have recently been discussed by Bartholomew and Ewing (2011) in a summary of the literature on accessibility- versus design-related effects of pedestrian and transit-oriented developments and are also highlighted in the new TOD Standard by the Institute of Transportation and Development Policy (2014).

Transport-related effects are frequently segregated into three categories: reduced congestion and improved air quality, better accessibility, and economic development. Mackett and Edwards (1998) reported all of them, showing that improving public transport reduces traffic congestion, serves the city centre better, improves the environment, and stimulates development. However, Prud’Homme and Lee (1999) suggested that by introducing urban and transport policies to contain urban sprawl and improve transport efficiency, significant urban productivity gains can be achieved. This is based on the formation of agglomeration economies (effective density), with improved opportunities for interaction, accessibility and concentration of labour, markets and economic activity (as well as specialisation and division thereof) within spatially confined but
well-organised and interconnected clusters. However, they are generators of congestion, which, in its turn, has a negative feedback influence on growth. Reducing traffic congestion was considered the most common reason for building new public transport systems (Hass-Klau et al., 2004). However, the nature and magnitude of effects seems to depend on the type of transport system, e.g. greater capacity and productivity of heavy rail over light rail and bus transit, but potential negative effects due to noise (Cervero and Duncan, 2002; Topalovic et al., 2012).

Land-related effects are however the aspects that make TODs stand out as a planning tool. The mix of facilities attracts residents and businesses. Some people move closer to TODs because of the housing stock and perceived surrounding amenities, rather than access to public transport; Cervero et al. (2002) observed that housing near a station means higher housing costs per m\(^2\) and a household may trade-off savings on their mortgage with moving further away. The review by Cervero and Duncan (2004) showed price premiums of 6.4 to 45% for houses located within \(\frac{1}{4}\) to \(\frac{1}{2}\) mile from a station; and the regression analysis by Debrezion et al. (2007) indicated 2.4% increases in property values for every 250 m closer to a station. Lower price increases occur for businesses: 0.1% for every 250 m (Debrezion et al., 2007) or 8-40% (Cervero and Duncan, 2004).

In Perth, empirical evidence indicated that affordable housing around TOD was a main pull-motivation for choosing residential location in precincts on the southern rail corridor, followed by locational and environmental attributes (Olaru et al., 2011). In the same study (and consistent with Theriault et al., 2005), it was found that TOD added value to housing, as a result of the bundle of accessibility and landscape changes with more consumer retail and services, pedestrian and cycling amenities. As stated by Cervero (2005:13), “TOD's synergy of proximity, density, mixed uses, and walking-friendliness, under the right conditions, gets expressed through geometric gains in property values”.

TOD modifications of the urban environment are expected to be an important enabler of physical activity and healthier lifestyles and to reduce costs associated with air pollution (Topalovic et al., 2012). Conversely, transport-related physical activity (TPA, walking or cycling for travel purposes) is positively addressing many public health and transport problems in a sustainable manner (Badland et al., 2008): increased engagement in sustainable, and physically active modes of transport is likely to reduce traffic congestion, CO\(_2\) emissions, and traffic infrastructure costs (Killingsworth and Schmid, 2001). Further, this will enhance perceptions of safety and visual amenity of the urban environment and overall physical activity levels. Moudon et al. (1997) examined 12 neighbourhood settings in Washington D.C., and identified increased physical activity that was three times more in traditional urban environments compared to the more recent suburban developments. Schlossberg et al. (2006)
supported the positive relationships between enhanced streetscape connectivity, physically active and environmentally friendlier modes of transport (EFM’s), and increases in walking for commuting purposes. Evans et al. (2007) also emphasised the role of the streetscape in encouraging walking trips – “a short walk made difficult by adverse environmental conditions such as high-speed traffic or lack of shade can seem longer while a long but pleasant and interesting walk can seem shorter” (Section 17 - P. 56).

With respect to access provided by public transport, Litman (2011) commented that TOD’s improved accessibility and affordable travel options alleviate exclusion of disadvantaged people, raising their productivity and opportunities. The bundles of transport and land use specific to TODs also affect community cohesion. Suburban locations are often considered highly livable because they are separated from disruptive activities, traffic, and delinquency. At the same time, rail stations may attract criminal activities (Loukaitou -Sideris et al., 2002), so it is the role of land-use to support social integration.

Related to accessibility, Murray and Wu (2003) drew attention to an apparent paradox. Transit access may suggest a greater number of stops, so travellers can easily “get in” the public transport. However, this degrades travel speeds, thereby limiting the geographical coverage in a given travel time. For TOD aiming to promote ridership, the stations should be seen as focal points of multi-modalism, providing good access to the final destination, accounting for the increased trip chaining in individuals’ daily travel (e.g. Kim et al., 2007; Ye et al., 2007).

To sum up, TOD impacts are observed in a number of areas: housing; access and inclusion; reduced car dependence and congestion; air quality and health. As described by the CTOD (2006), in US:

- TOD zones (800 m) support more race and income diversity than the average neighbourhoods, in both central and suburban contexts;
- TOD areas support important segments of the population in terms of both housing tenure and household size; they have a greater proportion of homeowners who spend more than 30% of income on housing;
- TOD zones reduce the attractiveness of car use and provide important mobility opportunities — and the economic benefits that accrue from it — that allow people to live with fewer cars and experience less congestion. In 3/4 of public transport zones, households have one car or less;
• TOD reduces congestion and promotes active transport;
• TOD may be a measure to address transport disadvantage and social exclusion\(^2\): in US, by 2030, more than 51% of demand of housing near TOD is likely to come from households with incomes below the area median income (US$50,000); 20% of households near public transport are likely to make less than US$20,000 a year.

Although not a standard in itself, CTOD set the scene for other policy documents, including the most current TOD standard. The 2014 standard is “an assessment, recognition and policy guidance tool uniquely focused on integrating sustainable transport and land use planning and design” (P.8) that outlined eight principles for TOD development: walk, cycle, connect, transit, mix, densify, compact, and shift, expected to form the assessment matrix for any existing or planned developments. The standard draws on research and practices around the world and is an easy tool to discriminate between TODs and non-TODs.

In order to achieve its goals of sustainability, TOD planning needs to pay attention to the spaces around public transport stops/stations (Institute for Transportation and Development Policy, 2014). Concerted efforts should promote genuine mixed-use land developments and multi-purpose activity centres, so that travellers are able to fulfil a variety of activity needs at a single location (without the need to undertake additional trips). This also means that transport interfaces at TOD stations are crucial for their success. In areas where high residential densities are not achievable, Park-and-Ride (P&R) facilities are a good “compromise” between car and public transport. Although less parking may be desirable (in the sense that it cuts “waste”/disamenity, reduces the separation of land uses, and increases infill development), when the car is a dominant means of connecting to public transport stations, particularly in suburbs, it is imperative to cater for the needs of these public transport riders (Cervero, 2001). “Insufficient park-and-ride parking at a TOD, without compensatory park-and-ride spaces elsewhere, can reduce transit ridership by limiting the auto access ridership component” (Transportation Research Board, 2007b: 17-66). Guidelines recommend 0.011 parking spaces /100 dwellings within 800m from a rail public transport station (Transportation Research Board, TRCP, 2007b, 17-58) for a good TOD.

\(^2\) TOD as an instrument is aimed primarily at addressing transport disadvantage. The reader is advised that transport disadvantage is not synonymous with social exclusion, but rather a component of it.
Any discussion about TOD seems to invariably conclude that: “It takes more than good transportation policy alone (land use and self-selection) to develop high-quality and effective TOD” (Transportation Research Board, 2007b: p.17-6) and I adhere to the same view. Section 3 outlines the local TOD characteristics and shows how the package of transport and land use is considered in WA planning policy.

2.7 Measuring Success of an Urban Planning Intervention

The objective of TOD is to reduce car dependence, increase the uptake of public and more active transport and provide enhanced local access to activities – with benefits spanning across economic, social, and environmental spheres (decreased congestion, economic development, increased liveability) – and benchmarking TODs will use these measures for comparison. Contemporary literature applies metrics referring to the amount of travel (distance, duration, mode share, trip chaining) (Gordon et al., 1989; Boarnet and Crane, 2001; Transportation Research Board, 2004; Hensher and Rose, 2007; Kim et al., 2007; Ewing and Cervero, 2010), to physical activity (Handy et al., 2002), accessibility (Geurs and van Wee, 2004; Theriault et al., 2005; Curtis and Olaru, 2010a), to value capture (Cervero, 2001; Curtis et al., 2009; Bartholomew and Ewing, 2011; Medda, 2012; Mulley, 2014), or to the changes in urban form (Ratner and Goetz, 2013), but often in a very sectoral manner.

Interestingly, some proposed best practice indicators, in fact represent descriptors of TOD rather than measures to monitor changes in travel behaviour. For example, Renne et al. (2005) collated supply-side metrics proposed by 30 professionals; the list includes public transport ridership, population, housing and employment density, qualitative rating of streetscape (pedestrian orientation, human scale), mixed-use structures, pedestrian activity counts, number of intersections or street crossings for pedestrian safety, estimated increase in property value, number of public transport services connecting to station, number of parking spaces, number of convenience and service retail establishments (see Evans et al., 2007, Table 17-43, 17-98). Many of them lack a behavioural connection or disregard the local view. Similarly, SNAMUTS (Curtis and Scheurer, 2010) characterise transport network configurations, but again without providing information on the usage of such urban and transport related services.

But even when indicators of urban form are applied, they cannot be evaluated individually. This highlights a critique that can be brought to these conventional success measures outlined in this section. The measures described are individual measures of success, often limited to supply side indicators. In reality they co-vary with each other and in consequence higher order constructs should be used (Harding et al., 2012). Bagley et al. (2002) summarised this by: “the concept of
As outlined in the previous sections, the relationships between urban form (here TOD) and travel are complex and multidimensional in their nature. Although transport modellers have a good grasp of the travel dimensions, including car ownership, number of trips, time-of-day, route choice, travel mode choice, purpose and chaining of trips (Ortúzar and Willumsen, 2001; Schwanen, 2002; Chen and McKnight, 2007) the numerous aspects of the urban form still need to be addressed in relation to these dimensions. Examples include: presence and connectivity of walk and bike paths, accessibility to public transport stops (Daniels and Mulley, 2013), land-use mix, street network density (such as average length of links and number of intersections per unit area), block sizes, and proportion of street frontage with buildings, all in relation to location and travel (Kamruzzaman et al., 2014). Consequently, this confirms the necessity to innovate by jointly considering supply and demand dimensions. In order to be able to create TODs or PODs that counteract urban sprawl, we need to understand first what aspects associated with TOD may be influencing a certain dimension of travel, and how.

This research views the success of TOD as a combination of measures, including both travel and locality. It proposes a geospatial tool - the Activity Space - as a construct able to incorporate richer information on the activity-travel needs of the household, as well as provision and usage of transport and urban services in TOD precincts. By capturing more than one dimension of demand and of supply (a holistic assessment of travel needs and urban characteristics), this measure differentiates itself from conventional yardstick and singular measurement approaches and thereby addresses a methodological gap in previous research that focuses on individual indicators alone.

Conventionally, practitioners in the urban planning and transport engineering field are relying on limited information when making policy decisions and forming judgments on success of a TOD implementation. They do not frame targets in terms of the spatial footprint of activities performed by a household but rather rely on analysis of hard-core metrics, like vehicle kilometres per capita, in their quest for developing more sustainable urban systems. However, human activities are distributed across time and space and the lack of spatial consideration presents a significant shortcoming in the current practice. Hence, activity space analysis can be seen as an optimal tool to bridge this gap in research and application, allowing a more comprehensive investigation of human activity travel behaviour. The Activity Space can therefore assist practitioners in unravelling some of these complexities and demystify the links between urban form and household activities, with potential to supply compelling arguments in support of the strategic goals of TOD. Whereas producing accurate models that describe travel demand is important, to provide meaningful answer for planning, analyses must consider at the
same time different elements of urban form. The two sides are inseparable. Combined measures or complex constructs, such as Activity Space, will inform practitioners about public responses to policies regarding neighbourhoods or environments in a complete way. By understanding the links between TOD and activity-travel patterns, policy interventions will not only improve the lives of the residents, but also minimise the risk of putting in place costly infrastructure that will not serve its purpose fully.

Section 3 will present the TOD characteristics and interventions in Australia, then Section 4 will introduce the Activity Space concept and metrics. The application will be described in Section 5. The geographical setting for this research is a 72 km railway corridor in Perth, Western Australia, opened in December 2007. Along this corridor, three TOD precincts with very different characteristics are investigated, measuring the changes in Activity Spaces before and after the railway opening and linking these Activity Spaces to TOD features and households’ characteristics and preferences for built environment and travel.
3. TOD in Western Australia

3.1 TOD in Australia

As shown by previous literature, Transit Oriented Development (TOD) has arisen as a model integrating land use and transport, discouraging car travel and promoting more active transport modes, injecting vitality and expanding lifestyle choices, whilst reducing urban sprawl (Newman and Kenworthy, 1998, 1999; Transportation Research Board, 2004; Dittmar and Ohland, 2004; Renne and Wells, 2004; Renne et al., 2005; Newman, 2012). Australian cities, and in this context Perth, are facing significant challenges for planning TODs in their low-density environments (including only statistical local areas with at least three persons per hectare, the average population density for Perth was 17 persons per hectare in 2011 (Loader, 2011). Its average urban density is 6 dwellings per ha (Weller, 2008) and around 40 to 45 dwelling units per hectare achieved in TOD centres (Johnson, 2008). Compared to the planned TOD target of 80 dwelling units per hectare and the recommended TOD population and employment densities that support effective public transport investments (Puget Sound Regional Council, 1999; Newman, 2005; Curtis, 2012; Guerra and Cervero, 2012), these results are modest. In this regard the Australian TODs and the ones presented in this research are atypical for the commonly accepted definitions in the US and Europe.

These unique conditions can be seen as a product of the relatively young history of urbanisation, the fact that concentration of the Australian population in cities is among the highest in the world, with 60 per cent of our total population residing in our five largest cities (Australian Bureau of Statistics, 2009) as well as associated metropolitan and transport planning paradigms in Australia, until recently influenced by the unlimited availability of land developable at low costs, and the ability to use a vehicle whenever it is needed (Section 2.3). Australia is one of the world’s most urbanised countries, with around 89% of Australians living in urban areas (World Health Organization, 2011) and in the face of recent vast demographic changes, the Australian cities have to adapt quickly. Unlike the Unites States of America, where people mainly settled the inland and only flooded into the cities during the 20th century, immigrants to Australia have always settled mainly in the state capital cities along the coastal line. This has seen the planning and policy framework strategically evolve over the last decade, with the idea to accommodate the pending population pressures, whilst maintaining the liveability and functionality of our urban areas.

Perth had the fastest growth of all capital cities in Australia (26%) in the last decade (ABS, 2011) and the trend continues with an overall estimated population growth to 4 million people by 2050, and a 45% increase from current levels by 2021 (Weller, 2009). Even under a more conservative estimate reaching nearly 2.3 million people by 2026 (Figure 4 – forecast band C.
equals overall forecast median), the urban landscape is confronted with issues of growth management and urban consolidation.

![Perth - Projected Population Forecast](image)

**Figure 4:** Perth - Projected Population Forecast (adopted from State of Western Australia, 2012)

The implications are profound and the surging demand will compound the pressure on Perth’s already congested transport network and urban services. Job accessibility, housing affordability and environmental constraints are fundamental questions hitting our planners (McQuirk and Argent, 2011) and TOD is a key component in tackling Perth’s urban development deficits.

### 3.2 Strategic Planning and Policy, Western Australia – State and Local Level

In the case of Western Australia, formalised strategic metropolitan planning commenced with the adoption of the Stephenson-Hepburn plan in 1955. This plan was replaced by the *Corridor Plan* (in 1970), *Metroplan* (in 1990) and then *Network City* (released in 2004). While earlier planning followed a traditional car-oriented approach, *Network City* differed. It focused on a connected network of activity centres, taking due cognisance of the important role of public transport in stimulating a significant amount of growth from within or in consolidation, i.e. through urban regeneration and densification of existing built-up areas. Thus, the centre-based strategic policy framework, defining spatial arrangements of density and land use parameters, was ideally suited to form one of the four key strategic planning tools required to support TODs, as suggested by Newman (2009). Newman’s other recommendations for essential strategic
planning tools were a policy for rail transport, statutory processes to implement TOD, and a public-private funding mechanism. Perth is currently playing “catch up” in developing these measures.

Despite its fresh approach, *Network City* was short-lived. It was replaced after just six years by Western Australia’s current strategic planning document, titled “*Directions 2031 and beyond - metropolitan planning beyond the horizon*” (State of Western Australia, 2010a). Directions 2031 outlines a spatial planning framework and strategic plan for metropolitan Perth and its surrounding region based on a balanced and managed approach to accommodate both urban growth and preservation, transforming from the linear development history to achieving a more compact and connected city. This plan gives a more balanced importance to greenfield and infill development and expands on the Network City approach.

*Directions 2031* presents three vital structural planning elements: 1) an integrated network of activity centres; 2) strategic movement webs; and 3) public green spaces to form the basis of the spatial framework. A categorised array of activity centres tags key locations for densification, intensification and expansion of public transport corridors and urban fabric, in conjunction with developments to accommodate increased housing needs while reducing car travel. Thus, activity centres form the backbone of the strategic direction (State of Western Australia, 2010b). They represent “*places, which vary in scale, composition and character but in essence are commercial*” and “*communal focal points*” (Department of Planning, 2012: 1). Their purpose is to integrate a range of activities, such as commercial, offices, retail, higher-density housing, entertainment, tourism, civic/community (higher) education and medical services, to enable urban diversity required for human activities. “*Activity centres vary in size and diversity and are designed to be well-serviced by public transport.*” (Department of Planning, 2012: 1). These characteristics resemble the TOD basic features.

It may appear that this sequence of documents puts WA in a great position to offer ‘gold standard’ urban planning, able to contain urban sprawl, while addressing the speedy and challenging growth. Nevertheless, this is more easily thought and said than done. Implementing TODs or any other smart ways to develop our urban areas has continued to be a bumpy ride, mainly due to misalignments and divergence between state and local governance, and between strategic planning and implementation. These interactions are further discussed below.

The saga of planning in Western Australia continues with the *Liveable Neighbourhoods* operational policy for design of urban development (compiled between 1998 and 2002, now available in its third, updated edition - State of Western Australia, 2009), developed simultaneously with the *Network City* policy (Western Australian Planning Commission, 2004). All twelve aims produced by the Western Australian Planning Commission in the *Liveable Neighbourhoods*
Neighbourhoods policy (State of Western Australia, 2009: 2-3) are inspired and consistent with TOD principles and subsume strategic development guidelines. Nevertheless, the process of implementation did not exclude potential inconsistencies with other strategic plans, for which the Western Australian Planning Commission urged prompt discussions between all involved stakeholders (State of Western Australia, 2009: 7).

In support of the implementation of the strategic direction, in 2010 the Western Australian Government released a new State Planning Policy Activity Centres for Perth and Peel (State of Western Australia, 2010b), making provisions for planning implementation and outlining a performance-based approach. While the document specified the main elements for the development of activity centres and gave housing and employment densities, the picture remained incomplete in terms of the minimum values and thresholds of performance parameters for retail, community services, health, recreation, hospitality, cultural, etc. This is astounding, considering that Network City provided some guidance in this respect a few years before. In any case, the roll-out of documents seemed to reflect a disconnect, which needs to be addressed to accommodate the growth that characterises our city.

Given the non trivial development tasks, planners and developers are confronted with a multitude of complex questions, such as: “What are the appropriate indicators of spatial activity arrangement and distribution to achieve functional activity centres?”; “Is there a right mix of activities?”; “How and where activities should be located to achieve optimum developments with beneficial economic and sustainability outcomes?”

Difficulty in answering these questions suggests the absence of an effective link between the strategic plan (Directions 2031 - State of Western Australia, 2010a) and its implementation framework, with critical elements caught in the crossfire of competing influences, such as localised and commercial interests, and routinely exposed to the political agenda at the local level (McQuirk and Argent, 2011). This is where the strategy is likely to face its limitations, considering the restricted power and availability of funds of metropolitan local governments and industry partners to reinforce the goals of high level strategic planning. Nevertheless, the divide is also alimented by a clear understanding of the complexity of the links between TODs and activity and travel behaviour. By examining Activity Spaces and their relations with changes in TODs and socio-demographics and attitudes, the intent of this research is to offer insights on how to improve the functioning of TOD within the context of a more sustainable urban environment.

In terms of policy implementation, the literature shows that, most often than not, this is left to market dynamics. The experience in Western Australia (by no means a unique scenario) broadly mirrors the universal reality of urban development. Given the fact that “urban form is the
accumulation of incremental investment decisions made at different times during the city’s history” (Anas, 1978: 67) we expect to see that “indeed, most urban development happens within the context of a market driven urbanism.... Private developers are the de facto city builders, and their actions are primarily motivated by profit rather than by a larger city-wide vision” (Loukaitou-Sideris, 2012: 468). With the limited capabilities of local government planning authorities and within a difficult economic climate, the statutory bodies are increasingly relying on scarce resources to deliver results that will ensure implementation of policy compliant development outcomes and individually refine and specify activity centres’ performance parameters within local planning schemes and/or activity centre structure plans. Combined with a lack of vision, the scarcity of resources increasingly leads to suboptimal development.

As a practitioner, involved in the planning agenda at a local government level (LGA), I frequently witness a lack of advanced or sufficiently detailed and integrated transport and land-use planning and modelling. Where forward planning occurs, it is frequently restricted by statutory boundaries between LGA’s or focused on isolated areas of increased development activity or pursued for a particular interest. Together with a decentralised management of spatial planning processes or ignorance to interconnected issues (multiple agencies, departments and interest groups are working in parallel and isolation to deliver their own agenda) this can best be described as a major weak link between transport and urban planning and prevails at both State and Local Government level. Transport decisions are often playing catch-up with urban sprawl; engineers, transport modellers, developers, urban planners and State Agencies actively communicate only when required, such as to fix an acute problem, rather than beforehand and in a proactive manner to plan for the future. The prevailing strategic transport models for Perth (STEM and ROM24) often lack the detail for local activities or have a modelling limitation in terms of the number of travel zones (up to recently STEM model used 472 zones - Taplin et al., 2014); our LGAs typically do not have a comprehensive and maintained land use-transport-environmental (LUTE) model. This means that the multilevel governance, the fragmentation and inconsistent integration of strategic planning and metropolitan or local level implementation remain challenges for successful creation of TODs and a priority for urban planning in our state. Unfortunately, the unsatisfactory coordination and integration of planning and implementation and dispersion of powers, abilities and interests at multiple levels are also reflected in one out of three TODs analysed in this research.

In Wellard, even after three years from the railway opening, the local main street precinct is yet to be built. The slow development, although heavily influenced by two Global Financial Crisis (GFC), also indicates that spatial organisation is inefficient and not coordinated/integrated with city planning.
3.3 A Practitioner’s View – Understanding Implications

Strategic policy and political decision makers in Western Australia are yet to fully apply the full range of TOD ideas and frequently fail to place more emphasis on improved public transport and passenger rail investments (Australian Conservation Foundation, 2011: 6). They do not facilitate the “vehicles” for implementation or provide market incentives to assist in delivery of successful TOD outcomes, e.g. through valuable and proven Public-Private-Partnerships, formed by State and Local Government Authorities, as well as development industry partners (Curtis et al., 2009).

Then again, in a market driven economy, which is still on a path of recovery (overcoming the negative impacts of the two recent global financial crises), it proves difficult to shift the mindset of developers and financiers, from a myopic view of short-term survival, preservation and cost recovery, to a longer-term vision. But if a development is delivered well, with a focus on people and their environment rather than on the product, and with a much longer planning and profit horizon, the development industry can ultimately capitalise on the benefits gained at residential level by using multiplier effects from the more liveable and attractive urban outcomes it creates. The industry would be able to capture lasting value for money outcomes rather than banking on a quick financial return. To this effect, good quality, functional and attractive urban forms, with a long-term increase in property values, supported by tax incentives seems to represent more promising means to achieve such efficient and sustainable urban planning outcomes.

At the local community level, a public lacking the understanding of even basic strategic planning principles appears evident. While most city planners have a good grasp of TOD concepts, the general public stays vastly unaware of its myriad advantages. Generally, the community seems to fear that denser urban development causes a lack of green space and lack of quality development, affecting their urban living negatively. Thus, changing or moderating individual attitudes and market dynamics are substantial barriers in advancing TOD implementation at a local level. In a re-development situation, this scenario is often further complicated by fragmented land parcels in multiple ownership and skewed interests, requiring amalgamation or conjoint development of various small landholdings and restricting the timely and systematic achievement of planned land-use, amenity and accessibility at the local level. Consequently, any kind of TOD proposal still faces huge obstacles in many communities.

As indicated, from an institutional perspective, disconnections between state and local authorities arise when plans are conceived and decisions made separately (and at times even in opposing directions), instead of jointly. A shift to integrated thinking and planning between various agencies seems imperative, with inter-agency collaboration recognised as a crucial
element on the TOD agenda (Cervero and Murakami, 2010); yet, historically, breaking down institutional barriers has been difficult, and not only in WA.

A potential solution adopted in Australia to address this issue was the creation of redevelopment authorities. These meso-level organisations are in charge of planning, development control, land acquisition and disposal in a particular area and rely considerably on local government funding to enable them to operate and respond to the needs of those areas. This approach has the potential to introduce market bias. With development gravitating towards those less regulated areas and favourable treatment of redevelopment agents who “bend the rules” (often by way of appeal in the State Administrative Tribunal), the new layer of redevelopment agencies may not necessarily lead to creation of exemplar TODs, if not carefully administered and integrated with the government and agencies responsible for planning of urban facilities and transport network services.

To overcome the wide-ranging dilemma that has been presented in this section, comprehensive guidelines for TOD implementation, recognising complexity of in-fill vs. green field locations, market forces and transport network policy, and outlining key components as well as specific parameters to qualify for government support, would assist in providing consistent conditions across potential (re-) development precincts (Liveable Neighbourhoods, R-Codes, Town Planning Schemes, etc.). Specifically, planning policies favouring mixed land-use and higher densities around public transport corridors and promoting activity centres that are well connected by public transport, need to be accompanied and reinforced by performance measures: i.e., split density coding, development incentives for higher density, minimum density and land-use mix criteria to be achieved. But instead of relying on point estimate “desirable” gross floor space for business activities, retail, commercial and office (which is not necessarily ensuring land-use mix), more detailed and supple/fluid measures should be put in place. These benchmarks should reflect international experiences and be flexible enough to allow for their review and adjustment in a timely manner as certain patterns emerge, letting redevelopment authorities, and local and state governments pursue their strategic targets within a collaborative framework.

A final point worth noting is the different approach adopted in delivering TOD-like developments for “greenfield” versus “brownfield” areas. While LGAs and state government are keen to deliver developable land (satisfying building and development industry demands, addressing population needs, obtaining revenues from stamp duty, rates, etc.), they run a risk of neglecting long-term adverse implications of disintegrated planning decisions. If the integration of mixed land-use (urban amenities) and transport access is not genuine, initial benefits will be negated by transport and exclusion impacts. After all, retrofitting of a TOD is expensive, if not unworkable, and requires major re-investment of public funds, evidently far beyond the initial
gains. Whereas greenfield creation of a TOD requires substantial initial funding, it appears to be a lot easier to design due to the favourable blank canvas that is on offer, compared to the transformation of a brownfield urban area, which requires careful thought and preparation for a wise use of resources and a transition with minimum tensions both for the public and for those involved in urban planning and operation. Brownfield TODs are therefore often less popular or brave decisions, supported by substantive planned investments in infrastructure and service delivery, will decide the success of the intervention.

In one of the precincts examined in this research, Cockburn Central, fragmented landownership, the need for services provision and upgrades, potential conflicts between local factions, businesses and redevelopment agents, have been translated into an initial mismatch between TOD principles and actions. Only the strong leadership at the local level and commitment to innovate and sustainable development, enabled Cockburn to overcome hurdles and engage on creating a new community that is well received by residents in the southern part of the city.

In summary, there is indeed a disconnect between research and practice and necessitates education of relevant stakeholders to raise awareness in the policy, planning and engineering community of the multiplicity of TOD impacts on urban development and travel behaviour. Only when decision makers and planning proposals account for and truly have an appreciation of the complex web of relationships, TOD success can be achieved. However, parties will need to collaborate since no party can achieve success individually. The results of this research and methodologies applied and presented can assist bridging this gap.

Chapter 5 will describe an approach to assess the success of high-density development integration with public transport and urban services investments and outlines the method adopted in this research.
4. Activity Space – Importance Definition, and Measurement

4.1 Human Activities in Space and Time

“No wild animal roams at random over the country; each has a home region, even if it has not an actual home.” (Seton, 1909: 26)

The motivation for people to travel is the wish for participation in activities required to satisfy daily individual needs and desires (Ortuza and Willumsen, 2001; Schonfelder and Axhausen, 2010). These activities are geographically spread and their location, timing, frequency, and duration are a function of the benefits (utility) they provide, of the time and budgetary restrictions, and of the availability of urban facilities to meet those needs and desires (Schonfelder and Axhausen, 2010). Since no one can perform all activities at the same time, there are complex choices regarding the sequence of activities and locations, in addition to mode, route, and duration choice (Ortuza and Willumsen, 2001).

Functionally, there are two different types of activities that people do on a daily basis - mandatory and discretionary. Despite the changes in the nature of human activities in space and time brought about by ICT (Information Communication and Technology) systems (Saxena and Mokhtarian, 1997; Mokhtarian, 2007), the daily time-space continuum is still constrained by numerous factors: accessibility, family, institutional constraints, etc. (Schonfelder and Axhausen, 2010).

This means that space/location and timing are essential for understanding daily activity and travel patterns (Kwan, 2007). Nevertheless, very few tools are able to simultaneously account for these dimensions: prism (Hagerstrand, 1970; Lenntorp, 1976) and fish-tank (Weber and Kwan, 2003; Kwan, 2007). The difficulty arises primarily from their individually-based definition versus the need to describe activity-travel patterns at population level. In the last decade, a few attempts have been made to understand the spatial reach, confidence ellipses, kernel densities and network bands (convex hull) (Axhausen et al., 2004a, b; Morency and Kestens, 2007) using samples of individuals and looking at changes over time. With several forms and definitions, the Activity Space concept has emerged as a tool to gain insights into the relationships between the demand for daily activity and travel and urban form by looking at the spatial spread of activities. Time was not explicitly incorporated in the measurements, but appeared through temporal changes and time constraints. As Weber (2003) indicated, various population groups have different needs and limitations, hence socioeconomic characteristics, in the form of time constraints, “are a more consistent and likely a more useful direction for understanding accessibility patterns” (Weber 2003: 66). This means population differences in terms of socio-demographics indirectly provide insights into temporal aspects and they should
be included when embarking on an exploration of interaction between urban landscape, travel behaviour and location. Overall, human movement patterns tell planners about the appropriateness of urban form in satisfying daily activity needs.

4.2 Spatial Cognition and Activity Spaces

“What I see here is a rising blur, perhaps with some peaks on it. Can I look under this blur and see anything more?” (Tukey, 1977: 205)

Activity Space was one of the first approaches to the estimation of human movements and spatial use. The concept was discussed early last century (Lefever, 1926) in the pioneering days of social sciences, and later embraced in behavioural ecology and biological research at the middle of the century (Buliung and Kanaroglou, 2006a, b). In this context, the concept was applied to explore habitat use, territoriality behaviour, and mammals’ home ranges (Burt, 1943; Hayne, 1949; Jennrich and Turner, 1969, Mazurkiewicz, 1969; Worton, 1989; Seaman and Powell, 1996; Simcharoen et al., 2008; Downs et al., 2011). Burt (1943) described the home range as the “area traversed by the individual in its normal activities of food gathering, mating and caring for young. Occasional sallies outside the area, perhaps exploratory in nature, should not be considered as in part of the home range” (p. 351). This definition emphasises the behavioural nature of the concept, covering the area where individuals survive, reproduce and maximise their fitness (Krebs and Davies, 1997: 3–15).

These biological measures were further developed during the 1970s as suitable ways to describe human spatial perception, spatial awareness and spatial use (activity) (Brown and Moore, 1970; Horton and Reynolds, 1971b, c; Dürr, 1979; Zahavi, 1979). From that point onwards, Activity Spaces attempted to describe the distribution of locations visited by an individual or known to an individual (as a result of day-to-day activities). To achieve this, Activity Spaces needed to incorporate two types of factors: the individual, with her/his characteristics and preferences and the environment, offering opportunities to the individual to perform various activities.

After a relatively quiet decade, in the late 1990s and 2000s application of the Activity Space concept surged. As Buliung and Kanaroglou (2006a) stated, the 1990s a shift in the scale of analysis and the momentum gained by the research using Activity Spaces were enabled by availability of detailed data and advancements of GIS science. GIS provided tools for detailed investigations of substantial quantities of data reflecting the ‘manifestation of one’s spatial life’, including spatial arrangements of travel and the use of space required to satisfy daily activity needs, and hence the spatial awareness/knowledge, with relative ease (Newsome et al., 1998;
Golledge, 2002; Botte, 2003; Axhausen et al., 2004a, 2004b). The concept has since been adapted to and applied in other areas, such as the analysis of crime incident locations (Levine, 2004, 2006), the assessment of “spatial lives” and the occurrence of substance misuse (Mason and Korpela, 2009), health promotion and environmental exposure (Kestens et al., 2010) or accessibility to health care services (Guagliardo, 2004; Sherman et al., 2005).

An important distinction needs to be made at this stage. The concept of Activity Space has evolved in two main directions: Realised Activity Space and Potential Activity Space (also known as Action Space). Looking at potentials for travel, such as via investigation of spatial knowledge and aspirations, geographic thinking/reasoning, or mental maps, represents a different way of exploring the choices for location and travel (Brown and Moore, 1970; Matthews, 1980; Golledge and Gärling, 2002; Hannes et al., 2008). The idea behind it is that frequent visits to places increase the individual’s knowledge of those locations, including their immediate surroundings, and subsequently influence the individual’s behaviour. One of the early attempts to capture this idea in a graphical manner is the conceptualisation by Horton and Reynolds (Figure 5). It is considered that individuals, in time, become more mindful of their surroundings and, after repetitive visits to an area, hence expected to be more flexible in their decision-making processes in relation to travel and location, thereby more likely to expand their set of activity and travel choices. This conceptualisation was later adopted by Golledge and Gärling (2002) and Schönfelder and Axhausen (2010).

![Activity Space Diagram](adapted from Horton and Reynolds, 1971: 41)
Notwithstanding the links between the two conceptualisations, planners are interested in how the spatial knowledge is expressed in actual use of physical space (the direct link between Activity Space and the spatial structure of urban environment), therefore realised/observed travel and its related spatio-temporal changes are potentially informing better policy making (Botte, 2003; Schönfelder and Axhausen, 2003b). This research will adopt the Realised Activity Space (RAS), which reveals the individual demand for activity participation and the supply of supporting activity facilities.

The eager reader is referred to Golledge and Gärling (2002) for a background summary on the emergence of the Activity Space and related concepts of knowledge space, mental/cognitive maps, Perchoux et al. (2013) for a review of the concept from an interdisciplinary perspective, and Schönfelder and Axhausen (2010), for a detailed review of measures capturing individual perception, use and knowledge of urban space.

4.2.1 Measures of Activity Spaces

"it is important to understand what you CAN DO before you learn to measure how WELL you seem to have DONE it” (Tukey, 1977: v).

In biology, a variety of methods have been established for measuring the home ranges, from minimum convex polygons (Blair, 1940; Odum and Kuenzler, 1955), to multi-dimensional relative frequency distributions of animal locations (Jennrich and Turner, 1969; Van Winkle, 1975) and kernel densities (Worton, 1989).

The human Activity Spaces, on the other hand, have been usually defined in a two-dimensional form, in particular: travel probability fields (Zahavi, 1979), standard distance, confidence ellipse, polygon, kernel density (Silverman, 1986; Worton, 1989; Fotheringham et al., 2000; Buliung and Kanaroglou, 2006a, b; Fan and Khattak, 2009), shortest path vectors (Schönfelder and Axhausen, 2010), minimum spanning tree, Minimum Convex Polygons and network buffers (Kwan, 1999; Schönfelder and Axhausen 2002, 2003a and b; Morency and Kestens, 2005, Sherman et al., 2005, Fan and Khattak, 2008, Chaix et al., 2012, Harding et al., 2012), but also three-dimensional: e.g. space-time prism (Burns, 1979; Lenntorp, 1976) or fishtank/aquarium (Kwan, 2000).

Regardless of their formulation, all Activity Space measures are intended to emphasise the various dimensions of choice that underlie travel behaviour: distribution, concentration or orientation of the travel field and the intensity in using the space – depending on the frequency and time spent on activities and travel. Without explicitly incorporating a temporal dimension, the Activity Space reflects decisions in time. The concept is related to the space-time path (Hägerstrand, 1970; Lenntorp, 1976; Miller, 1999a, 2004 or 2005) and prism (fish tanks or
aquariums - Kwan, 2000) demarcating possible activity locations that can be reached during a certain timeframe, based on the underlying speed of available transport services, as well as an array of potential constraints (Burns, 1979). 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 (larger areas that the traveller is able to reach within their travel episodes) or in time savings that can be embedded in stationary activity times. Similarly, Activity Spaces are adjusted dynamically as a result of changes in urban form and transport services, and they may increase or decrease depending on where the opportunities lie (near or far from home locations). Whereas “space-time geography” measures are useful for linking spatial mobility to temporal aspects, as well as individual and collective constraints, their complexity in visualisation and analysis (Kim and Kwan, 2003; Soo, 2009; Neutens et al., 2012) limits examination to limited sample selections at a time. By contrast, Activity Spaces accommodate large sample sizes for analytical assessments of spatial choice, although some aspects of time sequence may be lost. Consequently, Activity Spaces have the potential to offer responses to behavioural questions with less effort, especially where activity scheduling is not of primary interest (Botte and Olaru, 2010).

In geometric terms, the Activity Space reflects observed or realised time-travel patterns by encompassing the locations of activities that are visited/reached within a prescribed time frame (day or week) and under certain budgetary, coupling, and institutional constraints (Fan and Khattak, 2008). Home and work places or other key activity centres are known “pegs” (Golledge and Stimson, 1997) anchoring the schedule of daily activities. Consequently, the shape, scale and inherent structure of resulting Activity Space geometries are strongly conditioned and often polarised by the determinants of the household’s basic places (home and work or other frequently visited activity locations). But the Activity Spaces are also influenced by accessibility to the transport network, available transport options and other constraints (Golledge, 2002; Miller, 2005; Axhausen et al., 2004a, b), such as personal “time budgets” or trading hours (institutional or personal time constraints). As expected, teleworking was found to shrink the Activity Spaces (Saxena and Mokhtarian, 1997) and modify the spread of activity locations for other activities. Similarly, car ownership, as a constraint, affects the size of Activity Space. Olaru et al. (2005) and Harding et al. (2012) found smaller Activity Spaces for households without cars in Australia and Canada.

Activity Spaces can be constructed and used to describe activity travel behaviour at various geographical scales: individual, household, precinct or city level, revealing observed distribution of places visited and their importance in terms of frequency and duration (Botte and Olaru, 2010; Harding et al., 2012).
4.2.2 Examples of Studies using Activity Spaces

Following pioneering work that applied simple elliptical measures (Lefever, 1926; Holzapfel, 1980; Beckmann et al., 1983a and b), initial steps to apply the Activity Spaces in transport research have been slow, primarily due to the computational complexity and data requirements. As indicated by Buliung and Kanaroglou (2006a), the Activity Space developed momentum in late 1990s. The “fuzzy” nature and measurement of Activity Space, and a lack of standard tools and software applications for easy calculation, caused a time-lag in making the Activity Space a standard component of the travel behaviour toolkit. It has now become a family of geospatial, statistical measures, requiring detailed spatial data for application (e.g., 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).

Still, the data-hungry models mean that to date, a limited number of studies have been undertaken at the population level (using cross-sectional travel or time-activity data) to investigate the spatial behaviour of particular socio-demographic clusters (Schönfelder and Axhausen, 2003b; Olaru et al., 2005; Morency and Kestens, 2007; Harding et al., 2012). Empirical studies on realised, revealed Activity Spaces with large sample sizes are not the norm, and many scholars focus on activity and action spaces for small areas or reduced samples.

As physical planning can benefit from deeper insights into how individuals use spatial options, studies on revealed Activity Spaces have dominated the literature: Dijst (1999), Botte (2003), Axhausen et al. (2004a, b), Olaru et al. (2005), Buliung and Kanaroglou (2006a), Casas (2007), Morency and Kestens (2007), Páez et al. (2009), Kamruzzaman et al. (2011), Wang et al. (2012), Harding et al. (2012). Conversely, studies that are more focused on travel potentials or opportunities have been less frequent (see examples by Brown and Moore, 1970; Horton and Reynolds, 1971; Burns, 1979; Casas, 2007).

In the following I include examples of successful applications of RAS and their main findings.

Dijst (1999) analysed individual Activity Spaces in a case study of two Dutch communities and applied a typology of shapes based on various spatio-temporal elements. Axhausen and colleagues reported on Activity Spaces from Mobidrive and Borlänge, evaluating and visualising variation of Activity Spaces for individual travellers and testing their suitability for identifying social exclusion (Schönfelder and Axhausen, 2002, 2003a, b). An important finding was that full-time workers had larger Activity Spaces compared to part-time workers. Later, Axhausen et al. (2004a, b) applied Activity Spaces to the analysis of commuter movements in Switzerland over three decades and highlighted a substantial increase in their size during that period. In Australia, Olaru et al. (2005) found gender, household structure, and day-by-day
differences in Activity spaces in Sydney, using a structural equation modelling framework. Buliung and Kanaroglou (2006a, b) applied Activity Space measures and space-time trajectories for 4,000+ households in Portland. The results confirmed the positive association between car-ownership, presence of children and suburban location with the size of the Activity Space. Morency and Kestens (2007) reported on travel behaviour data of up to ~65,000 households collected during 1998 and 2003 in Greater Montreal. Similarly, their results revealed car unavailability as important constraint to spatial dispersion of activity points. While they observed a general decline in household car ownership levels and the number of activity location visited, an overall expansion of household Activity Spaces (measured with convex hull polygons) was evident over the 5-year period, indicating a general dispersion of activity locations. Household size, level of car ownership and again the level of suburbanisation of a household’s home location were also found to be driving forces behind Activity Space increase. At the same time, Casas (2007) jointly examined Activity Spaces and potential access (cumulative opportunities) for activity participation in Western New York, i.e. to identify differences between socio-demographic groups (similar to Schönfelder and Axhausen, 2003a, b; Olaru et al., 2005). Fan and Khattak (2008) compared multiple regression and spatial error models to understand the most significant predictors of spatial footprint for more than 3,400 households in North Carolina. More recently, Kamruzzaman et al. (2011) used Activity Spaces to assess the participation in activities by students in Northern Ireland and Wang et al. (2012) compared three types of neighbourhoods (institutionally, economically privileged enclaves and ordinary neighbourhoods) in Beijing to investigate socio-spatial segregation.

In summary, established Activity Space methodologies and formulations applied in past research tried to focus on the various dimensions of travel behaviour whilst drawing a connection to spatial aspects (distribution/ concentration/ spread) and temporal dimensions (Morency and Kestens, 2007). As Activity Spaces are dynamic in their nature and represent behavioural measure of the interaction between travel demand and the available transport services (a “people-based” accessibility measure as described by Miller, 2005) they are suitable for gauging spatial processes that cannot be otherwise captured in classical demand models (Botte and Olaru, 2010).

4.2.3 Main Uses of Activity Spaces

To date the Activity Space methodology has been applied to:

- understand travel behaviour (Newsome et al., 1998; Miller, 2005; Buliung and Kanaroglou, 2006a, b; Fan and Khattak, 2008);
- understand spatial awareness (Dürr, 1979);
- explore physical activity and health outcomes (Kestens et al., 2010, Villanueva et al., 2012);
- examine the relation between spatial lives and substance use (Mason and Korpela, 2009);
- investigate the connection between action space and the social network geography (Axhausen, 2007); and
- address social exclusion issues (Schönfelder and Axhausen, 2003b).

Nonetheless, to the best of author’s knowledge, prior to the commencement of this research the concept had not been applied to analyse TOD induced changes in travel behaviour.

This research aims to assess various Activity Space metrics for their suitability to explore association between TOD, socio-demographics and activity-travel patterns, ultimately with the aim to provide an easily comprehensible indicator (degree of “TODness”) as a tool to assist practitioners in the comparison and analysis of TOD effectiveness.

4.2.4 Activity Space in this Research

This research belongs to the stream of research exploring Realised Activity Spaces at both individual and aggregate level, in the context of TOD changes. It applies the concept at the household level to examine whether and to what extent TODs reduce Activity Spaces by providing a manifold of non-work opportunities in the near vicinity of the TOD precinct. As changes are not uniform for all residents across various TOD precincts, potential modifications can be assessed in relation to the daily routine needs for various categories of population (based on their circumstances). An innovation of the approach is the application of the Activity Space at the household level instead of an individual (person) level; as the location decisions are household based, the household unit becomes the core of attention, with Activity Spaces incorporating the space-time negotiation that occurs within families. Therefore, the household Activity Space is a more reliable measure to illustrate decisions on activities and travel of all household members (location, destination, mode and route choice, trip chaining).

This research adopted a quasi-longitudinal approach (multiple waves). The before and after data makes possible the analysis of changes in Activity Spaces in relation to urban form alterations, hence behavioural modifications (dynamic aspects of travel) induced by TOD, whilst accounting for self-selection. This method 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, the Activity Space concept has powerful implications for urban land-use policies aimed at increasing density or land-use mix, and lowering levels of car use.
Finally, this research compared various metrics for Activity Spaces and applied two of them (kernel density and confidence ellipses) as indicators of a latent construct, compared across three different TODs before and after a major urban infrastructure investment.

### 4.3 Definitions, Metrics for Realised Activity Spaces (RAS)

The intrinsic setting of this research’s study area offered an opportunity to explore and validate various known Activity Space metrics in a real world scenario. Based on theoretical application by Rai et al. (2007), new geometries of Activity Spaces (ellipses, super ellipses, Cassini ovals, and bean curves) as well as kernel densities could be tested, representing Activity Spaces of households residing within various unique and emerging TOD precincts along a new 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.

As outlined above, there are numerous ways to measure Activity Spaces. Previous research has identified limitations of some of these measures, which are not “detailed” enough to accurately represent Activity Spaces, and suggested that there is no single measure for RAS, but rather a set/vector of measures highlighting various aspects of the Activity Space (Schönfelder and Axhausen 2002, 2003a and b, 2004; Buliung and Kanaroglou, 2006a, b; 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; they are however the easiest to compute (along with standard distances) and historically were the earliest derivations (Axhausen, 2007); convex 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 because they require a minimum of three points (Boyle et al., 2008); buffers, spanning trees and network bands assume that narrow bands of space or urban form adjacent to 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 (Schönfelder and Axhausen, 2002). In the same line of thought, some measures such as space-time prisms are difficult to analyse quantitatively with the intent of identifying temporal dynamics in accessibility.
The review and comparison by Rai et al. (2007) of new geometries such as superellipses, Cassini ovals and bean curves represented a starting point of this research. Given the shortcomings of the convex polygon and network buffer and the relatively high correlations of the polygon with the standard deviational ellipse (Kamruzzaman and Hine, 2012), these measures were not applied here. Instead, this research examined only five metrics: kernel density (non-parametric), confidence ellipse, superellipse, Cassini oval and bean curve (parametric) formulations, as a means for representing Activity Spaces. These metrics are described in Sections 4.4 to 4.8. The detailed comparison of the five metrics will be further discussed in Section 7.1.1 with conclusions outlined in Section 7.2 and 7.3. From the practical perspective, this comparison showed that two metrics, Kernel Density and Confidence Ellipse, emerged as most appropriate tools for this research.

### 4.4 Confidence Ellipse

Activity Spaces are based on the spatial distribution density and intensity of activity locations visited as part of a temporal activity repertoire. The bivariate confidence ellipse (CE) can then 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%). Ground-breaking work was done by Lefevre (1926), who was the first to suggest that the use of a standard deviational ellipse should provide insights into the “ecological and sociological forces operating” in urban areas (p.88) by identifying foci of certain antisocial activities.

The size and the orientation of the confidence ellipse can be determined mathematically, and they can also incorporate 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 longitudinal studies (or at least week diaries rather than one day trip 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).

Drawing on Lefever (1926) and Yuill (1971), the confidence ellipse is defined by:

$$\frac{(x - \bar{x})}{a} \times \frac{(y - \bar{y})}{b}$$

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 $\theta$ is:

\[
\begin{align*}
    x &= a \cos t \cos \theta - b \sin t \sin \theta + \bar{x} \\
    y &= a \cos t \sin \theta + b \sin t \cos \theta + \bar{y}
\end{align*}
\]

(2) (3)

where the orientation $\theta$ provides the angle at which the area is minimum.

The area of the ellipse is given by

\[ A = \pi ab \]  

(4)

where $ab = 6\sqrt{S}$  

(5)

with $S$ the determinant of the covariance matrix $|S| = s_{xx} s_{yy} - s_{xy}^2$  

(6)

with

\[
\begin{align*}
    s_{xx} &= \frac{1}{n - 2} \sum_{i=1}^{n} (x_i - \bar{x})^2 \\
    s_{yy} &= \frac{1}{n - 2} \sum_{i=1}^{n} (y_i - \bar{y})^2 \\
    s_{xy} &= s_{yx} = \frac{1}{n - 2} \sum_{i=1}^{n} (x_i - \bar{x})(y_i - \bar{y})
\end{align*}
\]

(7) (8) (9)

A number of other indicators can be derived from the ellipse (angle or orientation, eccentricity) and they provide richer information on the orientation and “fullness” of the ellipse (Yuill, 1971). An example of a confidence ellipse for a household living in Perth is given in Figure 6 with a blue dotted line.

### 4.5 Super-Ellipse

The super-ellipse is a “generalisation” of the CE (when $r=2$), which means it can 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.

The super-ellipse is defined by the curve:

\[
\left| \frac{x - \bar{x}}{a} \right|^r = \left| \frac{y - \bar{y}}{b} \right|^r 
\]

(10)

with the parametric equations:
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 super-ellipse ($r=2$ for the normal ellipse); $a$ and $b$ are the lengths of the major and minor elliptical axes, and $\theta$ the angle of rotation of the shape.

If $r>2$, the hyper-ellipse resembles a rectangle, if $r<2$ a hypo-ellipse, with a shape of a diamond or even a cross can be derived.

As the aim here is to obtain the minimum Activity Spaces, only $r<1$ is of interest.

The area of the super-ellipse is equal to:

$$A = 4ab \frac{\Gamma\left(1 + \frac{1}{r}\right)^2}{\Gamma\left(1 + \frac{2}{r}\right)}$$

(13)

where $\Gamma$ is the Gamma function.

Figure 6 shows a brown hypo-ellipse including the locations visited by the Perth household.

4.6 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 require 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.

The Cassini oval is the locus of points for which:

$$(\bar{x}^2 + \bar{y}^2 + a^2)^2 - 4a^2\bar{x}^2 = b^4$$

(14)

Where $b>a$ and the parametric equations are:
The area of the oval can be calculated as:

$$A = \int_{-\pi/4}^{\pi/4} a^2 \left[ \cos(2\theta) \pm \sqrt{\left(\frac{b}{a}\right)^4 - \sin^2(2\theta)\sqrt{1 + 3\sin^2(\theta)}} \right] d\theta$$

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

For the household travel routines displayed in Figure 6, the Cassini oval with \(b>a\), is slightly larger than the confidence ellipse (Cassini oval drawn in red).

### 4.7 Bean Curve

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

The bean curve is defined by

$$(x^4 + x^2y^2 + x^4) = x(x^2 + y^2)$$

with the parametric form:

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

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

The area of the bean curve is given by:

$$A = \sqrt{2}ab \int_0^1 \sqrt{x(1 - x + \sqrt{1 + (2 - 3x)x})} dx \approx 1.058049ab$$

Figure 6 displays the bean curve for the same household activities in solid green line.
Interestingly, this simple example shows how different geometries can lead to various sizes of Realised Activity Spaces, and also different orientations. Whereas CE and Cassini oval have an East-West orientation and display the smallest areas, the bean curve and the super-ellipse seem to depict a North-South direction and are substantially larger.

![Figure 6: Example ellipse, hyper-ellipse, Cassini oval, and bean curves optimised for a daily Activity Space of an individual living in Perth](image)

Note: the coordinate system axes represent the Easting and Northing.

### 4.8 Kernel Density

The bi-variate kernel density estimator captures the activity intensity/density landscape without setting predetermined geometrical boundaries (beyond an initially specified raster cell size and within a predetermined bandwidth - based on a search radius, both specified by the analyst).

Kernel density is a non-parametric raster based approach, with the grid cell size of the raster determining the visual resolution ("pixelation") of the resulting density surface. Through sequential application of a preselected bi-variate density distribution over individual activity locations (point densities) in the raster, followed by a smoothing algorithm, the measure produces either individual, converging, continuous and/or clustered density surfaces, reflecting the activity patterns. The measure accepts consideration of frequency or duration of activities in particular locations (or varying spatial awareness) and both footprint and surface areas can be
considered at 100% (all inclusive non-zero activity density area) or any other specified confidence level (e.g. 95% interval). This allows 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 (outliers) and not representative for their daily routine behaviour.

The kernel density bivariate estimator calculates densities based on the locations visited by individuals and assumes no barriers in reaching those locations in any direction 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 of highly frequented locations (Schönfelder and Axhausen, 2010). This information is then reflected in a raster data set. Each cell in the raster is assigned a value calculated according to the distance from the starting feature (activity location) and the proximity to other features in the data set.

Mathematically, the kernel estimation transforms a set of point activities (observed) into a continuous surface of potential activities, where the individual kernel surface values reflect the intensity of using a particular location. The kernel density estimator can be written as:

$$f(x) = \frac{1}{nh^2} \sum_{i=1}^{n} w_i \lambda \left( \frac{x - X_i}{h} \right)$$ \hspace{1cm} (22)

where $X_i$ is the location of a particular activity point $i$, $n$ the total number of activity points, and $h$ is the specified bandwidth.

The kernel function $\lambda$ has the following expression:

$$\hat{\lambda} = \frac{3}{\pi \tau^2} \left[ 1 - \left( \frac{s_i}{\tau} \right)^2 \right]^2$$ \hspace{1cm} (23)

where $s_i$ represents the distance of a spatial event $i$ from the estimation point and $\tau$ the bandwidth, which affects the smoothness of the surface.

Since the publication of Worton’s (1989) seminal paper, density estimation techniques such as kernel smoothing have become the method of choice for quantifying utilisation distributions (Bailey and Gatrell, 1995; Kernohan et al., 2001; Laver and Kelly, 2008; Paéz et al., 2009).

The kernel approach has been used to describe spatial variation in various types of point events recorded in cross-sectional surveys. Examples include firm locations (Maoh and Kanaroglou, 2007), the incidence of disease (Bailey and Gatrell, 1995), and the spatial and spatiotemporal...
variation in activity–travel behaviour (Buliung, 2001; Kwan, 2000). Maoh and Kanaroglou (2007) for example, applied the following weighted bivariate kernel density $K$:

$$
\hat{f}(x, y) = \sum_{i=1}^{n} \left\{ \left[ w_i I_i \right] \frac{1}{2\pi \sigma^2} e^{\left(\frac{(x-\mu_x)^2 + (y-\mu_y)^2}{2\sigma^2}\right)} \right\}
$$

where $w_i$ is a weight attached to each location (firm) $i$ (retail square footage), $I_i$ is the intensity of the spatial point process at each observed location (i.e., the mean number of retail locations per unit area), $x$ and $y$ are planar coordinates for locations, and $\sigma$ is the bandwidth.

As suggested by relations (22)-(24), there are several decisions left to the analyst when applying kernel estimation. First, the kernel function ($\hat{K}$ or $K$) can take one of several possible forms (e.g., Gaussian, quartic, triangular), and second, the value for the scale parameter, $\tau$ or $\sigma$ has to be set (Bailey and Gatrell, 1995; Levine, 2006). The choice regarding the kernel function is typically guided by the application context. For example, regional scale analyses are potentially better suited to the application of the Gaussian distribution because the function returns estimates of spatial intensity for every tessellated location across the study area (Levine, 2006). With respect to the scale parameter, larger values of $\tau$ or $\sigma$ provide a smoother estimate of spatial intensity as a result of less variability between areas and narrower bandwidth produces a finer mesh density.

While empirical approaches to identify an appropriate bandwidth have been introduced to the literature (Bailey and Gatrell, 1995; Levine, 2006), selection has been traditionally made with a more ad-hoc approach where the analyst qualitatively evaluates successive interpolations.

Recently, automated, adaptive methods have been proposed by Amatulli et al. (2007), Lambert et al. (2009), and Botev et al. (2010).

This mechanism permits the analyst to expand or contract the bandwidth across cross-sectional units, conditional on the concentration of points, alleviating a potential problem associated with fixed bandwidth when data are quite sparse. Nevertheless, the computational sophistication makes the adaptive kernel limited in its applications.

In this research, a fixed approach, based on empirical evidence and expert knowledge, was deemed appropriate, given the relatively dense and homogeneously distributed data at the precinct level.

Section 5 continues with the description of the methodology adopted for describing the relationships between Activity Spaces and urban form in the three TOD precincts.
5. Research Methodology

The aim of this research is to provide deeper insights into the complexities surrounding the connection of urban form and travel by adopting a micro-level measure of travel behaviour, the Realised Activity Space. This is the key element of the research, enabling joint examination of activity-travel needs of the households, supply of urban and transport services available, and situational constraints and preferences of the population.

5.1 Research Objective and Questions

The motivation for this research was to unravel the web of relationships between urban form and activity-travel patterns and assist informed planning decisions in regard to TOD. Three main components are considered here: 1) spatial variation of RAS; 2) temporal changes of RAS related to changes in urban infrastructure and services; 3) multiple social, economic, environmental drivers of activity-travel patterns.

A series of specific research propositions arose:

- What metrics can be used to more accurately define activity-travel patterns and the urban space used to satisfy daily household needs? Are Activity Spaces reflecting these elements better? Are certain metrics more appropriate than others?
- Are the travel changes over time similar across all TODs (components 1 and 2)?
- Are RAS indicative of the degree of TOD (“TOD-ness”)? Are smaller RAS better? Related to this, to what extent is TOD decreasing car travel while increasing the uptake of walking and cycling in urban areas (component 1)?
- How strong is the impact of self-selection (personal attitudes and attributes) on travel behaviour, compared to provision of mixed land use and public transport services (component 3)?

5.2 Methodology

To answer these research questions, a conceptual framework has been developed (Figure 7). The ovals display three groups (vectors) of variables covering characteristics of urban form, location decisions, and travel decisions (via Activity Spaces). As urban decentralisation and mixed land-use in the form of TOD are believed to be effective in containing travel demand, the analysis compares three TOD precincts with very different configurations. Socio-demographics affect both types of mobility responses (location decisions and travel behaviour) and they can be
examined in the model either as mediators (e.g., location decision affects travel indirectly through household structure) or moderators (e.g., the relations between urban services and location are different across households’ lifecycle stages).

The blue solid lines in the diagram indicate hypothesised direct relationships, whereas the blue dotted lines show the feedback relations. For instance, increased demand for certain transport and urban services can change the frequency or hours for those services and even promote additional infrastructure investments (a pedestrian pathway, medical centre or a library). Similarly, the need to satisfy certain activities that are not provided in the area may lead to a relocation decision. These effects are expected to be seen as a reaction to urban modifications such as TOD, along with the obvious residential sorting associations with a particular type of natural and built environment and travel.

Figure 7: Conceptual model

The research adopted a mix of methodologies to analyse the relation of various configurations of TOD to travel patterns (mode, distances, route choice, and the shape, extent, and orientation of Activity Spaces), whilst accounting for socio-economic characteristics and attitudes. In particular a combination of data visualisation and multivariate data analysis was applied for

76
assessing the impact of urban form attributes on travel patterns. While the results of visualisation were mainly intended for exploration and display of the processes, multivariate data analysis (and specifically Structural Equation Modelling) and Artificial Neural Networks were applied to formally describe/test beliefs about travel-urban form processes. Unlike other scholarly work using instrumental variables or case control studies (the ample review by Cao et al., 2009, critically compares the approaches) this research applied before-after measurements to potentially control for households travel desires and attitudes. This combination of approaches ensures (and validates) the simultaneous assessment of linkages between urban space, travel, socio-demographics, and personal preferences. The validation is particularly important, as it provides credibility of the findings, yet is not a common practice in transport planning.

A combined GIS-data mining (Section 5.2) and multivariate analysis approaches (5.3 and 5.4) were adopted to simultaneously investigate the nexus between Activity Spaces and TOD characteristics and location.

The next sections describe in detail the methods applied for analysis, and the data requirements for them.

5.3 GIS-based modelling

“The greatest value of a picture is when it forces us to notice what I never expected to see.” (Tukey, 1977: vi)

The behavioural data of individual travellers in urban areas is essential for any travel demand analysis and prediction required in the planning and management of urban transport systems. Starting with the seminal work of Hägerstrand (1970), numerous excellent approaches have been developed to visualise and analyse travel behaviour in space and time: time-space prisms/"fish tanks"/aquarium, 3D GIS visualisation, accessibility measures (isochrones, areas of iso-utility), cumulative and gravity opportunity measures. However, varying resolution levels have complicated the application of measures and their interpretation at a larger population level. For this reason, this research has opted for application of the Activity Space measure at two levels: household, to benefit from the high resolution and dynamic elements, and TOD precinct level, to expose in an easy visual way the changes that occurred after the opening of the railway corridor.

Like Buliung and Morency (2009), who used examples from Canada to show how visualisation techniques can be used often in a complementary way to clarify transport- and land use-related
spatial, temporal and social processes, this research used a number of maps and tools for Activity Spaces to capture travel, urban facilities, and their use. The visual results (see Figures 9-17) display the land-use changes and the dynamic behaviour of households in the three precincts. Also, they present the use of space, reducing the complexity of tabular databases to visual constructs that reveal the demand for urban systems.

Although the visualisation is not analysis per se, it facilitates knowledge creation through the identification of patterns in spatial data. According to Buliung and Morency (2009) - who summarised the evolution of data visualisation and analysis and their role in revealing fundamental characteristics of spatial phenomena - the availability of software, coupled with the implementation of innovative approaches for data visualisation have made possible the advent of the state-of-the-art in visual communication of spatial, temporal, and social qualities of urban processes. Drawing a parallel with the arts, they compared geo-visualisation to an “anamorphosis interpreter” wherein the act of visualisation makes use of specialised devices which “compels the viewer to occupy a specific perspective” (p.121), in order to understand the underlying processes.

Their analysis substantiated the view that observed urban travel behaviour proceeds from and contributes to the structuring of transport and activity functions. Section 5 here gives a suite of visual tools, which represent a key ingredient for communicating results and complement or support the results of the formalised mathematical models.

5.4 Multivariate Data Analysis Models

Statistical approaches, e.g. multivariate data analysis including structural equation modelling, SEM, data mining (Golob, 2004; Chen and McKnight, 2007; Ye et al., 2007; Wang et al., 2011), as well as discrete choice modelling (Dugundji and Walker, 2005; Hensher and Rose, 2007; Bhat and Guo, 2007) have been extensively applied in transport modelling with the aim to identify relationships and test behavioural hypotheses (Mokhtarian and Cao, 2008).

As indicated by the literature review, a wide range of research projects has focused on travel decisions (mode, route, departure time, trip chaining complexity) and location (residential, office location/relocation) linked to build environment characteristics and personal socio-demographics and attitudes. But while the application of complex discrete choice models and multivariate analysis models has reached a certain stage of maturity, there has been limited progress in geo-spatial analysis. This is one of the main limitations highlighted by Páez (2006) and this research has incorporated spatial information to account for spatial dependence and heterogeneity.
As a consequence, this research integrated the physical and environmental dimensions of urban form and the attributes of individuals/households with their Activity Spaces. It should be emphasised one more time that a macro-approach combined with non-geographical models place severe limitations on the richness of questions and findings which can be addressed (Frazier and Kockelman, 2005; Páez, 2006).

A second important theoretical limitation in much of the current research is the treatment of time; this research has gone one step beyond the cross-sectional, static perspective, by comparing before-and-after changes in Activity Spaces, associated with changes in urban form. Although a truly dynamic analysis of changes would have been beneficial for research questions such as the ones formulated here, a detailed account of time was fraught (not surprisingly) with the practical difficulties of carrying out longitudinal data collection. Finally, bi-directional relationships among constructs such as urban form or Activity Space require a more sophisticated approach (non-recursive SEM with neighbourhood effects). Such holistic investigation has not been found in the literature and adds a significant understanding of TODs’ effects on travel behaviour.

This research has used multivariate analysis of variance (MANOVA) to compare vectors of quantitative variables regarding travel and Activity Spaces, as well as socio-demographics across the three TOD precincts before and after the opening of the railway corridor. Then a structural equation model has integrated the household behaviour and features of urban facilities as in the research framework presented in Figure 7. At this stage it is important to note that the structural model also included as inputs results from a stated preference survey on location choice, which were obtained outside of this research. They will not be discussed here and the reader is referred to Olaru et al. (2011).

### 5.5 Structural Equation Modelling (SEM)

SEM is a confirmatory dependence technique for testing structural relationships between various factors. The general formulation is:

\[ Y = By + \Gamma x + \xi \]

(25)

where \( y \) is a vector of endogenous variables, \( B \) a matrix of coefficients linking endogenous variables, \( \Gamma \) a matrix associated with exogenous variables and \( \xi \) vector of error terms (Hair et al., 2010). Besides the benefit of allowing for variables to be independent in some relations and dependent in others at the same time, SEM has the ability to construct latent variables, which are not measured directly. Hence, the structural model includes not only a structural part, but a
measurement model as well. In the measurement part, the latent constructs (reflective or formative) are estimated in the model from several indicators. This allows the researcher to explicitly capture the reliability of measurement in the model, which in theory allows the structural relations between latent variables $\eta$ (endogenous) and $\xi$ (exogenous) to be accurately estimated.

Relations (26) below present the general form of SEM.

$$\eta = B\eta + \Gamma\xi + \varsigma$$  \hspace{1cm} (26)

$$y = \Lambda\eta + \varepsilon$$  \hspace{1cm} (27)

$$x = \Lambda\xi + \delta$$  \hspace{1cm} (28)

SEM can be specified in several formats, either involving multiple matrices (as in relations 27 and 28) or graphical, as path diagrams. They are useful graphical tools depicting the relationships described mathematically by (26) and follow several conventions. Ovals or ellipses represent latent (unobserved) constructs, rectangles indicate observed variables, such as those measured in questionnaires, single-headed arrows are used for predictive relationships and double-headed arrows for covariances. The paths also include errors, either for items of a latent construct, or for endogenous variables.

SEM is estimated by comparing an implied structure of the variance-covariance matrix (model-based matrix) of the measures to an empirical or data-based variance-covariance matrix. If the two matrices are close to each other, then the SEM model can be considered a satisfactory, plausible explanation for relations between the measures (Hair et al., 2010).

This research adopted a two-step approach (Anderson and Gerbing, 1988), with testing of the measurement model first and then building uni-dimensional congeneric models to be used in the structural part of SEM. This was due to the limited sample size. In the second step, a number of competing structural equations models were tested, with the TOD precinct as the only moderator.

AMOS 18.0 was used to fit the models, using the maximum likelihood estimation method. Multiple item measures were used to help determine the latent constructs for Activity Spaces and attitudes towards built environment and the statistical analysis further ensured the internal consistency.
5.6 Artificial Neural Networks

Artificial Networks (NN) are inspired by the collective processes in the brain and provide a suitable framework for modelling nonlinear complex processes with numerous parameters (Haykin, 1999; Engelbrecht, 2002). NN have been successfully used in a variety of applications, including function approximation/prediction, control, pattern recognition and completion, optimisation, and classification. They are made of units/nodes/neurons connected by links serving to propagate activation from node to node (Smith, 1993; Hassoun, 1995; Haykin, 1999; Engelbrecht, 2002). Each link has a weight, determined by the strength and sign of the connection (input signals are inhibited or excited), and nodes compute a weighted sum of their inputs then apply an activation function to derive the output. Despite the variety of NN and their purposes, they are all arranged in layers such that each node receives input from units in the immediately preceding layers. Some networks implement a gradient descent approach in the parameters space to reduce errors in the outputs, others provide a recurrent feedback of the output in the inputs, or measure distances between inputs to identify commonalities. This research applied a supervised neural network, aiming to understand the associations between urban form, socio-demographics and Realised Activity Spaces.

5.6.1 Feed-forward back-propagation networks

Supervised NN discover patterns in the input-output data based on their associations. They generally include three layers: input, hidden (one or more), and output (Figure 8) and they are trained on a set of known data. The input is propagated through the network through interconnections between neurons. Each interconnection has a weight, which modifies the strength of the signal. The hidden neurons sum the inputs and pass the resulting signal to the output neurons by using an activation function and commonly insert a bias in order to shift the space of the nonlinearity (Martin and Morris, 1999: 202).

![Figure 8: Structure of a feed-forward back-propagation neural network](image-url)
Therefore, during forward propagation, we have the following transformations:

\[ S_j = \sum_i w_{ij} a_i \]  

(29)

and

\[ a_j = f(S_j) \]  

(30)

\( S_j \) is the sum of all products of weights and outputs from the previous layer \( i \), \( w_{ij} \) represents the relevant weights connecting layers \( i \) and \( j \), and \( a_i \) and \( a_j \) represent the activations of the nodes in the layer \( i \), respectively \( j \), \( f \) being the activation function.

The output of the network is then compared to the observed output and the deviation (fit measure) is fed back into the network (update of weights) in order to be gradually minimised. This is called the learning process.

The error function is commonly given as the sum of the squares of the differences between target (real) and actual value obtained at the output layer. For a particular training case, the error is given by:

\[ E = \frac{1}{2} \sum_n (t_{jn} - a_{jn})^2 \]  

(31)

The weights are adjusted iteratively on the training sample (this process is stopped when a sufficiently close match between the network outputs and the real data is attained) and then the network will be assessed on its “prediction” performance using a test data sample (Haykin, 1999).

A potential problem with NN is overtraining, when the network matches too well the results from the training set, being problematic when analysing completely new data, and affecting generalisability of findings.

In many cases NN have shown the ability to outperform the multivariate analysis approaches due to their non-linear learning and toleration of noisy inputs or multicollinearity (e.g., medical diagnostics, customer segmentation, stock predictions) (Kay and Titterington, 1999).

In this research, the NN was applied to cross-validate the results of the SEM. The estimation was done using the proprietary software Synapse 1.5.2 (Peltarion).
6. Empirical Data

This research used survey data collected in a Linkage ARC project, ‘Impacts of Transit Led Development in a New Railway Corridor’ (LP0562422), completed in 2010. This quasi-longitudinal study included three main stages of data collection, on a new railway linking Perth city to Mandurah, opened in December 2007. The first stage was conducted in 2006, a year before the opening, whereas stages two and three were after the railway commenced its operation, in July-August 2008 and then 2009. The second main source of data was geographical information from the Western Australia Departments of Planning and Transport. The two sources are described in more detail below and the description of the three precincts (Bull Creek, Cockburn Central, and Wellard) is given in Section 6.3.

6.1 Survey Data

Three household surveys deployed before and after railway opening have had the objective of assessing the behavioural responses to emerging TOD precincts along the railway corridor. The instruments varied between waves according to the research questions: whereas the first wave concentrated on location, attitudes towards built environment and travel, data collected after the opening of rail were aimed at changes in travel patterns (for additional information please see Curtis and Olaru, 2010a; Olaru et al., 2011). The three precincts were split into four travel zones: households within 5, 10, 15 min walk to the railway station and (the fourth zone) households within 5 min drive to the station, given the catchment area for rail stations in Perth. Random sampling was applied for selecting the households using a utility provider users’ list. The sample size was calculated to ensure 95% confidence interval for several socio-demographic statistics and parameter estimates and with a minimum quota of 50 households for each of the four travel zones. Whereas the first two waves used personal interviews (introductory letter, repeated visits, reminder, with follow-up for households who did not respond to identify potential sources of non-response bias), the last wave used a mail-out survey. And despite attempts to maintain a true panel, the decreasing response rate from wave to wave has led to replenishments, particularly with incoming households, as necessary. This approach to compensate for attrition however, has not achieved a similar sample size over the three waves.

Table 1 presents the data collected in the study and highlights (italics) the variables used in this research, where the emphasis is on trip making, use of space, and characteristics of urban form. The table shows that both revealed and stated preference data were collected, along with
household and individual characteristics, travel behaviour, location, physical activity and mobility restrictions.

Table 1: Contents of the Household Surveys (LP0562422)

<table>
<thead>
<tr>
<th>Type of information / Wave</th>
<th>Wave 1</th>
<th>Control</th>
<th>Wave 2</th>
<th>Wave 3</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Sample size</strong></td>
<td>N=1034</td>
<td>N=360</td>
<td>N=632</td>
<td>N=829</td>
</tr>
<tr>
<td><strong>Information on household:</strong> size, type of dwelling and tenure, when moved to the residence and plans to move from the area, number of cars, bicycles, scooters, motorcycles, parking bays (income and contact details at the end of the interview)</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
</tr>
<tr>
<td><strong>Information about vehicles:</strong> type, make, age, fuel, running costs and who bears them</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
</tr>
<tr>
<td><strong>Information on household members:</strong> relation to the interviewee, age, gender, education, work/education place, number of weekly hours involved in work and voluntary work, flexibility of work program, types of driving licences possessed, mobility restrictions due to physical condition (or imposed by parents on their children), physical activity</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
</tr>
<tr>
<td><strong>Travel diaries:</strong> collected as daily logs of all trips made by each household member on the specified travel day (origin, destination, departure and arrival time, purpose/activity, mode of travel, route, party size, out-of-pocket cost, parking, transfers)</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
</tr>
<tr>
<td><strong>Information on previous location:</strong> address, size, type of dwelling and tenure, number of cars, bicycles, scooters, motorcycles, parking bays, previous work/education location</td>
<td>✓*</td>
<td>✓*</td>
<td>✓*</td>
<td>✓*</td>
</tr>
<tr>
<td><strong>Push</strong> (26) and <strong>pull</strong> (14) reasons for moving from the previous residence to their current neighbourhood</td>
<td>✓*</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Stated importance of having access to various facilities when selecting the current location and residence (15 elements): availability of facilities within walking, cycling, and 5-min driving distance</strong></td>
<td>✓*</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Stated choice experiments:</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>- eight scenarios in a location choice experiment</td>
<td>✓**</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>- eight scenarios in a mode choice experiment</td>
<td></td>
<td></td>
<td>✓</td>
<td></td>
</tr>
</tbody>
</table>

* Questions only for those households who moved in the precinct area in the previous five years.
** Results from discrete choice modelling included in this research.
Because trip diaries provided the main data required for this research, in the following they will be the focus.

Twenty-four hour trip diaries chronicled the sequence and duration of activities undertaken by the respondents in their allocated weekday (always a Wednesday). Every household member travelling independently completed the trip diary (memory joggers were provided before the travel day in order to aid the completion of the trip diaries). The analysis was performed at the individual and household level and excluded cases where the household members worked from home (telecommute) or did not travel during the allocated day for various reasons (e.g. illness). Also, excluded from the analysis were the extra-urban long-distance trips (fly-in fly-out air-travel work or holiday trips).

The activities were also aggregated into five main categories: work or education, shopping (for grocery and for other), recreational activities (watching or participating in a cultural event, watching a sporting event, eating out, physical activities, visiting friends or receiving visitors), pick-up/drop-off, personal business.

### 6.2 GIS Data

Availability of transport and land use data (in an increasing variety of formats, and collected using a wide range of instruments), presents fresh opportunities to explore urban form characteristics and understand spatial patterns, as well as combine those with survey data for relevant applications. Moreover, the readiness of proprietary and open software environments, coupled with implementation of innovative approaches for data collection, foster the construction of spatiotemporal knowledge of transport and land use processes. This research makes use of secondary data and a number of GIS tools, which facilitated the visualisation and analysis of Activity Spaces.

Land-use and employment data were provided by the WA Department of Planning and GIS-based road network data by the WA Department of Transport. Profiling the three TOD precincts was based on Census 2006 data (ABS, 2006). The data was aggregated at suburb level and then precinct, for comparison with the whole metropolitan area.

Transport and land use data provided the support for data enhancement, geocoding and route imputation. The single major difficulty encountered in data preparation and cleaning prior to
analysis was the geo-coding. The trip diaries were manually\(^3\) geo-coded, after being checked for accuracy and consistency. And because Realised Activity Spaces rely on very detailed and precise data for the activities locations and times, incomplete data, where the specific address could not be exactly established, were not considered in the analysis. The Realised Activity Space analysis was performed at both the aggregated precinct and household levels.

The lack of information on the routes provided by the standard trip diary approach, forming the basis of the research, is considered a limitation in this research, when estimating the kernel density based Realised Activity Spaces. Ethical considerations and privacy issues currently limit large scale applications of more detailed and more passive survey approaches, such as GPS tracking technologies or the use of triangulation of mobile phone signals in the context of travel behaviour analysis. Therefore, only for small sub-sample of households (54), a method to enhance the survey dataset was also devised. Post-processing of the data considered the routes taken by the individuals, either indicated by them or imputed with the information at hand. The information on routes taken by individuals was imputed using Google Maps.

### 6.2.1 Why Generate Route Information?

Behavioural surveys based on questionnaires are not always sufficient for measuring microscopic travel behaviour in space-time dimensions (Kwan, 1999; Weber and Kwan, 2002; Axhausen et al., 2003), as required by Activity Spaces. Recently, the advances of GPS technology and mobile communication created the opportunity for these to be used as survey instruments for observing individual travel behaviour (Asakura and Hato, 2004; Witlox, 2007; Asakura and Iryo, 2007; Du and Aultman-Hall, 2007), eliminating the need for manual geo-coding and reliance on the reported times and routes taken by individuals.

However, little is known about the influence of detailed data on Activity Spaces. Using a pilot study, Olaru and Powell (2007) found that GPS-tracing improved assessment of Activity Spaces and at the time increased the spatial cognition of the travellers in a longitudinal 8-week study. More recent scholarly work seems to support the need for richer data. Advancements have been made in adapting the traditional kernel density measure by recognising spatial use constraints

\(^3\) Automation was not possible, as most of the locations did not have one or more of the four required elements of information: street or unit number, name of the street, type of the street, and suburb and/or postal code. As numerous addresses in Perth (and similarly in other Australian cities) have the same name of the street, without a correct type (one of more than 30 categories) and suburb, the location cannot be directly identified.
and space-use patterns within a network space (Downs and Horner, 2007). Okabe et al. (2009) provided evidence of bias associated with the traditional measurement approach (including only locations), which overestimates densities around activity locations. Their results confirmed that continuous density surfaces could be derived when considering network data in addition to locations. I concur and hence this research examines the changes in Activity Spaces as a result of including detailed information on re-created routes most likely travelled by individuals. As a consequence, this research offers more refined, continuous Activity Spaces, reflecting density and intensity patterns at an enhanced and close-to-reality resolution.

Using GIS coordinates for origin and destination locations as initial information, routes or sequences of travel data points (similar to GPS track-points) were constructed using an on-line route planner provided by Google Maps. The routes accounted for the constraints inherent in the choice of certain transport modes and considering the time of travel. Despite its benefits and easy access, batching of the operation was not possible; hence the relatively time-consuming processing of routes limited data imputation to 54 households only.

6.3 TOD Precincts

The new strategic railway corridor through metropolitan Perth’s southern suburbs to Mandurah has added in 2007 a further 72 km to the electrified passenger rail network. This rail line traverses partly through existing suburban development (disruption has been minimised by routing the railway along the centre of an existing freeway reserve) and partly through ‘greenfields’. In existing areas, the redevelopment approach has been to re-orient the land use activity towards the station. Greenfield areas have provided new opportunities and in order to further increase accessibility and economic opportunity, the government and the private sector have planned for new TOD communities at some railway precincts. This mixture of designs created a variety of emerging TOD precincts in Perth. At one end of the spectrum is the precinct that acts primarily as an origin station or transit interchange (rather than a destination station), the focus here being to achieve a high accessibility level (by car and feeder bus), with little attempt to plan for land uses designed to act as trip attractors. At the other end is the precinct designed around the TOD concept, aiming to create a mix of land uses and residential density (hence serving as a strong trip attractor), with access mainly by foot rather than car. Other stations fit within this continuum as recipes with various TOD ingredients. The three precincts selected in the LP0562422 research project (Bull Creek, Cockburn Central, and Wellard) represent different TOD environments. Figure F3 – Appendix presents the limits of the three precincts and their split into four access and travel zones. Throughout this dissertation,
characteristics of the three precincts will be displayed using colour coding: blue for Bull Creek, red for Cockburn Central, and green for Wellard.

6.3.1 Profile of the three precincts

The three precincts vary systematically not only in the TOD characteristics, but also in their citywide access and socio-economic profile (Tables 2 and 3). This allowed assessment of potential differences in the accessibility, design, density and diversity of the three precincts.

As detailed by Curtis and Olaru (2007), the primary focus at Bull Creek was the transit interchange. The station lies at the intersection of a primary distributor road (Leach Highway) and the main freeway (Kwinana Freeway). The freeway reserve effectively constrains the opportunity for development of a pedestrian scale precinct within close proximity to the station. The station caters for a high volume of car access (605 car parking bays) and a feeder bus system along the distributor road serving the surrounding suburbs.

At Wellard Station the design objective is to mirror both TOD and “New Urbanist” principles. The promise was to develop a mixed use ‘Main Street’ (including 4,070 m² of retail space) centred on the station, surrounded by higher density residential development. The street network is designed to give a good pedestrian environment, residential development is rapidly occurring, but the core of the precinct (retail, community, hospitality services, etc.) is yet to be achieved and five years after the railway opening this area remains a building site. Clearly, the development was affected by the global financial crisis, yet currently there is no firm commitment on when the ‘Main Street’ will come alive. The station benefits from 290 park-and-ride bays.

The Cockburn Central precinct features aspects of both Wellard and Bull Creek. It provides for high car access (884 park-and-ride car bays on both sides of the station and 928 car parks for the exclusive use of commercial premises) but the precinct is dissected by the 100-metre Kwinana freeway reserve, which reduces amenity for non-motorised modes. Like Wellard, development of a mixed-use town centre is designed to be part of the station. This multi-functional Town Centre is currently being built and will provide a range of recreational, commercial, entertainment and cultural facilities. The Cockburn “town” also includes a residential component, which started to receive residents in 2011. An existing big-box suburban shopping centre (Gateway) is located on the opposite road reserve side of the railway station and new Town Centre and is continuing its expansion; pedestrian access requires traversing a major urban arterial road (Beeliar-Armadale Rd).

Table 2 presents the main characteristics of the precincts compared to the whole metropolitan area.
Table 2: Profile of the three precincts vs. metropolitan area (highest values in bold)

<table>
<thead>
<tr>
<th>Variable</th>
<th>Bull Creek - BC</th>
<th>Cockburn Central – CC</th>
<th>Wellard – W</th>
<th>Metro Area</th>
</tr>
</thead>
<tbody>
<tr>
<td>Type of TOD</td>
<td>Brownfield/Transit Interchange Well-defined PT network in area</td>
<td>Brownfield/Land Agency Model Highest number of park-and-ride facilities</td>
<td>Greenfield/Private Sector Model</td>
<td></td>
</tr>
<tr>
<td>Distance from CBD (km)</td>
<td>12</td>
<td>21</td>
<td>39</td>
<td>0</td>
</tr>
<tr>
<td>Population density (pers/km(^2))</td>
<td>1,925</td>
<td>538</td>
<td>625</td>
<td>271</td>
</tr>
<tr>
<td>Dwellings/km(^2)</td>
<td>674</td>
<td>175</td>
<td>112</td>
<td>97</td>
</tr>
<tr>
<td>Persons per dwelling</td>
<td>2.85</td>
<td>3.07</td>
<td>2.90</td>
<td>2.78</td>
</tr>
<tr>
<td>Education &gt;= year 12</td>
<td>47.6%</td>
<td>33.1%</td>
<td>20.6%</td>
<td>36.8%</td>
</tr>
<tr>
<td>Born in Australia</td>
<td>59.5%</td>
<td>68.4%</td>
<td>65.8%</td>
<td>64.1%</td>
</tr>
<tr>
<td>Employed</td>
<td>50.4%</td>
<td>56.1%</td>
<td>38.6%</td>
<td>48.2%</td>
</tr>
<tr>
<td>Household car ownership</td>
<td>1.67</td>
<td>1.69</td>
<td>1.36</td>
<td>1.51</td>
</tr>
<tr>
<td>Median weekly household income</td>
<td>1,275</td>
<td>1,244</td>
<td>945</td>
<td>1,042</td>
</tr>
<tr>
<td>Median housing price 2006 (‘000)</td>
<td>553</td>
<td>394</td>
<td>272</td>
<td>380</td>
</tr>
<tr>
<td>Median housing price 2008 (‘000)</td>
<td>662</td>
<td>470</td>
<td>301</td>
<td>455</td>
</tr>
<tr>
<td>Journey to work</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>- Car only</td>
<td>69.8%</td>
<td>73.2%</td>
<td>74.0%</td>
<td>69.3%</td>
</tr>
<tr>
<td>- Public transport &amp; walk/cycle</td>
<td>16.1%</td>
<td>10.7%</td>
<td>9.9%</td>
<td>12.4%</td>
</tr>
<tr>
<td>City-wide road distance accessibility (2006)**</td>
<td>24.1</td>
<td>30.2</td>
<td>39.9</td>
<td></td>
</tr>
<tr>
<td>City-wide public transport centrality accessibility (time/freq/transfers) (2006)**</td>
<td>68</td>
<td>89</td>
<td>131</td>
<td></td>
</tr>
<tr>
<td>Composite local access (2006)**</td>
<td>18.9</td>
<td>16.2</td>
<td>17.4</td>
<td></td>
</tr>
</tbody>
</table>


** Details in Curtis and Olaru (2007) and Scheurer and Curtis (2008).
These three precincts have different levels of accessibility at both city-wide level and local level and different urban and socio-demographic fabric.

Bull Creek is the closest to the city, the most expensive (land and housing), has the highest proportion of more highly educated residents and the highest household income (although many households include retired or home duties members). Bull Creek has also the highest local access and city-wide distance and time access. Cockburn has the largest proportion of young families and the highest employment, as well as the highest proportion of Australian born residents. Cockburn Central records the lowest local access, due to less ‘pedestrian-oriented’ design. Wellard is the furthest precinct from the city, has the lowest employment, household income and car ownership, and the lowest real estate values. It also exhibits the lowest city-wide access, with possible implications on the lowest public transport and walk/cycle proportion of trips in the 2006 Census.

A comparison of the employment densities (Table 3) of all precincts further attests the differences in the three precincts. Here, the precincts are split into their component suburbs. Although Cockburn Central records the highest proportion of employed residents (56.1%), Bull Creek has the highest employment number. This is because of the higher density in Bull Creek, which offsets the highest number of retired residents. Table 3 also highlights the significantly low employment rate in Wellard.

In addition, Table 3 presents an entropy-like measure⁴ (Paéz, 2013: 120), indicating whether there are systematic patterns in the employment distribution across the three precincts. Source: Australian Bureau of Statistics (2006).

Compared to a random pattern of the eight types of employment used by the Australian Bureau of Statistics displayed at the top of the table (entropy = 2.08), the distribution in Bull Creek (entropy = 1.68) is more random/diverse than in Cockburn Central (entropy = 1.62) and in Wellard (entropy = 1.58), where the dominating sector is manufacturing. In relative terms, the entropy of Bull Creek is 81%, in Cockburn Central 78%, and in Wellard 76%. Although these elements of density and diversity do not refer to land-uses, they are indicative of the

⁴ The entropy \( h = -\sum_j p_j \ln(p_j) \) is bounded to 0 for total spatial organisation and to \( \ln(n) \), where \( n \) is the number of different uses \( j \). A standardised entropy measure is also included in the table (shown in square brackets) with values ranging from 0 to 100%.
heterogeneity in the three precincts. Density and diversity have also been previously linked to travel behaviour (Ewing and Cervero, 2010).

Table 3: Employment by precinct and suburb (2006)

<table>
<thead>
<tr>
<th>Precinct</th>
<th>State Suburb</th>
<th>Manufacturing</th>
<th>Construction</th>
<th>Retail Trade</th>
<th>Accommodation and Food</th>
<th>Professional, Scientific, Technical</th>
<th>Public Administration and Safety</th>
<th>Education and Training</th>
<th>Health Care and Social Assistance</th>
<th>Total Employment</th>
<th>Entropy of employment (standardised value)</th>
<th>Entropy Precinct (standardised value)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bateman</td>
<td></td>
<td>126</td>
<td>109</td>
<td>201</td>
<td>120</td>
<td>195</td>
<td>116</td>
<td>258</td>
<td>208</td>
<td>1,855</td>
<td>1.70 [82]</td>
<td></td>
</tr>
<tr>
<td>Booragoon</td>
<td></td>
<td>200</td>
<td>121</td>
<td>278</td>
<td>150</td>
<td>258</td>
<td>142</td>
<td>255</td>
<td>294</td>
<td>2,480</td>
<td>1.65 [79]</td>
<td></td>
</tr>
<tr>
<td>Brentwood</td>
<td></td>
<td>68</td>
<td>49</td>
<td>103</td>
<td>44</td>
<td>67</td>
<td>50</td>
<td>85</td>
<td>110</td>
<td>815</td>
<td>1.68 [81]</td>
<td></td>
</tr>
<tr>
<td>Bull Creek</td>
<td></td>
<td>310</td>
<td>241</td>
<td>407</td>
<td>233</td>
<td>368</td>
<td>264</td>
<td>477</td>
<td>462</td>
<td>3,881</td>
<td>1.70 [82]</td>
<td></td>
</tr>
<tr>
<td>Mount Pleasant</td>
<td></td>
<td>232</td>
<td>242</td>
<td>323</td>
<td>189</td>
<td>389</td>
<td>169</td>
<td>287</td>
<td>305</td>
<td>3,149</td>
<td>1.65 [79]</td>
<td></td>
</tr>
<tr>
<td>Riverton</td>
<td></td>
<td>205</td>
<td>179</td>
<td>248</td>
<td>122</td>
<td>162</td>
<td>141</td>
<td>239</td>
<td>252</td>
<td>2,314</td>
<td>1.64 [79]</td>
<td></td>
</tr>
<tr>
<td>Ross moyne</td>
<td></td>
<td>100</td>
<td>77</td>
<td>160</td>
<td>59</td>
<td>133</td>
<td>80</td>
<td>149</td>
<td>160</td>
<td>1,358</td>
<td>1.63 [78]</td>
<td></td>
</tr>
<tr>
<td>Shelley</td>
<td></td>
<td>198</td>
<td>133</td>
<td>237</td>
<td>103</td>
<td>173</td>
<td>154</td>
<td>267</td>
<td>249</td>
<td>2,147</td>
<td>1.68 [81]</td>
<td></td>
</tr>
<tr>
<td>Willetton</td>
<td></td>
<td>827</td>
<td>593</td>
<td>1,138</td>
<td>593</td>
<td>717</td>
<td>684</td>
<td>1,010</td>
<td>967</td>
<td>9,317</td>
<td>1.69 [81]</td>
<td></td>
</tr>
<tr>
<td>Winthrop</td>
<td></td>
<td>233</td>
<td>163</td>
<td>404</td>
<td>263</td>
<td>337</td>
<td>191</td>
<td>327</td>
<td>311</td>
<td>3,141</td>
<td>1.69 [81]</td>
<td></td>
</tr>
<tr>
<td>Bull Creek</td>
<td>Atwell</td>
<td>407</td>
<td>319</td>
<td>367</td>
<td>132</td>
<td>243</td>
<td>237</td>
<td>265</td>
<td>376</td>
<td>3,333</td>
<td>1.68 [81]</td>
<td></td>
</tr>
<tr>
<td>Cockburn Central</td>
<td>Beeliar</td>
<td>322</td>
<td>218</td>
<td>267</td>
<td>90</td>
<td>105</td>
<td>124</td>
<td>109</td>
<td>191</td>
<td>2,136</td>
<td>1.59 [76]</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Jandakot</td>
<td>189</td>
<td>155</td>
<td>234</td>
<td>77</td>
<td>132</td>
<td>80</td>
<td>131</td>
<td>170</td>
<td>1,780</td>
<td>1.60 [77]</td>
<td></td>
</tr>
<tr>
<td></td>
<td>South Lake</td>
<td>444</td>
<td>238</td>
<td>360</td>
<td>147</td>
<td>123</td>
<td>151</td>
<td>170</td>
<td>317</td>
<td>2,883</td>
<td>1.60 [77]</td>
<td></td>
</tr>
</tbody>
</table>

91
Finally Table 4 provides descriptive statistics of the three precincts, based on the survey data.

Table 4: Descriptive statistics by precinct and wave (statistically significant differences in *italics*)

<table>
<thead>
<tr>
<th>Variable</th>
<th>Before opening (Wave 1)</th>
<th>After opening (Wave 2)</th>
<th>Settled-in behaviour (Wave 3)</th>
<th>p (ANOVA) wave 1 / wave 2 / wave 3</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>BC CC W</td>
<td>BC CC W</td>
<td>BC CC W</td>
<td></td>
</tr>
<tr>
<td>Family size</td>
<td>2.85 3.00 2.76</td>
<td>2.79 2.92 2.59</td>
<td>2.90 2.97 2.47</td>
<td>0.075 (0.126 0.081)</td>
</tr>
<tr>
<td># bedrooms</td>
<td>3.63 3.73 2.75</td>
<td>3.68 3.70 3.13</td>
<td>3.80 3.75 3.58</td>
<td>0.258 (0.334 0.164)</td>
</tr>
<tr>
<td>Weekly working hrs/person</td>
<td>31.2 30.7 28.7</td>
<td>32.5 31.4 31.9</td>
<td>31.48 35.05 32.8</td>
<td>0.119 (0.305 0.163)</td>
</tr>
<tr>
<td>Car availability</td>
<td>1.95 1.94 1.83</td>
<td>1.86 1.98 1.69</td>
<td>1.89 1.82 1.85</td>
<td>0.180 (0.249 0.158)</td>
</tr>
<tr>
<td>Variable</td>
<td>Before opening (Wave 1)</td>
<td>After opening (Wave 2)</td>
<td>Settled-in behaviour (Wave 3)</td>
<td>p (ANOVA)</td>
</tr>
<tr>
<td>--------------------------------</td>
<td>-------------------------</td>
<td>------------------------</td>
<td>-------------------------------</td>
<td>-----------</td>
</tr>
<tr>
<td>Travel behaviour</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Daily travel time (min)</td>
<td>55.2</td>
<td>53.9</td>
<td>60.40</td>
<td>0.092</td>
</tr>
<tr>
<td></td>
<td>60.2</td>
<td>54.1</td>
<td>63.9</td>
<td>0.273</td>
</tr>
<tr>
<td></td>
<td>45.9</td>
<td>48.3</td>
<td>70.4</td>
<td>&lt;0.001</td>
</tr>
<tr>
<td>Daily travel distance (km)</td>
<td>33.5</td>
<td>34.2</td>
<td>28.18</td>
<td>0.007</td>
</tr>
<tr>
<td></td>
<td>44.36</td>
<td>41.85</td>
<td>38.05</td>
<td>0.054</td>
</tr>
<tr>
<td></td>
<td>45.94</td>
<td>42.30</td>
<td>45.14</td>
<td>&lt;0.001</td>
</tr>
<tr>
<td># legs/day and person</td>
<td>3.79</td>
<td>4.86</td>
<td>4.72</td>
<td>0.022</td>
</tr>
<tr>
<td></td>
<td>3.74</td>
<td>4.5</td>
<td>4.10</td>
<td>0.108</td>
</tr>
<tr>
<td></td>
<td>3.57</td>
<td>4.84</td>
<td>4.39</td>
<td>0.003</td>
</tr>
<tr>
<td>Trips by mode:</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>% private motorised</td>
<td>77.8</td>
<td>72.5</td>
<td>68.3</td>
<td>&lt;0.001</td>
</tr>
<tr>
<td></td>
<td>81.8</td>
<td>78.7</td>
<td>72.4</td>
<td></td>
</tr>
<tr>
<td></td>
<td>91.2</td>
<td>74.4</td>
<td>68.2</td>
<td></td>
</tr>
<tr>
<td>% public transport</td>
<td>5.9</td>
<td>11.6</td>
<td>6.9</td>
<td>0.036</td>
</tr>
<tr>
<td></td>
<td>5.8</td>
<td>7.3</td>
<td>7.1</td>
<td></td>
</tr>
<tr>
<td></td>
<td>1.3</td>
<td>7.4</td>
<td>14.3</td>
<td></td>
</tr>
<tr>
<td>% cycling + walking</td>
<td>15.4</td>
<td>15.0</td>
<td>24.8</td>
<td>&lt;0.001</td>
</tr>
<tr>
<td></td>
<td>11.0</td>
<td>13.3</td>
<td>20.5</td>
<td></td>
</tr>
<tr>
<td></td>
<td>7.5</td>
<td>14.6</td>
<td>17.5</td>
<td></td>
</tr>
<tr>
<td>Trips under 5km:</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>% private motorised</td>
<td>63.6</td>
<td>67.4</td>
<td>62.3</td>
<td>&lt;0.001</td>
</tr>
<tr>
<td></td>
<td>66.4</td>
<td>72.9</td>
<td>65.5</td>
<td>&lt;0.001</td>
</tr>
<tr>
<td></td>
<td>82.8</td>
<td>75.6</td>
<td>59.5</td>
<td></td>
</tr>
<tr>
<td>% walking + cycling</td>
<td>27.9</td>
<td>22.2</td>
<td>29.0</td>
<td>&lt;0.001</td>
</tr>
<tr>
<td></td>
<td>24.9</td>
<td>19.3</td>
<td>27.7</td>
<td></td>
</tr>
<tr>
<td></td>
<td>14.7</td>
<td>11.5</td>
<td>22.3</td>
<td></td>
</tr>
<tr>
<td>Parking space</td>
<td>2.86</td>
<td>3.02</td>
<td>2.97</td>
<td>0.080</td>
</tr>
<tr>
<td></td>
<td>3.14</td>
<td>3.13</td>
<td>3.02</td>
<td>0.413</td>
</tr>
<tr>
<td></td>
<td>3.15</td>
<td>3.18</td>
<td>3.14</td>
<td>0.102</td>
</tr>
<tr>
<td># bicycles for adults/hh</td>
<td>1.26</td>
<td>1.31</td>
<td>1.60</td>
<td>0.241</td>
</tr>
<tr>
<td></td>
<td>0.92</td>
<td>0.98</td>
<td>1.21</td>
<td>0.130</td>
</tr>
<tr>
<td></td>
<td>0.72</td>
<td>1.13</td>
<td>1.08</td>
<td>0.005</td>
</tr>
<tr>
<td># bicycles for children/hh</td>
<td>0.47</td>
<td>0.59</td>
<td>0.67</td>
<td>0.072</td>
</tr>
<tr>
<td></td>
<td>0.70</td>
<td>0.76</td>
<td>0.84</td>
<td>0.096</td>
</tr>
<tr>
<td></td>
<td>0.64</td>
<td>0.81</td>
<td>0.87</td>
<td>0.021</td>
</tr>
<tr>
<td>Mobility restrictions (%)</td>
<td>3.8</td>
<td>5.8</td>
<td>7.5</td>
<td>N/A</td>
</tr>
<tr>
<td></td>
<td>5.2</td>
<td>4.5</td>
<td>5.6</td>
<td></td>
</tr>
<tr>
<td></td>
<td>4.3</td>
<td>4.2</td>
<td>9.8</td>
<td></td>
</tr>
<tr>
<td>N</td>
<td>317</td>
<td>157</td>
<td>347</td>
<td></td>
</tr>
<tr>
<td></td>
<td>369</td>
<td>221</td>
<td>268</td>
<td></td>
</tr>
<tr>
<td></td>
<td>348</td>
<td>254</td>
<td>214</td>
<td></td>
</tr>
</tbody>
</table>
The sample statistics show significant differences across precincts in travel behavior, but not in socio-demographics. Remarkable is the fact that differences in travel distance, time, and mode split are maintained in all three precincts after the railway opening.

Having made this introduction to the features of the three precincts, Section 7 presents results of data visualisation and analysis.
7. Data Analysis and Results

Analysing associations of land-use and activity-travel is not a trivial task. Morency (2004) and Buliung and Morency (2009) proposed a comprehensive conceptualisation of the links between behavioural and physical aspects of transport and land-use in the urban realm via ten critical dimensions (A to J in Figure 9). What stands out in this framework is the multitude of connections (direct and feedback), and their interactions. Components B and G, referring to household characteristics and activity needs, affect travel through activity participation and use of resources (H). Residential location (C) and building construction (D), also reflecting household needs, determine the use of urban space (I). The distribution of activities (E) and the supply of transport services (I) enable the individuals/households to fully participate in activities or behave otherwise and the results of this interaction is seen in the use of resources (F and J). The close and intricate relations of activity–travel behaviour and space–time decisions are crucial for various stakeholders and they can be more easily obtained and presented/communicated using visual aids.

Figure 9: Conceptual framework for assessing relations between activity-travel and land-use

Source: Buliung and Morency (2009): 124
7.1 Data Visualisation

Although a “picture is worth a thousand words” and the mapping of spatial data appears only all too rational, data visualisation, for very descriptive purposes, was considered a relatively “soft” research approach for some time. This has recently changed with the advancement of geo-spatial techniques, which, due to their intuitive nature, have transformed maps into very attractive instruments that can enable a broader end-user participation as well as facilitate simpler extraction of information and knowledge creation e.g. through the identification of patterns (Buliung and Morency, 2009).

Similarly, this research uses spatial visualisation to identify, analyse and communicate land use, socio-demographic and behavioural patterns. For example, Figures 10 and 11 display household income and the socio-economical structure, by spatial units defined by the Australian Bureau of Statistics (census collection districts). This indicates figures are spatially constrained. The contours of the precincts are given in blue (Bull Creek), red (Cockburn Central), and green (Wellard). Figure 12 to 14 indicate the employment levels and opportunities available in each precinct. As shown in Section 6.2, Bull Creek appears to “lead” in opportunities for activity participation, Cockburn Central reveals the highest employment rates, and Wellard displays the lowest levels of density and diversity. The greater dispersion of activities for Wellard’s residents is not necessarily surprising. The effect of accessibility increases is not evident a-priori. The accessibility enhancement may produce the expected effects and reduce the need for travel. However, it may also cause reverse effects, in the sense that the accessibility gain may draw resources to the CBD core, which aligns with observations previously reported for some European TOD cases (Vickerman et al., 1999).

The maps indicate heterogeneity within each of the precincts, both in terms of density of employment (Figure 12) and diversity mix of employment (Figures 13 and 14). However, in addition to the information in Table 3 (Section 6.3), these maps also show the spatial mosaic and the position of precincts and their constituent suburbs, along with “white spots” which are mainly residential in nature and where there is a lack of economic activity.

Next, the mapping showing travel destinations for all trips before and after the rail opening may provide more insights than a basic comparison of travel distances only (Figures 16a, b and c to 17). It is noticeable that many trips originating in Bull Creek remain local or destinations are concentrated around the city centre, whereas trips from Cockburn Central are more directed to the North and West of the city (CBD, Fremantle, Osborne Park) and Wellard residents travel both locally or towards the South (Kwinana, Rockingham, Mandurah).
After the opening of the railway (“settled-in” behaviour in 2009) the destination pattern has changed, with greater dispersion visible in all precincts. However, the biggest change occurred in the case of Wellard, where the mapping now reveals activity distribution over a large area of the city, including the CBD (Figure 17). It should be noted Figure 17 has been obtained from a different source and the result shown for the precincts are given in green (Bull Creek), red (Cockburn Central), and blue (Wellard). A change in scale parameters between precincts is reflective of the inherent differences in the built environments of the three study precincts.

This result is somewhat unexpected since it was hypothesised that providing numerous (non-work) opportunities in the near vicinity of the TOD precinct will reduce the need to travel further, yet the greater dispersion of travel destinations for Wellard’s residents seems to suggest the opposite effect. As explained further, this may on the one hand be due to the delay in the physical completion of the TOD Village at Wellard and on the other hand be a result of induced travel to the CBD and Fremantle, both areas that are now much more accessible as a result of the rail corridor.
Figure 10: Household income by precinct (2006)
Figure 11: Index of Education and Occupation (2006)
Figure 12: Employment density in the three precincts (2006)
Figure 13: Proportion of employment by precinct and suburb (2006)
Figure 14: Employment by industry in each precinct and suburb (2006)
Figure 15: Types of urban facilities in the three precincts (2006)
Figure 16a: Destination of trips – Origin: Bull Creek (2006)
Figure 16b: Destination of trips – Origin: Cockburn Central (2006)
Figure 16c: Destination of trips – Origin: Wellard (2006)
Figure 17: Travel destinations in all precincts after opening of the railway (2009)

Source: Olaru and Curtis (2013)

### 7.1.1 Activity Spaces

As a main focus of this research, data visualisation was also applied for displaying Realised Activity Spaces. Activity Spaces were derived using confidence ellipses, convex polygons, or newer geometries such as hyper-ellipses, Cassini ovals, as well as bean curves. However, here the focus is on the analysis of Activity Spaces derived with kernel density, as they were found more accurate in representing the actual space covered by households in their daily travel (Botte and Olaru, 2010).

But before presenting RAS derived with kernel density, it is necessary to discuss an important methodological issue especially relevant to data visualisation and analysis. Kernel densities depend highly on the selection of an appropriate bandwidth for the kernel function, which is a critical step in the estimation. The bandwidth determines the amount of smoothing of the analysed activity point pattern. It defines the search radius of the kernel function, over each activity location within the raster, so that a large bandwidth may result in over-smoothing and for low-density values in generalised visualisation, whereas a small bandwidth can cause under-
smoothing, with the resulting visualisation mainly showing local variations in activity densities and little else in between.

The question of appropriate bandwidth selection is said to be often “more of an art than a science” and thus finding approaches for its determination through formal analysis and estimation have been the subject of many research papers. As indicated by Brunsdon (1995), optimising bandwidth remains one of the “biggest irresolvable problems” of using kernel densities and results of an analysis using kernel densities are sensitive to the choice of the smoothing parameter/bandwidth (Boyle et al., 2008). While mathematical algorithms (Silverman, 1986; Kao et al., 2002) promise an improvement of the selection process, making it more justifiable and scientifically robust, to date, these approaches have not been able to fully replace the analysts’ personal experience and knowledge of the study area, which allows for consideration of other attributes upon which density analysis is performed. The context-based approach, selecting bandwidths as a function on the specifics of the problem (commonly, the extent of the activity location pattern or the spatial distribution of activity locations), is recommended and remains preferred (Gibin et al., 2007). For example, O’Sullivan and Unwin (2003) explored bandwidths between 100 m and 1,000 m, consistent with the average distances between locations. In this research, a bandwidth of 10 km at the precinct level and 3 km at the household level were initially tested and applied. The 3 km value was based on the average trip distance and is also within on the accepted maximum walking and average cycling distance to the railway station. Then, for the smaller sub-sample of households with “imputed” travel routes, a more adaptive or dynamic bandwidth selection approach was explored, with the aim of enhancing the accuracy of the Activity Space for this limited sample. For example, for households with average distances of 4.5 to 5.5 km, a radius of 500 m was adopted, whereas for a household with more local activities – average distance of 2 km, a radius of 200 m. This meant a continuous adaptation of the bandwidth for each household by overwriting the ArcGIS default value, derived by the program through division of the length of the minimum spatial extent of the activity location pattern by a somewhat arbitrary factor of 30.

In order to avoid over- or under-smoothing and to derive a more refined household Activity Space, a bandwidth representative and suited to each household and its typical travel routines appears plausible. However, due to the lack of comprehensive data, the benefits of an adaptive and more flexible bandwidth selection (e.g., possible via a Python routine designed to automatically overwrite ArcGIS default values) could not be pursued further and beyond the limited exploratory analysis performed on the aforementioned small sub-sample.

To verify the adaptive or dynamic bandwidth selection approach, and to allow tracking of a household’s behaviour over time whilst maintaining comparability of results between households, consideration of more households and testing of a wider range of values...
(longitudinal data, more trips) would be required. It is therefore recommended that the approach be verified on richer data as part of future research.

Figure 18 presents three examples of Activity Spaces derived for three randomly selected households in the three precincts, measured with both the confidence ellipse (at 95% confidence interval) and kernel densities (with 3km bandwidth and shown at both 100% confidence level in the dark green area and 95% confidence level in the overlapping light green to red shaded area), whereas Figures 19-21 show before-after changes in Activity Spaces as kernel densities at the precinct level (with confidence intervals depicted in a similar manner).

The 3km bandwidth (Figure 18) seems to ignore the use of space between the activity locations, especially for the households from Bull Creek (i.e., the green area in the North of the city where the father works) and Cockburn Central (i.e., the light green area in the East, where the mother works). This suggests that the adjustment of bandwidth is necessary and also that information about the route between those locations needs to be considered in order to improve the precision of kernel density based Activity Space estimation representing the use of urban space.

When comparing kernel density areas before the opening of the rail (2006), shortly after the opening (2008) and following settling in behaviour (2009), it is obvious that the Activity Space areas have enlarged and spatial use expanded across all precincts, to a large extent in Cockburn Central (Figure 20) and Wellard (Figure 21), and to a lesser extent in Bull Creek (Figure 19). This indicates that at the precinct level the opening of the corridor is associated with changes in activity destinations and increased use of the corridor space (graphically displayed as a larger light green area in 2009). Although the easy visual interpretation is appealing, the reader must also be aware that the kernel areas are sensitive to the number of unique activity locations and time spent there by each individual, as well as dependent on the sample size (for the kernel built at the precinct level). As in this research the sample size diminished from wave to wave, there is no risk that the areas in 2009 are “overestimated” due to the sample size, on the contrary they represent rather conservative measures of spatial use at precinct level.

Numerical results displayed in the maps or associated with them will be presented in the next section.
Figure 18: Kernel densities and confidence ellipses for three households in three precincts

Note: Kernel density colours correspond to a “heat-map” – red indicates highest intensity of spatial use.
Figure 19: Kernel densities for all activities performed by Bull Creek residents (2006, 2008 and 2009)
Figure 20: Kernel densities for all activities performed by Wellard residents (2006, 2008 and 2009)
Figure 21: Kernel densities for all activities performed by Wellard residents (2006, 2008 and 2009)
7.2 Numerical Results at the Household Level

Table 4 (Section 6.3) provided a suite of travel behaviour indicators by precinct and by time period before and after the opening of the railway corridor – considering the travel and built environment changes associated with the infrastructure modification.

It was shown that residents in Wellard travel further and longer, they are still the heaviest car users and have the lowest share of active travel modes. Residents in Bull Creek walk and cycle the most and they drive the least. These results reflect both city-level access and the varying stages of TOD implementation in the precincts.

When comparing the number of legs before and after the railway opening, it becomes obvious that more residents are now multi-modal (rather than uni-modal) travellers. Car-based travel decreased significantly, whereas all precincts witnessed increases in walking, cycling, and public transport ridership.

Additional information is provided in Table 5, where the focus is on commuting and education trips and the total number of locations visited by households during the travel day. The largest commute is for residents of Wellard and the shortest by residents of Bull Creek. This could explain the consistently larger amount of travel time recorded for those living in Wellard, further away from the city and from the main activity centres in Perth.

Notably, in terms of locations visited by households, the largest number is for Cockburn Central households, which also have the highest number of household members (Table 5). This association confirms the a priori expectation that use or urban space (and hence visited locations) is likely to be larger for households with numerous daily activity needs. While the TOD precincts seem to be associated with locations and access to employment (ANOVA tests significant at 0.05 level), the changes over time (wave 1 vs. wave 2 vs. wave 3) are not. Average commuting distance increased in all precincts, most prominently in Wellard. Travel distance and travel time also appear to have increased in Wellard, despite the massive reduction of travel time by train to the CBD.
Table 5: Travel Behaviour – distance to work and number locations

<table>
<thead>
<tr>
<th>Variable</th>
<th>Before opening (Wave 1)</th>
<th>After opening (Wave 2)</th>
<th>Settle-in behaviour (Wave 3)</th>
<th>p (ANOVA) wave 1 / wave 2 / wave 3</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>BC</td>
<td>CC</td>
<td>W</td>
<td>BC</td>
</tr>
<tr>
<td>Average distance to work (km)</td>
<td>10.36</td>
<td>12.66</td>
<td>14.87</td>
<td>11.43</td>
</tr>
<tr>
<td>Daily travel time (min)</td>
<td>55.2</td>
<td>60.2</td>
<td>45.9</td>
<td>53.9</td>
</tr>
<tr>
<td>Daily travel distance (km)</td>
<td>33.5</td>
<td>44.36</td>
<td>45.94</td>
<td>34.2</td>
</tr>
<tr>
<td># legs/day and person</td>
<td>3.79</td>
<td>3.74</td>
<td>3.57</td>
<td>4.86</td>
</tr>
<tr>
<td>Average number of locations visited in a day by a household</td>
<td>16.26</td>
<td>20.04</td>
<td>14.93</td>
<td>15.07</td>
</tr>
<tr>
<td>N</td>
<td>317</td>
<td>369</td>
<td>348</td>
<td>157</td>
</tr>
</tbody>
</table>

Notes: The samples are representative for the three precincts (comparison was done with Census 2006 data from Australian Bureau of Statistics, 2006). The table indicates in **boldface** the highest values across TODs and in *italics* the lowest.

Table 6 presents the results of RAS for all three precincts before and after the opening of the railway. A number of shapes have been applied (see their definition in Section 5.3) and the results refer to optimised Activity Spaces with respect to area, including 95% of the locations visited by households in the three precincts. The objective of this investigation was two-fold: to examine the relationship between various geometries and to use them as indicators of a latent construct of Activity Space. The calculations were performed using Evolver TM add-ins for MS Excel, a package from Palisade Corporation. The heuristic used for minimising the areas is a genetic algorithm (Taplin et
al., 2005), with an initial population of 50, a crossover rate of 0.5 and mutation of 0.1, i.e., the default values of the package. This approach is different from Rai et al. (2007) who used a simplex algorithm modifying the orientation of the curves at steps of 22.5°. 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.

The parameters of the ellipses, Cassini oval, and bean curves varied across optimisations (Botte and Olaru, 2010). To calculate the fixed kernel density areas ArcGIS Spatial Analyst with a looping routine, written in Python, was applied to determine the areas of the kernel. The selection of the bandwidth allowed for inclusion of all local trips (3 km) and most locations outside of the TOD precinct (6 km).

The most striking result is the substantial variability of the Activity Spaces, both across precincts and over time. The analysis of the univariate distributions of Activity Spaces has also shown that all geometries have increased skewness. When comparing the parametric formulations, consistent with previous research, the results indicate that the confidence ellipses overestimated the Activity Spaces and that more research should examine alternative shapes, providing greater flexibility. However, the application of alternative geometries led to even greater areas. The bean curve and the super-ellipse were better suited for estimation at the precinct level with ‘richer’ data (more frequent locations – see Table 6), but not at the household level. Cassini ovals were the largest envelopes with values that could be explained by the suitability of the Cassini oval only for Activity Spaces with two clear clusters of activities. As suggested by Figures 19-22 small multiple clusters of activities, outside the precinct or the city, were identified for each precinct; hence Cassini ovals are not tailored for this case. The smallest Activity Spaces were obtained for kernel densities, followed by confidence ellipses.

Although there is no standard software for calculating Activity Spaces, Buliung and Remmel (2008) 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 converted into a Geospatial Modelling Environment. Levine and Associates offer CrimStat III for kernel density estimation. However this research has not applied any of these tools as none includes the new geometries.
Table 6: Activity space metrics for the three precincts (household level)

<table>
<thead>
<tr>
<th>Activity space</th>
<th>Before opening (Wave 1)</th>
<th>After opening (Wave 2)</th>
<th>Settled-in behaviour (Wave 3)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>BC</td>
<td>CC</td>
<td>W</td>
</tr>
<tr>
<td>Confidence ellipse - GA optimised (km²)</td>
<td>149.42</td>
<td>256.06</td>
<td>178.84</td>
</tr>
<tr>
<td></td>
<td>(105.68)</td>
<td>(271.09)</td>
<td>(182.95)</td>
</tr>
<tr>
<td>Hyper-ellipse - GA optimised (km²)</td>
<td>302.24</td>
<td>308.47</td>
<td>458.43</td>
</tr>
<tr>
<td></td>
<td>(315.48)</td>
<td>(316.70)</td>
<td>(490.10)</td>
</tr>
<tr>
<td>Cassini oval - GA optimised (km²)</td>
<td>298.68</td>
<td>428.94</td>
<td>579.80</td>
</tr>
<tr>
<td></td>
<td>(184.41)</td>
<td>(314.49)</td>
<td>(441.00)</td>
</tr>
<tr>
<td>Bean curve - GA optimised (km²)</td>
<td>240.12</td>
<td>328.25</td>
<td>232.33</td>
</tr>
<tr>
<td></td>
<td>(191.56)</td>
<td>(256.89)</td>
<td>(246.34)</td>
</tr>
<tr>
<td>Kernel density (km²) - bandwidth 3 km</td>
<td>43.70</td>
<td>41.03</td>
<td>43.27</td>
</tr>
<tr>
<td></td>
<td>(16.08)</td>
<td>(13.47)</td>
<td>(15.25)</td>
</tr>
<tr>
<td>Kernel density (km²) - bandwidth 6 km</td>
<td>138.80</td>
<td>114.27</td>
<td>138.78</td>
</tr>
<tr>
<td></td>
<td>(49.24)</td>
<td>(47.71)</td>
<td>(51.49)</td>
</tr>
</tbody>
</table>
Except for Cassini ovals and hyperellipses, which increased over time in all three precincts, Realised Activity Spaces appeared to have changed only moderately. The differences between precincts hold, with the smallest Realised Activity Space in Bull Creek and the largest in Wellard.

Although there are statistically significant correlations (<0.05) among the four geometries (Table 7), it is difficult to draw a pattern of variation over time (Table 6). There is also very little association between the geometries and the kernel density estimates (the only exception is between CE and KD) and this is considered an artefact of the derivation of kernel density, which regards only the spatial distribution of activities. Depending on the bandwidth, the kernel algorithm may not always form continuous shapes, due to the underlying spatial distribution and frequency/duration of activities at the visited locations. On the other hand, the four geometries (albeit indirectly and partially) incorporate the area between the spatially distributed activity locations (“filling” in the space). If the number of locations is reduced and activities are further apart, the kernel density based activity space is likely to result in a discontinuous area around those separate locations, whereas the confidence ellipse or the broad-shaped bean curve would form an elongated ellipse or narrow bean. In terms of magnitude, confidence ellipses are 3-4 times larger than Activity Spaces measured as kernel densities with a bandwidth parameter of 3 km.

Table 7: Correlations between Activity Space metrics

<table>
<thead>
<tr>
<th></th>
<th>Confidence ellipse - GA optimised (km²)</th>
<th>Hyper-ellipse - GA optimised (km²)</th>
<th>Cassini oval - GA optimised (km²)</th>
<th>Bean curve - GA optimised (km²)</th>
<th>Kernel density (km²)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Confidence ellipse (CE) - GA optimised (km²)</td>
<td>1</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Hyper-ellipse (HE) - GA optimised (km²)</td>
<td>0.252</td>
<td>1</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Cassini oval (CO) - GA optimised (km²)</td>
<td>0.670**</td>
<td>0.805**</td>
<td>1</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Bean curve (B) - GA optimised (km²)</td>
<td>0.782**</td>
<td>0.326**</td>
<td>0.553**</td>
<td>1</td>
<td></td>
</tr>
<tr>
<td>Kernel density (KD) (km²)</td>
<td>0.411**</td>
<td>-0.136</td>
<td>0.076</td>
<td>0.336</td>
<td>1</td>
</tr>
</tbody>
</table>
Despite the substantial computational time, the derivation of Realised Activity Spaces using the four geometries has not proved satisfactory. Without denying their potential richness in capturing individual and environmental differences, in this research, the limited frequency of visited locations by households during the travel day and their distribution affected the metrics. Hence, given the seemingly unrealistic size of areas defined by Cassini ovals, hyper-ellipses, and bean curves and their erratic behaviour, these Activity Spaces were not included in the subsequent analyses. The remaining tests and models therefore relied only kernel density estimators and confidence ellipses, considered for their suitability to a one-day travel diary, flexibility (KD) or ease of derivation (CE), and visualisation capability.

Both KD and CE significantly changed between waves (p<0.001), but only confidence ellipses varied significantly across precincts, with kernel density estimators (bandwidth of 3km) undistinguishable between Bull Creek and Cockburn Central. This would suggest that residents have taken advantage of the increased accessibility and now reach for further destinations.

Overall, the results have shown an increase in the size of Realised Activity Spaces with the distance from the city or accessibility, regardless of the wave of data collection.

When comparing the kernel density area and confidence ellipses between waves, a slight reduction in the Activity Space for Bull Creek precinct could be noticed during the second wave, but not so for Cockburn Central and Wellard. This finding could reflect the proclivity of individuals to convert reductions in generalised costs (improvements in city-wide access) into adjusted travel distances further away to other destinations.

As illustrated in Figures 19-21, 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). For residents of Bull Creek and Cockburn Central, the railway opening coincided with new opportunities for walking and cycling (Bull Creek) or presented by mixed land-use around the railway precinct (Cockburn Central), whereas for Wellard the railway meant primarily greater city-wide accessibility.

These results partially support the expected relationship between TOD and Activity Spaces that increased mixed-use, denser developments and better-connected streets in the neighbourhood are associated with smaller Activity Spaces. The smaller Realised Activity Spaces were deemed as “better”, and as such being indicators of local supply of services and of the potential for interactions around points of confluence within local areas (school, shopping, library, medical centre, or local associations). However, the expectation of significant reduction in their size after the opening of the railway was not confirmed.
Further analysis considered the size of the Activity Spaces as kernel density (KD) and confidence ellipse (CE) in a MANCOVA analysis with two factors and five household covariates. The results provided evidence that the vectors of Realised Activity Space metrics did vary between 2006 and 2009 across precincts (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 weekly paid and unpaid working/studying hours).

The number of residents was the most significant covariate (<0.001) followed by the number of vehicles (0.046). The level of busyness and the income were not associated with the size of the KD and CE. In Bull Creek, the number of vehicles within a household significantly influenced the size of all Activity Spaces and led to an increase in the AS areas, so did the household income, but with a reverse impact on AS size, reflective of the situation since the precinct contains a high share of pensioners. In Cockburn Central income and residents had a significant impact on Activity Spaces, whereas in the Wellard precinct the number of vehicles and the HH income showed significant signs.

In summary, the hypothesised shrinkage in the household Activity Spaces as a result of TOD developments was not found in this analysis of variance. Nevertheless, more detailed analysis is necessary to clarify the separate contributions (if any) of the presence of the railway and of the socio-demographic fabric and self-selection to the changes in Activity Spaces.

One qualification of observations is required at this point. These Activity Spaces included 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 then assessing modifications. However, due to the small number of daily trips reported by some households this was not possible with this data set.

Whereas this section presented results of Activity Spaces based on location (Origin-Destination data) only, Section 7.3 will now also consider route information.

### 7.3 Numerical Results at the Precinct Level

To check the validity of the kernel density results Activity Spaces were also compared at the precinct level. These kernel density areas include the locations of activities of all residents of the precinct and, as shown in Table 8, demonstrate the increase in Activity Spaces for all precincts. Another interesting finding relates to the comparison of 100% and 95% areas. By
including all locations (and thus outliers, infrequent activities), the kernel densities are overestimated by at least 30%.

Once more, the large variability indicates the dependency of the areas on the chosen shape and on the spatial distribution of activities, indicating there is no single best approach to define all Activity Spaces. As in the results at the household 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. The bean and super-ellipse curves were smaller than the confidence ellipses and they are likely to represent more accurately the area of activities at the precinct level.

Considering the importance of home and other pegs in the daily activities, this research derived the Activity Space measures using the weighted centre of gravity of activity locations. Clearly, the optimised areas may vary if this constraint is relaxed. Additional analysis was carried out to assess the impact of activity durations (similar to Kamruzzaman et al., 2011) on the size of RAS (modifying the centre of gravity), then again without finding substantial changes compared to the analysis based on frequency of activities.

It is important to note that the Activity Spaces were minimised to include a minimum of 95% of the activities. The excluded locations usually 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 hyper-ellipse or the bean shape).

The precinct Activity Spaces appear to adequately show linkages between travel behaviour changes, the built environment and the new railway intervention. Again, the reduced precinct Activity Spaces in Bull Creek and Cockburn Central compared to Wellard is not surprising, with opportunities/facilities and shorter distance to the CBD diminishing to a certain extent the need for travelling further. With the longest commutes and reliance on car, Wellard’s residents have the most dispersed map of visited locations and thus Activity Spaces. This is consistent with findings of Wang et al. (2012) in Beijing, where residents from institutionally privileged enclaves had more concentrated Activity Spaces than those living in ordinary neighbourhoods.
Table 8: Activity space metrics for the three precincts (precinct level)

<table>
<thead>
<tr>
<th>Activity space</th>
<th>Before opening (Wave 1)</th>
<th>After opening (Wave 2)</th>
<th>Settled-in behaviour (Wave 3)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>BC</td>
<td>CC</td>
<td>W</td>
</tr>
<tr>
<td>Confidence ellipse - GA optimised (km²)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>1,060.38</td>
<td>1,472.95</td>
<td>2,416.67</td>
</tr>
<tr>
<td>Hyper-ellipse (km²)</td>
<td>521.04</td>
<td>837.66</td>
<td>1,379.35</td>
</tr>
<tr>
<td>Cassini oval (km²)</td>
<td>1,669.86</td>
<td>2,670.02</td>
<td>2,726.48</td>
</tr>
<tr>
<td>Bean curve (km²)</td>
<td>1,222.47</td>
<td>1,183.24</td>
<td>1,560.36</td>
</tr>
<tr>
<td>Kernel density (km²) - bandwidth 10 km (100%)</td>
<td>465.60</td>
<td>559.61</td>
<td>731.29</td>
</tr>
<tr>
<td>Kernel density (km²) - bandwidth 10 km (95%)</td>
<td>338.19</td>
<td>357.15</td>
<td>319.12</td>
</tr>
</tbody>
</table>
7.4 Activity Spaces Embedding Trips –Benefits to Modelling

Figure 22 displays an example of CE and KD for a Wellard household on the sample day before the opening of the railway (2006). The Realised Activity Space measures are based solely on the coordinates of the visited activity locations, without any information on the routes between locations.

The comparison of household Activity Space measures (relying on locations’ coordinates) after the opening of the railway, is then provided in Figure 24. In both instances a consistently larger size of CE compared to KD can be noticed.

However, by applying detailed route data\(^6\), kernel density estimates provided in Figure 24 and Figure 25 appear in to be more realistic in both instances, as they follow the individuals on their travel between activities. At the same time, the imputation of route data also led to a refinement of the confidence ellipse based Activity Spaces (see also Botte and Olaru, 2012).

The route data imputation is therefore considered a data enhancement process and provides a powerful approach for both geo-visualising and analysing activity travel behaviour. For similar work relating to network-based time-geographic density estimation using hypothetical vehicle tracking data the reader is referred to Downs and Horner (2012).

\(^6\) Note: For clarity of the visualisation, Figures 22 to 24 show only the underlying public transport network and not the complete road network.
Figure 22: Kernel density and confidence ellipse for a Wellard household before the opening of the railway in 2006

Figure 23: Kernel density and confidence ellipse for a Wellard household before the opening of the railway in 2006 with additional information on trip routes.
Figure 24: Kernel density and confidence ellipse for a Wellard household after the opening of the railway in 2009.

Figure 25: Kernel density and confidence ellipse for a Wellard household after the opening of the railway in 2009 with additional information on trip routes.
The enhanced kernel density based Activity Spaces show how continuous travel pattern between activity locations (with no gaps between activity locations) might be represented on the basis of generated track point data. The route-based kernel densities provide a clearer image of the movements during the travel day and indicate the likely spatial awareness of the individuals.

However, delivery of this data enhancement process on a larger scale, in this case for a sample of 54 households that could be matched between the survey before (2006) and after the opening of the railway (2009), was not without challenges. Firstly, time consuming data generation for the routes and calculation of Realised Activity Spaces (in the absence of standard software and an automated processing approach to derive both the extra trip information and to facilitate the application of kernel density measures) had to be undertaken; and secondly, bias produced by tracking data (non-independent points linked by movement trajectories) needed to be taken into consideration.

The first challenge means that large scale studies, attempting to enhance datasets with additional route information for every household and each single trip, could achieve this only with a fully integrated software solution, designed to ensure the desired level of additional detail can be generated without major manual data handling and physical involvement. Here, for the current sample of households, data “enrichment” on a trip-by-trip basis was done in a semi-automated manner, applying various software packages and on-line route planning, which required a substantial time commitment (more than 100 hours). Presently, as in the reconstruction of missing GPS tracking data (e.g. due to satellite shading leading to GPS signal loss, see Cederholm, 2000; Schüssler and Axhausen, 2009), the construction of route information could be further improved through adjustment of individual route point assignment intervals based on network travel time projections (reflecting mode related travel speed) as well as through route selection based on mode availability or temporal congestion levels of the transport network. On the second issue, of bias, Downs (2010) has shown that using tracking data poses problematic for kernel density estimation. To overcome this limitation, some measures must be considered. Using tracking data from movements of a loggerhead turtle, Downs et al. (2011) proposed time-geographic density estimation (TGDE) to increase the precision of home ranges, showing that this method is highly dependent on the number of points/locations visited and that bias diminishes with larger sample sizes.

They suggested that GPS data may support the use of TGDE for exploring movements and space-use patterns; however, they acknowledged the need to adapt TGDE to travel on the networks and not in a continuous Euclidean space. Given the high resolution of the route tracking (100 m or less, depending on the road network configuration) and the consideration of
both road and public transport network, this limitation highlighted by Downs is not considered a methodological issue anymore.

As previous research emphasized, more detailed data for derivation of kernel densities is expected to mirror more accurately the daily Realised Activity Space. The analysis of a subsample of households has shown that kernel density areas increase on average by 25% when the imputed travel routes are added. Noticeable, there are also increases in the Realised Activity Spaces derived via confidence ellipses when adding these routes; nevertheless, they increased by a smaller extent, on average only 19%. This change can be explained by the fact that more locations are likely to modify the centre of gravity of the ellipse.

Finally, this part of the analysis also considered the changes in kernel density areas following a modified search radius/bandwidth, reduced from 1.5 km to 1 km. The results show the areas decreased – as expected - by 33%. Table 9 presents the correlations between kernel density and confidence ellipse areas, both including the likely travel routes as well as without them, obtained for a sample of 54 households.

Table 9: Correlations of Activity Spaces Measures (54 households)

<table>
<thead>
<tr>
<th></th>
<th>KDAR Radius = 1.5 km</th>
<th>KDAR Radius = 1 km</th>
<th>Kernel density area (only locations)</th>
<th>Confidence ellipse area (routes)</th>
<th>Confidence ellipse area (only locations)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Kernel density area (routes), KDAR Radius = 1.5 km</td>
<td>1</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Kernel density area (routes), KDAR Radius = 1 km</td>
<td>0.998**</td>
<td>1</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Kernel density areas (only locations)</td>
<td>0.353*</td>
<td>0.358*</td>
<td>1</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Confidence ellipse area (routes)</td>
<td>0.707**</td>
<td>0.695**</td>
<td>0.323*</td>
<td>1</td>
<td></td>
</tr>
<tr>
<td>Confidence ellipse area (only locations)</td>
<td>0.635**</td>
<td>0.637**</td>
<td>0.440**</td>
<td>0.810**</td>
<td>1</td>
</tr>
</tbody>
</table>

Note: ** significant Pearson correlation at 0.05 level; * significant at 0.01 level.
The results show moderate to high correlations between kernel densities and confidence ellipses (0.635 to 0.707), low correlations between the kernel density areas with and without the routes (0.353, 0.358), and high correlations between confidence ellipses areas (0.81). This suggests that data enrichment is beneficial for kernel densities, but only to a lesser extent for confidence ellipses.

Accordingly, Figures 24 and 25 show only a small correction in the observed changes for confidence ellipses with data enhancement, i.e. when routes are added. More specifically, the examples provided show a reduction and reorientation in the CE following data enhancement, both before and after the railway opening. Another interesting feature of this household’s Activity Spaces (the household is located within the Wellard precinct) is the considerable reduction in their Realised Activity Spaces as a result of more local travel. Although this cannot be extrapolated for the whole precinct, this is indicative that the residents may have taken up the opportunities and diverse urban services that have been made available in the neighbourhood as part of the TOD changes.

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 (Section 7.3 – Table 8).

To summarise, this research adopted kernel densities as the preferred measure for Activity Space analysis. They offer a sophisticated visualisation tool for meaningful representation of travel behaviour and provide the smallest Realised Activity Spaces, reflecting the use of space where activities and travel are undertaken. This is promising, not only from the viewpoint of the research analyst, but also for practical applications in urban planning - such as for trend analysis, benchmarking of urban environments, or advanced structural planning, as well as policymaking.

Although one-day travel diaries are not enough for capturing the daily routines (for geovisualisation purposes and identification of behavioural patterns a minimum one-week household panel survey would be necessary) the temporal and spatial (across precincts) comparison offered the possibility to identify associations between TOD features and travel behaviour. The findings however suggested that the richness of survey data and the range of survey parameters heavily influence the applicability and usefulness of various known Activity Space metrics in the analysis.

Particularly, the comparison of KD without route data and with route data confirmed the need for a richer “model diet” and data collection, in order to understand the households’ spatial use
and knowledge. Therefore, in order to fully examine TOD related aspects of travel behaviour and to identify the underlying elements affecting Activity Spaces (e.g., transport opportunities, network parameters, built form and the urban layout at a local scale), detailed route information and longitudinal trip data at the person or household level is required.

The approach adopted for adjusting the bandwidth was based on the distances between activity locations visited by each household; however, for greater generalisability, a fully adaptive procedure would be necessary. This represents a further research direction.

### 7.5 Structural Equation Modelling (SEM)

As demonstrated by previous scholars (Bhat and Guo, 2007; Cao et al., 2009), the relationship between built environment and travel behaviour may be overestimated if residential sorting and neighbourhood preferences are neglected.

This research has shown positive associations between the number of household members, number of children, as well as the number of working/studying hours with the Realised Activity Spaces. This is as expected, as the number and variety of daily commitments create the demand for activities in various locations, and are thus likely to expand Realised Activity Spaces. While these results are useful, more advanced research is required to model simultaneously built environment characteristics, socio-demographics, location preferences and attitudes towards urban structure with travel behaviour in a longitudinal approach. This would assist urban planners and transport practitioners to better ascertain the separate contributions of built environment features and transport services to achieving successful TODs.

Therefore, a structural equation model was developed with the aim to investigate multiple and complex interrelationships between measured variables representing revealed behaviour (Activity Spaces), socio-demographics, stated preferences for built environment (e.g. willingness to pay for location features), and the surrounding environment and characteristics of transport services. The model was estimated at the household level and followed the conceptual framework described in Section 5 (Figure 7). For estimation, two competing models were assessed, being a) a model with kernel density and confidence ellipse Realised Activity Spaces introduced separately; and b) and alternative model with kernel density and confidence ellipses introduced as simultaneous indicators of an Activity Space latent construct (Figure 26).
Note: Additional models were tested as part of the research for interaction effects; however, no statistically significant results were found. This is a reflection of the small sample size and a limitation that would need to be addressed by future work (longitudinal data or data based on at least multi-day survey/weekly travel diary).

It was found that the model considering the Realised Activity Space as a latent construct produced better estimation results; however, additional valuable insights were gained from the model with unique Realised Activity Space indicators. The results are discussed further in Sections 7.5.3 and 7.5.4.

To account for the spatial dimension, the structural models aimed to apply the expansion method, considering spatially varying regression coefficients in their specification (Casetti, 1972; Farber and Páez, 2012). However the sample size (of 530 records) limited the complexity of the model to the spatially varying intercepts. Notably, the standard spatially invariant specification, \( AS_i = \beta_0 + \sum_{j=1}^{J} \beta_j x_{ji} + \varepsilon_i \), (32) was not inferior to the trend-surface model, expanding the constant term \( AS_i = \beta_{01} + \beta_{02} \text{lat} + \beta_{03} \text{long} + \sum_{j=1}^{J} \beta_j x_{ji} + \varepsilon_i \) (33).

This suggests that distance measures may represent acceptable proxies for location. It is also important to stress that the models are not longitudinal, so they do not measure change.
7.5.1 SEM Inputs

As indicated in Figure 7, the SEM model included a number of various demand and supply factors, along with socio-demographic characteristics and attitudes towards the built environment.

They were categorised in four main categories, and included variables as follows:

- **urban form elements**: distance to Perth CBD, distance to local facilities (closest train station, school, medical centre, shop, and park); the type of TOD development (moderator);
- **household characteristics and circumstances**: household income and size; number of school-age children; number of vehicles used; household’s socio-economic disadvantage and education index (CCD level); dwelling size;
- **household preferences**: towards urban facilities (school facilities; transport facilities; dwelling and neighbourhood characteristics; cycling facilities; social dimension); willingness to pay for various urban features (train, school, shop, amenity, access); location (spatial coordinates of the home location);
- **travel behaviour**: Realised Activity Spaces.

Considering the sample size (in relation to the number of parameters in the model) and the presence of multicollinearity, the final model (Figure 26) included only a subset of these variables. However, the estimated model maintained variables from all four categories, to ensure that it was suitable for testing associations between urban form, location, and Realised Activity Spaces.

In terms of their source, many of these input variables were directly collected through the surveys, others were calculated based on the survey information. For example, the preferences for various urban facilities were obtained by factor analysing a batch of 15 indicators presented to respondents. The willingness to pay measures were derived from a stated choice survey on relocation. These analyses are described in Curtis and Olaru (2010), Olaru *et al.* (2011), and Smith and Olaru (2013) and their output variables were simply imported in this research.

7.5.2 Additional Spatial Analysis

With data embedding spatial characteristics, an additional step was undertaken (partitioned variance test) to assess whether a more sophisticated spatial analysis would be required to capture the underlying spatial processes and to enhance the robustness of the models.
This was done in the form of mixed model estimation, with houses clustered in suburbs, which in their turn were clustered in precincts. This approach then also tested the (non-)independence assumption of spatial correlation. Although the models with fixed and random effects showed slightly improved goodness-of-fit (GOF) measures (Akaike Information Criterion, AIC), the tests did not support the spatial variability between precincts and between suburbs.

Since the variance components for suburbs and precincts were not significantly different from zero, the null hypothesis could not be rejected. For example, when investigating the effect of the suburb, covariance parameter estimates (total intercept for variance) returned a value at around 1.2%. This lack of difference between suburbs could be due to a number of causes, such as: the lack of sufficient data and the relative closeness of dwellings; the inability of Realised Activity Space measures to fully capture differences between households across suburbs and precincts (discontinuity of KD, overestimation of CE); in addition, there was a small underlying variance between households’ observed travel on a single survey day.

These observations again support the call for longitudinal data (trip diaries for a minimum of one week) and refined tracking of daily activities, either directly via technology aided survey mechanisms (GPS devices), or automated, with retrospective inference from trip data based on “best-guess” route planning algorithms.

To further detect the presence of spatial autocorrelation of Realised Activity Space values in the residuals (prediction errors) from the regression analyses, the Durbin-Watson (DW) statistics were calculated (a relationship between values separated from each other by a given time lag), and the assessment returned no serial autocorrelation for both Realised Activity Space measures being the subjects of this investigation (DW~2).

Finally, Table 10 presents results of tests of spatial autocorrelation for the model inputs, with Moran’s I, a measure of global spatial autocorrelation, undertaken separately. A significant positive autocorrelation would mean that locations/households near to one another in each of the three precincts are likely to be more similar that households in different precincts, while a negative autocorrelation would indicate the opposite. For these calculations the variables were aggregated at the Census Collection District (CCD) level, the smallest spatial area unit for which the information was available.

The results showed no spatial autocorrelation for Realised Activity Space measures, nor for attitudes. However, positive autocorrelation (marginal) appeared for the willingness to pay for proximity to shops and amenity and for dwelling size, and significant autocorrelation was
recorded for median house price, as well as for the socio-economic disadvantage, resources and educational indices.

Table 10: Spatial Autocorrelations – Moran’s I

<table>
<thead>
<tr>
<th>Autocorrelation in CCDs</th>
<th>Moran's I</th>
<th>t Statistic</th>
</tr>
</thead>
<tbody>
<tr>
<td>Kernel Density (KD)</td>
<td>0.080</td>
<td>1.132</td>
</tr>
<tr>
<td>Confidence Ellipse (CE)</td>
<td>0.031</td>
<td>0.512</td>
</tr>
<tr>
<td>Optimised CE</td>
<td>-0.011</td>
<td>0.017</td>
</tr>
<tr>
<td>Number bedrooms</td>
<td>0.238</td>
<td>3.874</td>
</tr>
<tr>
<td>Facilities within walking distance</td>
<td>0.019</td>
<td>0.431</td>
</tr>
<tr>
<td>Cycling facilities</td>
<td>0.101</td>
<td>1.723</td>
</tr>
<tr>
<td>Dwelling and surroundings</td>
<td>0.073</td>
<td>1.277</td>
</tr>
<tr>
<td>Transport facilities</td>
<td>0.109</td>
<td>1.848</td>
</tr>
<tr>
<td>Index SE disadvantage</td>
<td>0.773</td>
<td>12.303</td>
</tr>
<tr>
<td>Index economic resources</td>
<td>0.657</td>
<td>10.469</td>
</tr>
<tr>
<td>Index education and occupation</td>
<td>0.921</td>
<td>14.629</td>
</tr>
<tr>
<td>Median housing price</td>
<td>0.798</td>
<td>12.697</td>
</tr>
<tr>
<td>Willingness to pay (WTP) for proximity to school</td>
<td>-0.013</td>
<td>-0.071</td>
</tr>
<tr>
<td>Willingness to pay (WTP) for proximity to shops</td>
<td>0.176</td>
<td>2.906</td>
</tr>
<tr>
<td>Willingness to pay (WTP) for amenity</td>
<td>0.173</td>
<td>2.863</td>
</tr>
<tr>
<td>Willingness to pay (WTP) for proximity to train</td>
<td>-0.023</td>
<td>-0.225</td>
</tr>
<tr>
<td>Willingness to pay (WTP) for city-wide access</td>
<td>-0.037</td>
<td>-0.455</td>
</tr>
</tbody>
</table>

Note: In bold, significant spatial autocorrelations measured as Moran’s I. Negative (positive) values indicate negative (positive) spatial autocorrelation. Values range from +1 (perfect correlation) to −1 (indicating perfect dispersion). A random spatial pattern is indicated by a zero value.

The observed similarity of the socio-economic disadvantage and house price variables indicates clustering of population groups based on socio-economic status, supporting the self-selection process, i.e. particular types of houses with comparable prices cluster within a neighbourhood area, families with similar educational levels within an area appear to “attract” each other, and these families have similar preferences for shops and amenity. However, the use of space, the perceptions and attitudes about built environment, as well as the willingness to pay for school, train, and city-wide access seem to be unrelated to location.
Considering all of these results, the SEM approach without a detailed hierarchical spatial structure seemed appropriate. Hence, the ability to undertake a simultaneous estimation, considering multiple (including spatial) factors and influences within one model represents a key advantage of SEM over other quantitative analyses.

7.5.3 SEM - Overall Results

Table 11 presents results of two SEM models, firstly considering the Realised Activity Space as a latent construct with two indicators (KD and CE); and secondly, using the two metrics of AS separately in the path diagram. Background information on data relied on as part of this analysis can be found in Olaru et al. (2011), Curtis and Olaru (2010a), Smith and Olaru (2013) as well as Olaru and Curtis (2015). As demonstrated by the Goodness-of-fit (GOF) measures, the model with latent construct is better than the one with separate Realised Activity Space.

Table 11: SEM for Realised Activity Space - Whole Sample

<table>
<thead>
<tr>
<th>Relationship</th>
<th>Realised Activity Space (RAS) as a latent construct</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>B</td>
</tr>
<tr>
<td>RAS (latent construct (cstr.)) → KD</td>
<td>1.000</td>
</tr>
<tr>
<td>RAS (latent cstr.) → CE</td>
<td>0.064</td>
</tr>
<tr>
<td>d from CBD → RAS</td>
<td>-13.814</td>
</tr>
<tr>
<td>d from public school → RAS</td>
<td>1.200</td>
</tr>
<tr>
<td>Latitude → RAS</td>
<td>1,455.473</td>
</tr>
<tr>
<td>Longitude → RAS</td>
<td>-51.167</td>
</tr>
<tr>
<td>Index education-occupation → RAS</td>
<td>0.081</td>
</tr>
<tr>
<td>Number bedrooms → RAS</td>
<td>2.067</td>
</tr>
<tr>
<td>Children below 14 years → RAS</td>
<td>1.703</td>
</tr>
<tr>
<td>WTP for proximity to train → RAS</td>
<td>-0.999</td>
</tr>
<tr>
<td>WTP for proximity to school → RAS</td>
<td>0.356</td>
</tr>
<tr>
<td>WTP for city-wide access (reducing travel time) → RAS</td>
<td>3.076</td>
</tr>
<tr>
<td>WTP for larger dwellings (blocks) → RAS</td>
<td>2.205</td>
</tr>
<tr>
<td>Children below 14 years → WTP for proximity to school</td>
<td>0.622</td>
</tr>
<tr>
<td>d from the train station → WTP for proximity to train</td>
<td>-0.004</td>
</tr>
<tr>
<td>d from CBD → WTP for proximity to train</td>
<td>-0.027</td>
</tr>
<tr>
<td>Number bedrooms → WTP for proximity to train</td>
<td>0.290</td>
</tr>
</tbody>
</table>
Note: Goodness-Of-Fit $\chi^2 = 487.72$ (67 df); Goodness-of-Fit-Index (GFI) = 0.868; Adjusted Goodness-of-Fit Index (AGFI) = 0.797; Root Mean Square Error of Approximation (RMSEA) = 0.109; Akaike Information Criterion (AIC) = 563.72 (210 – saturated; 823.97 independence). Parameters shown in bold are significant at 0.05 level; where shown in italics, parameters are significant at 0.1 level. B = Unstandardised Parameter Estimate. Mardia Index = 77.379, Critical Ratio (c.r.) =42.082.

The results consistently indicated that both the presence of children and location preferences were significantly associated with use of urban space, regardless of whether Realised Activity Space was considered as a latent construct or not. Unsurprisingly, households with more children were willing to pay more for a closer proximity to school and had larger Activity Spaces. In addition, bigger houses (more bedrooms) were associated with a higher preference for proximity to the train, and hence willingness to pay for closeness to train. Households willing to pay more for reducing their travel and for bigger properties were likely to have larger Realised Activity Spaces. However, households willing to pay more for proximity to train displayed smaller Realised Activity Spaces.

The socio-economic index of education and occupation seemed to be positively related to kernel density, but negatively related to the confidence ellipses. Finally, households disposed to trade-off location and housing conditions in favour of suburban lifestyle were thus willing to pay less for a closer proximity to the train. The opposite direction of relationships between RAS and WTP for train proximity versus RAS and WTP for city-wide access needs to be further investigated. This could be explained by limited flexibility in using public transport and/or stemming from the heavy use of the car for any distances, nevertheless suggesting a mismatch between the ‘desire to be close to everything’ and the amount of travel undertaken.

The model with the two measures of RAS taken separately also showed that latitude and index of education and occupation are associated with CE, i.e. households residing further south of the city have larger Activity Spaces measured as CE and households located in areas of higher index of education and occupation have smaller CE. Moreover, living further from the train is translated in higher willingness to pay for receiving that access. While only marginally significant, the parameter for index of education and occupation seems to positively affect the size of Realised Activity Spaces when measured via KD.

In spite of many of these findings being in agreement with the a priori expectations, the two final models did not display satisfactory goodness-of-fit measures, which indicated that the matrices of variances-covariances corresponding to the models were not close enough to the sample matrix. In addition, numerous non-significant predictors were present, which suggested that these models were not fully uncovering the hypothesised relationships. In consequence,
Section 7.5.4 presents results of an alternative SEM model, which includes the precinct acting as a moderator.

### 7.5.4 SEM - Precinct Differences

Table 11 showed that the nature and direction of many potential relationships between urban characteristics, household location preferences and Activity Spaces remained unknown. To further explore these relationships, a multi-group SEM model (with the same structure as the latent construct model estimated in Table 11) was tested. Results of this model are presented in Table 12 and the path diagrams displayed in Figures 27 to 29. Given that the coordinates of the home location were not statistically significant in previous models and acknowledging the collinearity with the distance from CDB, they were not further included in the following model by precinct.

Table 12: SEM by Precinct with Realised Activity Space (RAS) as Latent Construct

<table>
<thead>
<tr>
<th>Relationship</th>
<th>Bull Creek N = 187</th>
<th>Cockburn Central N = 190</th>
<th>Wellard N = 153</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>B</td>
<td>p</td>
<td>B</td>
</tr>
<tr>
<td>RAS (latent cstr.) ➔ KD</td>
<td>1</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>RAS (latent cstr.) ➔ CE</td>
<td>0.057</td>
<td>&lt;0.001</td>
<td>0.021</td>
</tr>
<tr>
<td>d from CBD ➔ RAS</td>
<td>2.789</td>
<td>0.022</td>
<td>-0.355</td>
</tr>
<tr>
<td>d from public school ➔ RAS</td>
<td>-5.241</td>
<td>0.010</td>
<td>-0.303</td>
</tr>
<tr>
<td>Index education-occupation ➔ RAS</td>
<td>0.001</td>
<td>0.976</td>
<td>0.058</td>
</tr>
<tr>
<td>Number bedrooms ➔ RAS</td>
<td>2.918</td>
<td>0.032</td>
<td>1.306</td>
</tr>
<tr>
<td>Children below 14 years ➔ RAS</td>
<td>-3.832</td>
<td>0.009</td>
<td>1.122</td>
</tr>
<tr>
<td>WTP for proximity to train ➔ RAS</td>
<td>-1.604</td>
<td>0.082</td>
<td>0.036</td>
</tr>
<tr>
<td>WTP for proximity to school ➔ RAS</td>
<td>0.316</td>
<td>0.122</td>
<td>0.374</td>
</tr>
<tr>
<td>WTP for city-wide</td>
<td>3.425</td>
<td>0.018</td>
<td>2.292</td>
</tr>
<tr>
<td>Relationship</td>
<td>Bull Creek N = 187</td>
<td>Cockburn Central N = 190</td>
<td>Wellard N = 153</td>
</tr>
<tr>
<td>------------------------------------------------------------------------------</td>
<td>-------------------</td>
<td>--------------------------</td>
<td>---------------</td>
</tr>
<tr>
<td>access (reducing travel time) (\rightarrow) RAS</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>WTP for larger dwellings (blocks) (\rightarrow) RAS</td>
<td>1.988</td>
<td>0.233</td>
<td>2.674</td>
</tr>
<tr>
<td>Children below 14 years (\rightarrow) WTP for proximity to school</td>
<td>-0.330</td>
<td>0.551</td>
<td>1.183</td>
</tr>
<tr>
<td>d from the train station (\rightarrow) WTP for proximity to train</td>
<td>0.054</td>
<td>0.723</td>
<td>-0.253</td>
</tr>
<tr>
<td>d from CBD (\rightarrow) WTP for proximity to train</td>
<td>-0.163</td>
<td>0.130</td>
<td>-0.005</td>
</tr>
<tr>
<td>Number bedrooms (\rightarrow) WTP for proximity to train</td>
<td>0.257</td>
<td>0.055</td>
<td>0.297</td>
</tr>
</tbody>
</table>

**GOF**

\[\chi^2 = 280.79\text{ (144 df)}\]

GFI = 0.911; AGFI = 0.856

RMSEA = 0.042; AIC = 460.79 (468 – saturated; 666.15 independence)

Notes: In **boldface**, parameters significant at 0.05 level; in *italics*, parameters significant at 0.1 level. B = Unstandardised Parameter Estimate.

Testing of normality (skewness and kurtosis) revealed the underlying distributions of the surveyed number of vehicles and revealed CE were highly skewed and kurtotic, hence requiring transformation. A non-parametric test confirmed a logarithmic nature of the CE based AS results. This allowed transformation of the data and re-introduction into the model, which in turn led to an improvement of the models predictive power for CE. Other transformations were not pursued, given the difficulty in interpretation.

The goodness-of-fit of the model demonstrates that by freeing the parameters for each of the precincts, the matrices of variances-covariances of the precinct samples were closely replicated by the model estimated matrices, even with substantial non-normality present in the data (Mardia Index BC = 31.941; Mardia Index CC = 54.413; Mardia Index W = 76.917).
Many of the trends were persistent (e.g., positive relationship between willingness to pay for city-wide access and Realised Activity Spaces or between willingness to pay for a closer school and Realised Activity Spaces), while others changed across precincts (e.g., number of children, willingness to pay for bigger houses, distance from the CBD and distance from public school and Realised Activity Spaces).
Figure 27: Unstandardised SEM Results – Bull Creek precinct
Figure 28: Unstandardised SEM Results – Cockburn Central precinct
Figure 29: Unstandardised SEM Results – Wellard precinct
Table 12 and the path diagrams reveal a different number of predictors statistically relevant for each precinct. Specifically, the strongest predictors of Realised Activity Spaces for Bull Creek were the number of children under 14 years of age, the distance from the closest public school, distance from CBD, willingness to pay for reducing travel time (WTP for city-wide access) and for living closer to a train station. This contrasts with the findings for the other two precincts where the most important explanatory variables were willingness to pay for city-wide access and for school. Additionally, the Realised Activity Spaces in Cockburn Central were strongly related to the number of children under 14, followed by the index of education and occupation, whereas Realised Activity Spaces in Wellard were related to the WTP for larger properties and proximity to school.

The distance from the CBD, as a measure of accessibility, indicated that Bull Creek households residing further away from the city had larger Realised Activity Space areas. Activity Spaces did not appear to be directly affected by the number of residents within a household; however, they were positively associated with the size of the house. This may imply small collinearity effects and also suggests that co-location or scheduling of activities between various household members may have taking place. Besides, the number of bedrooms was positively associated with the WTP for train. Remarkably, the number of primary school age children and distance from school were negatively associated with the size of Realised Activity Spaces. The high proportion of senior people living in this established precinct, being very mobile, and of whom many are still involved in voluntary work, can explain this result. A relevant result was the negative association between WTP for train and the size of the Realised Activity Space. This revealed that residents of Bull Creek, willing to pay more for better access to train, had smaller Activity Spaces, in other words emphasising a predisposition for reducing the need to travel farther. The single predictor significant across all precincts and with the same direction of association was the WTP for city-wide access. Households with lower access and willingness-to-pay for enhancing their accessibility experience the largest Realised Activity Spaces.

For the households residing in Cockburn Central, WTP for school and the number of school children were strong predictors of larger Realised Activity Spaces. This is in accord with the profile of the precinct, which registers the largest and youngest families and has the largest employment. An increase in the number of children under 14 is linked to an increase in the willingness to pay for proximity to school and an increase of Realised Activity Spaces. Whilst the size of Realised Activity Spaces generally increased in line with a reduction of the socio-economic disadvantage indicators, this finding was marginally statistically significant only for Cockburn Central.
In Wellard, the findings are similar to Cockburn Central, with willingness to pay for proximity to school increasing the size of Realised Activity Spaces. In addition, households interested in larger properties and willing to pay more for owning them, have larger Realised Activity Spaces.

All other input elements appeared to be non-significant: financial resources and socio-economic household characteristics in general did not influence Activity Space areas in a profound manner; also not relevant were the distances to parks, shopping or medical centres.

While the former could be explained by the inclusion of the willingness-to-pay measures, which indirectly accounted for budgetary restrictions, the latter could be a result of the limited sample size and the lack of trips undertaken to these facilities during the survey day. Moreover, the trip diaries revealed an overall dominance of car travel, alongside a prevailing pendulum travel pattern for work and education purposes. Hence, it is to be expected that significant parameter estimates would be obtained primarily for WTP for travel time and proximity to the train station.

Finally, household attitudes towards urban features were initially included in the models in the form of latent constructs (reflecting preferences for dwelling characteristics and features of the surrounding environment, preferences for public transport facilities, bicycle availability, and a social dimension). However, none of them proved to be significant in the precinct level models, hence, they were discarded from the final models, results and discussion.

Tables A1 to A6 (Appendix) provides direct and total effects obtained from the multi-group precinct model. It is important to note that the distance from home to the train station and to the CBD, the size of the dwelling, and the number of children under 14 had a substantial indirect effect on the size of Realised Activity Spaces.

Figure 26 also presents a number of feedback relationships. A non-recursive model with feedback relationships from the Activity Space latent construct AS to the WTP measures was ultimately estimated.

Unfortunately, only two parameters were significant at the 0.05 level: the effect of Realised Activity Spaces on WTP for proximity to train in Bull Creek (p=0.042) and the effect of Realised Activity Spaces on the WTP for larger properties in Wellard (p=0.031). Although the change in $\chi^2$ was dramatic when compared with the recursive model (from 280.79 in Table 12 - to 201.20), the feedback model did not provide additional insights; therefore detailed results are not presented here.
To summarise the findings in the SEM model by precinct:

- In Bull Creek, the number of bedrooms significantly influenced the size of Realised Activity Spaces and led to an increase in the RAS areas; so did the number of children under 14 and distance from public school, however with a reverse effect on the RAS size. The distance from the CBD and WTP for time (reflecting the city-wide access) positively affected the RAS, whereas the WTP for train was negatively related to RAS. Since this precinct contains a high share of elderly population, this finding could be reflective of the level of mobility and of the financial situation of this group. Additionally, this may reveal the relatively reduced number of households with school-aged children within the sample who provided complete information for the survey.

- In Cockburn Central a slightly different scenario surfaced, with the number of children having a positive impact on RAS sizes, as well as positive impact of the WTP for proximity to school and for travel. This potentially could be indicative of the high number of families with children and of the largest employment across the three precincts. Numerous blue-collar workers residing within the area are employed either at the Rockingham and Kwinana industrial precincts or represent fly-in-fly-out labour force. Again, other socio-economic characteristics did not show any relevance in statistical terms for this precinct.

- Lastly, for the Wellard precinct, all WTP measures showed significant effects on RAS. Similar to Bull Creek, the WTP for proximity to train is inversely related to the size of RAS. Surprisingly in this precinct the number of school children positively affected the WTP for proximity to school. The fact that households willing to pay more for larger houses had larger RAS was not expected either and this aspect is recommended for follow-up research.

Altogether, the introduction of WTP aspects into the SEM models of Realised Activity Spaces resulted in a major increase in the models’ goodness-of-fit, which was foreseeable, given the highly complex nature of these measures. The feedback relationships between RAS and WTP appeared natural, with the repetitive daily (travel) patterns affecting longer term decisions (and hence residential location choice and WTP); however, only two bi-directional relationships were significant (RAS on WTP for proximity to train and for larger houses) and weaker in their magnitude when compared to the direct relationships. This raises further questions on whether these feedback effects could be easily captured in these types of models.

Before cross-validation of these results and their discussion, it should be added that the conceptual model envisaged a strong spatial effect and a significant impact of the attitudes and
lifestyles on the travel patterns measured as Activity Spaces. When building the SEM models, it became apparent that the precinct had a major influence, playing the role of location and being an adequate proxy for self-selection and preferences (by constraining the model parameters to be equal, the model fit worsened significantly, confirming the moderating effect of the precinct variable). Hence, in order to capture any associated heterogeneity effects, the survey precincts were introduced as groups within the multi-group model. Similarly, even though it was anticipated that the richness of socio-demographic information surveyed would contribute substantially in the overall estimation, the limited sample size and collinearity restricted the inclusion of socio-demographics and latent constructs of attitudes in the models. To add to these, the latent constructs of attitudes displayed considerable homogeneity across the three precincts.

7.6 Artificial Neural Networks (NN) Results

As indicated in Section 5.5, a feed-forward neural network with three layers, regarded as a general non-linear function for linking two sets of variables (Hassoun, 1995; Karlaftis and Vlahogianni, 2011) was applied to map the relationships between urban characteristics, household socio-demographics and preferences for location and built environment, and their Realised Activity Spaces. This model was built to confirm (or otherwise) the findings of the SEM model. Nevertheless, the replication could not be complete, as the NN finds the associations between inputs and outputs “in one go”, without the possibility of explicitly modelling moderating effects, or of treating a variable at the same time as input and output (exogenous for some relationships and endogenous for others).

The NN had three layers: the input layer included 29 neurons (variables); the output two neurons (Realised Activity Spaces measured as KD and CE); and a hidden layer. A number of networks with different number of neurons in the hidden layer were tested; however, the results presented here refer to a network with a single hidden layer/slab with 35 neurons (i.e., a “29-35-2” architecture).

At each hidden neuron (and then output neuron), the inputs were combined as a weighted sum, followed by a transformation, according to the activation function that was chosen. The NN applied for this problem used the logistics sigmoid function, given by:

\[ g(i) = \frac{1}{1 + e^{-i}} \]  

(34)
The network was trained with 424 records, minimising the sum of squared errors between the network outputs and the two measures of Realised Activity Spaces.

As the error space is highly non-linear in neuron weights (the space could be visualised as a landscape with mountains and valleys), some algorithms searching for the minimum may become trapped in a local valley/point. A class of algorithms that are able to escape local optima and provides the possibility to find global values across the space of solutions is represented by genetic algorithms, GA (Holland, 1975). They have been successfully used in many domains, including applications in transport (Taplin et al., 2005). Therefore, for the NN used in this research to emulate the SEM model selected, a GA-optimised structure was selected.

The learning by the network continued as an iterative process, with the weights being recalculated after each error minimisation (learning rate of 10%), until the reduction in error fell below 0.002 and a minimum of 20,000 events had passed since the last minimum error (the stopping criteria).

One hundred and six records (20%) were set aside for testing the network. This means that the optimised NN using training data was evaluated on its performance when modelling the 106 cases of new data that were not part of the training set. Statistics for the amount of variance explained by the model are presented in Table 13 and the contribution factors aggregated for both outputs in Table 14.

Table 13 suggests that the selected trained network had adequate flexibility and did not fit the white noise. Its errors were the minimum over 20 different networks that were explored, with a variable number of hidden neurons between 5 and 50. As expected, the Realised Activity Spaces measured using kernel density was better predicted, with a correlation between the actual vs. predicted outputs of 0.52 and an average absolute error of 0.932 km$^2$. $R^2$ (Table 13), which compares the NN model in terms of accuracy with a trivial benchmark model using the mean of all samples, had substantially higher value for describing the relations between households, location, urban environment and size of kernel density KD (0.265) than the size of confidence ellipse CE (0.218). At the bottom of the table network results, categorised as list of percentages within the ranges 0-5%, 5-10% and so on, indicate the proportion of NN answers within the specified % of the actual output values that were used to train/supervise the network. They revealed that while 45-50% of the results were within a 10% margin of error, there were still over 15% of cases in the network with errors over 30%.
Table 13: Artificial Neural Network results for test set

<table>
<thead>
<tr>
<th>Output:</th>
<th>Confidence ellipse</th>
<th>Kernel density</th>
</tr>
</thead>
<tbody>
<tr>
<td>R squared:</td>
<td>0.218</td>
<td>0.265</td>
</tr>
<tr>
<td>Mean squared error:</td>
<td>120.965</td>
<td>1.844</td>
</tr>
<tr>
<td>Mean absolute error:</td>
<td>7.221</td>
<td>0.932</td>
</tr>
<tr>
<td>Min. absolute error:</td>
<td>0.003</td>
<td>0.002</td>
</tr>
<tr>
<td>Max. absolute error:</td>
<td>63.175</td>
<td>5.408</td>
</tr>
<tr>
<td>Correlation coefficient r:</td>
<td>0.485</td>
<td>0.523</td>
</tr>
<tr>
<td>Percent within 0% to 5%:</td>
<td>28.11</td>
<td>20.94</td>
</tr>
<tr>
<td>Percent within 5% to 10%:</td>
<td>25.66</td>
<td>22.45</td>
</tr>
<tr>
<td>Percent within 10% to 20%:</td>
<td>20.94</td>
<td>29.25</td>
</tr>
<tr>
<td>Percent within 20% to 30%:</td>
<td>8.49</td>
<td>10.75</td>
</tr>
<tr>
<td>Percent over 30%:</td>
<td>16.79</td>
<td>15.66</td>
</tr>
</tbody>
</table>

When interpreting the results, the list of contribution factors (based on the weights of the trained NN) consistently presented the willingness to pay for proximity to train and city-wide access as the key predictors of Realised Activity Spaces (Table 14) in all tested networks.

The results imply that the NN lent support for the SEM model and also provided additional insights. Explanatory variables, such as preferences for dwelling and neighbourhood features, social dimension, and preferences for local facilities that were non-significant in the multivariate SEM model, are now in the top half of the contribution factors list. On the other hand, the distance from CBD appeared to have lost its prominence. The least significant predictor in the list, the index of socio-economic disadvantage, is about half of the value of the first predictor, the willingness to pay for proximity to train. The strong values for WTP measures and the fact that each predictor has some contribution can be explained by the combined effect of these predictors in the NN, which is largely missing in the SEM based model.
Table 14: Artificial Neural Network Contribution factors

<table>
<thead>
<tr>
<th>Ranking</th>
<th>Variable</th>
<th>Contribution</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>WTP for proximity to train</td>
<td>0.1163</td>
</tr>
<tr>
<td>2</td>
<td>WTP for city-wide access</td>
<td>0.1137</td>
</tr>
<tr>
<td>3</td>
<td>Preferences for dwelling and neighbourhood features</td>
<td>0.1116</td>
</tr>
<tr>
<td>4</td>
<td>WTP for an extra floor in the house</td>
<td>0.1105</td>
</tr>
<tr>
<td>5</td>
<td>d from closest public school</td>
<td>0.1065</td>
</tr>
<tr>
<td>6</td>
<td>Number of bedrooms</td>
<td>0.1058</td>
</tr>
<tr>
<td>7</td>
<td>Social dimension (latent construct)</td>
<td>0.1023</td>
</tr>
<tr>
<td>8</td>
<td>Index of economic resources</td>
<td>0.1015</td>
</tr>
<tr>
<td>9</td>
<td>Preferences for local facilities</td>
<td>0.1012</td>
</tr>
<tr>
<td>10</td>
<td>Preferences for transport facilities</td>
<td>0.1010</td>
</tr>
<tr>
<td>11</td>
<td>Precinct</td>
<td>0.1000</td>
</tr>
<tr>
<td>12</td>
<td>Number vehicles</td>
<td>0.0985</td>
</tr>
<tr>
<td>13</td>
<td>Index of education-occupation</td>
<td>0.0975</td>
</tr>
<tr>
<td>14</td>
<td>Latitude</td>
<td>0.0952</td>
</tr>
<tr>
<td>15</td>
<td>Children under 14 years of age</td>
<td>0.0944</td>
</tr>
<tr>
<td>16</td>
<td>d from the closest train station</td>
<td>0.0938</td>
</tr>
<tr>
<td>17</td>
<td>d from the closest private school</td>
<td>0.0912</td>
</tr>
<tr>
<td>18</td>
<td>WTP for larger dwelling (block)</td>
<td>0.0892</td>
</tr>
<tr>
<td>19</td>
<td>d from the closest park (&gt;5,000m²)</td>
<td>0.0882</td>
</tr>
<tr>
<td>20</td>
<td>WTP for proximity to school</td>
<td>0.0881</td>
</tr>
<tr>
<td>21</td>
<td>d from the closest shopping</td>
<td>0.0862</td>
</tr>
<tr>
<td>22</td>
<td>d from CBD</td>
<td>0.0859</td>
</tr>
<tr>
<td>23</td>
<td>Household size</td>
<td>0.0858</td>
</tr>
<tr>
<td>24</td>
<td>Longitude</td>
<td>0.0837</td>
</tr>
<tr>
<td>25</td>
<td>d from the closest medical centre</td>
<td>0.0826</td>
</tr>
<tr>
<td>26</td>
<td>WTP for proximity to shops</td>
<td>0.0818</td>
</tr>
<tr>
<td>27</td>
<td>Preferences for cycling facilities (latent construct)</td>
<td>0.0748</td>
</tr>
<tr>
<td>28</td>
<td>Block size (m²)</td>
<td>0.0739</td>
</tr>
<tr>
<td>29</td>
<td>Index of socio-economic disadvantage</td>
<td>0.0678</td>
</tr>
</tbody>
</table>

Note: Predictors shown in bold were statistically significant in the SEM.
Despite the difficulties associated with the lack of statistical measures (e.g., the contribution factors do not have a test) and with the interpretation of the results (which is not clear-cut, especially for synaptic weights), the feed-forward networks are recognised for their capability to approximate functions well. Provided there are sufficient hidden neurons, it has been shown that the NN can represent any continuous mapping, defined over a finite range of the input values, with certain accuracy (Engelbrecht, 2002). Here the NN captured the underlying trends in the links between household preferences and circumstances, urban form and location, and RAS.

NN provided evidence for cross-validation of the SEM model. This is essential for increasing the robustness of the findings. Moreover, new associations were suggested, mainly due to NN’s capacity to overcome the limiting assumption of linearity specific to the multivariate approaches and to its ability to combine effects. Finally, the sample size does not pose a constraint any more (41 parameters and 530 observations), and the statistical distributions of the data are not concerning, aspects which make NN more robust for data analysis (Engelbrecht, 2002; Karlaftis and Vlahogianni, 2011; Taylor, 2006). The latter two aspects were of specific interest in this research, because of the moderate sample size and the substantial multivariate non-normality of the data, produced by several skewed and kurtotic variables.
8. Conclusions and Limitations

8.1 Conclusions

This research applied geospatial analysis tools that can assist practitioners in gaining a better understanding of the complex links between urban form (supply of services) and travel patterns and the use of space, with the potential to develop strong arguments in support of TOD. Following comparison of a variety of geometries for Activity Spaces, this research applied confidence ellipses and kernel densities as indicators of a latent construct of Activity Space to benchmark, monitor, and analyse planning outcomes from TOD designs.

The results indicate that Activity Spaces vary in time and differ by TOD precinct; they are also associated with household circumstances and location preferences. These findings add to the body of knowledge that supports the role of both built environment and residential self-selection in travel behaviour. The research presents contributions to research methodology and to practice (Table 15), and they are discussed in detail in Sections 8.1.1 and 8.1.2.

From the methodological point of view, it provides a critical review of numerous metrics proposed for Activity Spaces and then applies the measures found most appropriate into a structural equations model to explore simultaneously connections between urban form, preferences, socio-demographics and Activity Spaces, highlighting the roles of TOD in these relationships. To the best knowledge of the author, this has not been attempted before.

Further, the validation of the results via artificial neural networks lends support to the multivariate model and offers additional insights into how transport and urban policies affect travel and urban space for various population groups. These findings are discussed in more detail in the next section.

Likewise, urban planning in Western Australia can benefit from an improved understanding in the TOD knowledge realm, such as how changes can be measured and what are the preferred facilities in TOD precincts. In Perth, the urban landscape varies substantially across the metropolitan area. This is also reflected in the three precincts chosen for analysis. However, in the newly planned TOD precincts, as well as in the precincts retrofitted and transformed, travel has become to a greater extent multi-modal and less reliant on the car. Both, at the household level, as well as at the precinct level, Realised Activity Spaces (measured with different metrics) decreased slightly immediately after the railway opening, but then expanded again later on, suggesting that residents have started to take up new opportunities provided by the rail corridor.
## Table 15: Main Contributions

<table>
<thead>
<tr>
<th>Methodological</th>
<th>Conclusion/Recommendation</th>
<th>Managerial/Political</th>
<th>Recommendation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Analysis of multiple metrics of RAS</td>
<td>Cassini Oval, hyperellipse, bean curve are excessively overestimating Realised Activity Spaces and are “data hungry”. Kernel Density is the preferred metric.</td>
<td>Kernel Density based Realised Activity Spaces incorporate the match of supply of urban services and household activity needs, especially when combined with data from location-aware devices.</td>
<td>Activity Space analysis should become part of the standard toolkit (strong visualisation, enhanced communication with stakeholders)</td>
</tr>
<tr>
<td>Comparison of Kernel Density with and without route data</td>
<td>Data enhancement is beneficial (when automated). Multi-day trip diary is recommended.</td>
<td>TOD is associated with RAS, Personal characteristics, household size, and children under the age of 14 years, income, and willingness to pay for urban facilities. Potential feedback effects are identified.</td>
<td>The Built Environment matters. After rail opening and TOD change, travellers are more multimodal, using more active transport and taking up opportunities along the corridor (change in destinations).</td>
</tr>
<tr>
<td>Spatial and temporal analysis of RAS changes (Multivariate and ANN) including built environment and personal characteristics (self-selection)</td>
<td>RAS increase with distance from CBD. Kernel Density based RAS do not display spatial dependence. Latent construct RAS is better than individual indicators. Cross-validation: ANN vs. SEM</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Hence, a varying degree of TOD success, reflected by differences across precincts, is consistent with the observed concentration of daily activity locations alongside the railway corridor from the city centre down to Wellard and furthermore, to the next urban area, Mandurah. This will be further detailed in Section 8.1.2.

Overall, the main findings are that RAS increase with the distance from the CBD, aligned with the willingness to pay for city-wide access and school proximity, and with a change in socio-demographics such as number of children and socio-economic status. Although individual/household travel-related attitudes were also included as part of the assessment, i.e. in order to control for self-selection bias and with the aim to uncover the influence of built environment on travel behaviour (Handy et al., 2005; Cao et al., 2009; Ewing and Cervero, 2010; Kamruzzaman et al., 2014), these elements did not appear statistically significant within any of the structural equation models tested. Unsurprisingly, the location and travel decisions of the households however (as reflected in RAS) appeared to be strongly dependent on a combination of socio-economic elements, i.e. similarity in circumstances, education and income levels and changes in accessibility.

8.1.1 Academic Contributions

The behavioural approach to activity-travel patterns and the hybridisation of geographical, transport techniques with data mining created the premise for several significant innovations and for increased reliability of the results: proof of concept for kernel densities in measuring RAS, comparison of various geometries, use of RAS with and without detailed routing data, as well as structural relations validated by Artificial Neural Networks.

Based on trip diaries data (after excluding extra-urban long-distance trips), four different parametric geometries were optimised using genetic algorithms (GA). This approach has the benefit of a quick and efficient computation, with the possibility to include multiple variables into the optimisation (here, simultaneous minimisation of Activity Spaces). Calculation of Activity Spaces is another example of successfully applying heuristics such as GA in transport expanding the range of applications presented by Taplin et al. (2005).

This research also provides new ideas on how to apply kernel densities (KD) for capturing RAS and demonstrates the tool’s capability in a practical application as an indicator of the match between supply of urban services and actual demand, expressed by households’ activities and travel behaviour. The results further show the impact of enriched data on the measurement accuracy of Activity Spaces with kernel densities: if modellers and planners are willing to include route data in their spatial tools, the Activity Spaces are more refined and likely to reflect...
more closely the space individuals use for their daily activities. Since contemporary technologies are now capable of tracking individuals in their daily travel, this aspect should be kept in mind at an early stage and as part of the design of data collection approaches. Otherwise, any reliance on a re-construction of detailed route information, such as by using shortest paths algorithms, is not only time consuming, but also prone to error (the researcher’s assumptions may not be consistent with the individuals or households’ spatial knowledge and behaviour). Researchers should also be aware that confidence ellipses remain relatively “immune” to the new data and thus are not benefitting appreciably from a more sophisticated survey approach.

When comparing the four geometries for Activity Spaces, their mutual associations as well as the associations with kernel densities were not strong. This is explained by the fact that hyper-ellipses, Cassini ovals, bean curves and confidence ellipses typically incorporate the area between the spatially distributed activity locations, thus “filling” the space. With a sufficiently large number of locations (e.g., here at the precinct level or by using multi-day trip diaries) the differences generally attenuate. However, if the number of activities is reduced and their locations are further apart, the kernel density measure likely results in a discontinuous activity surface around those separate locations, whereas the confidence ellipse and the bean Activity Space become elongated convex areas. In terms of magnitude, confidence ellipses of daily activities were here found to be 3-4 times larger than Activity Spaces measured as kernel densities with a bandwidth parameter of 3km. Given their relative benefits and limitations (easy calculation of the confidence ellipse and its properties as well as taking account for activity intensity, but with overestimation; more accurate representation of the daily movements by kernel density, though requiring greater computational effort), this research included both measures as indicators of a latent construct for the Realised Activity Space.

Previous research has shown that confidence ellipses are highly correlated with the convex hull (Kamruzzaman and Hine, 2012) ($r^2=0.952$). But kernel estimators have been shown to be more accurate than the minimum convex polygon (Börger et al., 2006; Boyle et al., 2008). Numerous software packages are available for the calculation of these metrics, nevertheless the polygon does not allow for weighting and it requires as an absolute minimum three non-collinear points for calculation, hence leaving the confidence ellipse a widely adopted metric for representation of Activity Spaces. Historically, confidence ellipses (CE) were the first tools to be applied and continued to successfully produce the desired results when sufficient data was available. As shown by the pioneering work of Lefever (1926) on activity areas frequented by delinquents, confidence ellipses under these circumstances can provide insights into the “ecological and sociological forces operating on and produced by the factors plotted” (p. 88). However, this
situation changes when only a limited number of visited locations are provided, such as for analysis at the individual (person) level.

Without denying the potential richness of other metrics in capturing individual and environmental differences, in this research the reduced frequency of location visits by households during the travel day (and their distribution) affected their suitability for more detailed investigations. Given the seemingly unrealistic size of areas defined by Cassini ovals, hyper-ellipses, and bean curves and their observed erratic behaviour, these metrics for Activity Spaces were not included in the subsequent analyses. The remaining tests and models used only kernel density estimators and confidence ellipses, considered to be more appropriate for a one-day travel diary. Their flexibility (KD) and ease of derivation (CE), as well as their visualisation capabilities, also contributed to this decision.

At the local level, where the TOD-induced travel changes were of higher interest, KD was deemed more appropriate. Kernel density based Activity Spaces represent a more sophisticated visualisation tool, sensitive to data richness (here, adding the imputed travel routes increased KD areas on average by 25%) and useful for communication of results to all stakeholders. KDs are also sensitive to granularity/bandwidth. When reduced from 1.5 km to 1 km, the results showed the Activity Spaces decreased – as expected - by 33%.

When including Activity Spaces into the structural model, the model with latent construct performed much better than the model with individual indicators. This is consistent with the expectation that richer representations of RAS result in an improved way of capturing the interrelations between household travel patterns, preferences and the built environment. Acknowledging the role of spatial resolution on the assessment of these complex relationships and its impact on results, this research conducted the analysis at two levels: household level and the precinct level. As O'Sullivan and Unwin (2003) rightly pointed out, an ecological fallacy appears at any time when an association at the aggregate levels is based on individual observations. Realised Activity Spaces, both at the precinct and individual household levels, indicate a negative association between size of urban space used for conducting daily activities and the level of accessibility. Households residing further away from the city and with limited local access to urban services and amenities have significantly larger RAS compared to households enjoying higher levels of access to the city opportunities.

The SEM findings support the contribution of this research to the debate on the relative roles of built environment and personal preferences and attitudes in shaping travel behaviour. They also support prior work that built environments and personal preferences jointly influence travel
patterns. This work however, does so less in terms of behavioural preferences and choices, and more in terms of spatial activity patterns. This allows policy makers to frame targets beyond traditional measures which do not say much about the cause and effect of planning interventions (targets are commonly tied to much simpler measure, such as reduction of vehicle kilometres per capita to achieve carbon reductions as part of climate action plans). With the inclusion of the spatial aspects of travel, via the RAS measures introduced as part of this research, policy targets can be refined, since activity travel behaviour and their spatial footprint can be captured and analysed to better understand the impact of planning interventions.

By drawing on multiple sources of data and modelling techniques, this research provides further evidence that TOD is associated with more multimodal travel and modified Activity Spaces even after accounting for preferences and attitudes. The benefit of SEM is that it allows investigation and measurement of indirect effects and feedback mechanisms otherwise not able to be considered. Furthermore, the SEM also incorporates both the supply and the demand elements that are influencing daily activities and travel in a geospatial framework.

In terms of the modelling results, the kernel density (KD)-based Activity Spaces consistently revealed higher loadings within the SEM, confirming them as superior indicator to describe the RAS at the household level. Unlike much of the previous scholarly work, this research also examined the effects of spatial dependence and revealed that a structural model, without a detailed hierarchical spatial structure, seemed appropriate.

The findings indicated that households’ circumstances and location preferences are positively related to Activity Spaces. Notably, the distance from the CBD is a significant predictor of RAS along this rail corridor, explained by Perth’s radial structure along the main transport arteries and by the relative concentration of economic and cultural activity in the heart of the city (more than 150,000 employees). Hence, when combined with the level of access to local urban amenities, the analysis of distance from the CBD translated into smaller Activity Spaces in precincts with higher access.

This research then applied a different modelling technique - the Artificial Neural Networks model (NN) - to cross-validate the results of the structural equation modelling. This approach, while useful to support the credibility of a model, i.e. to further its “accreditation” by the scientific community (Marks, 2007; Petty, 2010), is perceived as onerous and therefore is seldom applied. In this case the Artificial Neural Networks model not only supported to the SEM model, but also provided additional insights. Explanatory variables non-significant in the multivariate SEM model, such as preferences for dwelling and neighbourhood features, the
social dimension and the preferences for local facilities appeared in the top half of the list of contribution factors for the NN model, whilst the distance from the CBD appeared to have lost its prominence. In relative terms, the least significant predictor in the NN model, i.e. the index of socio-economic disadvantage, had about half of the value of the first predictor, i.e. the willingness to pay for proximity to train. Notwithstanding, the overall results produced strong values for Willingness To Pay measures. The fact that each predictor made some contribution to the size of RAS can be explained by the combined effects of the predictors in the NN. These links are largely missing in the SEM. Altogether, this co-use of modelling techniques presents a major improvement compared to traditional modelling approaches, considering subsets of various aspects or lacking altogether the validation step.

8.1.2 Contributions to Practice

The results reinforce the existing belief that urban places have to be designed for people. While accounting for various human attitudes, places must offer flexible, dynamic mixes of urban services together with good access to public transport, in order to increase the ridership.

This research provides practitioners with new ideas on how to measure, monitor, analyse and compare the match between supply of urban services and households’ travel behaviour, i.e. by applying Activity Spaces. It also demonstrates that applying kernel density indicators is within the reach of many government organisations, which already collect or have access to data at a high-resolution level. Thus, in their practical applications, analysts, as well as urban designers and planners, could embrace the Activity Space concept, alongside other geospatial analysis tools and GIS technologies already forming part of their usual practice as part of their daily assessment routines.

The research showed that the RAS metrics are heavily dependent on the abundance of data and provided support for the preferential use of kernel densities and confidence ellipses as rich dynamic measures linked to urban form. The distribution of locations, frequency of activities, as well as the presence of the travel routes, affected the measures, but to a varying extent. Data enrichment did not have the desired impact on confidence ellipse measures, but notably improved the kernel density estimates. The results support further investigation of the kernel density based RAS measure, as this can offer continuous Activity Spaces, reflecting density and intensity patterns at an enhanced and close-to-reality resolution (Figure 6, Section 5.7).

Through the SEM, preferences (i.e. considering what the residents valued) and socio-demographics were tested. This analysis offered insights into flexible planning solutions that may be applied, whilst catering for the diversity in population. Whereas RAS measured via
confidence ellipses had huge variations, kernel densities did not remarkably vary across precincts or before and after railway opening. The relative “stability” of kernel density estimates is consistent with the observed “inelasticity of travel with respect to changes in built environment”, as highlighted by Ewing and Cervero (2010) in their meta-analysis of over 200 studies published in the last decade on this topic (Figure 8, Section 5). These two insights are useful for planners: a) they can organise and budget for data collection with full awareness of the implications of a more detailed travel data survey on the analysis of Activity Spaces; and b) they have the support for modulating their decisions based on the residents’ preferences.

The results are provided at various spatial scales and from multiple angles. Planners can select or adopt various ways/levels of applying Activity Spaces in their work: from simple comparisons of Realised Activity Spaces between locations or socio-demographic groups, to complex structural models such as those estimated in this research. For example, findings referring to the negative associations between RAS and level of access or referring to the differences between Activity Spaces for households with and without cars have immediate direct implications for policy. This research offers not only the empirical support for the existence and the value of these links – but specifically after controlling other factors that may otherwise contaminate the associations. The results are also consistent with work done elsewhere (Harding et al., 2012; Olaru et al., 2005; Morency et al., 2009).

Furthermore, relevant for practitioners is the spatial account that this research considered. Because of the need to explore inherently spatial processes, it was essential to assess and account for the dependencies between household measures to ensure they did not affect the parameter estimates. Whereas Moran’s I showed neither a spatial autocorrelation for Activity Space measures nor for attitudes, a marginal positive autocorrelation appeared for the willingness to pay for the proximity to shops and for amenity as well as for dwelling size. A significant autocorrelation was recorded for median house price, also for the socio-economic disadvantage, resources and educational indices. Hence, practitioners should be aware of these aspects, especially when using data from different sources and at different spatial levels. For example, the census indicators and real estate prices are often available and applied at zone level (suburb, traffic zone, collection district), whereas the household or individual measurements are collected and applied at the point level. As already highlighted, an ecological fallacy may therefore affect the results with severe impacts for decision-making.

In addition, without spatial knowledge, planners run a larger risk of creating spatial conditions that do not satisfy the individual needs and desires, and therefore their practices could encourage non-sustainable travel behaviours. Here, data shows that places are different and
hence different patterns have emerged and most likely will continue to change. Smaller Realised Activity Spaces in denser precincts indicate more reliance on or use of local facilities together with higher neighbourhood interactions, which “may strengthen neighbourhood attachment and foster social ties” as suggested by Fan and Khattak (2008): 105.

The pursuit of activities (out-of-home and at home), as expressed through Realised Activity Spaces, is not only a function of the available opportunities (urban form), but also depends on personal circumstances and preferences. Consistent with Newsome et al. (1998), who found that household size and location variables are more important in explaining Realised Activity Spaces (CE) and therefore “should be thoroughly considered in the planning process” (p.376), this research indicates that presence of children, dwelling size, and location preferences, as expressed by willingness to pay measures for various local facilities and access, were significantly associated with use of urban space, regardless of the consideration of the Activity Space either as a latent construct or not. The relative location of households from the CBD and the proximity to a school and a train station were also significant predictors of the Activity Space, even after attitudinal factors were controlled for (Cao et al., 2009). Thus, the planning framework should allow for a healthy mix of places and opportunities that meets the broad array of residents’ needs and wishes.

Interestingly, proximity to the train station and distances to parks, schools, medical centres and shopping opportunities did not appear to be significant factors influencing the Realised Activity Space (RAS) in the structural equations model. However, built environment features at the local scale did matter. These results could be due to the limited sample size and the small number of activities and trips recorded in the trip diaries collected as part of the available surveys.

Whilst the size of RAS generally increased in line with a decrease of the socio-economic disadvantage indicators, this finding was not found to be statistically significant. Overall, it appeared that financial resources and socio-economic household characteristics did not influence Activity Space areas in a significant manner, a surprising finding, which should form part of further investigations and is suggested for follow-on research.

The feedback relationships between RAS and WTP measures are also important for practitioners: the repetitive daily (travel) patterns affect longer-term decisions such as relocation (expressed as WTP), reflecting a continuous dynamic learning process. The fact that these relationships proved bi-directional raises the question on whether other indirect effects could exist and need to be modelled.
Given the low densities in WA, and the time lag between infrastructure provision and settle-in behaviour, a staged approach for planning may also be useful. This would require specific consideration within the statutory planning context. For example, building and opening commercial or office front areas in newly developed estates may be inefficient until the residents have moved in to support these pursuits, but if, for example, for a limited time period the spaces are allocated to service another function or use, this adaptability could then address the ridership problem and could create a pathway to additional revenues.

Another observation is that car travel should not be isolated from public transport and rather be integrated, allowing ease of access to public transport facilities in support of an increased ridership. Overseas, park-and-ride (PnR) spaces have in this manner been adopted even in association with light rail (Hess and Almeida, 2007; Dickins, 1991; Duncan and Christensen, 2013). In Western Australia, some resistance to broader scale PnR has been evident, based on the idea that the focus of TOD should all be on walking, cycling, and public transport. However, the local context with such reduced densities of activities also seems to require more transitional approach, which has been supported by some (Martinovich, 2008; Orlar et al., 2013; Public Transport Authority, 2012). Change towards more active transport may be stimulated; however, it cannot be prescribed. Hence, every non-car trip, even for a segment of the journey, would lead to improvements of overall travel conditions, while still respecting individual preferences.

The story appears conclusive: a policy framework that is too rigid is likely to fail; transport and urban planners need to be flexible in the TOD design and provide attractive places that work for people. Although it is premature to draw the conclusion that TOD has essentially changed the travel behaviour of households in Perth, there are significant associations between TOD features (density, diversity, and destination choices) and trip making, as reflected in the RAS. The Activity Spaces are smaller in precincts with higher access (Bull Creek) and this pattern is maintained after the opening of the railway corridor (Table 4, Section 6). However, not all precincts experienced the same changes. The increased time accessibility brought about by the railway corridor enabled 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 mixed land-use around the railway precinct (Cockburn Central).

The modelling has shown positive associations between the number of household members, number of children as well as “busyness” with the RAS measures. This was anticipated, as the number and varieties of daily commitments create the demand for activities in various locations, hence, are likely to expand Activity Spaces. This is again essential information for planning
professionals to nuance their approaches, offering gateways to developing a more attractive urban canvass.

As with any research, data resolution, data quality, and other survey attributes dictate what can eventually be examined. The comparison of KD based RAS, with and without route data, confirms the need for more detailed data collection in order to better understand spatial use and knowledge. Therefore, in order to fully examine TOD related aspects of travel behaviour and to identify representative spatial patterns with underlying influential elements, such as availability of transport opportunities, network parameters, urban layout at a local scale, detailed route information and longitudinal trip data collection over a minimum time period of one week are highly recommended.

Finally, the availability of GIS, and activity–travel micro-data presents new opportunities to more vividly/effectively communicate to stakeholders how cities and urban services are used in space and time. In this case, practitioners can increase the use of GIS not only for deriving measures of Activity Spaces, but also for connecting with policy makers and urban communities during the consultation process, thereby fully taking advantage of geo-visualisation.

8.2 Limitations

Activities differ with respect to their “pliability” in space and time. This research seized the use of urban space through observed Realised Activity Spaces, based on trip diaries, highlighting locations where the households are able to engage in activities. As acknowledged at the outset, due to the nature of data available (the data available for this research was limited to 24 hour trip diaries) it was necessary to focus with this research in particular on spatial pattern analysis, with only limited consideration of temporal dimensions, an otherwise natural extension of this research (longitudinal data collected e.g. via multi-week trip diaries).

However, the lack of detailed route information also meant that the confidence ellipses, kernel densities, and other metrics “ignored” the transport network. As indicated, this research has shown the beneficial effect of routing data on a small sub-sample of households. This attempt to surmise the routes (using shortest paths) has its own problems, as it relied on assumptions regarding the transport route choice sets available for the travellers. Nevertheless, the imputation provided more detail than the RAS without routes.
Due to the onerous manual reconstruction process, the routes were built using Google Maps, and then imported into ArcGIS for analysis. This could be made easier through either developing sophisticated methodologies to incorporate GPS tracking or mobile phone positioning (Ahas, 2010), by building automated computational tools based on Google Earth/Maps, or by designing an integrated network routing model within the GIS software (with the latter currently being further explored). Aligned with suggestions by Axhausen (2007), there is a call for new methodological approaches, “as current efforts using a small number of supposedly key locations have not so far been successful” (p.31).

The author faced substantial difficulties that prevented imputation of routes for all households in the dataset: in the absence of advanced programming skills or access to affordable and qualified contractors, and without an off-the-shelf software solution available, the time requirements for data processing and joining data sets across different software platforms were extremely high, translating into many weeks of work. This could however be easily accommodated in a large organisation where a pool of various resources exists, or where sufficient funds are available to support specialised software development of a GIS add-in.

Related to data availability (24-hour trip diaries), another limitation of the current model refers to the inclusion of both work and non-work activities into RAS. As TOD benefits are expected to be prevalent at a local level, further research would require a larger dataset that would allow removal of work- and study-related travel from the Activity Space analysis, and subsequent reassessment of the TOD implications. Similarly, analysing RAS not only in terms of temporal variations in daily travel behaviour, but also by travel mode, would be beneficial to identify areas where certain modes have deficiencies.

This is a significant limitation of this research and the analysis of RAS by travel mode would almost certainly present as the most appropriate approach to optimise and judge the success of TOD projects. However, here the analysis has been based on all modes of transport in a pooled manner, which is a reflection of the limitation of the trip diaries available for this research, which did not provide a sufficient number of trips to facilitate an analysis my travel mode. The advanced research steps outlined above all require longer-term data collection, which is often difficult to achieve.

Lastly, data restrictions also affected the ability to further apply the automated and adaptive bandwidth selection for kernel density estimators. In this research, a number of bandwidths were considered (1.5 km, 3 km and 6 km) depending on the average distances travelled by households, overwriting the default ArcView™ GIS value. With substantially more trips (and
locations) and ideally better long-term consistency of sample households between waves, a more sophisticated application of an adaptive bandwidth selection may be possible.

But data limitations do not solely relate to the amount or trip making information for households alone. The overall sample size (number of households) is also affecting the modelling approach and results. The sample used here (530 households), whilst moderate by multivariate standards (SEM have been estimated with smaller sample sizes, e.g., 306 in Wang et al., 2012), did therefore constrain the precinct scale model in terms of its complexity. Non-normality (skewness and kurtosis) for the Activity Spaces measures (CE and KD) also requires consideration and would call for larger sample sizes.

Even though it was anticipated that the richness of socio-demographic information surveyed would allow for their inclusion in the overall estimation framework as moderators, i.e. to investigate different models for varying socio-economic groups, the limited number of households restricted the use of socio-demographic effects in the model as mediators.

**8.3 Further research**

The limitations of this research suggest the main directions for future research. They can be classified in two main categories: data collection and methodologies.

Under the first category, richer data (capturing at least a week of travel data, perhaps associated with automated GPS-enabled or position-aware devices), in longitudinal studies, and with larger sample sizes, will not only enable longitudinal analysis of temporal dimensions, but also allow the calculation of individual Activity Spaces by mode and by travel purpose, with adaptive kernel bandwidth. This extended data set will thereby facilitate more detailed comparisons across time and space, such as analysis of KD for different waves by means of a ratio of kernels to conduct a comparative analysis of accessibility (see Páez et al., 2010). This would considerably facilitate visualisation of differences in the distribution of activities between waves. The data will also permit the analysis of time budget restrictions and their strong role on travel decision-making by members of individual households (e.g., examining the need for negotiation, scheduling and joint trip making).

Related to the availability of sufficiently detailed data, it would also be useful to test within a range of other geographical settings whether the associations among parametric indicators obtained here still hold. This research provided evidence in favour of kernel density-based
Activity Space analysis, but this may also be an artefact of the low-densities and thus large spatial distribution of activities experienced in Australia.

Moreover, the refinement of algorithms, such as to correctly identify activity locations, trips patterns and transport modes from GPS data (Thierry et al., 2013:9) or development of software applications to automatically impute or record/retain the route choices taken by travellers from traditional panel surveys will reduce the time required for calculation of Activity Spaces and enhance the accuracy of the kernel estimators.

In terms of methodologies, the findings further support the need for growth models. Despite promising results, more advanced research is now required to simultaneously model built environment characteristics, socio-demographics, and attitudes with travel behaviour in a longitudinal approach. Spatial dependencies between cross-sectional units may lead to bias, inefficient, or inconsistent estimates (Cho, 2008: 182), but longitudinal data would assist urban planners and transport practitioners to ascertain more reliably the separate contribution of built environment features and transport services to achieving successful TODs. Finally, from a methodological perspective this research also demonstrated that alternative models (SEM and NN) cross-validated and complemented each other. More work would be required to reveal the importance of direct and indirect effects of urban form elements on Activity Spaces and on the links between various modelling approaches.

For practice, this research encourages the uptake of Activity Spaces and more advanced models. Although it is not argued that this is the “best-practice”, a move towards applying models that deal with people and their activities is necessary. And since analytical tools are becoming more prevalent in daily practice and hence often readily accessible, there is a need for up-skilling and incorporating recent developments within this sector into decision-making processes.

8.4 Final words

Knowledge of human activity travel patterns enables urban designers and planners to better facilitate spatial conditions conducive to sustainable activity behaviour, or conditions that could assist in reducing social exclusion and in limiting the likelihood of undesirable behaviours developing within an urban area. Modelling and analysis of human Activity Spaces provides insights into spatial and temporal interactions between activity patterns, physical infrastructure, socio-economic clusters and networks and the urban functions (Schaick and Spek, 2007). Activity Space analysis, with its diagnostic tools, can thereby assist in unravelling these
complexities within the web of urban relationships between supply of services and demand of human daily activities.

This research evaluates the association between different TOD opportunities and household travel behaviour via Realised Activity Spaces. It applied Realised Activity Spaces at the household and precinct level to investigate whether and to what extent TODs modify or reduce their size.

The before and after railway opening data allow an improved analysis of built environment 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. The comparison here was made using multivariate analysis (MANCOVA and SEM) to model the differences between Realised Activity Spaces of households in the three precincts and between-and-after opening of the railway corridor, accounting for several socio-demographics. The results, showing changes in travel behaviour post opening of the rail corridor, are “good news” for planning. The author, a practitioner at the local government area, is facing every day the challenges of inertia, disengagement, lack of action or fear of responsibility for “bigger things” under the excuse of ambivalent research findings. In fact, no matter how small or slow the changes associated with infrastructure improvements may be, there is always a role for actively taking up new tools, methodologies, findings, and making decisions accordingly. With a judicious selection of the solutions, there is hope that our cities will become even greater homes for us and the generations to come!
9. Bibliography


Golledge, R.G. (1976) *Cognitive configuration of a city*. Volume I, II, OSU Research Foundation, Department of Geography, Ohio State University, Columbus, OH, USA.


Institute for Transportation and Development Policy (2014) *TOD Standard v2.1*, Despacio, New York, USA.


White (1992) *Artificial Neural Networks*, Blackwell, Cambridge, MA, USA.


10. Appendices
## Tables

### A.1 SEM Results - Direct Effects (BC - Default model)

<table>
<thead>
<tr>
<th></th>
<th>Distance from train station</th>
<th>WTP for larger dwellings</th>
<th>WTP for City wide accessibility</th>
<th>Children under the age of 14</th>
<th>Number of bedrooms</th>
<th>Distance to Public school up to Year 12</th>
<th>Index of education and occupation</th>
<th>Distance from CBD</th>
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### A.3 SEM Results - Direct Effects (CC - Default model)

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<td>0.374</td>
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A.6 SEM Results - Total Effects (W - Default model)

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A.7 SEM for Realised Activity Space - Whole Sample with KD & CE indicators

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<th>Relationship</th>
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<tr>
<td></td>
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</tr>
<tr>
<td>RAS (latent construct (cstr.)) ➝ KD</td>
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</tr>
<tr>
<td>RAS (latent cstr.) ➝ CE</td>
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</tr>
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<td>d from CBD ➝ RAS</td>
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<tr>
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<tr>
<td>Children below 14 years ➝ RAS</td>
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<tr>
<td></td>
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<th>Goodness-Of-Fit</th>
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<td></td>
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<tr>
<td></td>
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## A.8 Correlations Variables Included in the SEM for Realised Activity Spaces

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<tr>
<td>3. d from the train station</td>
<td>-0.089*</td>
<td>-0.389**</td>
<td>1</td>
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<tr>
<td>4. d from public school</td>
<td>-0.409**</td>
<td>-0.145**</td>
<td>-0.143**</td>
<td>1</td>
<td></td>
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<tr>
<td>5. d from CBD</td>
<td>-0.935**</td>
<td>-0.728**</td>
<td>0.233**</td>
<td>0.372**</td>
<td>1</td>
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<tr>
<td>6. Index education-occupation</td>
<td>0.846**</td>
<td>0.758**</td>
<td>-0.343**</td>
<td>-0.167**</td>
<td>-0.896**</td>
<td>1</td>
<td></td>
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<tr>
<td>7. KD</td>
<td>-0.078</td>
<td>-0.07</td>
<td>-0.059</td>
<td>0.081</td>
<td>0.053</td>
<td>-0.024</td>
<td>1</td>
<td></td>
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</tr>
<tr>
<td>8. CE</td>
<td>-0.279**</td>
<td>-0.187**</td>
<td>-0.022</td>
<td>0.215**</td>
<td>0.228**</td>
<td>-0.201**</td>
<td>0.621**</td>
<td>1</td>
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<tr>
<td>9. WTP for proximity to school</td>
<td>-0.004</td>
<td>0.034</td>
<td>-0.056</td>
<td>-0.024</td>
<td>0.011</td>
<td>-0.016</td>
<td>0.198**</td>
<td>0.063*</td>
<td>1</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>10. WTP for proximity to train</td>
<td>-0.074</td>
<td>-0.031</td>
<td>-0.099*</td>
<td>0.012</td>
<td>0.06</td>
<td>-0.061</td>
<td>0.091*</td>
<td>0.027</td>
<td>0.031</td>
<td>1</td>
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<tr>
<td>11. WTP for larger dwellings</td>
<td>0.243**</td>
<td>0.247**</td>
<td>-0.003</td>
<td>-0.077</td>
<td>-0.204**</td>
<td>0.262**</td>
<td>0.031</td>
<td>0.015</td>
<td>-0.009</td>
<td>-0.013</td>
<td>1</td>
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<tr>
<td>12. WTP for city-wide access (reducing travel time)</td>
<td>0.255**</td>
<td>0.178**</td>
<td>-0.098*</td>
<td>0.06</td>
<td>-0.043</td>
<td>0.052</td>
<td>0.01</td>
<td>-0.057</td>
<td>0.129**</td>
<td>-0.093*</td>
<td>-0.032</td>
<td>1</td>
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<td></td>
</tr>
<tr>
<td>13. Children below 14 years</td>
<td>-0.072</td>
<td>0.033</td>
<td>-0.012</td>
<td>0.016</td>
<td>0.068</td>
<td>-0.068</td>
<td>-0.098*</td>
<td>-0.046</td>
<td>0.108*</td>
<td>-0.007</td>
<td>0.015</td>
<td>-0.054</td>
<td>1</td>
<td></td>
</tr>
<tr>
<td>14. Number bedrooms</td>
<td>0.121**</td>
<td>0.195**</td>
<td>-0.055</td>
<td>0.077</td>
<td>-0.109*</td>
<td>0.221**</td>
<td>0.100*</td>
<td>0.017</td>
<td>-0.022</td>
<td>-0.031</td>
<td>0.067</td>
<td>-0.075</td>
<td>0.119**</td>
<td>1</td>
</tr>
</tbody>
</table>

** Significant correlations at the 0.01 level (2-tailed); * Significant correlations at the 0.05 level (2-tailed).
A.9 Additional Resources on Artificial Neural Network Modelling


White (1992) *Artificial Neural Networks*, Blackwell, Cambridge, MA, USA.


210
Figures

F.1 Artist’s Impression – Wellard TOD (Landcorp)

Source: Landcorp (2006)

F.2 Structure Plan Cockburn Central

Source: Cockburn Central Town Centre Structure Plan, City of Cockburn
F.3 Metropolitan station precincts: Actual land uses at 2007 (net density shown)

Source: Curtis (2012: 93)
F.4 Directions 2013 – Indicative Policy Application Area

Source: State of Western Australia (2006)
F.5 Standardised SEM Results – Bull Creek precinct

F.6 Standardised SEM Results – Cockburn Central precinct
F.7 Standardised SEM Results – Wellard precinct
F.8 Map of Perth’s Rail Network and Study Area

Source: adapted from Australian Rail Maps (2014)
P.1 Program Source Code – Calculate Kernel Density Loop Tool

## Purpose: Create Kernel Density Grids

Description:
- Creates grid files for each set of UniqueIDs (intHH_IDs) contained within a shapefile
- Each set of UniqueID points is selected by iterating through unique HH_IDs
- Kernel Density is calculated for the selected points and a grid
- The grid file is created, then saved to output folder specified by the user

Software Requirements:
- Spatial Analyst Extension

Required inputs:
- 1.) Trips in point Shapefile, with a field containing Unique IDs (intHH_ID)
- Unique IDs must be defined as an integer field.
- 2.) Summarized table of intHH_IDs with each record representing a unique HH_ID

Output:
- Kernel Density GRIDs (name based on HHID ) for each HH_ID

Build upon scripts found at:

# Import system modules
import sys, string, os, arcgisscripting
import arcpy
from arcpy import env
from arcpy.sa import *

# Create the Geoprocessor object
gp = arcgisscripting.create(9.3)

# Overwrite any existing files in directory
gp.Overwriteoutput = 1

# Notify User that calculations are starting
gp.AddMessage ("Starting calculations")

# Check out any necessary licenses
arcpy.CheckOutExtension("spatial")

# Local Variables – Obtain Parameter Variables
InputPoints = gp.GetParameterAsText(0)
tblUniqueIDSumm = gp.GetParameterAsText(1)
fldPopulation = gp.GetParameterAsText(2)
fldUniqueID = gp.GetParameterAsText(3)
dblCellSize = gp.GetParameterAsText(4)
dblSearchRadius = gp.GetParameterAsText(5)
AreaUnits = gp.GetParameterAsText(6)
wkOutWorkspace = gp.GetParameterAsText(7)

###########################################################################
## Module to determine workspace extent + factor for graphical representation
###########################################################################

def newExtent(fc, factor):
    shapefldName = gp.Describe(fc).ShapeFieldName
    searchRows = gp.SearchCursor(fc, '"' + fldUniqueID + '" = ' + str(currentID))
    searchRow = searchRows.next()
    #obtain the 1st features extent
    extentObj = searchRow.getvalue(shapefldName).extent
    xMin = extentObj.xmin
    yMin = extentObj.ymin
    xMax = extentObj.xmax
    yMax = extentObj.ymax
    searchRow = searchRows.next()  # now move on to the other features
    while searchRow:
        extentObj = searchRow.getvalue(shapefldName).extent
        if extentObj.xmin < xMin:
            xMin = extentObj.xmin
        if extentObj.ymin < yMin:
            yMin = extentObj.ymin
        if extentObj.xmax > xMax:
            xMax = extentObj.xmax
        if extentObj.ymax > yMax:
            yMax = extentObj.ymax
        searchRow = searchRows.next()
    xMin = xMin - factor
    yMin = yMin - factor
    xMax = xMax + factor
    yMax = yMax + factor
    del searchRow
    del searchRows
    return str(xMin) + " " + str(yMin) + " " + str(xMax) + " " + str(yMax)

###########################################################################
## Python Function to increase extent size by a given factor
###########################################################################

def increaseExtent(extent, factor):
    XMin = extent.XMin - (factor*extent.XMin)
    YMin = extent.YMin - (factor*extent.YMin)
    XMax = extent.XMax - (factor*extent.XMax)
    YMax = extent.YMax - (factor*extent.YMax)

    return arcpy.Extent(Xmin, YMin, XMax, YMax)
try:

# Create a feature layer for each unique ID
lyInputPoints = gp.MakeFeatureLayer(InputPoints, "lyInputPoints")

# allocate obtained table location
tblSummHHID = tblUniqueIDSumm

# Set up a search cursor
rowsSummHHID = gp.SearchCursor(tblSummHHID)

# Initiate cursor
# Note row is singular not plural
rowSummHHID = rowsSummHHID.Next()

# Initial portion of loop to iterate through rows in the summary table of HH_ID
while rowSummHHID:

    # Get HH_ID from cursor
    currentID = rowSummHHID.GetValue(fldUniqueID)

    # Print HH_ID from cursor – optional to monitor progress
    gp.AddMessage(str(currentID))

    # Select points by HH_ID current value
    gp.SelectLayerByAttribute_management("lyInputPoints", "NEW_SELECTION", \"" + fldUniqueID + \"\" = \"\" + str(currentID))

    gp.Workspace = wkOutWorkspace

    result = gp.GetCount_management("lyInputPoints")
    countSelRows = int(result.GetOutput(0))

    gp.AddMessage("Counted features is : " + str(countSelRows))

    # Getting Extent from module above
    scale = int(dblSearchRadius) + 100
    gp.AddMessage("Scale factor is : " + str(scale))

    testExtent = newExtent("lyInputPoints",scale)

    # Print ID and Extent values to Message Window
    gp.AddMessage("Current ID is: " + str(currentID) + ", Extent is: " + testExtent)

    # Set workspace to user defined output workspace
    gp.Workspace = wkOutWorkspace

    # Set name of Output Raster = H and uniqueID
    outRaster = wkOutWorkspace + \"\HH\" + str(currentID)
    # If the selected features in fcLocData are > 1, then enter into loop to calculate Kernel
if countSelRows > 1:
    # Set Extent to Extent derived from module above
    gp.Extent = testExtent

    # Calculate Kernel Density
    gp.AddMessage("Extent set")

    # Calculate Kernel Density
    gp.AddMessage("Calculating Kernel now")
    gp.AddMessage("Population" + str(fldPopulation))
    gp.AddMessage("Raster" + str(outRaster))
    gp.AddMessage("Cellsize" + str(dblCellSize))
    gp.AddMessage("Radius" + str(dblSearchRadius))
    gp.AddMessage("Units" + str(AreaUnits))
    outKdens = KernelDensity("lyInputPoints", fldPopulation, dblCellSize, dblSearchRadius, AreaUnits)
    gp.AddMessage("Kernel done")
    outKdens.save(str(outRaster))
    gp.AddMessage("Kernel saved")

    # Delete testExtent output
    del testExtent
else:
    gp.AddMessage("No kernel density created for " + str(currentID))

    # Move to next search row and back to top of the loop
    rowSummHHID = rowsSummHHID.Next()

del rowsSummHHID, rowSummHHID, outRaster, result

gp.AddMessage("Script is complete.")
gp.AddMessage("Kernel Density Tool completed successfully")

except:
    gp.AddMessage()
P.2 Program Source Code – Slice Grid Tool

###########################################################################
## SliceKernelDensityGrid.py       ##
###########################################################################
# Last edited: 24 Jan 2010
# Purpose: Slice Kernel Density Grids
# Description:
# Slices a range of values of the input cells of a raster by zones of equal interval,
# equal area, or by natural breaks. If equal intervals are required with 5% breaks, then
# standard base value is 0, slice value is 21 - 20 slices are created representing 5% each slice.
###########################################################################
# Software Requirements:
# Spatial Analyst Extension
# Required inputs
# 1.) Input raster file directory/workspace
# 2.) Output directory/workspace
# 3.) Slice type: equal interval, equal area, natural breaks
# 4.) Base zone
# 5.) Number of slices (e.g. base zone 0, number of slices 21 – then purge first slice
# representative of 5% to retain a95% kernel.
###########################################################################
# Outputs
# 1.) Reclassified/sliced grid file
###########################################################################

# Import system modules
import arcgisscripting, arcpy

# Create the Geoprocessor object
gp = arcgisscripting.create(9.3)

gp.OverWriteOutput = 1

# Local Variables – Obtain Parameter Variables
InWorkspace = gp.GetParameterAsText(0)
OutWorkspace = gp.GetParameterAsText(1)
BaseZone = gp.GetParameterAsText(2)
Slices = gp.GetParameterAsText(3)
SType = gp.GetParameterAsText(4)

# Set the workspace environment
gp.workspace = InWorkspace
out_workspace = OutWorkspace

# Check out any necessary licenses
gp.CheckOutExtension("Spatial")

###########################################################################
## M A I N  P R O G R A M ##
###########################################################################

# Set the base zone value and the number of slices
baseZoneForInput = BaseZone
numberOfSlices = Slices
slicetype = SType

rasters = gp.ListRasters("", "GRID")

for raster in rasters:
    gp.AddMessage(str(raster))
    inRaster = raster
    outRaster = out_workspace + "/s" + raster

    # Process: Slice
    gp.Slice_sa(inRaster, outRaster, numberOfSlices, slicetype, baseZoneForInput)

    gp.AddMessage("Grid reclassification/slicing completed successfully")
P.3 Program Source Code – Calculate Kernel Density Areas

###########################################################################
# CalculateArea_CrtTblv02.py       ##
# Last edited: 15 Jan 2010
# Purpose: Calculate Kernel Density Areas
# Description:
# Develops a List of Reclassified Rasters using ListRasters from a user specified
# directory/workspace to get file names of reclassified/sliced density grids,
# enumerates through the grids and creates RasterLayer to query by Attributes,
# sets Search Cursor on MakeRasterLayer where Value >= (to get access to COUNT value)
# Adds new row and populate with values from raster name and row information to new*.dbf
###########################################################################
#Software Requirements:
# Spatial Analyst Extension
# Required inputs
# 1.) Input raster file directory/workspace
# 2.) Output directory/workspace
# 3.) Bottom range for calculation of cumulative area
# 4.) Top range for calculation of cumulative area
# 5.) Scale factor (e.g. from km2 to m2)
###########################################################################
# Outputs
# 1.) *.dbf file with raster areas for each Kernel Density grid raster
###########################################################################
# Import system modules
import arcgisscripting, os, sys

# Create the Geoprocessor object
gp = arcgisscripting.create(9.3)

# Overwrite any existing files in directory
gp.OverWriteOutput = 1
#gp.SetProduct("ArcInfo")

# Local Variables – Obtain Parameter Variables

# (1) Directory containing reclassified rasters
RastDir = gp.GetParameterAsText(0)

# (2) Bottom Range of Integer Value to develop query from
BottRangeVATValue = gp.GetParameterAsText(1)

# (3) Top Range of Integer Value to develop query from
TopRangeVATValue = gp.GetParameterAsText(2)

# (4) Area Multiplier Value
AreaMult = gp.GetParameterAsText(3)

# (5) Output table
OutputTbl = gp.GetParameterAsText(4)

# Set Workspace

gp.Workspace = RastDir

# Check out any necessary licenses
gp.CheckOutExtension("Spatial")

#########################################################################
##  M A I N  P R O G R A M  ##
#########################################################################

# Notify user
gp.AddMessage("Creating Table")

# Setting and notifying output table name
dbfOutName = os.path.basename(OutputTbl)
gp.AddMessage(dbfOutName)

# Process: Create the empty table
gp.CreateTable(gp.Workspace, dbfOutName)
gp.AddMessage("Adding fields")

# Process: Add attribute fields to table
gp.AddField(dbfOutName, "HHID", "text", 20)
gp.AddField(dbfOutName, "COUNTSUM", "long")
gp.AddField(dbfOutName, "AREAKD", "double", 18, 11)

# Creating a new table adds a token 'Field1' field that can be deleted.
gp.DeleteField_management(dbfOutName, "Field1")

# Set Insert Cursor
rowstbl = gp.InsertCursor(dbfOutName)

# Create Python List of Rasters
rerasters = gp.ListRasters("", "GRID")

for reraster in rerasters:
    # Formatting to get name of raster
    InReRaster = RastDir + "/" + reraster
    OutLyr = "templyr" + reraster

    hhid = str(reraster)
    gp.AddMessage(str(hhid))

    # Process: MakeRasterLayer_management
    gp.MakeRasterLayer_management(InReRaster, OutLyr)

    rows = gp.SearchCursor(OutLyr, ""Value" >= ' + str(BottRangeVATValue) + ' AND "Value" <= ' + str(TopRangeVATValue))
    row = rows.Next()
    sum = 0

    while row:
        sum = sum + row.count
        row = rows.next()
gp.AddMessage(str(sum))
areakd = int(sum) * int(AreaMult)
rowtbl = rowstbl.NewRow()

rowtbl.SetValue("HHID", hhid)
rowtbl.SetValue("COUNTSUM", sum)
rowtbl.SetValue("AREAKD", areakd)
rowstbl.InsertRow(rowtbl)

gp.AddMessage("Count is: " + str(sum) + ", Area is: " + str(areakd))
del sum
print gp.GetMessages()

del InReRaster, OutLyr

gp.AddMessage("Kernel Density Calculation completed successfully")
del rowstbl, rows