Department of Spatial Sciences

Spatio-temporal Modelling of Accessibility to Train Stations for Park and Ride (PnR) Users

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DECLARATION

To the best of my knowledge and belief this thesis contains no material previously published by any other person except where due acknowledgment has been made.

This thesis contains no material which has been accepted for the award of any other degree or diploma in any university.

Human Ethics (For projects involving human participants/tissue, etc) The research presented and reported in this thesis was conducted in accordance with the National Health and Medical Research Council National Statement on Ethical Conduct in Human Research (2007) – updated March 2014. The proposed research study received human research ethics approval from the Curtin University Human Research Ethics Committee (EC00262), Approval Number **RD-02-13**

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RELATED PUBLICATIONS

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5Ds	Distance, Density, Diversity, Design and Destination accessibility
AASHTO	American Association of State Highway and Transportation Officials
ABS	Australia Bureau of Statistic
ANOVA	Analysis of Variance
API	Application Program Interface
ASGS	The Australian Statistical Geography Standard
BnR	Bus and Ride
CBD	Central Business District
CORBA	Common Object Request Broker Architecture
DoP	Department of Planning
DoT	Department of Transport
E3SVFCA	Three-step Variable Floating Catchment Area
EDA	Exploratory Data Analysis
EM	Expectation Maximization
ESRI	Economic and Social Research Institute
FCA	Floating Catchment Area
GIS	Geographic Information System(s)
GPS	Global Positioning System(s)
IDW	Inverse Distance Weighted
ITS	Intelligent Transportation Systems
LBS	Location-Based Service
LOS	Level of Service
LRT	Light Rail Transit
LRT	Light Railway Transit
MAUP	Modifiable Areal Unit Problem
MNL	Multinomial Logit
PC	Parking Capacity
PnR	Park and Ride
PPA	Potential Path Area
PPS	Potential Path Space
PT	Public Transport
PTA	Public Transport Authority
ROM	Regional Operations Model
RPC	Remote Procedure Calls
RUM	Random Utility Models
SDR	Supply Demand Ratio
SOAP	Simple Object Access Protocol
STEM	Strategic Transport Evaluation Model

TIN	Triangulated Irregular Network
TOD	Transit Oriented Design
WnR	Walk and Ride

ABSTRACT

Accessibility, focusing on people's ability to access valued facilities or destinations based on current or planning infrastructure, has been of critical importance to physical planning over the past 60 years. Understanding and improving accessibility is a key aim for transport planning and policy worldwide. Accessibility could be measured through a plethora of concepts including freedom, opportunities, benefits and ease. Nevertheless, in the literature, for the concept of ease to reach the destination, there remains a lack of a methodology framework to understand, measure and model Park and Ride (PnR) users' accessibility to train stations from a spatial perspective, specifically including the characteristics of catchment areas, spatial boundary of catchment areas, and spatial and temporal modelling of accessibility to a train station.

Perth (Western Australia) is a low-density and high car ownership city with a long railway development history. In recent years, PnR has become a key ingredient to generating a high volume public transport train ridership, especially on newly constructed lines. This is because a well-developed railway PnR system makes rail service more comparable to door-to-door car travel, with increasing traffic congestion and increasing parking costs in the city centre. However, research addressing PnR in Perth is limited and what there is, is relatively ad-hoc.

The aim of this research is to provide a consistent and robust methodology for understanding and evaluating PnR users' accessibility to train stations over space and time in Perth. This methodology has four major components: Exploratory Data Analysis (EDA), catchment area modelling, macro spatial-temporal accessibility modelling and micro spatial-temporal accessibility modelling.

The EDA aims to understand station catchment areas and accessibility based on collected survey data. EDA consists of three components. Firstly, a novel spatial segmentation method is developed to understand the characteristics of the train station's catchment area and factors that affect the size and shape of the catchment area. Secondly, the shape of a station catchment area or the trip direction is investigated from centrality of the station, spatial integrity and trip frequency perspectives. Thirdly, a spatial analysis of elderly persons' accessibility to a train station is explored using a gravity based measure.

A modified Huff model and linear referencing are adopted to model the catchment area of train stations for PnR users. The model is validated by the Kappa coefficient (0.74) and overall accuracy (0.88) statistics (one means perfect agreement). This suggests that the model is robust for the train station catchment area delineation.

Macro accessibility modelling applies the Enhanced Three-step Variable Floating Catchment Area (E3SVFCA) measure to explore the accessibility improvements after the opening of a new train line (Mandurah line). E3SVFCA quantifies the potential demand based on the catchment area and station choice probability from the modified Huff model and improves the distance decay function by calibrating it to the journey to work data from ABS. There was a significant accessibility improvement along the new train line but the supply-demand ratio of train stations along the existing train lines decreased due to rapid demand growth. For example, the suburb of Success, near the Cockburn Central station accessibility increased from 0.000002 to 0.38 before and after the opening of the train line while the average supply-demand ratio of train station along the Joondalup line decreased from 0.59 in 2006 to 0.42 in 2011.

Micro accessibility modelling produces a dynamic accessibility measure based on TomTom® travel time information. A space-time accessibility continuum model is developed to derive the dynamic accessibility to train stations at any location at any time. Therefore, the system enables users to query accessibility to train stations in a space-time environment.

This research establishes a methodology for modelling the spatio-temporal pattern of PnR users' accessibility to train stations with useful framework and practical results. It can help transport policy makers and practitioners to better manage travel demand, understand accessibility variations over space and time and to design solutions aimed at increased accessibility to train stations.

CHAPTER 1 INTRODUCTION AND OUTLINE

1.1 INTRODUCTION

Accessibility, a concept that focuses on people's ability to access valued facilities or destinations via existing or planned transport infrastructure, has been of critical importance to transport planning over the past 60 years, since its first real definition and application by Hansen in 1959. Understanding and improving accessibility is a key aim for transport planners and policy makers.

Perth has a long railway history, dating back to 1881 when the first line, Fremantle-Perth-Guildford, was opened, followed soon afterward (1893) by the Armadale line

(PTA, 2014). After a hiatus of 100 years, the Joondalup line opened in 1992 followed by the most recent addition, the Mandurah line, on December 23, 2007 (PTA, 2009). The state government is currently planning a $2.2 billion Forrestfield-Airport link, due to open by 2020 (Probert, 2014). In the 2014-15 financial year the total number of train boardings was 64.2 million (PTA, 2015a). Thus, Railway transport constitutes a sizeable share of daily travel made by travellers in Perth. It is likely to play an increasingly important role in mitigating traffic congestion.

The transportation strategy developed for Perth in the 1950s assumed that mobility could be achieved by private vehicle usage (Curtis, 2012; Curtis & Mellor, 2011) and Perth now has the highest level of car ownership in Australia (Curtis & Mellor, 2011). As a consequence, traffic congestion, inequitable access to jobs and services, and increasing transport costs are becoming major transport problems in Perth. Park and Ride (PnR) first introduced in Oxford and Leicester in the 1960s (Cairns, 1998), is a travel mode that allows commuters to drive to public transport facilities, park and then transfer to public transport. It is considered to be "*the most important innovation in urban public transportation since the Second World War*" (Boyce et al., 1972) and is thought to be one of the key solutions to the existing transportation problems in low population density cities such as Perth. It marries the flexibility of the car with the efficiency of mass transit, thereby reducing congested car travel and minimising the parking cost, (i.e. avoiding CBD parking charges) for its users.

Although various applications of accessibility analysis have been developed since Hansen first introduced the issue of accessibility to spatial planning in 1959 (El-Geneidy & Levinson, 2006), research is limited into the assessment and modelling of PnR behaviour at a detailed level, especially from spatial and temporal perspectives. To this end, this study develops a consistent and robust for understanding PnR user accessibility to train stations from spatial and temporal perspectives, starting from simple exploratory analyses to more advanced spatial analyses to spatio-temporal modelling.

1.2 RESEARCH OBJECTIVES

The main aim of this project is to model accessibility to train stations for PnR users over space and time focusing on two main areas of study: 1) the catchment area of a train station, and 2) accessibility to train stations. This study will assist public transport planners, consultants and developers in understanding how PnR user catchment areas, latent demand and accessibility to train stations change over space and time, both quantitatively and qualitatively. It will also help decision making on accessibility improvements and the selection of new train station locations. Additionally, it will assist in answering such questions as: what is the dominant market segment(s) of the train station and where future marketing should be targeted, where to improve the existing train services to increase a train station's accessibility and where to locate a new train station to ensure equal access from all directions. The key project tasks to achieve these objectives are therefore:

Regarding the catchment area of a train station:

- (I): explore the characteristics of a station catchment area to better understand the factors that most influence catchment areas;
- (II): develop a model to investigate PnR user station choice behaviour and estimate the catchment area of train stations for PnR users;

Regarding accessibility to train stations:

- (III): identify the factors that affect accessibility to train stations for PnR users;
- (IV): develop a directional accessibility index and framework to understand the accessibility equality of different trip directions;

- (V): develop a composite accessibility measure to measure the elderly's accessibility to train stations.
- (VI): develop a model to examine the accessibility to train stations variations before and after the opening of the Mandurah line (macro accessibility modelling);
- (VII): develop a model to evaluate the dynamic accessibility to train stations over space and time (micro accessibility modelling).

1.3 RESEARCH SIGNIFICANCE

Evaluating accessibility to public transport is important for public transport planning, policy making, and social exclusion research. The significance of this research is in the development of a robust methodology to understand the PnR user accessibility to train stations in Perth over space and time that would result in a number of benefits including those below.

1.3.1 Social and community benefits

- Ability to understand commuter station choice behaviour in Perth which will contribute to improving the existing strategic transport models (STEM and ROM) ;
- Ability to reveal the dominant market segment(s) for more targeted marketing, better service provision and hence greater patronage;
- Ability to inform on and better understand Perth train station characteristics such as surrounding land use, parking supply and demand ratio and level of service and facilities;
- Ability to examine the latent PnR demand of train stations over time, especially the ability to quantify the potential change in demand at existing train stations when a new station is proposed nearby; and
- Providing scientific evidence to identify areas with poor accessibility to train stations and to assist in developing proposals to improve their accessibility.

1.3.2 Research contributions

In addition to the new framework to understand PnR user accessibility to train stations over space and time, other contributions of this research include:

- Extending the application of spatial analysis to accessibility to train stations by addressing the accessibility by different user groups (such as age/gender/travel mode) and different directions;
- Proposing novel methods of measuring accessibility from directional and land use distribution perspectives, (such as a train station centrality index and a land use spatial integrity index), which fill the gaps in existing accessibility measures literature;
- Developing a new framework for the automatic generation of high accuracy train station PnR catchment areas;
- Improving the Floating Catchment Area (FCA) based accessibility measure by quantifying demand more precisely and developing a more accurate distance decay function; and
- Proposing a space-time accessibility continuum with the ability to derive accessibility at any location and at any time.

1.4 RESEARCH METHODOLOGY

This study develops rigorous, realistic and easily computed accessibility modelling methods that examine PnR accessibility to train stations in Perth from spatial and temporal aspects. Initially, exploratory data analysis is undertaken on the data collected via an intercept survey to better understand PnR user travel behaviour and station catchment areas. Then, a model is developed, by modifying the Huff Model, to allocate PnR trips to train stations. Next, two models are developed to measure the spatio-temporal accessibility to train stations for PnR users from a geographic perspective at two levels: the macro and micro. The temporal resolution at the macro level is measured in census years (5 years) and represents changes in accessibility after major infrastructure construction (such as expansion of the rail network). Accessibility at the micro level focuses on the daily variations in accessibility, i.e. at a temporal resolution of minutes.

1.5 THESIS STRUCTURE

The structure of the thesis is illustrated in Figure 1.1. The thesis comprises ten chapters that present the key tasks as set out in Section 1.2. The catchment area tasks, (with relevant chapter), are shown in dark red dashed boxes and the accessibility tasks, (with relevant chapter), in blue dashed boxes.

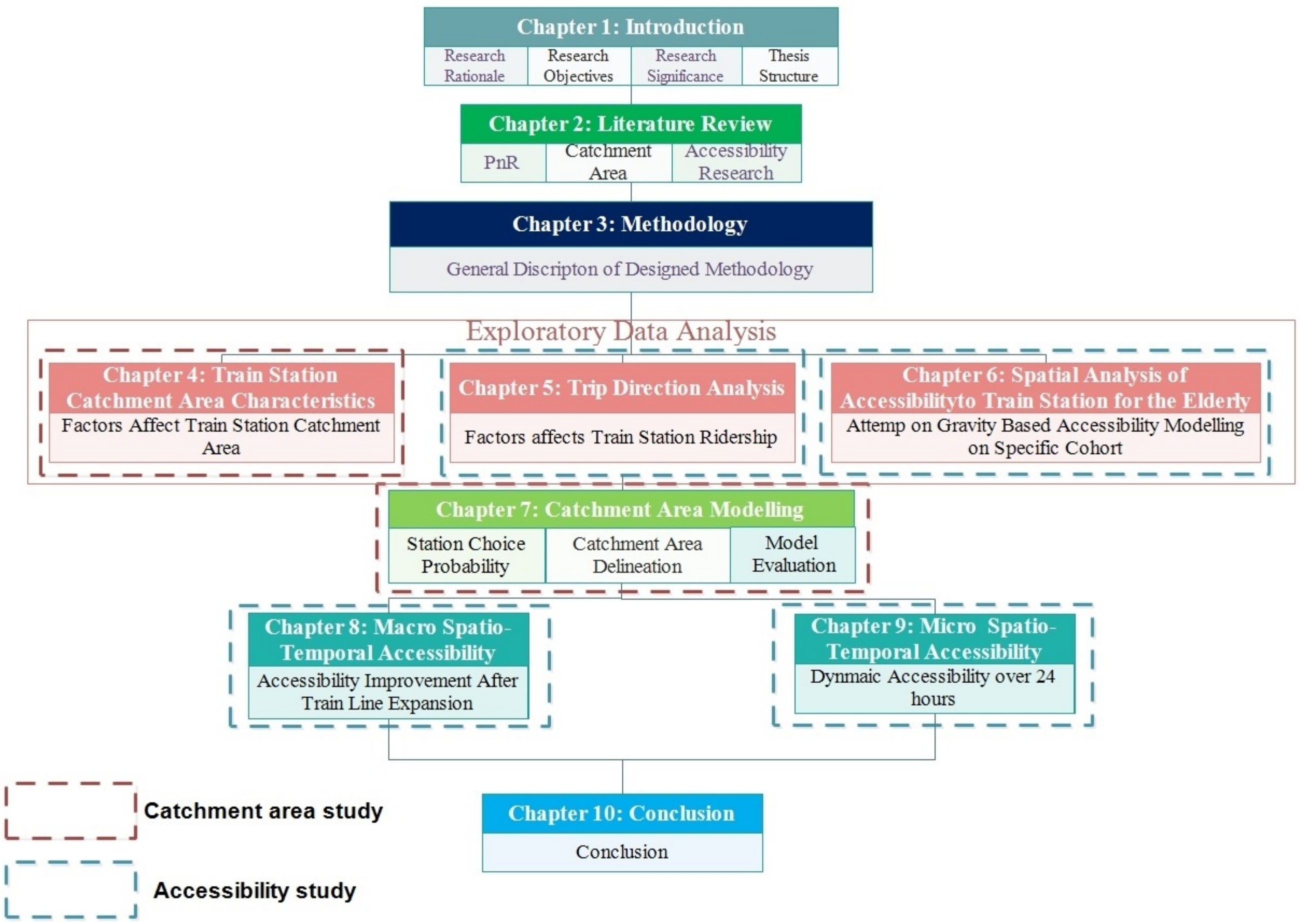

Figure 1.1 Research structure and relationship to the chapters of this thesis

Chapter 2 reviews the relevant literature on PnR facilities, train station catchment areas and the spatio-temporal modelling of accessibility. The history of PnR and its benefits are explored together with the factors that affect PnR user accessibility to train stations. Existing research on catchment areas, the methods for modelling the spatio-temporal accessibility to train stations at the macro and micro level and accessibility measures and modelling techniques are discussed.

Chapter 3 establishes and presents a theoretical framework for spatio-temporal accessibility modelling. The methodology for exploratory data analysis, catchment area modelling and spatial-temporal accessibility modelling are briefly discussed. Also included in this chapter are the required data and software for the implementation of the methodology.

Chapter 4 develops a process for exploring the characteristics of a train station catchment area through two attributes: area and shape. A novel spatial market segmentation method is proposed to help understand the main segment(s) of the train station users. Task I and part of Task III (see Section 1.2) are covered in this chapter.

Chapter 5 explores train ridership from a trip direction perspective, trying to understand directional accessibility based on trip directional distribution and also to identify the factors that affect train ridership spatially. Task IV is covered in this chapter.

Chapter 6 develops a composite measure to analyse elderly accessibility to a railway station in WA. The accessibility measure is categorised by three access modes, Walk and Ride (WnR), PnR and Bus and Ride (BnR). The result from the composite measure is validated based on the survey data. Part of Task III is covered in this chapter.

Chapter 7 develops a modified Huff model to generate train station catchment areas. From this model, the trip distribution and the probability of choosing the three nearest train stations are computed. Then based on the station choice probabilities, the origins are adjusted and the catchment area of train stations is generated. Task II is covered in this chapter.

Chapter 8 presents an enhanced three-step floating catchment area method to understand the spatial distribution of accessibility and the variations in accessibility before and after the opening of the Mandurah line. Task V is covered in this chapter.

Chapter 9 explores the variations of PnR accessibility to train stations over 24 hours. Actual travel time to train stations is extracted through TomTom® APIs. Space-time continuum theory is used to construct a seamless space-time model to examine the variations in train station accessibility throughout the day. Task VI is covered in this chapter.

The thesis concludes, in **Chapter 10**, with a summary of the major findings and limitations of the research in relation to the stated objectives and recommendations for the future research.

1.6 SUMMARY

This chapter has established the objectives and rationale of the research on spatial and temporal modelling of accessibility to train stations for PnR users and sets out the key tasks and thesis structure. The next chapter will review the literature relevant to PnR, catchment area, the factors related to accessibility for PnR users and accessibility modelling methods.

CHAPTER 2 LITERATURE REVIEW

2.1 INTRODUCTION

This chapter reviews previous research into the spatial and temporal modelling of PnR users' accessibility to train stations. This review identifies gaps in the research to date that will be addressed by this research. It begins with a review of the development of PnR travel schemes. Next, relevant research into catchment areas is discussed, including their definition, significance, related factors and modelling methods. Then definitions of accessibility, accessibility measures and factors affecting accessibility to train stations for PnR users are presented. Lastly, the literature on modelling accessibility over space and time is discussed.

2.2 RESEARCH ON PNR

2.2.1 A short review of PnR

PnR stems from the well-known problems caused by the prevalence of private vehicles in the second half of the 20th century, such as traffic congestion, parking scarcity in central areas and adverse impacts on pedestrians and walkability. It is obvious that the root of the problem is the high number of vehicles trying to enter central areas that are usually quite limited in size. The idea of PnR was developed to decrease the number of vehicles entering those central areas. PnR encourages motorists to undertake their journeys in two parts (Cairns, 1998): firstly, driving to a car park adjacent to a transit station and then taking public transport into the central area. It combines the flexibility of the private car for travelling in low density areas with the efficiency of public transport to move large numbers of people into central areas (Cairns, 1998).

PnR originated in England with the first services being bus-based. Leicester was the first city to implement PnR in the 1960s, with the aims of reducing car traffic, increasing economic development and as a traffic management measure (RPS, 2009). Oxford and Nottingham operated similar services from the 1970s onwards and then a few other cities (such as Bath and Chester) followed in the 1980s. The existing Oxford PnR scheme has been running for 43 years and is the oldest continuously operating service in the UK (Meek, Ison, & Enoch, 2008; Parkhurst, 1995). The prevalence of PnR began in the 1990s, evolving from historic cities to a range of urban areas and from UK to worldwide (Meek, Ison, & Enoch, 2009). The rapid and widespread expansion of PnR was due to the evidence of their success coming from the cities that were operating PnR. The benefits of PnR can be summarised as (Karamychev & van Reeven, 2011; Mingardo, 2013; Parkhurst, 1995; RPS, 2009):

- Reducing the number of motorists using the urban road network which provides local congestion relief and a reduction in energy consumption and air pollution in central areas;
- Increasing the overall supply of available parking spaces (by reducing parking demand in the city and relocating PnR parking outside) which increases the accessibility of the city centre;
- More economically beneficial land use development in the city centre as less land and lower expenditure are required for parking. Most of the parking is relocated outside, where land is usually cheaper;
- Improving the suburban development; and
- Providing an efficient and less stressful travel mode that encourages public transport ridership.

However, opposition to PnR started to appear in the mid 90s (around 1994) (Meek et al., 2008). PnR schemes were criticised as inappropriete for the 21st century as their disadvantages were beginning to be recognized. Mingardo (2013) listed the evidence of unintended negative effects of PnR schemes across four countries in Europe (UK, Netherland, Germany, Switzerland), and in the USA. The main concerns included (Karamychev & Van Reeven, 2011):

- Free parking in suburban areas acts as a subsidy to car drivers and makes car use much more attractive, by removing or reducing the cost and stress of parking in city and town centres;
- PnR tends to encourage commuters to use a private vehicle for part of their journey which might not reduce the total traffic level;
- Vehicle miles and atmospheric pollution may increase overall. This is because of the externalities of increasing car usage due to the benefits and efficiency PnR

brings to the individual compared with using public transport for the whole trip; and

- PnR simply redistributes the traffic and increases the social exclusion of those without access to a car.

In addition, with respect to urban and TOD (Transit Oriented Design) development, it is said that PnR can act as a deterrent to building medium density mixed land-use settlements around these transport nodes (Cervero et al., 1995; Curtis, 2008). A principle of TOD development is that the catchment zone has medium to high density residential lots and that most of these lots are within walk or cycle distance of the major transport node, with well-routed feeder buses servicing the outer regions of the zone (Olaru et al., 2014) . The success of a TOD is usually evaluated using the 5Ds – Distance, Density, Diversity, Design and Destination accessibility (Cervero & Murakami, 2008). However, PnR may adversely impact on these 5Ds (Duncan & Christensen, 2013):

- It uses the scarce land adjacent to the transport node for parking facilities which reduces the land available for TOD and impacts on its design;
- Parking lots make for poor pedestrian environments; and
- PnR weakens the economic incentives for concentrated development.

In providing an overview of the development of PnR, Meek et al. (2008) summarized the development of PnR into four phases: emergence phase, national awareness phase, promotion phase and cautionary development phase. Although the recognition of PnR were not all positive, PnR did play an important role in transport policy, planning and management (Meek et al., 2008). It was unclear whether other transport schemes could provide a service as efficient and flexible as PnR and it was only through PnR that mass rapid transport was feasible in the outer suburban areas (Martinovich, 2008; Meek et al., 2008).

Perth (Western Australia) is a low-density city with high car ownership (around 723 vehicles per 1,000 people) (Curtis, 2008). It makes the delivery of a high-frequency public transport system very challenging. Perth's transport plan since the 1950s has a key assumption that the personal mobility in Perth could be achieved by private car usage (Curtis, 2012; Curtis & Mellor, 2011). Promoting private car usage causes a lot of major transport problems in Perth, such as traffic congestion, inequitable access to transport and services and increasing transport. Those problems will continue to worsen due to its high population growth rate. It is estimated that 2.2 million people will live in Perth and Peel by 2031 (Department of Planning, 2010).

A shift from car-dependent development to public transport dependent development transport policy is the direction required. Due to the high construction costs for infrastructure, there is a need to optimise the efficiency of the current system (Beyer, 2008). Perth has a long history of rail, dating back to 1881 when the Fremantle-Perth-Guildford line was first opened. Train services, recognised as safe, reliable and comfortable, have been adopted by the public as the preferred way to travel especially by those who work in the CBD. In Perth, the central objective of the new railways design was to be able to compete with the car in terms of travel time to the Perth CBD and therefore the new railway lines, (i.e. excluding the heritage lines), are primarily in the freeway median. To this end, PnR has been introduced in Perth to encourage public transport usage and thereby alleviate the accessibility problems to Perth city centre (Curtis, 2008).

2.2.2 PnR research in the literature

Over the last two decades there has been a large amount of research into PnR, originally in England where PnR started, then spreading around the world as PnR schemes themselves have spread. In summary, the research can be divided into two groups (Holguı´n-Veras et al., 2012; Mingardo, 2013):

- Policy design guidelines, implementation and effects of PnR schemes; and
- Computational techniques to analyse and model PnR facilities.

Policy design guidelines, implementation and effects of PnR schemes

There is a large body of research on PnR scheme guidelines to guide the planning and design of park-and-ride facilities. For example, Bolger, Colquhuon, and Morrall (1992) developed planning guidelines for LRT park-and-ride facilities, including location criteria, access and egress considerations and the number and location of parking bays. Spillar (1997) focused on the assimilation of reliable methods for selecting optimum locations for PnR facilities in terms of maximising demand and promoting community integration. AASHTO (2004) provided a detailed guide for the design and planning of PnR facilities, including how to design the facilities, the planning process and how to operate and maintain the facilities. Unfortunately, there is no real consensus over these design guidelines (Holguı´n-Veras et al., 2012). Take the location of PnR facilities as an example. Cox (1982) suggested that PnR facilities should be located on the perimeter of the area of major congestion but not less than four miles from the CBD. Other researchers suggested a distance of around 10 miles (Burns, 1979; Fradd & Duff, 1998).

There is also plenty of research examining existing PnR schemes. For example, Dickins (1991) examined the performance of 25 cities in Europe and North America to check the effects of PnR schemes with significant increase to LRT patrons. He also examined the locations of the PnR facilities and found that most of those PnR facilities were not in the best locations. Cairns (1998) reviewed the current PnR schemes in Scotland and uncovered similar issues. Karamychev and Van Reeven (2011) analyzed the overall impact of PnR on total car traffic and welfare. Bos et al. (2004) used a hierarchical information integration method to evaluated the attributes of PnR facilities in Nijmegen, (in The Netherlands).

Literature on the effects of PnR schemes includes, (to name a few) the following. Parkhurst (1995) discussed the effects of PnR on the level of car traffic. Mingardo (2013) conducted a survey at nine rail-based PnRs located around the cities of Rotterdam and The Hague, (The Netherlands), to review the unintended effects of PnR identified in previous literature and also to identify any additional effects, such as ‘transfer from bike or bike and ride to PnR’ and ‘park and walk users’.

Computational techniques for PnR services and facilities analysis and modelling

A number of researchers have studied PnR locations and facilities using computational techniques. For example, Horner used a flexible GIS model to determine the potential locations of PnR facilities (Horner and Grubesic, 2001; Horner and Groves, 2007) and Farhan developed a method for delineating market areas for PnR facilities and a multi-objective spatial model to site PnR facilities (Farhan & Murray, 2005, 2008). Duncan and Christensen (2013) used a logit model to predict the presence of parking at LRT stations in the US. It was found that parking facilities occur much more frequently in lower density environments where the land is cheap and available and are also related to the characteristic of the municipality where the station is located. Wang et al. (2004) developed a numerical model to illustrate how to choose the location for the PnR facilities according to profit maximization and social cost minimization objectives. Liu et al. (2009) proposed a deterministic continuum equilibrium model to characterize commuters' mode choices and PnR transfer behaviours along a travel corridor where PnR is competing with the highway system.

In comparison with the wealth of research in Europe and the USA, there is limited PnR research in Australia. Hamer (2010) carried out a survey at selected stations on the Victorian metropolitan and regional rail networks to identify the extent of mode shift from car-only to more sustainable transport modes by developing an efficient PnR system. Wiseman et al. (2012) captured the travel behaviour changes facilitated by the newly established PnR facilties situated on the fringe of Adelaide's CBD. It was found that the new facilities encouraged commuters to transfer from using public transport for the whole trip to a car-mass transit combination. Curtis (2008) reported the efforts and history of Perth's planning policies and strategies on TOD development. She discussed the opportunities and constraints presented by each travel model, including PnR, WnR and BnR. Olaru et al. (2014) examined the attitudes of PnR travellers and Z. Chen (2014) developed location based departure station choice services for PnR users using a case study in Perth. Shao et al. (2015) used logistic regression models to analyse the nearest train station choice in Perth. Lin et al. (2016) and Ryan et al (2016) focused on the level of accessibility to train stations for the "elderly" cohort and the differences between age groups (young, middle aged and elderly) for all travel modes.

From the present PnR literature, there is limited research on the impacts of PnR in Australia, particularly from both spatial and temporal perspectives simultaneously. Hence, this research will focus on this research gap.

2.3 RESEARCH ON CATCHMENT AREAS

2.3.1 What is a catchment area and why is it important

The term catchment area comes originally from the field of hydrology. It is the area that drains into a particular river or body of water and is also called the catchment basin. It is defined by a number of factors including topography, land use, vegetation coverage, soil types and bedrock types (Wagener et al., 2007). The idea of a catchment basin is useful, as it is the standard landscape functioning unit. Inside the catchment area, all elements (e.g. water, soil, plants and animals) are linked together. In Catastrophology, (the study of catastrophes), the catchment area is one of the most important factors determining the chance and level of flooding.

Human geography and other disciplines borrowed the idea of the catchment area from hydrology as it is vital to the understanding of latent demand (potential customers) (Banister, 1980), market share (the portion of a market) (Lee & Masao, 1988, p. 17-19) and accessibility (ability to reach) (El-Geneidy & Levinson, 2006). In these disciplines, the catchment area is defined as the area from which a service attracts the users of that service (such as water, transport, school, health or energy). For example, a school catchment area is the geographic area to intake the student and a retail catchment area is the geographical extent of its customers (Bhatia, 2008).

Catchment area studies have been conducted for many different purposes. For example, during the retail location selection process, the retailers are usually faced with the problem of determining the area they wish to move into and from that where to best locate their new store within that area. The retail catchment area is useful in establishing the profiles of populations and to analyse customers' lifestyles and shopping behaviour, for clustering analysis and market forecasting. It helps the retailers get a better understanding of the area that they plan to serve. For a health facility or service, defining a catchment area for a cancer centre, for example, allows the centre to determine its primary patient population and to assess its performance (Wang & Wheeler, 2015). Governments and community service organizations often define catchment areas to ensure universal access to services like emergency departments, police offices and hospitals. For the academic, catchment areas are more related to market share or latent demand estimation, new store/facility location selection (Bhatia, 2008; Goodchild, 1984), or gravity model based accessibility analysis (Delamater, 2013; Langford, Higgs, & Fry, 2012; Luo, 2004; Ngamini Ngui & Vanasse, 2012; Wan, Zou, & Sternberg, 2012).

Catchment area research is vital to PnR transport studies because it is used to investigate the potential number of travellers to the station as well as market share and station choice (Anersen & Landex, 2009). However, literature is limited due to the lack of useful data (Lieshout, 2012). The majority of the research focuses on threshold research such as the walking distance to the Light-Rail Transit Stations (O'Sullivan & Morrall, 1996), whether the half mile catchment area is or isn’t representative in the UK (Guerra, Cervero, & Tischler, 2012), catchment area delineation method comparison (Holguı´n-Veras et al., 2012; Landex & Hansen, 2006) (Section 2.3.2), or the train ridership related factor analysis with indirect indication of catchment area analysis (Section 2.2.3).

2.3.2 The measurement of catchment areas

Measurement of catchment areas in transport

Methods to measure the catchment or service area of a transit stop have been developed since the 1970s (El-Geneidy et al., 2014; Guti & Garc, 2008; Hsiao et al., 1997; Neilson & Fowler, 1972; O'Neill, Ramsey, & Chou, 1992; Zhao et al., 2003) . Four types of methods have been identified:

The first is a simple buffer method, which uses a circular buffer with a radius equal to the travel distance or time. For example, circles of 400 or 800 m radius, (or 5 or 10 minutes), can be used to define the walk catchment of a transit stop. However, this method was criticised for not taking the geographical surroundings into account and only considering the Euclidean distance, i.e. ignoring indirect paths, obstructions, or breaks in the network (Upchurch et al., 2004). Zhao et al. (2003) developed distance decay functions to estimate pedestrian accessibility to transit stops at the home end and discovered that half a mile or 800 m walk distances were acceptable. This distance has been widely accepted as the walk catchment area to transit stations. However, according to El-Geneidy et al. (2014), the 800 m distance underestimates the catchment area. Based on their study in the Montreal region, they found 85th percentile walk distances of 1,219 m and 1,095 m measured from/to the origin and the destination respectively. This could mean that the catchment area varies depending on the location of the station or characteristics of individuals. For example, O'Sullivan and Morrall (1996) identified that average walking distances to a light-rail transit station in a suburb, (648 m with a 75th-percentile distance of 840 m), is larger than to one in the central business district, (326 m with a 75th-percentile distance of 419 m).

The second method type is a transport network based service area, which uses travel time, (e.g. 5, 10, or 15 minutes travel time), to define the service area by travel modes, based on the surrounding transport networks (Landex & Hansen, 2009). The network based service area avoids the inherent problem of the simple circular buffer. The shape of the calculated service area accounts for the transport network and surrounding land use. However, the populated catchment area does not consider the effect of the facility itself and it also has the same threshold problem as the simple buffer method, (i.e. the difficulty in defining boundaries for generating service areas).

The third method type is based on geocoded trip surveys. Travel data are analysed first and then the boundary is delineated based on the convex hull, using various administrative boundaries (Durr, Graham, & Eady, 2010). Usually, only 90% of the survey data are used in order to exclude the effect of outliers (Durr et al., 2010; Irvine, 2011). The trip survey based catchment area method has three steps: geocoding the trip data; excluding outliers, (10% most extreme data); and delineating the catchment area. The travel surveys collect the origins and destinations of trips, as well as the time and cost of each trip. The location may be given as an address that needs to be geocoded into an appropriate geo-coordinate system, for example, latitude and longitude. More recently, with the aid of GPS technologies, this geocoding process has become automated. As the catchment area is determined by the survey data, the representativeness of the sample is crucial, a sample of limited size potentially not revealing the real boundary of the catchment area.

The fourth method type is based on transport modelling. As the catchment area is determined by the passengers' choice, efforts have been made to define catchment area using transport modelling, although the literature to date on this is limited. Lieshout (2012) presented a methodology to estimate the size of an airport's catchment area and its market shares based on a MNL airport choice model. Holguı´n-Veras et al. (2012) proposed an analytical formulation to estimate the parabolic catchment areas of PnR facilities. Farhan and Murray (2005) delineated catchment areas using three methods: parabolic approach, travel cost approach and accessibility approach. These three approaches were all implemented through the PnR facilities choice process. It was concluded that the use of a parabolic shape to determine PnR catchment areas performed worse than the other two methods and that the traditional parabolic shape PnR catchment area method needs further improvement.

Measurement of catchment area in other disciplines

As described above, the concept of catchment areas comes from physical geography, but is broadly applied in human geography, especially in retail. In this section, methods used to measure retail catchment areas are thoroughly reviewed, providing useful insights into how to measure train station catchments. The methods include (Bhatia, 2008, p. 194-200):

- Customer spotting

This method is based on shopper surveys, either using surveyors to ask the questions or self-filled-in questionnaires. Alternatively, an analysis could be made of customer bank card details, for those paying by card, where this information can be accessed, (confidential issues permitting). Through geocoding, the home locations of customers can be plotted on a map and the boundary of the catchment area determined. The spotting map is usually analysed using a concentric zones approach (Sullivan & Adcock, 2002). Three bands (or zones) are identified that comprise a range of visit probabilities; high (primary zone), medium (secondary-zone) and low (tertiary-zone). Typically, around 60% of customers come from the primary zone, 25% from the secondary zone and 15% from the tertiary zone.

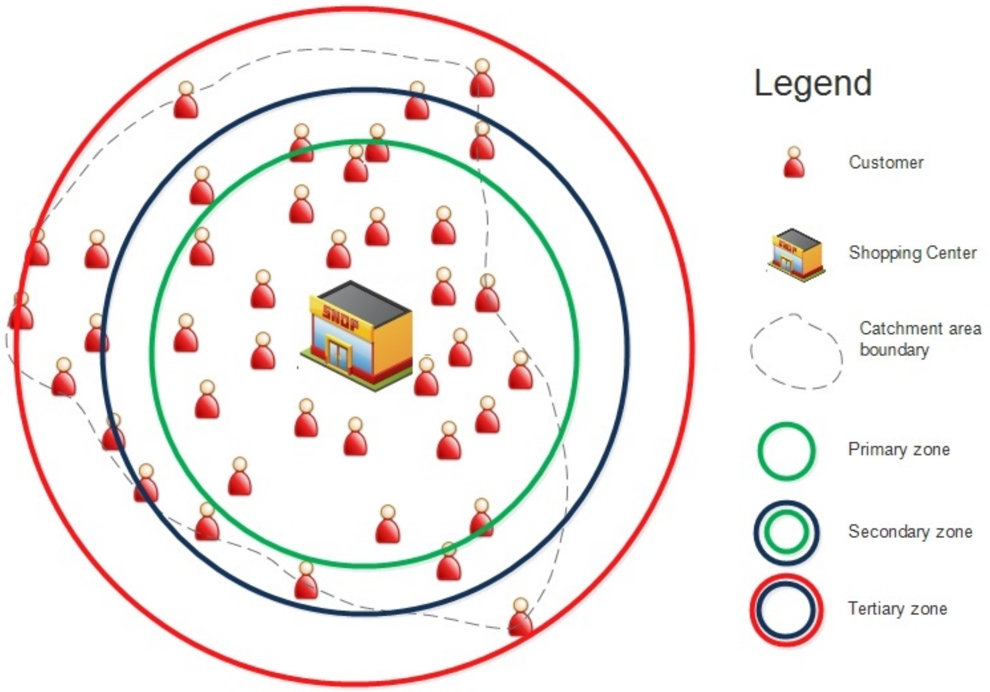

Figure 2.1 Customer spotting (adapted from Dunne, Lusch, & Carver, 2013)

- The Law of Retail Gravitation

The 'Law of Retail Gravitation' was originally developed by William Reilly in 1925. It is a gravity based model that measures the pulling power of competing locations, and its influence on the customers inside the boundaries. Figure 2.2 shows an example of applying Reilly's law to define the catchment area. The catchment area is defined by the breaking point of two centres. The breaking point formula is (Sullivan & Adcock, 2002):

$$B_{ij} = \frac{D_{ij}}{1+\sqrt{P_j / P_i}} \qquad \text{2-1}$$

Where:

B_{ij} is the location of the breaking point from centre *i* to center *j* ;

D_{ij} is the distance of the breaking point from centre *i* to center *j*;

P_i is the size of centre *i*; and

P_j is the size of centre *j*.

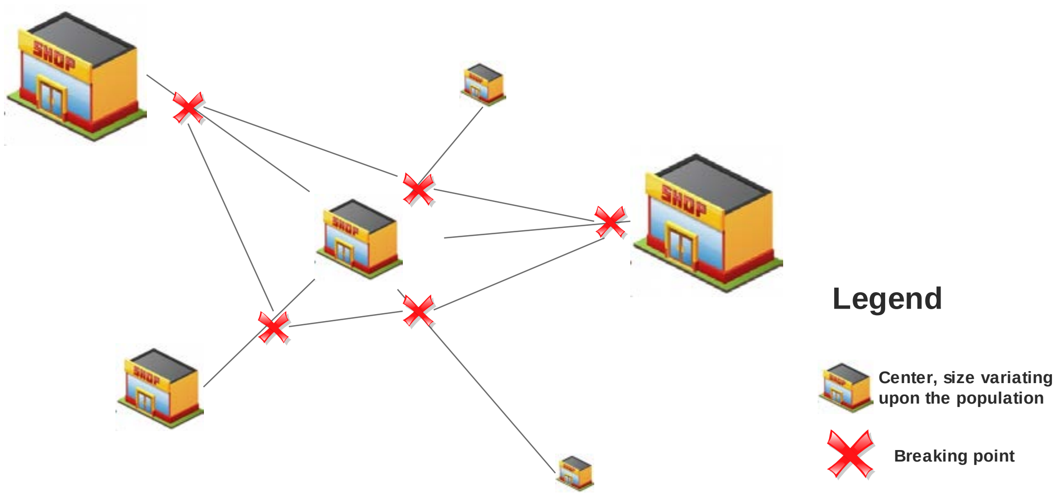

Figure 2.2 Example of Reilly's law (adapted from Sullivan & Adcock, 2002, p. 103)

- Huff's probability model

Similar to Reilly's model, this also can be used to define a store's trading or catchment area. However, the pulling power in Huff's model depends on store size, distance and the types of product on sale and it outputs the probability of a customer visiting the store. The catchment area from Huff's model is also defined by probability. The formula is (Huff, 1963):

$$P_{ij} = \frac{S_j / T_{ij}^b}{\sum_{j=1}^{n} S_j / T_{ij}^b} \qquad 2\text{-}2$$

Where

P_{ij} is the probability of a customer at given point of origin *i* travelling to a particular shopping centre *j*;

S_j is the size of shopping centre *j*;

T_{ij} is the travel time of a customer at given point of origin *i* travelling to a particular shopping centre *j*; and

b is exponent that reflects the effect of the travel cost.

Figure 2.3(a) shows the probability to visit store1 with the influence of nearby store 2 and store 3 and its distance to store2 from Huff model. Figure 2.3(b) shows the market areas from Huff model.

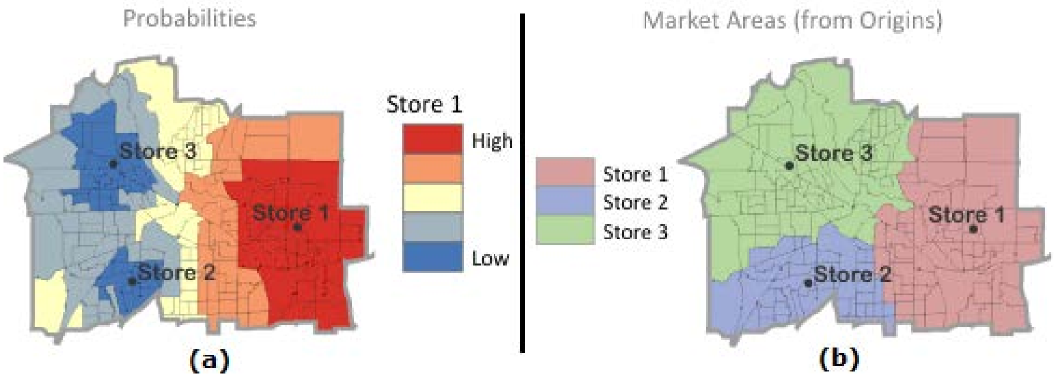

Figure 2.3 Example of market share from Huff model (adapted from Flater, 2010)

2.3.3 Factors that affect train station catchment areas

Cervero et al. (1995) found that catchment areas were not "*simple, tidy concentric patterns*" but could be diverse shapes affected by natural features, property developments and zoning. Bolger et al. (1992) identified that the size and shape of catchment areas varied depending on station spacing and the road network of its adjacent station. The characteristics of a train station, such as train frequency, location, parking supply and surrounding land uses, can also affect the size and shape of a station catchment area. Stations with higher train frequencies were found to be preferred by commuters and more likely to have larger catchment areas than those with lower train frequencies (Debrezion, Pels, & Rietveld, 2009; Sanko & Shoji, 2009).

Similarly, parking capacity was identified as a strong determinant of travel mode to stations, which can affect the catchment area. For example, Cervero et al. (1995) found that car use was the main access mode for stations that have large parking areas, homogenous land use mixes and low residential densities. Debrezion et al. (2009) and Duncan and Christensen (2013) also discovered that the presence of car parking encouraged commuters to drive to the station, especially those who did not live near the station. Furthermore, in the literature, terminal stations were found to have larger catchment areas than stations along a train line.

The potential demand is higher at stations located in the intermediate areas than at the most central and peripheral stations (García-Palomares, Gutiérrez, & Cardozo, 2013). In addition, mixed land use and more functional and aesthetic features around transit stations were proven to encourage transit use and walking to transit stations (Cervero et al., 1995; Etman et al., 2014; Frank & Pivo, 1994; Stead & Marshall, 2001; Zhao et al., 2003). Cervero et al. (1995) examined the influence of the built environment on variations in both modes of access and catchment area sizes and concluded that suburban walk catchment sizes tended to be 8 to 10 times larger than those of downtown station areas and 3 to 4 times larger than those of urbanized areas. Street and transit network characteristics, such as street intersection density, train availability, location and transit mode (train vs. bus) were found to affect bicycle access distances (Hochmair, 2015). For example, higher street intersection density was shown to result in shorter bicycle access distances, while a higher percentage of dead ends was found to relate to longer bicycle access distances (Hochmair, 2015).

2.3.4 Conclusions on the catchment area literature review

Catchment areas are important for planning, service assessment, market share, latent demand estimation and new store/facility location selection. In the literature, the catchment areas are usually depicted in a rather simplistic manner although some more advanced modelling methods have recently emerged. The traditional PnR catchment area is based on a parabolic shape assumption, but better methods are being identified and developed to describe the catchment area of PnR facilities. Catchment areas could take diverse shapes affected by natural features, property developments, zoning, parking capacity, location of train station and surrounding land use (Cervero et al., 1995; Debrezion et al., 2009; Sanko & Shoji, 2009). They also vary with the characteristics of the station and services or even the characteristics of individuals. Research is needed to define catchment areas from a more comprehensive point of view and to suggest methods that can capture catchment areas more rigorously and effectively, by considering a variety of factors.

2.4 ACCESSIBILITY

2.4.1 Definition of accessibility

The term accessibility was firstly used by Hansen (1959) in his classic and much cited paper “How Accessibility Shapes Land Use”. Since then, accessibility has been widely used in various disciplines, such as transportation, road engineering, geography, urban economics, pedestrian planning, social planning, civil engineering and even information technology. Accessibility is a composite word, combining the two words "access" and "ability". It means the quality of being able to approach or reach some places or something literally. Gould (1969) noted, "*accessibility … is a slippery notion… one of those common terms which everyone uses until faced with the problem of defining and measuring it*". It has been defined from many different angles (See Table 2.1). In this section, a review of the notions of accessibility in research related areas is provided and then a working definition of accessibility as used in this paper is given.

Table 2.1 Samples of accessibility definition

Author	Definition
Hansen (1959)	The potential opportunities for interaction.
Dalvi and Martin (1976)	The ease of reaching activities via a particular transport system.
Burns (1979)	The freedom of an individual to decide whether or not to participate in different activities
Ben-Akiva and Lerman (1985)	The benefits provided by a transportation/land use system
Jones (1981)	The ease of reaching opportunities.
Bhat et al. (2000)	The ease of an individual to pursue an activity of a desired type, at a desired location, by a desired mode, and at a desired time.
Ross (2000)	The ease of reaching the destination, and may include real or perceived costs in terms of time or money, or distances travelled, level of comfort or any combination of these.
Geurs and Van Eck (2001)	The extent to which the land use – transport system enables (groups of) individuals or goods to reach activities or destinations by means of a (combination of) transport modes(s).
Bertolini, Le Clercq, and Kapoen (2005)	The amount and diversity of places that can be reached within a given travel time and/or cost.
Litman (2012)	The ability to reach desired goods, services, activities and destinations which together are called opportunities.
Weibull (1980)	A measure of an individual's freedom to participate in activities in the environment.

Transportation

Accessibility research is popular in the transportation area as accessibility is the ultimate goal of any transportation system and plays a crucial role in mainstream transport planning and policy making.

In the transportation field, accessibility mainly focuses on the ease of reaching destinations or the ease of a destination being reached, based on the existing and/or potential future transport systems. Accessibility has often been confused with mobility, (El-Geneidy & Levinson, 2006; Halden, Jones, & Wixey, 2005; Hansen, 1959; Litman, 2012), but they are, in reality, different concepts. Mobility is concerned with the performance of transport systems and is measured in terms of the resources and characteristics of travellers or by the behaviour of these travellers (e.g. car ownership or physical disabilities, travelled distance, and travel speed). Accessibility adds the interplay of other components of transport systems, (such as services and facilities quality and land use patterns), as a further layer of analysis. Hansen (1959) characterised mobility as the potential for movement, while accessibility is the potential for interaction. Therefore, mobility refers to the ability to move, while accessibility refers to the ability to reach.

Geography

In the fields of geography, accessibility usually refers to the relative ease of reaching a particular location or area (Litman, 2012). This definition emphasizes "relative ease" which implies differences between spatial locations. Affected by "Tobler's first law of geography" which is "*Everything is related to everything else, but near things are more related than distant things*", accessibility in this area is mostly explained by the gravity model. Therefore, the "ease" is determined by the opportunities in the area, such as the spatial distribution of potential attractions, quality, magnitude and the attractiveness of activities and the cost to reach the area, such as distance to the area.

Planning

In general, the aim of planning is to allocate resources with the goal of optimising the balance between supply and demand, which makes those resources accessible to everyone. It emphasizes demand patterns and predicts user responses to policy and management options (Wu & Miller, 2001). Therefore, in this area, accessibility is defined as "*people's ability to use services and opportunities*" (Litman, 2012) and is a function of the relationship between supply and demand. Land use planning concentrates on supplying the required land use types to satisfy the projected demand, for example, a new shopping centre to serve the nearby new residential area's shopping demand. Accessibility in land use planning generally focuses on geographic accessibility (Litman, 2012). In transportation planning, the focus is to construct new facilities to satisfy the increasing travel demand, allowing people to move from one area to the other. Therefore, it mainly focuses on mobility and this is one of the reasons why the concepts of mobility and accessibility are often confused. However, it is highlighted in the literature by Litman (2012) that transportation planning should be evaluated using accessibility, which will deliver a more practical and robust planning outcome. As demand is determined by the characteristics of people and place, (e.g. age, gender, mobility, country, metropolitan), accessibility could be expressed according to the characteristics of these groups, for example, "elderly" accessibility, "disadvantaged groups" accessibility, or accessibility to "someplace in the metropolitan area".

A working definition of accessibility to train stations

The review of the definitions of accessibility in the above three related areas, has identified that accessibility definitions have four key components. These were first proposed by (Genurs & Van Wee, 2004), and are:

- Land use component, which reflects the availability of the opportunities;
- Transportation component, which describes the transport ability of the transport system;
- Temporal component, which reflects the temporal constraints; and
- Individual component, which describes the characteristics of individuals or groups of similar individuals.

This research concentrates on access to train stations by car. Hence, the working definition of accessibility adopted in this research is: **the relative ease of reaching train stations by PnR travel mode**.

The concept of "ease" here has two components:

- Attractiveness in terms of the level of services and facilities provided and surrounding opportunities; and
- Cost in terms of moving around in the transport system, such as time, distance and vehicle operating costs.

2.4.2 Factors that affect accessibility to train stations

Usually, when dealing with factors that influence accessibility, people tend to think of proximity (i.e., distance from point A to point B) in the first instance. However, a Dutch railway survey, for example, identified that less than half of the passengers chose the nearest station when using the train (Debrezion, Pels, & Rietveld, 2007). This indicates that distance is important but is clearly not the only factor. From a cross-section of the literature, a more extensive list of potential factors is provided in Table 2.2. Surveys are the most common methods to understand those potential factors. For example, C. Chen et al. (2014) utilized intercept questionnaire survey to investigate PnR users station choice uncertainty. Foote (2000) and Syed, Golub, and Deakin (2009) used license plate survey to determine how parking fees will affect PnR ridership and also to determine the sample of future survey.

In summary, variables affecting accessibility to train stations can be categorised into three types: 1) user- specific variables, such as affordability (Halden et al., 2005), mobility (Hess, 2009), time, budget and other general individual needs or purposes (Geurs & Van Wee, 2004). For example, a commuter might choose a transit station along the way towards their destination instead of using the nearest station in order to save ticket fares on trains (Jansson & Angell, 2012; Shao et al., 2015); 2) station-specific variables such as service and facility quality (Debrezion et al., 2009; Litman, 2011), surrounding land use (Geurs & Van Wee, 2004; Levinson, 1998) and intermodal connectivity (Moniruzzaman and Páez,2012); and 3) travel-specific variables such as travel time, distance, cost, travel reliability (Hensher & Stopher, 1979; Scheurer & Curtis, 2007), time of day (Halden, 2011) and road network connectivity (Geurs & Van Wee, 2004; Scheurer & Curtis, 2007). For accessibility by PnR specifically, only limited literature could be found. Nevertheless, the three types of factors described above appear to apply to PnR as well.

Table 2.2 Factors that influence accessibility (from literature review)

Location of Study	**Focus of Study**	**Factors**	**Author**
Australia	Urban and Regional Planning	distance, travel time, travel cost, service quality, opportunities, travel purpose, network	Scheurer and Curtis (2007)
	Urban Study	public transport supply and usage, population and dwelling density, amenity and functionality of the transit city	Scheurer, Mayes, and Raimondo (2008)
Worldwide	Land-use and Transport	land-use, transportation (e.g. travel time, travel cost, travel reliability/comfortable), temporal (time variation), and individual (e.g. personal needs)	Genurs and Van Wee (2004)
	Transport planning	time factors (journey times, time budgets), cost factors (transport fare, affordability), reliability (uncertainty about journey time), security/safety, quality, comfort/stress, Information	Halden (2011)
	Transportation Planning	transit service quality	Litman (2011)
	Transportation Planning	transportation demand, mobility, quantity and quality of transport modes and services, user information, integration, parking, affordability, land-use, network connectivity	Litman (2012)
	Railway accessibility	services quality	Debrezion et al. (2009)
	Transit accessibility	demographic and socio-economic characteristics of travellers, levels of service, land use, intermodal connectivity	Moniruzzaman and Páez (2012)

2.4.3 Accessibility measures

A large number of measures of accessibility have been proposed since Hansen first introduced the idea of accessibility to spatial planning in 1959 (El-Geneidy & Levinson, 2006; Taylor, Sekhar, & Este, 2006). Accessibility measures have been reviewed by others (Baradaran & Ramjerdi, 2001; Geurs & Van Wee, 2004; Miller, 1999; Scheurer & Curtis, 2007). There are also many ways to organise the measurement categories. For example, Miller (1999) divided the measures into three main categories: attractiveness accessibility measures, utility accessibility measures and constraint based accessibility measures. Geurs and Van Wee (2004) categorised the measures into infrastructure-based measures, location-based measures, person-based measures and utility-based measures. In this research, the Scheurer and Curtis (2007) and El-Geneidy and Levinson (2006) approach has been adopted and then extended further.

Spatial Separation Measures

This class of metrics focuses on the travel impediment or resistance, which can be measured in various ways, for example, travel distance and travel time (Scheurer & Curtis, 2007). It is a very widely accepted method, which may be attributed to the reasons that: 1) it only takes geographic spatial separation into account thereby excluding other considerations such as socio-economic status, traveller's behaviour differences and location differences (Baradaran & Ramjerdi, 2001); 2) its methodology is conceptually clear as it only measures the travel impediment or resistance; and 3) it is relatively stable over time. ABS (Australian Bureau of Statistics) used Metro ARIA (Metropolitan Accessibility/Remoteness Index of Australia) as an accessibility index. It is a continuously varying index with values ranging from 0 (high accessibility) to 15 (high remoteness). It combines remoteness derived from measures of road distances between populated localities and service centres (education, health, shopping, public transport, and financial/postal services) (APMRC, 2013). Similarly, Bhat et al. (2000) used the physical distance between infrastructure elements as input and Haugen (2012) used the proximity and distance as straightforward representations of the physical spatial separation between locations. In the literature, there are two types of distance: 1) the Euclidean distance; and 2) the network distance. The measure of distance is always GIS based and the network distance is much more precise if a road network is available. Travel time and generalised travel costs have also been used as travel impedances, depending on the research aims (El-Geneidy & Levinson, 2006). A simple functional form for this class of measure is presented by equation 2-3 (Baradaran & Ramjerdi, 2001).

$$A_i = \sum_{j \in L} \frac{1}{f\left(C_{ij}\right)} \qquad \text{2-3}$$

where

A_i is the measure of accessibility at location *i*;

L is the set of the all locations; and

$f\left(C_{ij}\right)$ is the deterrence function where C_{ij} is a variable that represents travel cost between nodes *i* and *j*.

Network Measures

Network measures focus on the road network topology, which is a key factor related to mobility and has a critical effect on accessibility. The network measures can be grouped into two categories: network connectivity measures and centrality measures. Network connectivity measures investigate the connection of nodes and links in the network topology. A large number of indices have been developed to describe and evaluate network connectivity. For example, Porta, Crucitti, and Latora (2006) provided several network measures such as K_i (Degree of Node), $L_m(G)$ (number of stations), $L_t(G)$ (number of route segments), $E_g(G)$ (the global efficiency), $E_l(G)$ (the local efficiency). Furthermore, El-Geneidy and Levinson (2006) used the network size as an index and Dill (2004) utilized the street network density, connected node ratio, intersection density and link-node ratio as network measure indices. However, the gamma index (γ) and the alpha index (α) developed by Garrison and Marble (1965) are regarded as the most popular measures of network connectivity. The alpha index measures circuitry, i.e. the degree to which nodes are connected by circuits or alternative routes, while the gamma index measures connectivity in terms of linkages (Garrison and Marble, 1965). The equations of the alpha and gamma indices are:

$$\alpha = \frac{\#links - \#nodes + 1}{2(\#nodes) - 5} \qquad 2\text{-}4$$

$$\gamma = \frac{\#links}{3(\#nodes - 2)} \qquad 2\text{-}5$$

In social science, there is an indicator called centrality that identifies the most import node/most influential person(s) in a social network. In other words, centrality is a measure of the structural importance of the node. Recently, it is much more intensively used in transport-network analysis apart from traditional social-network analysis (Carrington, Scott, & Wasserman, 2005; Choi, Barnett, & CHON, 2006; Rubulotta et al., 2012; Saito & Nishizeki, 1981; Turner, 2007; Wang et al., 2011). In the view of Geurs and Van Wee (2004), the locations with the highest accessibility scores are necessarily the ones with the highest degree of centrality in the transport network. It is said the accessibility and network centrality approaches open up new perspectives on the complex connection between land use and street features (Kang, 2015).

There are three popular indices to measure the different aspects of centrality: degree, closeness, and betweenness (Neal, 2012). A node's degree centrality is measured by counting the total number of edges that are connected to it. Closeness centrality focuses on how close a node is to every other node in the network with the measure being the ratio of the shortest path between nodes and total path length. Betweenness centrality is defined as the average proportion of paths between any two nodes within the network that traverse node, out of the total number of possible paths between these two nodes (Neal, 2012; Scheurer & Curtis, 2007). In the train station accessibility research, the concept of centrality can be used to identify how central the train station is compared to the geometry centroid of the catchment area and whether train users within the catchment have the equal access to the service. The existing degree, closeness, and betweenness centrality measures cannot measure. A new centrality index is needed.

Contour Measures

Contour measures, also known as isochoric or cumulative opportunity measures in the literature, seek to describe the accessibility of a location in terms of the number of opportunities that can be reached within a specified period of time (El-Geneidy and Levinson, 2006, Scheurer and Curtis, 2007). The equation is presented by (El-Geneidy and Levinson, 2006):

$$A_i = \sum_{j=1}^{J} B_j a_j \qquad \text{2-6}$$

where

A_j is the accessibility at point *i* to potential activity in zone *j*;

j is the number of points inside the potential activity zone catchment area.

a_i is opportunities in zone *j*; and

B_j is a binary value equal to 1 if zone *j* is with the predetermined thresholds and 0 otherwise.

The Department of Planning, Western Australian adopted this to measure accessibility (McCarney, 2012) . They define accessibility as the total time it would take all people living in the Perth and Peel region to access any destination zones. Therefore, accessibility is calculated by multiplying the number of people in an origin zone by the time it takes to travel from that zone to a particular destination zone. Similarly, The Department of Transport and Main Roads, Queensland has developed the Land Use & Public Transport Accessibility Index (LUPTAI) based on this theory, where the threshold of the destination is 400 m for bus stops and 800 m for train stations while for the origin it uses thresholds of 350 m for bus stops and 750 m for train stations (Pitot et al., 2005). It is simple to understand and calculate, but the thresholds are somewhat arbitrary and experimental. In addition, it uses rigid thresholds which suggest that, for example, opportunities 399 meters away are valuable but those 401 meters are not (El-Geneidy & Levinson, 2006). According to Equation 2-6, if the threshold is 400, 401 m is beyond 400 m and it will get B_j equals to 0 and then A_j value is 0 as well.

Gravity Measures

Gravity measures are based on Isaac Newton's law of gravity, with the most basic form of the gravity model given as (Hansen, 1959):

$$A_{1-2} = \frac{S_2}{T_{1-2}^{\beta}} \qquad 2\text{-}7$$

where

A_{1-2} is the relative measure of accessibility at Zone1 to an activity located within Zone2;

S_2 equals the size of the activity in Zone2; such as number of jobs or people;

T_{1-2}^{β} equals the travel time or distance between Zones 1 and 2; and

β is an exponent describing the effect of the travel time between the zones.

The gravity model is composed of two basic components: 1) attractiveness, which is the numerator in the fraction; and 2) the travel cost (e.g. travel time or travel distance) which is the denominator in the fraction. The numerator can be multiplied by many different related factors, which is the biggest advantage of this approach. However, there are also some points of weakness such as the complexity of the calculations involved and the need for substantial data to determine the constants, i.e. to calibrate the model.

Numerous modifications and developments have been proposed since it was first introduced in the literature. For example, Jones and White (1994) found that the variables that best explained interurban flows were the origin and destination zone populations and the separation between them. The equation is transformed to a function of origin population (P_i), destination population (P_j) and distance (D_{ij}) such as $(K*P_i^a*P_j^b)/D_{ij}^c$; where K, a, b, c are scaling constants. Khadaroo and Seetanah (2008) included additional factors such as TR (Tourist arrival), GDPO (Income of origin), CPI (Relative Prices), DISTAN (Distance) into the gravity model when measuring tourism developments. Further, El-Geneidy and Levinson (2006) converted the equation into a more general and commonly used form:

$$A_{im} = \sum_j O_j f(C_{ijm}) \qquad 2\text{-}8$$

where

A_{im} is the accessibility of point *i* to potential activity at point *j* at using mode *m*;

O_j is the opportunities at point *j*; and

$f(C_{ijm})$ is the impedance or cost function to travel between point *i* and point *j* using mode *m*.

Throughout all these transformations of the original formula, the common thread is that the gravity model is composed of two basic components. The first is the attractiveness/opportunity, the numerator in the fraction. Attractiveness is usually measured through surrogates such as the size or variety of the opportunity (e.g., store size and range of products for retail opportunities) (Wu & Miller, 2001). They can be multiplied by different related factors which is the biggest advantage of this approach. Many factors can be integrated into the model. The second component is the travel cost, (travel cost through physical distance, travel time, or monetary cost), which is the denominator in the fraction. However, there are also some points of weakness associated with gravity models including the need for sufficient data to accurately calibrate the parameters and aggregated measures which tend to ignore the differences between individual travellers (Scheurer & Curtis, 2007).

Random Utility Measures

The fifth category of accessibility metrics involves the use of utility theory. Random Utility Models (RUM) represent the amount of 'benefit' travellers obtain from travel (Ben-Akiva & Lerman, 1985). Recently, this has become a more popular measure

(Cascetta, 2009; Diana, 2008; Fukuda & Yai, 2010; Golob & Beckmann, 1971). The basic underlying assumption is that every individual is a rational decision-maker and she/he chooses the alternative that gives her/him the highest level of utility. The utility has a deterministic component, which can be calculated based on observed characteristics, and an unobserved / stochastic error component (Golob & Beckmann, 1971). The equation of the utility measure is defined as (Cascetta, 2009):

$$U_j^i = V_j^i + \varepsilon_j^i \qquad \forall j \in I^i \tag{2-9}$$

where

I^i is the generic decision-maker *i*'s choice set;

j is each alternative;

V_j^i represents the mean (expected value) utility perceived by all decision-makers having the same choice context (alternatives and attributes) as decision-maker *i*; and

ε_j^i represents the (unknown) deviation of the utility perceived by decision-maker *i* from this mean value.

There are some relationships between other models and the utility model. Koenig (1980) took the average maximum utility as $\log A_i$, where A_i is a gravity-type accessibility. As Lei and Church (2010) pointed out: "*… all approaches could be viewed from a utility theory …It typically considers a wider range of variables…*" (Lei & Church, 2010, p. 288). However, this increases its complexity and the empirical link between the infrastructure provision and economic performance for the utility model is tenuous and contested (Scheurer & Curtis, 2007).

Competition Measures

The Competition, or Constraints-Based, Measure incorporates the constraints of activities into an accessibility measure from a regional perspective. For example, Joseph and Bantock (1982) took into account the availability of physicians, suggesting that in less heavily populated catchment areas physicians are more likely to be available, due to lower demand. The Floating Catchment Area based measure applies supply-demand ratios to incorporate the competition effects between facilities (Dony, Delmelle, & Delmelle, 2015;Luo, 2004, 2011,2014; Luo & Qi, 2009; Luo & Whippo, 2012). Genurs and Van Wee (2004) summarized three different approaches: 1) dividing the opportunities by potential demand to incorporate the effects of competition (Knox, 1978; Wee, Hagoort, & Annema, 2001; Weibull, 1976); 2) using the quotient of opportunities (Shen, 1998); and 3) using balancing factors (Wilson, 1971).

Place Rank

Place rank is a flow-based accessibility measure (El-Geneidy & Levinson, 2011; Vega, 2012) that directly employs flow data from different traffic zones, in contrast to the traditional accessibility measures that use travel time and land use data. It is an indicator based on actual choices of origins and destinations, measuring real rather than potential opportunities (El-Geneidy and Levinson, 2011).

The mathematical formulation of the model is (El-Geneidy & Levinson, 2006):

$$R_{j,t} = \sum_{i=1}^{I} E_{ij} * \mathrm{P}_{it-1} \qquad \text{2-10}$$

$$\mathrm{P}_{it-1} = \left[E_j * \left[R_{j,t-1} / E_i \right] \right] \qquad \text{2-11}$$

where:

$R_{j,t}$ is the place rank of *j* in iteration *t*;

I is the total number of *i* zones that are linked to zone *j*;

E_{ij} is the number of people leaving I to reach an activity in *j*;

P_{it-1} is the power of each person leaving I in the previous iteration;

E_j is the original number of people destined for *j*; $E_j = \sum_i E_{ij}$

$R_{j,t-1}$ is the place rank of *j* from the previous iteration; and

E_i is the original number of people destined for *j*; $E_i = \sum_j E_{ij}$

2.4.4 Modelling accessibility over space and time

In the past two decades of social science research, space and time has become two important components (Goodchild et al., 2000). Especially for human behaviour related research, space and time dimensions are inseparable as all human activities take place in space and time (Hägerstrand, 1970). For accessibility studies, Kwan (1998) suggested that temporal constraints can impact significantly on the ability to participate in activities and it needs to be considered when modelling accessibility. Analysing and modelling accessibility over space and time is pivotal.

In space and time research, the most power conceptual framework is Hägerstrand's time-geography (1970) that incorporates spatial, temporal and transportation elements, i.e. the elements that affect accessibility within a geographic environment. It is considered to be a powerful conceptual framework to assess the ability of individuals to travel and participate in a given environment as it captures both spatial separation and temporal constraints (Wu & Miller, 2001).

The first advantage of Hägerstrand's space-time framework is that it defines an individual's activity axioms. These axioms are (Burns, 1979):

1) Individuals are indivisible, that is no person can be at two or more places simultaneously;

2) Movement is time consuming;

3) Every activity has duration;

4) Every situation is inevitably rooted in a past situation; and

5) Space has a limited packing capacity.

These axioms can be represented diagrammatically as in Figure 2.4. The geographical space is compressed into a two-dimensional surface and time is the vertical axis. From the figure, an individual's existence, i.e. where he is and at what time, can be described by an unbroken trajectory. When he is moving in space, he is also moving in time.

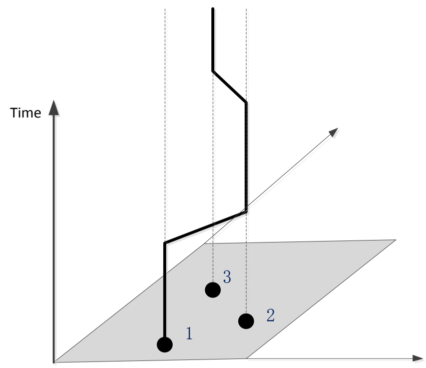

Figure 2.4 Hägerstrand's space-time representation of human activity

(adpated from Burns, 1979)

Another advantage of the Hägerstrand's space-time representation is the definition of the space-time prism. Figure 2.5 illustrates the classical form of a space-time prism, which is defined by the origin and destination coupling location constraints as well as the travel speed. The volume of the space-time prism is called the potential path space (PPS) and the area of its projection is called the potential path area (PPA).

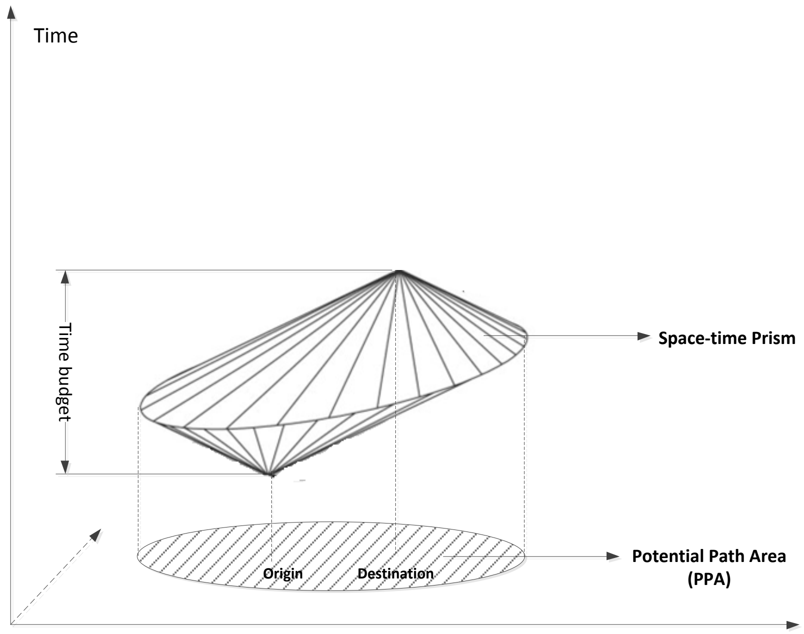

Figure 2.5 Individual's space-time prism

(adpated from Neutens et al., 2012)

Most space-time accessibility research in the literature is based on Hägerstrand's (1970) space-time prism (STP), including Burns (1979), Miller (1999) ,Miller and Wu (2000), Wu and Miller (2001), Kwan (1998), Kwan, Janelle, and Goodchild (2003), Fang, Li and Shaw (2010), and Neutens et al. (2012). Kwan (1998) estimated accessibility using the lengths of arcs, number of opportunities and the weighted area of opportunities contained in the prism; Fang, Li and Shaw (2010) used the cumulative available activity time of all available activity places in an STP as an accessibility indicator; Neutens et al. (2012) evaluated accessibility using possibility (POS), spatial choice (SC), spatial proximity (SP) and temporal extent, (flexibility), (TE). It is concluded that the space-time prism based approach expresses accessibility in terms of space-time feasibility (Kwan, 2000), which is noted as "Freedom" by Burns (1979).

An aim of this research is to examine the ease of reaching train stations over space and time. The popular STP based space-time accessibility measure and modelling approach cannot be used in this study as it focuses on the freedom measure in the limited time budget for the individuals, (i.e. in the space-time prism, the potential path area is used to indicate the area that people could move within the limited time budget). There is limited research examining the **ease of access** to destination over space and time and this could be amplified when the research field is narrowed to accessibility to train stations.

2.5 SUMMARY

This chapter reviewed previous research into PnR accessibility. The history of the development of PnR schemes and related PnR research in the literature were reviewed first. Research on catchment areas was discussed afterwards, including the definition and significance of catchment areas, the existing methods of measuring them and the factors affecting their size and shape. Then the extant accessibility literature was reviewed, including the different accessibility definitions within the relevant disciplines, accessibility related factors, existing accessibility measures and time-geography theory.

Therefore, this thesis, in the next chapter, will develop a theoretical framework and methodology to model the spatio-temporal accessibility of PnR users to train stations. The concepts and theories related to the methodology of how to determine the related factors, the catchment area modelling and the macro and micro level space-time accessibility modelling will be discussed.

CHAPTER 3 RESEARCH FRAMEWORK

3.1 INTRODUCTION

The previous chapter identified a number of gaps in the research into modelling accessibility for PnR users over space and time. These include the limited research on PnR in Perth, the characteristics of catchment areas, their precise spatial boundaries and the spatial and temporal modelling of accessibility.

Both industry and research require a consistent and robust methodology to understand, measure and model PnR users' accessibility to train stations over space and time. This chapter presents an overview of a research framework to this end.

3.2 STUDY AREA

The study area for this research is Perth, the capital of Western Australia. Perth was chosen for three reasons. Firstly, Perth has a long railway history dating back to 1881 when the Fremantle-Perth-Guildford lines were opened, followed by the Armadale line in 1893. In 1992 the Joondalup line opened, followed by the Mandurah line in 2007 (PTA, 2009). The Joondalup line was recently extended to Butler (Transperth, 2014) but this new section is not included in the study area. Overall, the Perth passenger train network consists of 70 train stations on 173 kilometres of track (Australian Department of Infrastructure and Transport, 2014). There are significant differences between the pre-1900 (heritage) lines and the newer lines, their train stations and the surrounding land uses due to changes in society over the intervening 100 years.

Secondly, the rail network plays an important role in the overall passenger transport task in Perth. In the 2014-15 financial year the total number of train passengers was 64.2 million (PTA, 2015a). Railway transport constitutes a sizeable share of daily travel made by travellers in Perth. In Perth’s 2031 year transport infrastructure plan, nearly 75 percent of a planned $2.9 billion budget, (about $2.2 billion), provided by government is allocated to establishing a light rail network and extending the existing heavy rail network (Department of transport, 2016). Critical to this plan is the need to ensure train stations are accessible to the population of Perth and will remain so over the longer term.

Thirdly, Perth is a low-density city, (310 people per square kilometre for Greater Perth), and with a high car ownership of 723 vehicles per 1,000 people, (Australian Bureau of Statistics, 2012-2013; Curtis, 2008). This has made the delivery of a high-frequency public transport system a major challenge. The PnR system is widely recognised as having had a positive influence on public transport demand in a low density city (Olaru et al., 2013). In recent years, PnR has become increasingly important in generating a high volume of public transport train ridership, especially on the newly constructed lines. This is because a well-developed PnR system, together with increasing traffic congestion and high parking costs in the city centre, make rail service more comparable to the convenience of door-to-door car travel.

3.3 RESEARCH WORKFLOW

The research methodology for the spatio-temporal modelling of accessibility to train stations for PnR users comprises five major steps: data collection and preparation, exploratory data analysis (EDA), catchment area modelling, macro accessibility modelling and micro accessibility modelling.

These steps and the order in which they were processed are outlined in the workflow diagram (Figure 3.1) and described below.

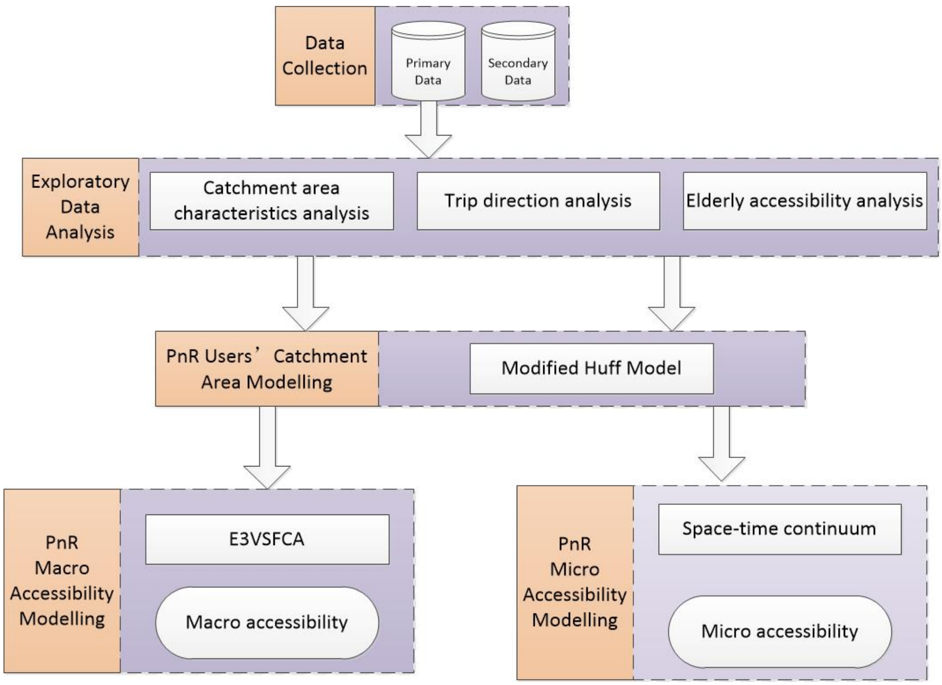

Figure 3.1 Workflow for modelling accessibility to train stations for PnR users over space and time

3.3.1 Data collection and preparation

In this first step, the data required to conduct the research were collected. The data can be categorized into two types: primary data and secondary data. Primary data refer to data that are observed and collected from first-hand experience whilst secondary data refer to the data that is previously gathered by someone else for other purposes (Stevens, 2006, p. 90). Details of the data collection and preparation process can be found in Section 3.4.

3.3.2 Exploratory Data Analysis (EDA)

The aim of the EDA step is to understand the three interconnected core research areas, i.e. train station catchment areas, ridership and accessibility. These areas are of interest because they are required to: (1) model the catchment areas of the train stations for PnR users, (2) understand directional accessibility and the factors that affect the train station ridership and (3) find the best model to analyse accessibility.

The catchment area analysis investigated the characteristics of train station catchment areas and the factors that affect their size and shape (Section 3.5.1 and Chapter 4). The train station direction analysis identified train station ridership from the trip direction perspective, using a series of indices including centrality, spatial integrity and trip frequency (Section 3.5.2 and Chapter 5). The accessibility analysis focused on identifying factors to improve accessibility for elderly patrons. It applied a gravity model based accessibility measure, (composite measure), to determine accessibility of the elderly to a train station based on the perceived accessibility levels of respondents obtained in the survey, i.e. based on real survey data. The aim of this chapter was to examine the suitability of the gravity based measure for measuring accessibility to train stations (Section 3.5.3 and Chapter 6).

3.3.3 Catchment area modelling

From this step onwards, the research focused on the modelling of PnR user spatio-temporal accessibility to train stations. As the physical boundary of catchment areas is crucial in understanding accessibility, the spatio-temporal modelling started with defining the catchment areas using a modified Huff model. Details of the catchment area modelling can be found in Section 3.6 and Chapter 7.

3.3.4 Macro accessibility modelling

Macro accessibility modelling aims to model accessibility over a longer timescale than micro accessibility modelling. Specifically, the longer timescale in this research is five years after the opening of the train line to Mandurah. The Enhanced Three-step Variable Floating Catchment Area Measure (E3SVFCA) has been used to explore the accessibility improvements after the new train line opened. Details of the macro accessibility modelling are presented in Section 3.7 and Chapter 8.

3.3.5 Micro accessibility modelling

Micro accessibility modelling measures accessibility in a real, dynamic traffic environment and over a relatively short timescale (e.g. every 15 mins) compared to macro accessibility modelling. The space-time continuum method, based on gravity theory and accessibility dichotomy, has been used for this analysis (Section 3.8 and Chapter 9).

3.4 DATASET COLLECTION AND PREPARATION

This research used multiple sources of primary and secondary data. Table 3.1 summarises the data collected by this study based on these two categories.

Field Surveys were conducted to collect information on commuters' trips and their attitudes to accessibility, station facilities and service quality. Seven train stations were surveyed: Warwick, Greenwood, Murdoch, Warnbro, Midland, Cannington, and Claremont. These stations were selected in consultation with industry partners because they either had known issues or had not been investigated previously. Other selection criteria were:

- At least one station per train line must be selected;

Railways in Perth have a long history, with three lines built before 1900 and the remaining two after 1990. The land uses around, and locations of, the train stations on the heritage lines are very different to those around the stations on the new lines. These significant differences result in the train stations having different characteristics.

- Two adjacent stations must be selected;

Adjacent train stations can compete with each other for patronage. At least two adjacent stations (e.g. Greenwood station and Warwick station), on at least one line, should therefore be selected so that this competition effect can be investigated.

- Greater focus on the newly opened Mandurah line;

The Mandurah line is the newest train line in Perth and has had the greatest impact on PnR accessibility since the opening of the Joondalup line in 1992. At least two stations along the Mandurah line (Murdoch station and Warnbro station) are required to measure performance and impact on accessibility in the corridor.

- At least one station must be a terminal station, i.e. located at the end of a train line.

Terminal train stations often serve large areas and may be significantly different to other train stations. The Midland train station was chosen to satisfy this criterion.

At each station, an intercept survey was conducted. A random sample of boarding passengers was selected. Each passenger was asked questions about his/her travel mode, travel purpose and attitudes to train station facilities. They were also asked to rank a number of accessibility factors and the overall accessibility of the train station based on their travel mode (Appendix E/F/G). Although the surveys only covered people who used the train services at the station and are a snapshot of only a couple of days, they provided sufficient and comprehensive data, including trip origins and overall accessibility from the passengers' perspective. The survey data were then converted into GIS data (geocoded) by applying the Google geocoding APIs. In the questionnaire, trip origins and destinations were defined by their nearest road junction rather than house address, to protect the privacy of respondents. In some cases, these junctions were not provided and origins and destinations were geocoded at the suburb level only.

A survey of the PnR facilities at each train station on the Perth network was conducted in April, 2012. This identified a total of 27 different types of facilities including emergency call points, public telephones, seating, undercover waiting rooms, toilets, office railway personnel, security personnel, disabled access/lift, and convenience stores. (Appendix H). This survey provided the second primary data source for the research.

Figure 3.2 Study area

Secondary data were collected from the Department of Transport (DoT), Public Transport Authority (PTA), the Department of Planning (DoP) and the Australia Statistics Bureau (ABS). These data included geographical data (e.g. land use, Railway, Road), floating car surveys, number plate surveys, station PnR capacities and demographic data. A summary of the data obtained is provided in Table 3.1.

Table 3.1 Data collection summary table

	Primary data source			
	Name	**Stations involved**	**Sample number**	**Time period**
1	**Intercept survey 1**	7	940	31/07/ 2012- 1/8/2012 (6:00AM - 4:00PM)
2	**Intercept survey 2**	7	323	19-20/ 09/ 2013 (7:00AM-12:30PM)
3	**Intercept survey 3**	3	19	8-10/05/2013 (9:00AM – 3:30PM)
3	**Facilities survey**	69[1]		April 2012
4	**Factors importance ranking survey**[2]		17	December 2013
	Secondary data source			
	Name	**Stations involved**	**Time period**	**Source**
1	**Network data**			Provided by DoP
2	**Walk Score**	69		Work Score (https://www.walkscore.com/)
3	**Licence plate survey**	22	2006-2008	Provided by DPI
4	**TransPerth timetable**	69		PTA (2015b)
5	**Car park full time survey**		2014	Parliament of WA (2014)
6	**Statistical boundaries**		2011	ABS (http://www.abs.gov.au)
7	**Journey to work**		2011	Census Australian Bureau of Statistics (2011b)

[1] A new station (Butler) opened in Perth, 2014

[2] 17 policy makers from government agencies

3.5 EDA

3.5.1 Catchment area analysis

Research literature on the characteristics of catchment area analysis is limited even though a good understanding of catchment areas is required to analyse accessibility (refer to Section 2.3). This section developed methods for systematically investigating the size and shape of different user group catchment areas and determining the spatially dominant user characteristics of train catchment areas, using the spatial market segmentation concept. Four key steps were involved in the analysis (Chapter 4):

Step 1: User group catchment area delineation using minimum bounding geometry approach

The minimum bounding geometry, (Convex Hull) approach is a popular method for determining the boundary of a catchment area (Cervero et al., 1995; Guerra, Cervero, & Tischler, 2011). This method is based on computational geometry theory to derive a convex hull of 90 percent of the trip origin location points (the last 10% of trips were discarded based on the network distances to train station. The fastest 10% distance origins were regarded as outliers). The boundary of the catchment area is a series of line segments, each segment joining two adjacent outermost points (De Berg et al., 2000). Catchment areas were determined for each different user group, i.e. by age (young, middle aged, elderly), gender (male, female), trip direction (inbound, outbound) and station access mode (PnR, Bus and Ride (BnR)).

Step 2: Catchment area size and shape measure

The size of each user group's catchment area was calculated using a standard GIS approach. For the shape of catchment area, the compactness measurement, which is the ratio of the area of the shape to the area of the maximum circle of the defined catchment area, has been adopted as shape measure in the study. The value of the compactness is between 0 and 1, with 1 meaning complete isotropy, i.e. a circle. The catchment areas and compactness (shape) were then compared by train station and user group using statistical techniques. The results for each user group were mapped for each of the seven train stations to allow visual interpretation and comparison.

Step 3: Characteristics of train station catchment analysis

This section emphasises how the characteristics of train stations affect the size and shape of their station catchment areas. These characteristics include train frequency, bus frequency, location of train station, (at the end of a train line or along a line), parking capacity around a station, competitive index, land use diversity and the percentage of residential land use in the catchment area. The Independent Samples *t*-test, (or independent t-test, for short), was used to determine if a difference exists between the means of two independent groups on a continuous dependent variable (Green, 2010, p. 162-175). For the independent groups that have more than two categories, ANOVA was used (Green, 2010, p. 182-255). Furthermore, correlation analysis was used to test the degree of association between variables (Green, 2010, p. 256-311).

Step 4: Train station spatial segmentation analysis

Spatial segmentation explores market segmentation from a spatial analysis perspective. The fundamental assumption of the spatial market segmentation method is that the size and compactness of a station catchment area varies depending on the user group. The larger the size and the higher the compactness of a catchment area for a particular user group, the more attractive the train station is for that user group. In order to identify dominant characteristics of a station catchment area, two new measures were developed: a disaggregate market segment area ratio and a composite ratio. The area ratio is the ratio of the size of a particular user group's, (i.e. market segment's) catchment area (e.g. female) relative to the size of the overall (all user groups combined) catchment area. The composite (or shape) ratio, is the area ratio multiplied by the compactness.

3.5.2 Trip direction analysis

Most of the accessibility analysis found in the literature review evaluated accessibility from attractiveness, utility, freedom and opportunity perspectives with very little from a spatial trip direction perspective. However, trip direction analysis is important as it can help in understanding the accessibility implications of the train station location and the factors and constraints that contribute to the trip distribution asymmetry. Based on the train ridership data collected from the intercept survey, this section analysed accessibility from a trip direction perspective (Chapter 5).

Step 1: Rose diagrams generation

Rose diagrams have been used to illustrate the number of trips, (trip frequency), by direction of approach at each of the seven train stations. The first step was to draw the smallest circle possible that included all of the surveyed trip origins (with 10% of outliers removed). The circle was then divided into twelve 30 degree azimuthal segments and the number of trip origins in each segment calculated (Figure 3.3). These segments represent trip directions in terms of the compass, (north, east, south and west) and their intermediate directions. From the Rose diagram, the number of trips by direction can readily be seen.

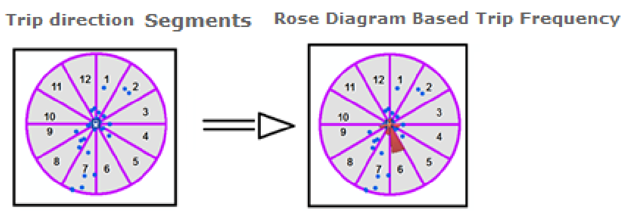

Figure 3.3 The illustration of rose diagrams generation

Step 2: The trip frequency and direction related factors analysis

Many factors could affect trip frequency and direction. The factors considered in this study are population density, road network density, spatial integrity of residential land use, average travel distance, the direction of trip destination and more than one train station in the same zone. These factors were measured for each segment for the seven train stations. From this, an understanding of why there are more trips from a certain direction than from others can be gained. In this study, the diagram segments have been divided into two groups: segments with another station(s) and segments without another station. The Independent t-test was used to test whether the means of trip frequency in the two groups were statistically different from each other. The segments were also divided into two types by primary direction of travel on the train (towards/further away from city centre). Outer segments were defined as those further away from the city centre than the train station and were coloured red, (see Figure 3.4). Inner segments were those closer to the city centre than the station and were coloured green. The relationships between the above factors and trip frequency were calculated separately for the outer and inner segments using a correlation method.

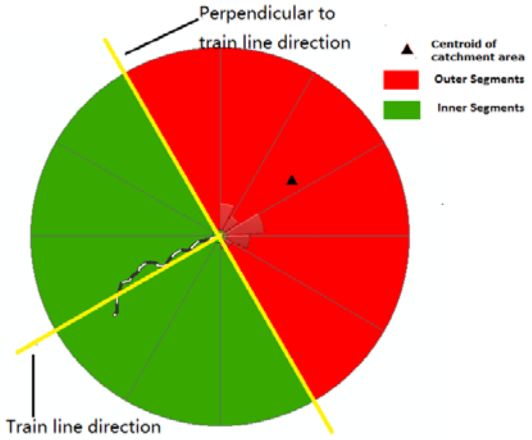

Figure 3.4 Inner segments and outer segments

Step 3: Centrality analysis of a train station

A rose diagram illustrates the trip magnitude and directions in a disaggregate way but does not provide a quantitative measure of trip directions in an aggregate manner. The centrality measure indicates how central a station is in relation to the measured catchment area. In this study, a new spatial measure of station centrality has been developed in terms of the area of the catchment, the location of the train station and the centroid of catchment area. The relationships between the location of the centroid and the above factors have been explored at the individual segment level.

3.5.3 Elderly accessibility analysis

As a part of data exploratory analysis (EDA) step, the elderly cohort has been chosen for a more detailed accessibility analysis because the aging of the population is unprecedented, ubiquitous and enduring (Division, 2002). The EDA of elderly accessibility also explores the suitability of a gravity based model in the context of this research. The method adopted is called the composite measure, which is a transform of the traditional gravity model. The main function of this measurement is to identify those factors impacting most on train station accessibility and the relationships between those factors, (i.e. how to combine those factors).

Three steps of analysis were undertaken (Figure 3.5). The first step identified the elderly cohort's most and least favourite stations, based on the level of rail station patronage. Next, the variables affecting railway station patronage were investigated. Based on these variables, accessibility indices were developed to measure elderly accessibility to train stations for WnR, BnR and PnR respectively (Step 3, Figure 3.5). The accessibility to the train station for the elderly was thoroughly evaluated and compared with the perceived accessibility obtained from the intercept survey.

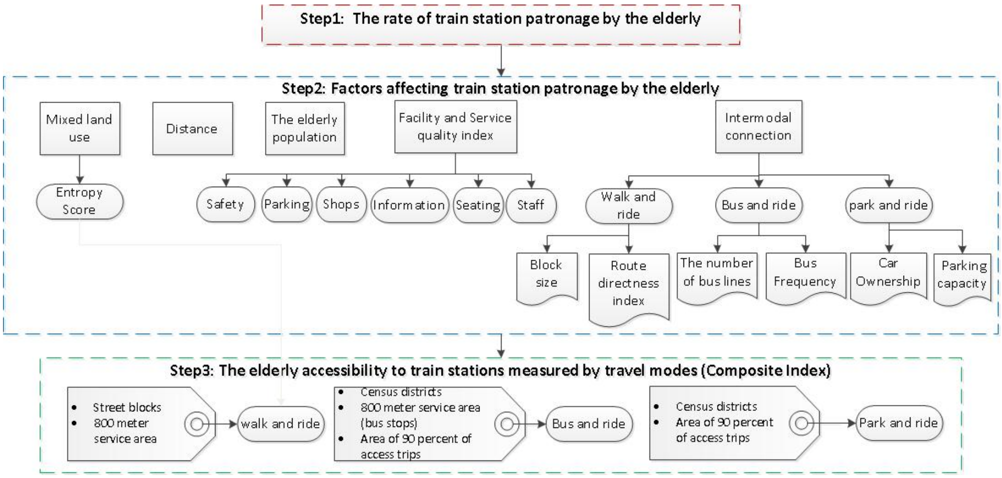

Figure 3.5 The framework of measuring elderly accessibility to train stations

3.6 CATCHMENT AREA MODELLING

Buffer rings and service areas, based on travel time or distance, are common methods used to define catchment areas. However, these methods have been criticised due to their use of somewhat arbitrary time and/or distance thresholds. Hence, there is a need to develop a more holistic methodology to define the catchment areas of transport facilities, using a wider range of criteria that include transport and urban facilities, population characteristics and their varying travel capabilities and requirements.

The Huff model has been applied to determine the catchment areas of the railway stations but it has been modified to meet the modelling requirements of this research project. Three steps were involved:

Step 1: Station choice modelling using modified Huff model

The first step applied a modified Huff model to determine the probabilities of choosing potential stations. Factors affecting station choice behaviour were integrated by using MCDA-derived weights as attractiveness. The factors include:

- Parking bay index (the number of available parking bays at the train stations);

- On street parking index (dummy variable, indicating whether street parking is available around a station 1 or not 0);
- Land use diversity index; and
- Service and facility quality index.

As these factors are measured in different units, they were "standardised" using the score range (benefit criteria) method, before they were combined into one attractiveness index.

Step 2: Origin calibration using linear referencing

The modified Huff model outputs the probability of a station being chosen by a traveller starting his/her journey from a particular origin. In this case study, the geographical centroids of the suburbs have been adopted as the trip origins. For each suburb, the probabilities of travelling to the nearest three stations were calculated. In order to make a fair allocation, the centroid of the suburb was relocated using the linear referencing method. The underlying principle is that the probability of station choice is inversely proportional to the distance between a suburb and a station. If the probability of a station being chosen is lower, the origin point was moved closer to the station.

Step 3: Catchment area delineation

Once these probabilities had been calculated and the origins calibrated, the next step was to determine the spatial boundary of the catchment area for each train station. As each calibrated origin point represents a suburb, the spatial boundary of a train station was drawn by selecting the intersected suburbs of a station and dissolving or aggregating the boundary of selected suburb polygons into one area of the station using the ArcGIS™ software.

3.7 MACRO ACCESSIBILITY MODELLING

Macro accessibility modelling models the change in accessibility over time or either side of a major intervention. In this case the major intervention is the opening of the Mandurah train line. The gravity based Floating Catchment Area (FCA) accessibility measure provides a unique and intuitive way to measure accessibility because it is a combination of a Supply-to-Demand Ratio (SDR) and a distance decay function. In this part, the Three-step Variable Floating Catchment Area (E3SVFCA) was developed by modifying and improving the existing FCA measures by:

- Quantifying the potential demand from the individual catchment areas and station choice probability from the modified Huff model; and
- Improving the distance decay function from ABS census journey to work survey.

Three steps were involved:

- ***Step 1:*** the probabilities of choosing potential train stations were calculated based on the Huff model;
- ***Step 2:*** The SDR (parking bays to the number of potential PnR users) was calculated for each train station; and
- ***Step 3:*** The accessibility from each origin was calculated based on the SDR from step 2 and the distance decay function.

In the literature, there is no agreement on which distance decay function is best. This research therefore used observed data to derive, calibrate and then validate the distance delay function, consistent with the observed distance decay pattern. Three steps were required to derive the function.

- ***Step1:*** Calculate the network distance of SA1 centroid to the nearest train station;

- ***Step2:*** Count the number of PnR users per unit area (from ABS census journey to work data), inside each distance ring (e.g. 1 km-2 km, 2 km-3 km); and
- ***Step3:*** Determine the best distance decay function using the Matlab™ curve fitting function.

3.8 MICRO ACCESSIBILITY MODELLING

In contrast to macro accessibility, micro accessibility models accessibility changes over short timescales, (e.g. every 15 minutes), and are based on dynamic road network and travel conditions. It has been developed from a merger of gravity and accessibility theory. It focuses on the real-time travel impendence, (dynamic travel time), and measures how accessibility changes over time, e.g. throughout the day. The longer the travel time, the lower the level of access to the facility. Four steps are involved:

Step 1: Study station determination

Travel times variations were determined from floating car surveys conducted by Main Roads Western Australia in 2013-2014. Eleven routes were chosen to represent the Perth metropolitan road network with all routes surveyed in both directions of travel. An analysis of the variations in route travel times found the biggest variations in peak and off-peak hours travel times occurred inside the Warwick station catchment area. Therefore, Warwick station was chosen as the study station.

Step 2: Data collection

TomTom® APIs were applied to obtain useful real-time and historical travel time information. TomTom® uses a wide range of GPS probe data from fleets, Portable Navigation Devices (PNDs), smartphones, in-dash systems and other data sources to generate precise real-time traffic information. It also provides an online routing API to access the abundant real-time traffic data. The catchment area of Warwick station was divided into Voronoi polygons based on the centroids of SA1s inside catchment area of the Warwick station. Inside each Voronoi polygon, it is considered as a proximity and homogeneous area. The centroid of each Voronoi polygon was used to represent this proximity area and it is defined as origins. The travel information was collected from midnight to midnight at 15 minute intervals over five consecutive work days, i.e. Monday to Friday.

Step 3: Statistical analysis of dynamic travel times

Four different methods were used to analyse the collected dynamic travel time to train station data: descriptive statistics analysis, the ANOVA test, curve plotting and hot spot analysis. Descriptive statistics were used to describe quantitatively the main features of the data. The ANOVA test helped to determine whether or not there were any significant differences over the five days. Curve plotting explored the variations within each day and the hotspot analysis helped to understand the location of the significant dynamic accessibility variation areas.

Step 4: Dynamic accessibility modelling

Space-time continuum is a framework developed in this research to predict accessibility at any given time and location in the study area. It uses the First Law of Geography and the accessibility dichotomy to construct the space-time continuum. Kriging interpolation was implemented to construct the space continuum based on the collected data. A spline function was used to construct the time continuum, meaning that time is continuous over any given interval. The spline functions of each location at each time interval were estimated in Matlab^{TM} using scripting.

3.9 SOFTWARE

3.9.1 GIS software

Most of the data processing, spatial data analysis and spatial data storage were implemented in ArcGIS 10.2.2 and its extension Network Analysis (Esri, 2014), with the geodata stored in Esri shapefiles and geodatabases. Tools to automate the analysis processes were developed using Model Builder™ and Python scripts. These tools were developed specifically for this research to automate the steps for modelling accessibility to train stations for PnR users.

3.9.2 Programming and modelling software

LINGO™ is a comprehensive software package designed to build and solve linear, nonlinear and integer optimization models. The pairwise comparison matrix of AHP (Analytical Hierarchical Process) was calculated in LINGO™ automatically (Chapter 6 and Chapter 7).

Matlab™ (MathWorks, 2013) was applied throughout the research to derive the distance decay functions and the dynamic time continuum (Chapter 8 and Chapter 9). SPSS™ (IBM, 2013) was used for the various statistical tests, including the independent t-test, and the ANOVA test (Chapter 4, Chapter 5 and Chapter 9). VESPER (Minasny, McBratney, & Whelan, 2005) was used to help with space interpolation to construct the space continuum. Microsoft Visual Studio was used to develop the web application to communicate with Google APIs and TomTom® APIs, geocode the origins and destinations, calculate route directness and collect dynamic traffic data.

3.10 SUMMARY

This chapter has established the framework of the methodology for the spatio-temporal modelling of PnR user accessibility to train stations. The framework starts from the data collection and ends with the two different time scale spatio-temporal accessibility modelling. In order to achieve the final spatio-temporal modelling, EDA and catchment area modelling were utilised. Those sub-components intersect with each other to form the whole framework of this spatio-temporal accessibility research. The key steps and methodology of each process were addressed individually. The chapter ends with the software packages used in the research.

The next chapter describes the first component of the exploratory data analysis, the catchment area analysis. The concepts and methods related to catchment areas, including the size and shape measures, dominant factors exploration and the catchment area characteristics analysis are also discussed.

CHAPTER 4 EXPLORING THE CHARACTERISTICS OF THE TRAIN STATION CATCHMENT AREA

4.1 INTRODUCTION

The previous chapter established the framework of the methodology for the spatio-temporal modelling of PnR user accessibility to train stations. An essential component of this framework is an in-depth understanding of train station catchment areas, their characteristics and the factors that determine and influence them. Therefore, this chapter presents the first Exploratory Data Analysis (EDA) of the project, an EDA of the train station catchment areas.

The chapter is organised as follows. Section 4.2 presents a literature review of catchment area measures, factors affecting their size and shape, characteristics of train users and their trips, characteristics of train stations and the market segmentation methods. Section 4.3 focuses on discussing how to prepare the data for analysis and analytical methods. The results and findings are presented in Section 4.4 and discussed in Section 4.5.

4.2 RESEARCH CONTEXT

4.2.1 Catchment areas

A train station's catchment area refers to the area from which the majority of users will typically be drawn (Dolega, Pavlis, & Singleton, 2016). It is vital for understanding latent demand (potential customers) (Banister, 1980), market share (the portion of a market) (Lee & Masao, 1988, p. 17-19) and accessibility (ability to reach) (El-Geneidy & Levinson, 2006). Various catchment area estimation methods have been developed in the literature (Cervero et al., 1995; Lin et al., 2014; Zhao et al., 2003). The most commonly used method is the proximity method, which uses buffer rings or network-based service areas to determine the spatial extent of a catchment (Landex & Hansen, 2009) or the convex hull (see Section 2.3.2). Many studies have been conducted to identify and understand the factors that affect catchment size and shape such as land use diversity and density, transit service and facilities and accessibility to train stations (El-Geneidy et al., 2014; García-Palomares et al., 2013; O'Neill et al., 1992; O'Sullivan & Morrall, 1996). It is found stations with high train frequencies were found to be preferred by commuters and more likely to have larger catchment areas than stations with lower train frequencies (Debrezion et al., 2009; Sanko & Shoji, 2009). Similarly, parking capacity was identified as a strong determinant of PnR travel mode to stations and could affect the catchment area. For example, Cervero et al. (1995) found car use was the main access mode for stations that have large parking areas, homogenous land use mixes and low residential densities. Debrezion et al. (2009) and Duncan and Christensen (2013) also discovered that the presence of car parking encouraged commuters to drive to the station, especially those who did not live near the station. Furthermore, in the literature, terminal stations were generally found to have larger catchment areas than stations along a train line. Few studies have been conducted into understanding the individual differences in the spatial extent of the train station catchment areas of different user groups. This chapter fills this research gap by comparing the size and shape of the train station catchment areas of different user groups, (e.g. by age and gender), and developing a novel spatial market segmentation method to determine the spatially dominant user group(s).

4.2.2 Market segmentation

Since it was first introduced by Smith (1956), market segmentation has become a key concept in both marketing theory and practice. Although many definitions of market segmentation have been found in the literature, the original definition by Smith is still agreed upon and adopted by most researchers. It is: "*Market segmentation involves viewing a heterogeneous market as a number of smaller homogeneous markets, in response to differing preferences, attributable to the desire of consumers for more precise satisfaction of their varying wants*" (Smith, 1956; Wedel & Kamakura, 2012). It is the process of grouping customers/potential customers into different groups/segments according to their similar needs (McDonald, 2012). Through dissecting the marketplace into submarkets, market segmentation allows organizations to focus their resources more effectively and with a greater chance of success. It can help in product and service development and marketing. Weinstein (2013, p. 3) stated it as "*the key to marketing success*" and "*segmentation imperative*". It is widely used in many sectors of industry and has been described as the cornerstone of modern marketing and is at the heart of marketing strategy, helping to bridge the gap between diverse customer needs and limited business resources (Dibb, 1998).

Market segmentation is the first stage of a market matching strategy which consists of segmentation, targeting, (the process of reviewing market segments and deciding which ones to pursue), and then positioning, (establishing a differentiating image for a product or service in relation to the competition). In order to determine the effectiveness and profitability of marketing strategies, the derived market segments should meet six criteria: identifiability, substantiality, accessibility, stability, responsiveness and actionability (Wedel & Kamakura, 2012, p. 4) . Usually, there are five basic types of variables that can be used when segmenting a market, either individually or in combinations of one or more. The five variable types are geographic, demographic, psychographic, behavioural and beneficial (Reid & Bojanic, 2009).

Segmentation is essentially a grouping task and there are a large number of methods available to undertake this grouping. Wedel and Kamakura (2012) classified the current segmentation methods and techniques into four categories that are combinations of two major classifications (a-priori or post-hoc and descriptive or predictive)(Monte et al., 2013). The resulting categories are: a-priori descriptive, post-hoc descriptive, a-priori predictive and post-hoc predictive(Kuo, Chang, & Chien, 2004). In a-priori descriptive segmentation, the type and number of segments are determined before data collection; whilst in post-hoc descriptive methods, the segments are identified after data collection based on grouping heterogeneous data together, (clustering analysis being the most popular approach). In a-priori predictive segmentation, the segments are based on a pre-determined set of criteria and then subsequently, the predictive models are used to describe the relationship between the segment membership and a set of independent variables. In post-hoc predictive segmentation, the identification of the segments is on the basis of the estimated relationship between a dependent variable and a set of predictors. AID (Automatic Interaction Detection), CART (Classification and Regression Trees), clusterwise regression and Artificial Neural Network (ANN) are all methods that can be used in the post-hoc predictive segmentation process. However, these approaches result in segmentations that are primarily from an empirical, statistical or mathematical perspective. The literature review has identified a lack of research that considers the segmentation problem from a spatial perspective. This chapter, to the knowledge of the authors, will be the first attempt to fill this gap.

4.3 METHODOLOGY

Four steps of analysis were taken. The first step was to determine the individual user group station catchment areas. This was followed by measuring the size and shape of each catchment area and then exploring the differences between the various user groups. Then, characteristics of train station catchment analysis were conducted to understand how the characteristics of train stations affect the size and shape of their catchment areas. Finally two new indicators, the area ratio and the composite ratio, were developed to determine the key market segment(s) based on the spatial market segmentation method.

4.3.1 Data used in the study

The data used in this study are from the intercept survey, (see Section 3.4). Table 4.1 provides a breakdown of the survey responses for each station by segmentation variable, (i.e. age, gender, trip direction and travel mode). Generally, the elderly (over

60) group sample size is smaller than the middle-aged (25-59) and young (18-24) group sample sizes. Except for the Greenwood station survey, which is dominated by middle-aged users, there is no significant difference between the young and middle-aged survey sizes at the other stations. The inbound (towards city centre) survey sample size is much larger than the outbound (away from city centre) sample size due to the majority of train trips being to the central area and the seven stations being outside this central area. Claremont and Greenwood stations tend to be more likely to accommodate PnR users, whilst at Warwick and Murdoch stations, BnR is the dominant travel mode.

Table 4.1 Survey sample characteristics by train user types and stations

	The sample size by train user and station						
Station	**Cannington**	**Claremont**	**Greenwood**	**Midland**	**Murdoch**	**Warnbro**	**Warwick**
All*	152	107	161	120	117	159	135
Young (18-24)	61	40	37	45	57	83	64
Middle (25-59)	67	48	106	40	37	50	53
Elderly (over 60)	14	14	14	29	20	17	15
Male	91	51	79	56	64	78	58
Female	80	56	82	64	53	81	77
Inbound (towards city centre)	132	82	152	120	97	153	116
Outbound (away from city centre)	20	25	9	0	20	6	19
Bus and Ride	57	8	3	24	52	48	43
Park and Ride	40	42	79	56	22	49	42

*The number of sub categories don't sum to the total number due to missing information

4.3.2 Delineation of train station catchment areas

The research aims to better understand not only the size of a catchment area but also its shape. Hence the determination of the spatial boundaries of the catchment areas is crucial. In this study, the catchment areas were determined by initially plotting the survey data, i.e. by geocoding the location of each trip origin using a Google application programming interface (API). Then, the minimum bounding geometry Convex Hull approach (Cervero et al., 1995; Guerra, Cervero, & Tischler, 2011) , was adopted to determine the boundaries of the catchment areas. This method uses computational geometry theory to derive a convex hull containing 90 percent of the trip origin location points, (as 10 percent of the sample data are considered as spatial outliers and are removed). The boundary of the catchment area is a series of line segments joining the outermost points so that all remaining points are enclosed (De Ber et al., 2000). Figure 4.1 illustrates the convex hull method. An advantage of this method is that it captures the spatial boundary of the catchment area based on the location of individual trip origin data in a disaggregated manner, thereby reflecting the actual shape of the catchment area more exactly. The disadvantage of this method is that it needs a relatively large sample size in order to make a catchment area representative and it is sensitive to spatial outliers. In order to determine the key spatial segments, a separate catchment area was determined for each segmentation variable (i.e. age, gender, trip direction and travel mode) for each station. The size of each of these separate train station catchment areas was then determined using ArcGIS^{TM} 10.2 software by ESRI (Esri, 2010).

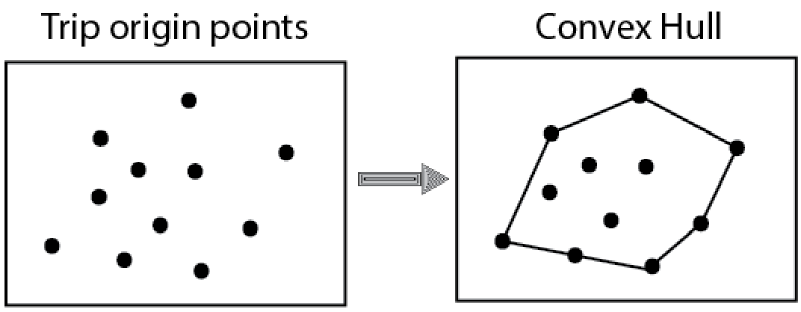

Figure 4.1 An illustration of the minimum bounding geometry approach

4.3.3 Catchment shape measures: compactness measure

Shape measures quantify aspects of the catchment area shape, such as compactness of shape (Li, Goodchild, & Church, 2013) and can be used to exhibit transportation efficiency and homogeneity of the regions around a station in terms of symmetry of network and accessibility of service (Maceachren, 1985). Maceachren (1985) stated that shape measures allow "*a measure of shape uniqueness by which any shape can be distinguished from all other shapes and similar shapes result in similar descriptions*." Shape measures have widespread applications especially in landscape ecology and geography (BÉLanger & Eagles, 2001; Flaherty & Crumplin, 1992; Gardoll, Groves, Knox-Robinson, Yun, & Elliott, 2000; Maceachren, 1985; Moser et al., 2002; Taylor, 1973; Wentz, 2000). Hundreds of metrics exist for measuring the characteristics of shapes (Angel, Parent, & Civco, 2010).

Compactness is acknowledged as one of the most intriguing and important properties of a shape (Angel, Parent, & Civco, 2010) and is widely used as a descriptor in various disciplines (Li et al., 2013). It quantifies how compact a shape is. Maceachren (1985) categorised the compactness of geographic shape measures into four groups: perimeter-area measurements, single parameters of related circles, direct comparison to a standard shape and dispersion of elements of an area around a central point.

This study adopted the compactness measurement of single parameters of related circles because a station catchment area has no hole inside and is scale-invariant. A train station is easier to travel to if the shape of its catchment area is roughly circular rather than long and thin. The compactness of a shape measure is defined as (Cole, 1964):

$$\mathrm{C} = \frac{A}{\pi R^2} \tag{4-1}$$

where

C is the compactness of a catchment area;

A is the area of a catchment area; and

R is the radius of the smallest circle that encloses the catchment area (see Figure 4.2).

The compactness of a catchment area of a train station is between *0* and *1*. One means the catchment area is a perfect circle, i.e. the catchment is "completely isotropic". If the compactness value is close to *0*, the catchment area is almost a line, which means people come from only one orientation, (e.g. north/south or east/west) to reach a train station and the catchment is "completely anisotropic. A station is not necessarily located at the centre of its catchment area (per Figure 4.2). Note that the above compactness measure does not take this into consideration; it is purely a function of the catchment shape compared to a circle. The compactness was also calculated for each segmentation variable (i.e. age, gender, trip direction and travel mode) for each station. The results of the compactness analysis for the seven stations in the case study are presented in Section 4.4.

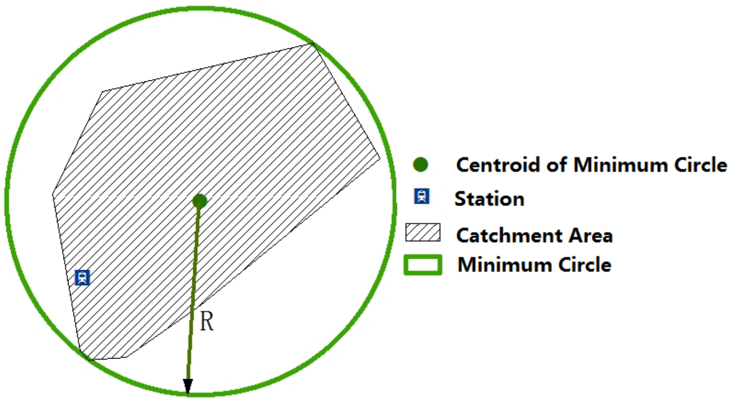

Figure 4.2 An illustration of compactness calculation

4.3.4 Relationship between the characteristics of a train station and the size and shape of its catchment area

This section explores how the characteristics of a train station may affect the size and shape of its catchment area. These characteristics include train frequency, bus frequency, station location (the end of a train line or along a line), parking capacity around a station, competitive index, land use diversity and the amount of residential land use within the catchment area. The parking capacity refers to the number of parking bays around a station, (as provided by Public Transport Authority in Western Australia). The bus frequency is the number of buses stopping at or close to the train station over 24 hours on a typical weekday. The train station comparative index refers to the total distance from the subject station to the six nearest stations. Land use diversity was measured using the following land use entropy equation (Frank et al., 2006; Lin et al., 2014):

$$Landusemix = -A / (\ln(N)) \tag{4-2}$$

$$A = \sum_{i=1}^{4} (b_i / a) * \ln(b_i / a) \tag{4-3}$$

where

b_1: the area of the Education land use type;

b_2: the area of the Entertainment, Recreational &Cultural land use types;

b_3: the area of the Health, Welfare & Community Services land use types;

b_4: the area of the Cultural, Shop &Retail land use types;

a: the total area of all four land use types if they are present in an 800m buffer around a train station; and

N: the number of the land use types present.

The independent-samples *t*-test (or independent t-test, for short) was used to determine if a difference exists between the means of two independent groups on a continuous dependent variable. For the independent groups that have more than two categories, the ANOVA was used. Further, correlation analysis was used to test the degree of association between variables.

4.3.5 The spatial market segmentation concept

The fundamental assumption of the spatial market segmentation method adopted in this chapter is that the size and compactness of the station catchment area varies depending on the user group and that the larger the size and the greater the compactness of the catchment area of a particular user group, the more attractive the station is for that group. This means that if a particular user group, say young train users, is willing to travel longer distances and from various directions to reach a transit station, the station is more attractive to this user group than to other user groups.

The key research question is therefore: how large or how compact does a particular user group's station catchment area need to be for that user group to be considered a key market segment, i.e. how close to the overall catchment size? In order to identify dominant segment of a station catchment area, two new measures were developed: a disaggregate market segment area ratio and a composite ratio.

- *Area ratio*

The area ratio is the ratio of the size of the catchment area for a particular subgroup or market segment, (e.g. Female), to the size of the overall catchment area, i.e. for all user groups combined.

$$r_{Aij} = A_{subij} / A_{wholej} \qquad 4\text{-}4$$

where

r_{Aij} is the area ratio of subgroup *i* at station *j*;

A_{subij} is the catchment area for subgroup *i* at station *j*; and

A_{wholej} is the catchment area for all subgroups combined at station *j*;

The area ratio is between 0 and 1. The higher the area ratio value, the more dominant a market segment is in terms of catchment area. For example, the area ratio of middle-aged is 0.98 for one of the train stations, which is almost the size of the overall catchment area. This could mean that the middle-aged travellers are the dominant user group at that station and are willing to travel longer distances to reach the station. However, this measure has the disadvantage of only comparing the catchment areas against each other, i.e. does not consider the actual shape (compactness) of the catchment area. Due to this limitation, another measure was developed, the composite ratio, which includes a shape (compactness) component.

- *Composite ratio*

. The composite ratio is calculated as follows:

$$r_{Comij} = r_{Aij} * C_{ij} \qquad 4\text{-}5$$

where

r_{Comij} is the composite ratio of subgroup *i* at station *j*;

r_{Aij} is the area ratio for subgroup *i* at station *j*;and

C_{ij} is the compactness of a catchment area for subgroup *i* at station *j*;

The composite ratio is between 0 and 1. The higher the composite ratio value, the more dominant a market segment is in terms of the size and compactness of catchment area, i.e. a dominant or key market segment is one that is more likely to travel longer distances and from diverse directions.

4.4 RESULTS

4.4.1 The size and compactness of a catchment area

The size and compactness of the catchment areas were calculated for all users combined and separately for each user group at each of the seven stations (Table 4.2 and Figure 4.3). Midland station has the largest overall catchment area, nearly 23 times larger than the smallest one, the catchment area of Claremont station. This is probably because Midland station is located at the end of Midland rail line and serves a large urban and semi-urban area. On the other hand, Claremont station serves a small area constrained by the Swan River, is a short distance from adjacent train stations, (0.7 km to the nearest inbound direction station, Showgrounds, and 1.1 km to the nearest outbound direction station, Swanbourne), and with a large part of the catchment area covered by non-residential land uses including lakes, park lands and recreation facilities (Shao et al., 2015). The catchment area of Cannington station is the second largest. This could be due to the presence of the Westfield Carousel shopping centre, which is one of the largest shopping/activity centres in Western Australia and located approximately 600 m from the train station. When comparing the catchment areas of the three age groups, the catchment areas of the elderly are, with the exception of Greenwood, the smallest. The young user group catchment areas are the largest at five stations.

The compactness results in Table 4.2 indicate that Claremont station's catchment area has the longest and thinnest shape with the lowest compactness value of 0.28. It also had the lowest number of boarders. Warwick station had the highest compactness value (0.69) and the second highest number of boarders. It could be that compactness has some positive relationship with train station ridership. Furthermore, the compactness value for the overall catchment area is not always the highest when compared to the value for an individual user group. For example, at Cannington station, the catchment area for young (18-25 years old) users has the largest compactness value (0.57), which means that young train users are more likely to travel from diverse directions to reach the station than the other age groups. However, the compactness of the young adult group catchment areas across the seven stations was found to vary more, (SD = 0.17), than the compactness values for the other two age groups. Midland station has the highest variation between different user groups (SD = 0.10) compared with Cannington with the lowest variation (SD = 0.04). This is illustrated on Figure 4.3. The compactness of a catchment area can also indicate potential station accessibility problems for certain user groups. For example, although Warwick station generally has good accessibility by most user groups, the elderly mainly access the station from a narrow area to the southwest. This could simply be due to fewer elderly living in the other areas (producing less demand), or could be due to some barriers hindering elderly access from the other directions, which would warrant further investigation.

Figure 4.3 provides a graphical representation of the data in the above tables, i.e. the spatial boundaries of the seven stations and their subgroup catchment areas. Note that the spatial boundaries of the Greenwood BnR catchment areas are not displayed due to lack of sufficient data. The size and shape of catchment areas vary greatly among train stations and their subgroups. For example, Greenwood station has the highest variation in the size and shape of subgroup catchment areas compared to the overall catchment area. Elderly and female train users tended to come from areas north of the station whilst young and male train users were more likely to come from areas south of the station. However, the catchment area of the middle-aged group was distributed in an east-west direction. Generally, young people had relatively larger catchment areas than elderly and middle-aged users. The size and compactness of PnR and BnR user group catchment areas were heavily influenced by the surrounding road network and bus routes as well as the frequencies of bus and train services. For example, at Greenwood, the BnR catchment area is much smaller than the PnR catchment area due to the station only being serviced by one bus route. The inbound and outbound catchment areas were not necessarily directly related to their direction of travel. In some instances, people chose stations that were located further away from their destination.

Table 4.2 Size and compactness of the seven station catchment areas

Station	Size of catchment area (Km^2)										
	Cannington	Claremont	Greenwood	Midland	Murdoch	Warnbro	Warwick	Including Midland		Excluding Midland	
								Mean	SD	Mean	SD
All	165.06	46.56	80.85	1062.35	112.05	74.34	81.95	231.88	368.09	93.47	40.81
Young	136.01	37.13	44.47	584.82	86	68.68	80.97	148.3	195.19	75.54	35.45
Middle	104.93	45.88	36.92	739.44	78.82	46.63	65.45	159.72	256.69	63.11	25.52
Elderly	69.55	21.2	43.15	337.92	52.57	38.81	23.21	83.77	113.3	41.42	18.25
Male	139.04	34.45	51.6	662.03	101.37	60.11	80.84	161.35	223.48	77.9	37.93
Female	113.36	46.49	51.26	800.48	90.92	61.47	69.45	176.2	276.27	72.16	25.56
Inbound	155.59	45.95	57.46	1062.35	107.33	74.34	65.33	224.05	371.51	84.33	40.65
Outbound	78.2	21.73	29.93	0	48.11	10.61	56.47	35.01	27.45	40.84	24.86
BnR	104.97	23.97	0	323.17	73.02	41.26	63.06	89.92	108.35	51.05	37.34
PnR	125.59	41.95	60.9	693.11	47.48	61.81	81.95	158.97	237.18	69.95	30.58
Mean[1]	114.14	35.42	41.74	578.15	76.18	51.52	65.19				
SD[2]	28.28	10.67	18.43	313.68	22.65	19.55	18.15				

Station	Compactness of catchment area										
	Cannington	Claremont	Greenwood	Midland	Murdoch	Warnbro	Warwick	Including Midland		Excluding Midland	
								Mean	SD	Mean	SD
All	0.51	0.28	0.52	0.53	0.56	0.33	0.69	0.49	0.14	0.48	0.15
Young	0.59	0.22	0.49	0.34	0.54	0.3	0.68	0.45	0.17	0.47	0.18
Middle	0.41	0.28	0.37	0.44	0.44	0.44	0.58	0.42	0.09	0.42	0.1
Elderly	0.54	0.26	0.42	0.27	0.4	0.41	0.49	0.4	0.1	0.42	0.1
Male	0.52	0.23	0.55	0.33	0.55	0.31	0.68	0.45	0.16	0.47	0.17
Female	0.49	0.28	0.5	0.46	0.59	0.29	0.62	0.46	0.13	0.46	0.15
Inbound	0.57	0.28	0.5	0.53	0.54	0.33	0.58	0.48	0.12	0.47	0.13
Outbound	0.5	0.31	0.44		0.38	0.34	0.48	0.41	0.08	0.41	0.08
BnR	0.55	0.16		0.57	0.53	0.4	0.56	0.46	0.16	0.44	0.17
PnR	0.56	0.28	0.53	0.38	0.52	0.33	0.69	0.47	0.15	0.49	0.15
Mean	0.53	0.26	0.48	0.42	0.50	0.35	0.60				
SD	0.04	0.05	0.06	0.10	0.07	0.05	0.08				

Station	Daily station boardings (September 2011)[3]						
	Cannington	Claremont	Greenwood	Midland	Murdoch	Warnbro	Warwick
Total Daily Boarding	3,165	1,967	2,143	3,899	7,898	2,735	5,867
Bus to Train transfers	1,129	227	4	1,211	4,430	736	2,480

1 Mean for subgroup 2 SD for subgroup 3 Source - PTA

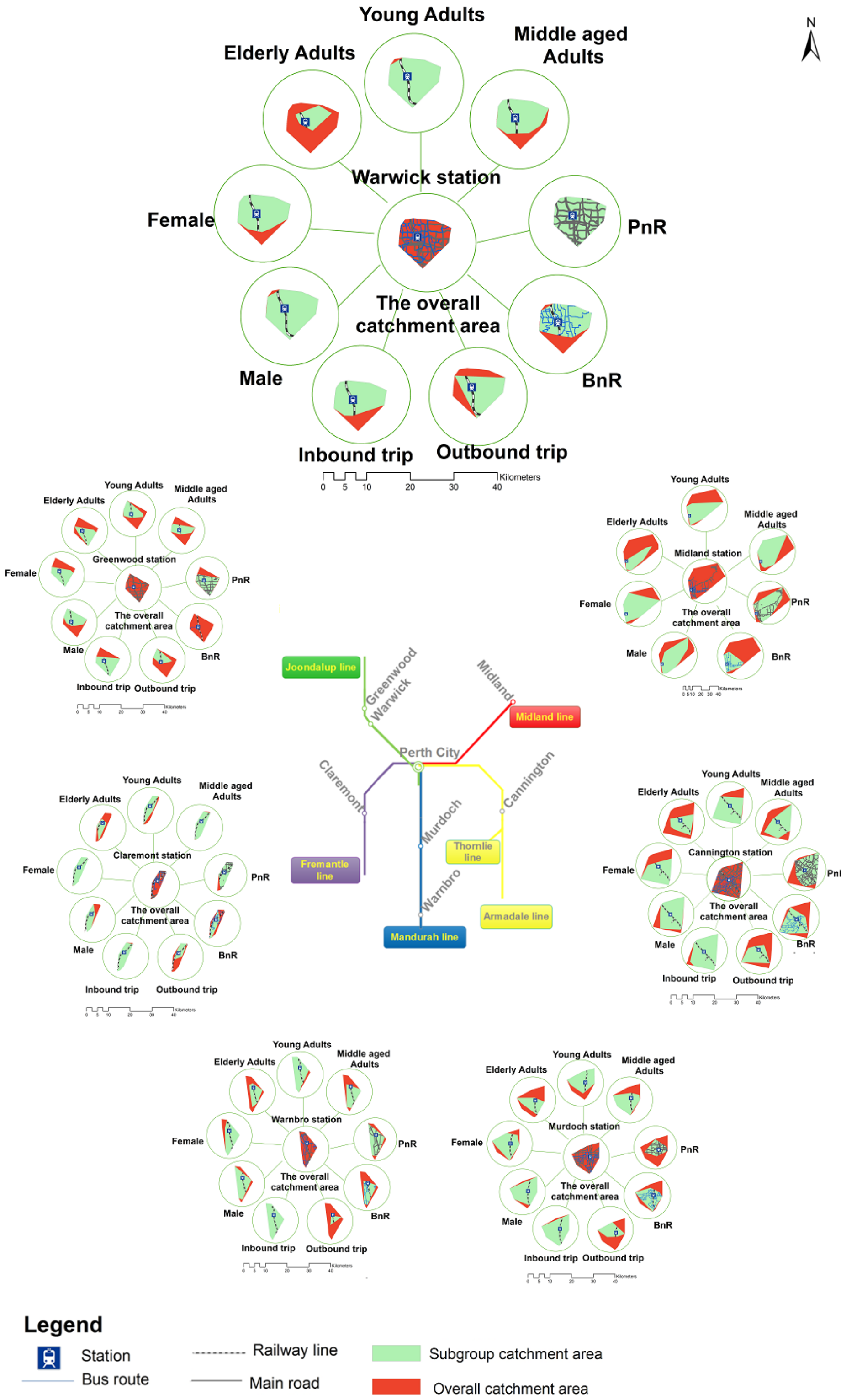

Figure 4.3 The spatial boundary of train station and its subgroup catchment areas

4.4.2 Disaggregate market segment area ratio and composite ratio

As discussed in Section 4.3, area ratio and composite ratio measures were developed as part of the spatial segmentation analysis. The area ratio is the ratio of the size of a subgroup catchment to the size of the overall catchment. The purpose of this ratio is to identify a key market segment, i.e. one that is willing to travel a longer distance to reach a train station. The area ratio ranges between 0 and 1, the closer to 1, the closer the size of that user group catchment area is to the size of the overall catchment area and the more likely it is that user group is a key market segment. Table 4.3 and Figure 4.3 present the user group area ratios for the seven train stations. A number of useful insights emerge from this analysis:

- The area ratio of the female user group for Claremont station is one.

  This means that the size of the female catchment area is equal to the size of the overall catchment area. In other words, the female catchment area spatially defines the overall station catchment area. Therefore, it might reasonably be concluded that the female group is one of the key market segments for Claremont station.
- The inbound, middle aged and PnR user groups are also relatively important market segments for Claremont station.
- Greenwood station has the lowest subgroup area ratios compared to the other train stations whilst Warwick station has the highest. Nevertheless, the PnR user group was found to be a key market segment for both stations.
- Most stations have a larger PnR than BnR area ratio except for Murdoch station.
- It can also be seen in Figure 4.3 that the PnR catchment area is much smaller than the BnR catchment area for Murdoch station.

The composite ratio is the area ratio weighted by the compactness of the catchment area. Again, the composite ratio ranges between 0 and 1, the higher the value, the more likely that user group is to be a key market segment. The results for the seven stations are also presented in Table 4.3. The key market segments determined from the composite ratio vary slightly from those determined from the area ratio. For example, compared to the area ratio results, the composite ratios indicate that the young aged group becomes more important than the male group for Cannington station, which means that the shape of the young aged catchment area is more compact than the shape of male user group catchment area, (the most dominant area from the area ratio results). Although, in general, the two methods provide similar results with respect to dominant user groups, the composite ratio is more sensitive to the shape of catchment area. An example is Claremont station which has long narrow catchment areas, high area ratios but low composite ratios.

Table 4.3 Spatially dominant market segments for each station

Rank	Area ratio						
	Cannington	**Claremont**	**Greenwood**	**Midland***	**Murdoch**	**Warnbro**	**Warwick**
1	InBound (0.94)	Female (1.00)	PnR (0.75)	InBound (1.00)	InBound (0.96)	InBound (1.00)	PnR (1.00)
2	Male (0.84)	InBound (0.99)	InBound (0.71)	Female (0.76)	Male (0.90)	Young (0.92)	Young (0.99)
3	Young (0.82)	Middle (0.99)	Male (0.64)	Middle (0.70)	Female (0.81)	PnR (0.83)	Male (0.98)
4	PnR (0.76)	PnR (0.90)	Female (0.63)	PnR (0.65)	Young (0.77)	Female (0.83)	Female (0.85)
5	Female (0.69)	Young (0.80)	Young (0.55)	Male (0.62)	Middle (0.70)	Male (0.81)	Middle (0.80)
6	BnR (0.64)	Male (0.74)	Elderly (0.53)	Young (0.55)	BnR (0.65)	Middle (0.63)	InBound (0.80)
7	Middle (0.64)	BnR (0.51)	Middle (0.46)	Elderly (0.31)	Elderly (0.47)	BnR (0.56)	BnR (0.77)
8	OutBound (0.47)	OutBound (0.47)	OutBound (0.37)	BnR (0.30)	OutBound (0.43)	Elderly (0.52)	OutBound (0.69)
9	Elderly (0.42)	Elderly (0.46)			PnR (0.42)	OutBound (0.14)	Elderly (0.28)
Rank	**Composite ratio**						
	Cannington	**Claremont**	**Greenwood**	**Midland**	**Murdoch**	**Warnbro**	**Warwick**
1	InBound (0.54)	Female (0.28)	PnR (0.40)	InBound (0.53)	InBound (0.52)	InBound (0.33)	PnR (0.68)
2	Young (0.48)	Middle (0.28)	InBound (0.36)	Female (0.35)	Male (0.50)	Middle (0.28)	Young (0.67)
3	Male (0.44)	InBound (0.28)	Male (0.35)	Middle (0.31)	Female (0.48)	Young (0.28)	Male (0.67)
4	PnR (0.42)	PnR (0.25)	Female (0.32)	PnR (0.25)	Middle (0.42)	PnR (0.28)	Female (0.53)
5	BnR (0.35)	Young (0.18)	Young (0.27)	Male (0.20)	BnR (0.34)	Male (0.25)	Middle (0.47)
6	Female (0.33)	Male (0.17)	Elderly (0.22)	Young (0.19)	Middle (0.31)	Female (0.24)	InBound (0.47)
7	Middle (0.26)	OutBound (0.15)	Middle (0.17)	BnR (0.17)	PnR (0.22)	BnR (0.22)	BnR (0.43)
8	OutBound (0.24)	Elderly (0.12)	OutBound (0.16)	Elderly (0.08)	Elderly (0.19)	Elderly (0.21)	OutBound (0.33)
9	Elderly (0.23)	BnR (0.08)			OutBound (0.17)	OutBound (0.05)	Elderly (0.14)

4.4.3 The relationship between size and compactness of station catchment area and station characteristics

This section discusses the relationships between the size and compactness of a station catchment area and the station's characteristics. As stated in section 3.4, the assumption in this research is that the location of stations, frequency of train and bus services, parking capacity of train stations, the distance to nearest stations (comparative index) and the surrounding land use diversity could influence the size and compactness of catchment areas. These characteristics are show in Table 4.4. The relationships between the size and compactness of station catchment areas and these station characteristics are shown in Table 4.5.

Table 4.4 Summary of the train station characteristics

Characteristic	Station						
	Cannington	**Claremont**	**Greenwood**	**Midland**	**Murdoch**	**Warnbro**	**Warwick**
Land use diversity value	0.41	0.33	0.37	0.44	0.35	0	0.21
Predominant land uses	Residential Recreational Shops	Residential Recreational Shops	Residential Recreational Educational	Residential Shops Recreational	Residential Health, Recreational	Residential Recreational	Residential Recreational Educational
Competitive index (km)*	16.4	11.9	37.8	23.1	45.2	100.1	41.7
PnR Parking capacity	244	45	931	609	1152	790	978
All-stop (1) or non-all-stop (0)	1	1	0	1	1	0	1
Buses per Day	306	102	32	330	365	36	522

The first column in Table 4.5, (catchment size by station location), provides evidence to support the hypothesis that the size of the catchment area of a station at the end of train line is much larger than that of a station along the train line. The overall train station catchment area at the end of train line, (1062.35 km^2), was 11.37 times larger than the average catchment area of stations along the line, (93.47 km^2). For the subgroup catchment areas, it ranged from about 8 to 13 times larger. Train frequency can also affect the size of catchment areas, (see the train frequency column in Table

4.5). The two columns of figures are the average size and shape of the catchment area for those stations with high train frequencies and those with low frequencies. For example, the average size of the whole catchment area of those stations with a high train frequency, (excluding Midland), is 101.4 km^2, which is around 1.3 times larger than the average for those stations with a low train frequency. For each segment catchment area, the catchment area is consistently larger if the station serves express trains (high frequency), except for elderly user catchment areas which weren't affected by train frequency. This may be because the elderly usually travel at off-peak times when trains run less frequently. Stations with higher train frequencies seem to encourage users to not only travel longer distances to access the station but also to travel from more diverse directions.

The correlation between the size of the catchment area and the train station characteristics and the correlation between the compactness of the catchment area and the train station characteristics, such as parking capacity, have also been calculated, (see Table 4.5, the last four columns). An increase in land use diversity was found to increase transit use by authors such as Cervero and Kockelman (1997) and Frank and Pivo (1994). From our result, there is positive relationship between the size of the train station catchment area with the land use diversity which means that an increase in land use diversity surrounding a train station may translate into an increase in the catchment area size by attracting users from further away or a change of the catchment area shape by attracting users from different directions.

Table 4.5 The relationship between the size and compactness of station catchment areas and station characteristics

User Subgroup	Average size of catchment area by station location (Km2)		Average size of catchment area by train frequency (Km2)		Parking Capacity	Bus Frequency	Comparati-ve Index	Land Use Diversity
	End of line	**Between the line**	**High**[2]	**Low**	**Correlation (*p*-value)**			
All	1062.35 (11.37)[1]	93.47	101.40 (293.59)	77.59	-0.02 (0.98)	0.41 (0.42)	-0.22 (0.68)	0.43 (0.40)
Young	584.82 (7.74)[1]	75.55	85.03 (184.99)	56.58	-0.05 (0.92)	0.56 (0.25)	-0.11 (0.83)	0.20 (0.70)
Middle Aged	739.44 (11.72)[1]	63.10	73.77 (206.90)	41.77	-0.13 (0.80)	0.65 (0.17)	-0.34 (0.52)	0.40 (0.43)
Elderly	337.92 (8.16)[1]	41.42	**41.63** **(100.89)**	**40.98**	0.01 (0.98)	0.06 (0.91)	-0.08 (0.88)	0.40 (0.43)
Male	662.03 (8.50)[1]	77.90	88.93 (203.55)	55.85	0.05 (0.92)	0.60 (0.21)	-0.18 (0.73)	0.34 (0.51)
Female	800.48 (11.09)[1]	72.16	80.06 (224.14)	56.36	0.00 (1.00)	0.56 (0.25)	-0.19 (0.72)	0.34 (0.50)
BusnRide	323.17 (3.08)[1]	104.91	66.25 (117.64)	41.26	0.14 (0.82)	0.57 (0.31)	-0.26 (0.68)	0.50 (0.39)
ParknRide	693.11 (9.91)[1]	69.95	74.24 (198.02)	61.35	-0.25 (0.64)	0.38 (0.46)	-0.23 (0.67)	0.21 (0.69)
InBound	1062.35 (13.23)[1]	80.30	87.50 (282.47)	65.90	0.06 (0.91)	0.39 (0.44)	-0.04 (0.93)	0.27 (0.61)
OutBound	N/A	44.88	**57.18** **(57.18)**	**20.27**	0.18 (0.73)	0.73 (0.10)	-0.31 (0.56)	0.43 (0.39)

Compactness	**The average compactness of catchment areas by location**		**The average compactness of catchment areas by train frequency**		**Parking Capacity**	**Bus Frequency**	**Competitive Index**	**Percentage of residential area**
	End of line	**Between the line**	**High**	**Low**	**Correlation (*p*-value)**			
All	0.53	0.48	0.51	0.42	0.60 (0.16)	0.790* (0.03)	-0.17 (0.71)	-0.16 (0.73)
Young	0.34	0.47	0.47	0.40	0.49 (0.27)	0.69 (0.09)	-0.11 (0.82)	0.25 (0.59)
Middle Aged	0.44	0.42	0.43	0.41	0.63 (0.13)	0.73 (0.06)	0.35 (0.45)	-0.14 (0.76)
Elderly	0.27	0.42	0.39	0.42	0.27 (0.55)	0.30 (0.52)	0.19 (0.69)	0.48 (0.27)
Male	0.33	0.47	0.46	0.43	0.61 (0.15)	0.59 (0.16)	-0.05 (0.92)	0.29 (0.53)
Female	0.46	0.46	0.49	0.40	0.63 (0.13)	0.757* (0.05)	-0.21 (0.65)	0.04 (0.94)

BusnRide	0.57	0.44	0.48	0.40	0.58 (0.23)	0.74 (0.09)	0.04 (0.94)	-0.36 (0.48)
ParknRide	0.38	0.48	0.49	0.43	0.50 (0.26)	0.67 (0.10)	-0.14 (0.77)	0.19 (0.68)
InBound	0.53	0.47	0.50	0.41	0.43 (0.33)	0.74 (0.06)	-0.29 (0.53)	-0.23 (0.62)
OutBound	#NULL!	**0.41**	0.42	0.39	0.18 (0.74)	0.54 (0.27)	-0.30 (0.57)	-0.34 (0.52)
Average	0.43	0.45	0.46	0.43				

1: Value in the bracket shows how many times the catchment area at the end of train line is larger than the catchment area along train line.

2: Value on the top shows the average size of train station catchment area calculated without Midland station; Value inside the bracket shows the average size of train station catchment area calculated with Midland station.

* : Correlation is significant at 0.05 level (2-tailed).

4.4.4 Spatial segmentation with traditional clustering analysis based segmentation

Expectation Maximization (EM) clustering is the algorithm used to detect clusters in the observations or variables and assign those observations into clusters. Table 4.6 shows the clustering results based on the EM algorithm in Weka^{TM}. The α column gives the proportion of train users assigned to each cluster. For example, 36% of train users were assigned to cluster one for Cannington station. The output numbers for each cluster (row) and category such as gender, (column) are frequency counts, i.e. how many train users belong to the female user subgroup in cluster one. The frequency counts can be fractional because the EM algorithm is a soft clustering method, i.e. each train user is assigned to a cluster based on probabilities. (Witten & Frank, 2005). The grey shaded cells indicate the dominant characteristics for each cluster.

As mentioned, the spatial segmentation method, either by area ratio or composite ratio, is able to identify the dominant clusters. The same as EM algorithm. Table 4.7

summarizes the most dominate cluster based on three methods. It is found consistently for three different methods in Table 4.7 although with a slight difference. For example, it is found that in Claremont station, the dominant segment is female, PnR, middle, inbound commuter which the output of three different methods are consistent. For Cannington station, it is a slight different, for example, it is examined by EM algorithm that BnR is dominant but in the other two methods PnR is. However, the other dominant subgroups are the same which are: male, young, inbound.

Table 4.6 Clustering analysis based on EM algorithm

Station	Cluster	α	Gender		Travel mode		Age			Trip Direction	
			M	F	BnR	PnR	Young	Middle	Elderly	Inbound	Outbound
Cannington	1(68)	0.68	45.20	22.04	52.34	15.20	41.47	19.15	7.93	55.92	11.61
	2(29)	0.32	12.50	20.96	6.66	26.80	7.53	21.85	5.08	32.07	1.38
Claremont	1(19)	0.37	18.79	1.73	4.93	15.61	4.14	9.69	7.69	16.60	3.93
	2(22)	0.44	1.93	22.01	4.05	19.89	7.15	15.81	1.98	21.60	2.35
	3(8)	0.19	2.28	9.25	1.02	10.50	8.07	1.49	2.33	1.80	9.73
Greenwood	1(82)	1	38	46	4	80	22	54	9	80	4
Midland	1(29)	0.36	1.97	29.01	5.10	25.88	12.73	14.07	5.18	29.98	
	2(18)	0.24	18.99	1.89	2.30	18.57	7.85	1.94	12.08	19.87	
	3(14)	0.18	14.82	1.86	3.06	13.62	1.83	14.08	1.77	15.68	
	4(19)	0.22	9.23	10.24	17.54	1.93	15.59	1.90	2.97	18.47	
Murdoch	1(16)	0.29	8.30	15.16	8.69	14.77	12.03	8.42	4.01	21.31	2.13
	2(45)	0.52	30.63	9.58	32.10	8.11	24.04	12.50	4.66	36.47	3.73
	3(13)	0.19	2.07	14.27	14.21	2.11	9.92	3.08	4.33	3.20	13.12
Warnbro	1(97)	1	51	48	49	50	53	32	15	95	4
Warwick	1(29)	0.39	13.48	12.83	21.63	4.68	15.79	9.29	2.24	12.63	13.68
	2(71)	0.61	24.51	38.17	23.36	39.32	20.21	34.70	8.76	60.37	2.32

Table 4.7 Key Segments as Identified by the EM algorithm and spatial segmentation methods

Station	EM algorithm	Spatial segmentation by area ratio	Spatial segmentation by composite ratio
Cannington	Male,BnR, Young,Inbound	Male,PnR, Young,Inbound	Male,PnR, Young,Inbound
Claremont	Female,PnR, Middle,Inbound	Female,PnR, Middle,Inbound	Female,PnR, Middle,Inbound
Greenwood	Female,PnR, Middle,Inbound	Male,PnR, Young,Inbound	Male,PnR, Young,Inbound
Midland	Female,PnR, Middle,Inbound	Female,PnR, Middle,Inbound	Female,PnR, Middle,Inbound
Murdoch	Male,BnR, Young,Inbound	Male,BnR, Young,Inbound	Male,BnR, Middle,Inbound
Warnbro	Male,PnR, Middle,Inbound	Female,PnR, Young,Inbound	Male,PnR, Young,Inbound
Warwick	Female,PnR, Middle,Inbound	Male,PnR, Young,Inbound	Male,PnR, Middle,Inbound

4.5 DISCUSSIONS

4.5.1 Spatial market segmentation

Traditional market segmentation methods derive the dominant segment(s) of users based on the frequency or probability of those characteristics occurring in the data (Witten & Frank, 2005). However, the spatial market segmentation methods developed in this study identify key market segments by exploring the size and shape of their train station catchment areas. An area ratio and a composite ratio have been developed to identify the dominant segment(s) of train station catchment areas from a spatial perspective (distance and direction). The area ratio identifies which user groups travelled longer distances to access stations. The composite ratio identifies user groups that travelled both longer distances and from diverse directions. User groups who are willing to travel longer distances to reach a station do not necessarily access the train station from diverse directions. Identifying the spatially dominant characteristics of users could assist transport planners and operators in managing the demand and supply sides of train services. For example, on the demand side, information such as the core users (dominant characteristics) could be a valuable source for targeted marketing to further promote train services or to market some relevant business by using customised business advertisements at or around train stations. On the supply side, information about the catchment areas of non-dominant users could facilitate an understanding of the problems or barriers to train service use by certain user groups. Therefore, further interventions or strategies could be put in place to encourage these users to use train services (Mulley et al., 2012).

4.5.2 Characteristics of a catchment area

The most noticeable result from this study is that different user subgroups have catchment areas of varying size and shape, which may influence or reflect their travel behaviour. For example, the size of the middle-aged catchment area is larger than that of other age groups. However, the compactness of the young user group catchment is higher than that of other age groups. The middle-aged group travel longer distances to reach a train station, while the young user group travel from more diverse directions to access a train station compared to other age groups. According to the ABS (2013) social trends survey, young people had one of the highest shares of travel by public transport to get to work or study (28%) , whilst the middle-aged population (55-64 years) were the most likely to drive to work or study (78%). Delbosc and Currie (2014) also identified reasons why young Australians may be turning their back on the car, such as a reduction in those getting a driving license, a change in the social status of the car, greater awareness of the environment and the role of electronic communications. All these may explain why the young user group catchment area is more compact than that of older age groups. Although PnR catchment sizes are larger than those for BnR, the compactness of the PnR and BnR catchment areas is similar. This may indicate that PnR is more flexible than BnR, i.e. it allows PnR users to drive longer distances to access a train station.

Good train services alone may not attract diverse and intense usage. An integrated transport system has been proven to be a more efficient way to increase the mobility of a community (Cervero & Kockelman, 1997; Ewing & Cervero, 2010; Sung et al., 2014; Zemp et al. , 2011). The spatial market segmentation methodology in this paper used a limited number of user characteristics, such as age and gender, selected based on the data available to this study. The key segments identified were therefore limited to these pre-selected segments. The methodology described can however be used to identify other potential key market segments, such as disaggregation by income level, ethnicity and affordability or social mix which are all known to affect rail ridership (Lucas & Jones, 2012). In addition, Walk and Ride (WnR) was excluded from the analysis due to limitations in the survey. This is clearly another area for future analysis.

4.5.3 Catchment area measures

There has been some debate over the validity and limitations of the convex-hull method. Some studies suggest that convex hull polygons are inferior in the applications of potential path areas and activity spaces. The main reasons are 1) the convex activity-space polygon might overestimate or underestimate the activity space due to sampling limitation (Chaix et al., 2012). and 2) the convex hull polygon method is sensitive to spatial outliers (Thériault, Claramunt, & Villeneuve, 1999). However, the choice of methods depends on the purpose of the study. In this research, the catchment area of a train station was defined as an area within which local residents could potentially use train services. Therefore, it would be reasonable to include some areas where residents haven't used train services yet but could potentially use the services in the future. In addition, in order to avoid spatial outliers, 10% of data, which could be spatial outliers, were removed for the analysis. Other methods, such as spatial outlier detection algorithms could be used to improve the validity of the convex hull polygon methods (Lu, Chen, & Kou, 2003; Shekhar, Lu, & Zhang, 2003). In the future, a study will be developed to systematically evaluate the efficiency of spatial outlier detection methods on the improvement of the convex hull polygon method. Compactness is a good measure of the shape of catchment areas, which can indicate the trip direction. However, this direction refers to the centre of the catchment area rather than the train station itself, (which is rarely in the centre of its catchment area). In future research, a station centrality measure will be developed to account for train stations rarely being in the centre of their catchments.

The size and shape of a catchment area are sensitive to the sample size because its spatial boundary is determined based on the origin locations of individual travellers. Although the survey was conducted from 6:00am to 4:00pm and covered the period when most trips used a station as the origin station, the sample size of some of the subgroups, (e.g. the elderly), is not that large. Therefore, the catchment areas may not be fully representative. Further analysis has been conducted to test the influence of sample size on the catchment area by comparing the elderly group catchment areas derived from 2012 data only with those derived from the 2012 plus 2013 data,. The results, presented in Table 4.8, show that both the size and shape values change with changes in the sample size. For all stations except Cannington station, the catchment area size increase as the sample size increases. There is a notable size change at Midland, Claremont and Greenwood stations. Interestingly, Midland has a very large catchment area, whilst Claremont station has a very small catchment area. Perhaps when the catchment area is extremely large or small, it is more sensitive to spatial outliers. For Greenwood station, the threefold increase of the sample size (5 to 14) might be the reason for the change of the catchment area size. In addition, the size and shape of catchment areas may be closely related to residential locations. For example, trip directions mostly align with residential locations. Figure 4.4 illustrates the residential location of the elderly. Many retired people live on the southeast side of

Midland station. The shape of the elderly catchment area of Midland station was elongated in this direction (See Figures 4.3 and 4.4).

Table 4.8 Elderly catchment area comparisons

Station	The elderly segmentation									
	2012 only				2012+2013				Change (2012/(2012+2013))	
	Sample Size(All data)	Sample Size(Outliers removed)	Size (Km2)	Shape	Sample Size(All data)	Sample Size(Outliers removed)	Size (Km2)	Shape	Size Change	Shape Change
Cannington	16	13	94.35	0.45	20	14	69.55	0.54	1.36	0.83
Claremont	11	10	7.28	0.47	16	14	21.2	0.26	0.34	1.8
Greenwood	5	5	10.35	0.26	18	14	43.15	0.42	0.24	0.62
Midland	28	21	85.68	0.56	33	29	337.92	0.27	0.25	2.07
Murdoch	15	15	48.78	0.37	20	20	52.57	0.4	0.93	0.93
Warnbro	13	12	34.43	0.4	18	17	38.81	0.41	0.89	0.99
Warwick	14	13	18.91	0.61	18	15	23.21	0.49	0.81	1.26

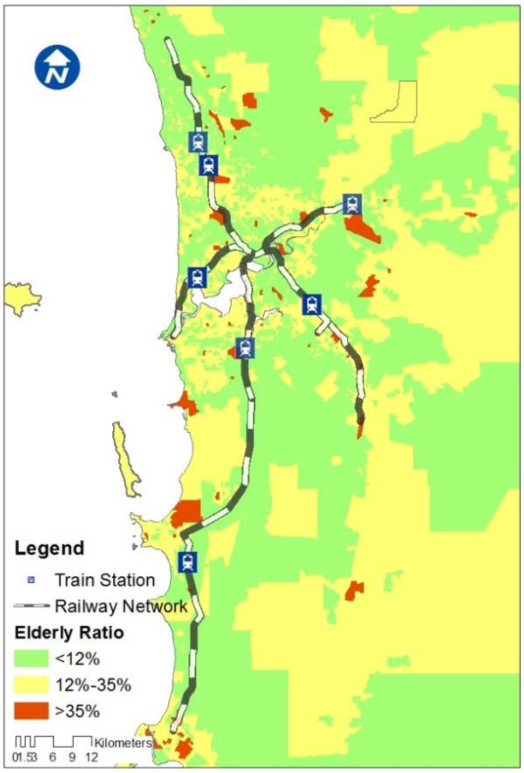

Figure 4.4 The map of the elderly distribution

4.6 SUMMARY

Identifying the size and compactness of train station catchment areas is an important input to the understanding of distance travelled and the trip direction of transit users (El-Geneidy et al., 2014). It is also important to investigate the different types of transit users and the distances and directions they travel for marketing purposes. In this chapter, GIS techniques have been applied to derive and visualise the spatial distribution of catchment areas by various user groups, which have been shown to clearly relate to distance travelled and travel direction. According to findings in this chapter (see Figure 4.3), it is found that if train users accessed a train station from a small, thin and long catchment area, this might indicate that this station could have some potential accessibility constraints or problems hindering users. If the size and shape of the catchment areas for different train user groups vary significantly or a train station only attracts a certain group of users from a certain direction, it may indicate that some characteristics of a station or its catchment area are playing a negative role in attracting this group of train users. In addition, this chapter has developed a novel method for identifying the spatially dominant market segments of train services. Understanding the size and compactness of catchment areas by different user groups and target markets of stations is a vital component of integrated transport planning and promoting train services.

The next chapter will discuss the second component of the exploratory data analysis, the trip direction analysis. The concepts and methods related to the trip frequency measure, centrality and spatial integrity will be discussed.

CHAPTER 5 TRIP DIRECTION ANALYSIS

5.1 INTRODUCTION

The previous chapter explored the characteristics of train station catchment area and proposed a novel method for spatial market segmentation which provided a clear picture on the train station catchment area characteristics, relevant factors that affect catchment area shape and size and understanding of main segmentation of each surveyed station from spatial view. This chapter will continue with our data exploratory analysis but will focus on the trip direction analysis. Trip direction analysis is vital for understanding trip distribution and also very important for understanding directional accessibility.

5.2 RESEARCH CONTEXT

Trip direction indicates where trips come from to access a facility, such as a train station. Understanding trip distribution in different directions is essential for transport forecasting as a more accurate trip generation model requires the understanding of interaction between trips and a variety of relevant factors such as land use pattern and development, socio-economic, and nature extent of the transport system. For example, a practical in Australia used gross floor area, gross leasable floor area, and dwelling units in trip generation modelling.(Mousavi, Bunker, & Lee, 2012). Kim and Susilo (2013) applied Poisson regression and negative binomial regression to estimate the pedestrian trips using a series of variables such as socio-economic variables (including household size, age, income, race, education, car ownership, and driver status), land-use patterns (population density and household size, more detailed information on land use and the built environment). However, a symmetrical analysis of the relationship between those factors and the amount of trips observed from different trip directions is limited in the current literature.

Additionally, trip direction is an important indicator to understand directional accessibility to a facility. Liu et al.(2012) investigated the distributions of the distance and direction of the extracted trips. It was found that the anisotropic trip distribution is usually caused by geographical constraints, such as the street network. Furthermore, if land use types around a train station are mainly non-residential, e.g., lakes, parks, shopping centres or recreation centres, and distribute fragmentally, this might force train users to come from only certain directions (Lin et al., 2016). If a train station has better train services and facilities, such as higher train frequency and safer and cleaner cabins, people are more likely to access the train station from diverse directions. Trip direction analysis is vital to transport planning. Currently, quantitative measures of relationship between trip directions and these factors have not been reported in Western Australia and our knowledge about characteristics of trip directions is very limited.

A catchment area refers to the areal extent from which the majority of trips originated (Dolega et al., 2016). The relation between trip direction and catchment area is obvious. When people access a station from a diverse direction with equal frequency and distance, the catchment area of the station will be a near circular shape and the train station will locate at the centre of the catchment area. However, in reality, this almost perfect spatial pattern of the catchment area and station seldom occurs. Instead, asymmetrical shape of a catchment area and the centroid of the catchment area locating away from the train station are common practice (Vincent, 2007). For example, Turnbull et al. (2004) suggested that the catchment area of Park and Ride (PnR) stations tends to be a parabolic shape with a directional axis oriented to a major destination, such as towards the central business district (CBD) because train patrons seldom choose to backtrack. Therefore, it is interesting to explore the location of centroid of the catchment area caused by trip asymmetrical distribution from various directions.

The concept of centrality, originating from graph theory, is a consolidated issue in social science, geographic and land-use modelling, and, more recently, intensively used in social-network analysis and transport-network analysis (Carrington et al., 2005; Choi et al., 2006; Rubulotta et al., 2012; Saito & Nishizeki, 1981; Turner, 2007; Wang et al., 2011). However, the literature regarding centrality is not rich, with the exception of social studies. In social science, it is an indicator to identify the most import node/most influential person(s) in a social network. In other words, it is a measure of the structural importance of the node. However, social network centrality study has some similarities with the concept of centrality in transport. The road network could be treated the same as a social network. The person, who is central in the social network, might have higher influence to the rest of the network than the nodes located at the edge of the network. This is the same to a node, such as a train station, which locates centrally. In the view of Geurs and Van Wee (2004), the locations with highest accessibility scores are necessarily the ones with the highest degree of centrality in the transport network. It is said the accessibility and network centrality approaches open up new perspectives on the complex connection between land use and street features (Kang, 2015).

There are three popular indices to measure the different aspects of centrality: degree, closeness, and betweenness (Neal, 2012). A node's degree centrality is measured by counting the total number of edges that are connected to it; closeness centrality focuses on how close a node is to every other node in the network with measure of the ratio of the shortest path between nodes and total path length; betweenness centrality is defined as the average proportion of paths between any two nodes within the network that traverse nodes, out of the total number of possible paths between these two nodes (Neal, 2012; Scheurer & Curtis, 2007). In the train station centrality research, in the concept of centrality, the most interesting thing is to identify how central the train station is located comparing to the geometric centroid of the catchment area and if the train users inside the catchment have equal access to use the service, which the existing degree, closeness, and betweenness centrality cannot measure. A new centrality index is needed.

Spatial integrity is commonly used in environmental studies for understanding how perforated and fragmented a region is (DeMers, 2008). For example, if a habitat of grizzly bears has a high integrity value, it reveals that the habitat is quiet well reserved and remains less modified by human activities. A common numerical measure of spatial integrity is the Euler function named after the Swiss mathematician (Bogaert, Hecke, & Ceulemans, 2002). Spatial integrity, in this paper, was studied from an integration of transport and land use perspective. It indicates geographical constraint on land use development, such as, residential land use, around a train station. The higher the spatial integrity of developed land use around a station, the more likely patrons come from diverse directions to reach a train station and the more trips are generated. Spatial integrity is one of important factors affecting trip directions and the centrality of and accessibility to a train station.

In summary, the centrality of a train station and spatial integrity of land use are vital to understand accessibility to a train station. So far, very few efforts have been made towards developing quantitative measures of them based on the spatial distribution of train stations' catchment areas. This study fills in this research gap in three new ways:

- Develop new spatial tools to investigate trip directions by measuring the centrality of train stations in relation to their catchment area and the shape of station catchment areas;
- Establish new tools such as spatial integrity index based on land use within catchment areas, more specifically residential-to-non-residential land use ratio (r/nr ratio) to understand why more frequent trips at certain directions occur; and
- Create new geovisualisation methods to understand trip directions using geographic information systems (GIS).

The aim of this study is to develop new spatial methods for understanding trip directions to access a train station and factors influencing the trip directions. In order to achieve this primary goal, the following methods were developed:

- Derive the catchment area of train stations based on trip survey data using convex hull methods;
- Measure aggregate trip directions using the centrality of train stations and the compactness of the station catchment area. The less the centrality of a train station, The longer the distance between a station and the centroid of its catchment area, the more directional trips are.
- Measure disaggregate trip directions based on trip frequency and direction using rose diagram

- Identify factors affecting trip directions, such as spatial integrity, population density, road network density and occurrence of multiple train stations using regression models.

5.3 METHODOLOGY

5.3.1 Data used in the study

The trip direction and catchment area of seven train stations were derived using the origin – destination (OD) matrix of trips collected by the intercept surveys which were conducted on 31 July - 1 August 2012 (between 6:00 am and 4:00 pm) and19 and 20 September 2013 between 7:00 am and 12:30 pm. Around 10% trips of the total are far from a station and were considered as outliers of trips and removed from the sample. Therefore, the 951 records were used in this study. The inbound (towards central business district (CBD) area) trip size (852) is much larger than that of the outbound (away from CBD) (99) due to most train trips being to the CBD during the day. We also obtained Perth population data from Australian Bureau of Statistics (ABS) and road network data from Main Roads Western Australia. The data used in this study are from the intercept survey. For details please refer to Section 3.4.

5.3.2 Trip frequency and direction measure using rose diagrams

We developed a three-step procedure to measure and illustrate trip directions, viz: 1) determine the catchment area of a train station; 2); generate a rose diagram; and 3) identify factors affecting the trip frequency and direction.

- Determine the catchment areas

The catchment area of a train station was determined from the travel survey data. The survey collected the origin and destination of commuters, which were geocoded to delineate the catchment area. As mentioned above, only 90% of trip data were used in the study (Cervero et al., 1995), with the remainder excluded as outliers (Durr et al., 2010; Irvine, 2011). The spatial boundary of a station's catchment area was derived using convex hull methods and ArcGIS™ 10.2 software by ESRI (Esri, 2010). The convex hull is the minimum convex set containing existing trip origin points (Durr et al., 2010) and is illustrated in Figure 5.1. Claremont station is shown as an example of the method. Some 119 responses were collected from the intercept survey, (see Figure 5.1a), with the points used in this study, i.e. with the 10 percent of outliers removed, shown in Figure 5.1b. The blue line is the spatial boundary of the catchment area drawn using the convex hull method, (Figure 5.1c). The centroid is the centre point of the catchment area. The size of the sample is vital for the convex hull method as too small a sample may not accurately reveal the actual boundary of a catchment area. Detailed discussion on this issue can be found in Lin et al. (2016).

- Generate rose diagrams

A train station can attract users from a variety of directions, with more people potentially coming from some directions than others. Rose diagrams can be used to illustrate this, as shown in Figures 5.1e to 5.1g. Based on the catchment area of a train station, the first step was to draw the smallest outer circle, centred on the train station that included all the 90% trip points (see Figure 5.1e). This circle was then divided into 30 degree azimuthal segments, with each of the 12 segments representing a specific direction of accessing the train station by users. The number of trips that occurred in each segment was counted (Figure 5.1f), and then displayed graphically. The resulting diagram clearly illustrates in which directions train users came from and how many trips occurred in each of these directions.

- Identify factors affecting the trip frequency and direction

Many factors can affect the number and direction of trips to a train station. The factors considered in this study were population density, road network density, the spatial integrity of the surrounding residential land uses, average travel distances, the direction of the trip destination and the number of train stations present in the catchment area of a train station.

These factors were measured and analysed for the above 12 directional segments for each of the seven train stations. The aim was to achieve a better understanding of why there were more trips in a particular direction(s) than in other ones.

In this study, the 12 segments were further divided into two groups: segments with at least one other station and segments without another station. The independent *t*-test was used to test whether the means of the number of trips in the two groups were statistically different from each other, based on the assumption that the presence of other stations within the segment would introduce competition between train stations, thereby affecting the number of trips in that segment to the particular station being considered.

In general, there are more trips in upstream segments located in the directions away from CBD area, (defined here as outer segments), than there are in the downstream segments located in the direction towards CBD area, (inner segments). This is due to the tendency for travellers to head to a station closer to their final destination, rather than backtracking to a nearer station, i.e. if it is further away from the final destination (Vincent, 2007). This is illustrated on Figure 5.1g with trips within outer segments shown in red and trips within inner segments shown in black. The relationships between these factors and the number of trips were computed separately for the outer and inner segments using Pearson correlation methods.

5.3.3 The centrality of a train station

The rose diagram illustrates the trip directions and magnitude for 12 segments. However, it does not provide a single quantitative measure of accessibility by trip direction. The centrality measure is one way to provide this as it indicates how central a station is in relation to its measured catchment area. If a station is located at the centre of its catchment area and the catchment area shape is close to circular, it indicates that train users are coming from diverse directions and traveling similar distances to reach the station. On the other hand, if a station is far from the centroid of its catchment area, this denotes that train users are more likely to approach the station from certain directions than from others. Based on this characteristic, a new spatial measure of station centrality has been developed that considers the size of a catchment area and the location of its train station with respect to the centroid of that catchment area. The equation for measuring centrality is defined as:

$$\text{SCI} = \left| \frac{A_{CA} - A_{CI}}{A_{CA}} \right| * \frac{A_{CA} \cap A_{CI}}{A_{CI}} \qquad 5\text{-}1$$

where

SCI is the centrality of the train station;

A_{CA} is the area of a station's catchment area (CA); and

A_{CI} is the area of a circle centred at the train station and its radius is the distance between the centroid of the CA and the train station (See Figure 5.2).

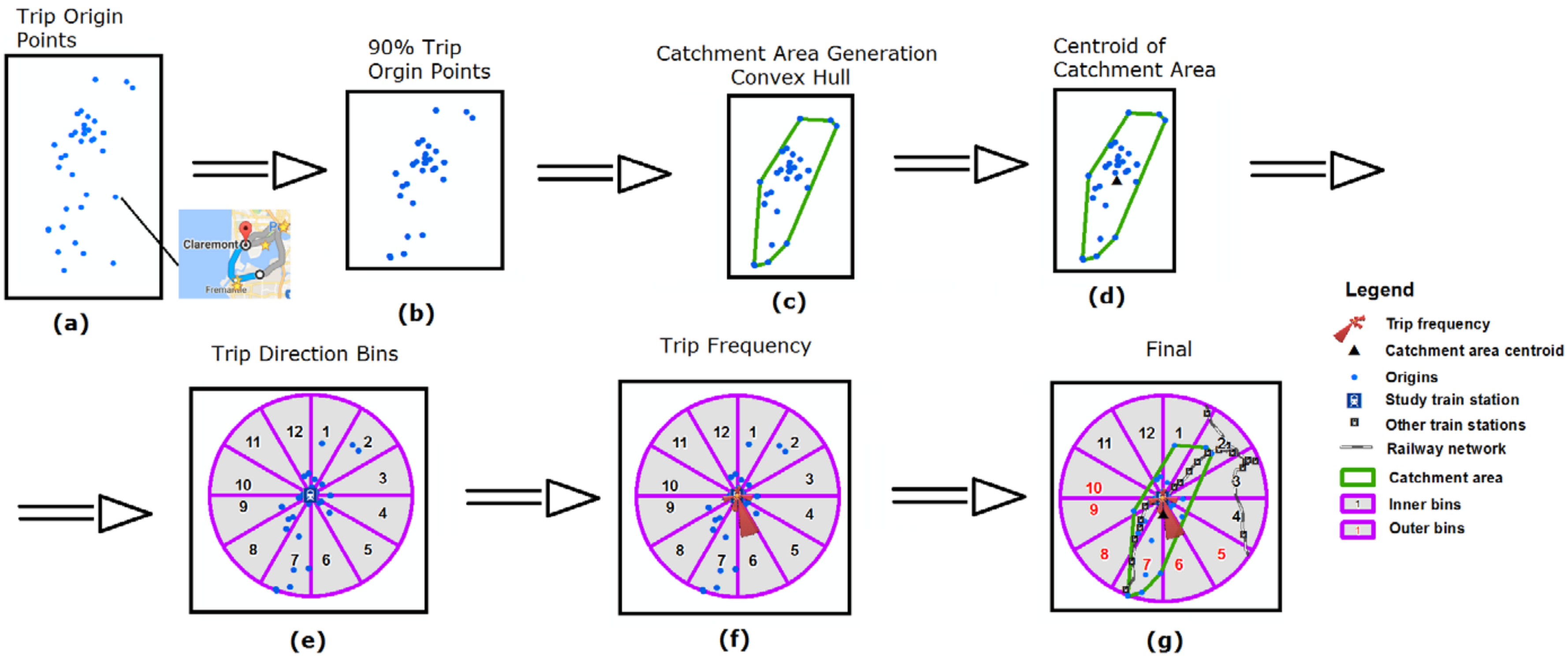

Figure 5.1 Illustration of rose diagram generation

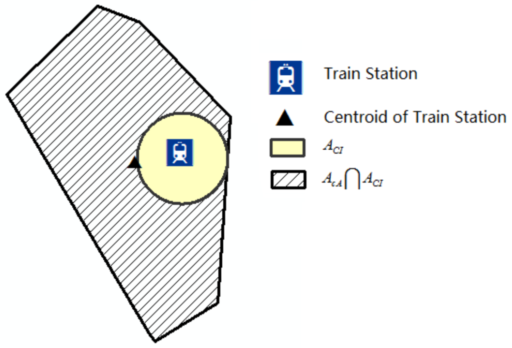

Figure 5.2 Illustration of station centrality calculation

The centroid is the geometric centre of the catchment area of a train station. It is also considered as the centre of gravity around which a higher concentration of train users might be found and around which the distribution of trips is balanced. The diagram segment in which the centroid is located indicates the directions from which a greater proportion of train users originate. The closer a train station is to the centre of gravity of a train station, the higher the centrality of a train station within its catchment area and the better aligned it is with its surrounding area. This study proposes the use of this centre of gravity theory for understanding the trip directions. This study compared the segment containing the centre of gravity with the other segments in the catchment area. This comparison was carried out for the number of trips, average travel distance, road network density and population density in order to look for evidence to support the proposed centre of gravity theory.

5.3.4 Spatial integrity index

The spatial integrity of land use around a train station is a measure of how fragmented the residential areas are and how far they are from the station compared to other, i.e. non-residential, land uses. If the residential areas are highly fragmented by other land uses, (e.g. industrial or parks), and/or geographical features, (e.g., rivers or lakes) and/or are located far away from a train station, the train station would have a low spatial integrity value. Consequently, such a station would be likely to have lower accessibility and therefore lower demand. In this study, we measured the spatial integrity of the residential areas around the seven train stations for each of the 12 segments. Hence, the variations of the spatial integrity by directions were able to be determined. The higher the spatial integrity, the less fragmented the residential areas are. The formula for the spatial integrity (*SI)* index is:

$$SI = \frac{\sum_i \frac{A_{iR}}{D_{iR}^{\beta}}}{\sum_i \frac{A_{inonR}}{D_{inonR}^{\beta}}} \quad (5\text{-}2)$$

where

A_{iR} is the area of residential land use (polygon) *i*, which also includes hospitals due to a number of night shift workers staying at the hospitals over night;

D_{iR} is the Euclidean distance of residential area (polygon) *i* from the train station;

A_{jnonR} is the area of non-residential area (polygon) *j*;

D_{jnonR} is the Euclidean distance of non-residential area (polygon) *j* from the train station; and

β is the distance decay parameter. It was determined based on the total number of train users at statistical area level ones (SA1s) and distance between these SA1s to it's the nearest train station. SA1s are the smallest areal unit for the Australian Bureau of Statistics (ABS) Census data. The numbers of train users were extracted from the 2011 ABS Census Journey to Work data.

5.4 RESULTS

5.4.1 Trip direction measure using rose diagram

Trip frequency was calculated for each rose diagram segments of seven stations. Midland station located at the end of Midland train line, has 11 times more trips located at outer zones than inner zones. Warnbro station with a large distance to the next train station (Rockingham station (4.2 km), Mandurah station (23.5 km)), has around 85% trips located in the outer zones. Ticket price is another important factor affecting trip frequency. For example, Greenwood station located at the edge of zone two (the second lowest price zone) and has large parking facilities available to park and ride users. It attracts a large amount of trips in the outer zones. In addition, for stations located along train line, such as Claremont, Murdoch, Warwick and Cannington station. The largest trips coming from directions almost 90 degree to the train line with a large residential catchment area and less competition between stations. We also test whether there are differences of trip frequency between segments with other train stations present and without other stations present in segments. A statistically significant difference was found (See Table 5.1). More trip frequency was discovered without other stations present in the segments than with other stations present in the segments. It might due to competition between stations. In addition, Trip frequency was discovered to be statistically significant higher in outer segments than inner segments. People are more likely to choose stations on the way towards their destinations.

Table 5.1. Independent T-test

	Mean	SD		P	t	df
Other Station in the Segments	6.45	7.275	Equal variances assumed	0.001	-2.833	82
No Other Station in the Segments	14.19	14.126	Equal variances not assumed	0.006	-3.307	80.987
Inner Segments	6.38	7.012	Equal variances assumed	0	-3.906	82
Outer Segments	16.29	14.864	Equal variances not assumed	0	-3.906	58.387

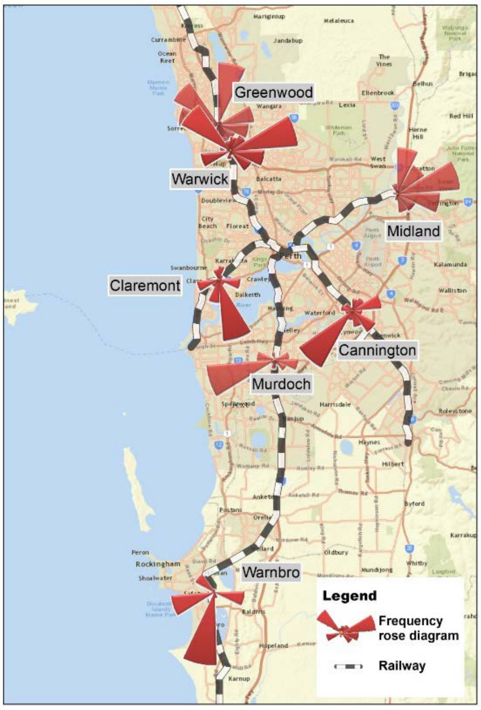

Figure 5.3 Rose diagram of seven train stations

5.4.2 Factors affecting trip directions

The values of a number of factors affecting trip directions were calculated for each diagram segment for each of the seven train stations. The factors were spatial integrity, average travel distance, road network density and population density. The results are shown on Figure 5.4. The number of trips is illustrated using rose diagrams. The spatial integrity values for each segment were labelled on the graph. The distance decay parameter estimated from our data is 1.325. The values of other factors were displayed using thematic mapping methods. The segments with higher values were coloured in darker red, the segment with lower values in lighter red. The segment number in the outer zones is labelled within a circle, while the segment number in inner zones is labelled without circle.

Midland train station has the lowest average spatial integrity at 0.27. Warwick station has the highest average value at 2.78, with residential land use comprising the majority of the areas in each segment. The highest value, (8.778), occurs in segment *11*, i.e. the segment to the northwest of the station. The number of trips, population density and road network density also tend to be higher in this segment than in most other Warwick segments. Generally, stations located at the end of train line, such as Midland, have the largest catchment areas. Train users mainly come from the outer zone, although the segments in the outer zone have lower population density, road network density and longer average travel distances. This is probably typical of end of line stations, which tend to draw a significant proportion of their patronage from areas beyond the station, i.e. from areas that have no alternative station choice, the users being “captive” to that station.

Segment *6* at Claremont station has the highest number of trips and the lowest average travel distance, compared to other segments of this station. It also has the second highest spatial integrity value, even though there are shopping and recreation facilities located in this segment. Warnbro station has relatively low spatial integrity of residential land use because the eastern side of the catchment area consists of a native vegetation conservation area and Lake Walyungup, while the western side of the catchment area is a narrow strip of residential development bounded by the ocean. Segment 7 has the highest number of trips, average travel distance and relatively high population density and road network density compared to other Warnbro segments.

The relationships between the number of trips and the above factors were further explored using a Pearson correlation method. For all data, a statistically significant weak positive correlation between trip frequency and average travel distance was found. For trips in the inner segments, (trip direction is away from the destinations of most boarders), a statistically significant moderate positive relationship between number of trips and spatial integrity, average travel distance and population density respectively was found (see Table 2). No relationship was discovered for trips in the outer segments.

Table 5.2 Correlation between trip frequency and its factors

	Spatial Integrity	**Average Travel Distance**	**Road Network Density**	**Population Density**
	All			
Correlation	0.174	0.225*	0.010	0.011
(*p*-value)	0.113	0.039	0.927	0.923
	Inner Segments			
Correlation	0.633**	0.427**	0.307*	0.313*
(*p*-value)	0.000	0.005	0.048	0.043
	Outer Segments			
Correlation	0.137	0.007	0.062	0.066
(*p*-value)	0.387	0.967	0.697	0.676

** Correlation is significant at the 0.01 level (2-tailed) * Correlation is significant at the 0.05 level (2-tailed)

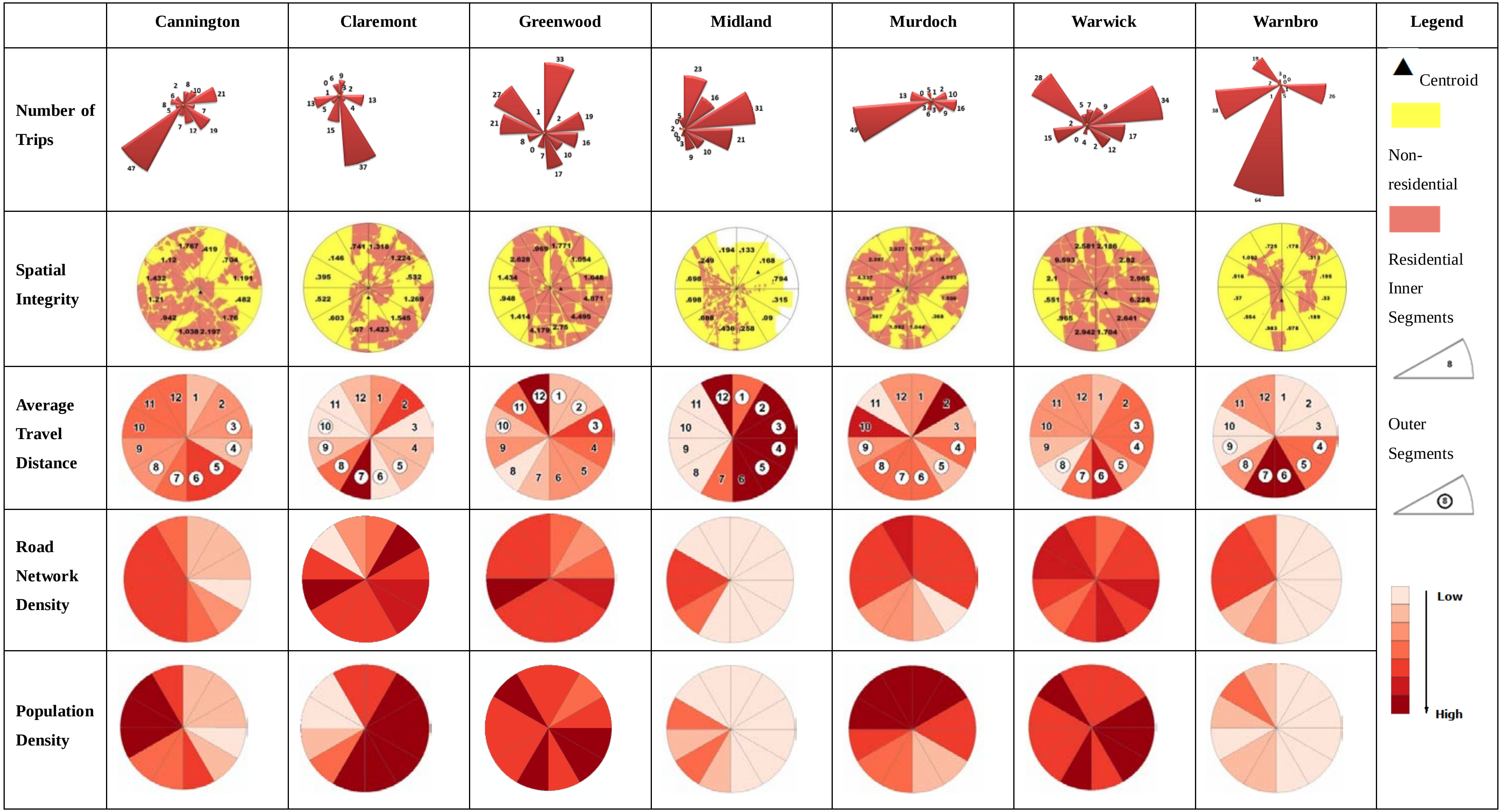

Figure 5.4. Factors affecting trip directions

5.4.3 Station centrality and centre of gravity

Table 5.3 represents the centrality values for the seven stations, with a value close to 1 indicating a station is near the centre of its catchment and a value close to 0 indicating a station is near the edge of its catchment. Midland station has the lowest centrality value and Murdoch station the highest. Midland station is located at the end of the train line and serves a large hinterland. Train users mostly come from the outer sections and travel longer distances. On the other hand, Murdoch station is surrounded by diverse land use types, such as education, health, recreation, shopping and residential land use, with relatively higher population and road network density. Claremont and Warnbro train stations have the next lowest centrality values, (albeit much higher than Midland), likely due to geographical constraints mentioned in Section 5.4.2.

Table 5.3. The centrality of seven stations

Station	Centrality
Cannington	0.924
Claremont	0.877
Greenwood	0.911
Midland	**0.120**
Murdoch	**0.936**
Warnbro	0.775
Warwick	0.914

Table 5.4 presents the number of the segment containing the centroid and the rankings of each variable for that segment for each station. For example, the Cannington station centroid is in segment 6 which has the third highest number of trips, i.e. is ranked 3, (1 is the highest). The centroid of a catchment area is generally located in or near to a segment with the highest number of trips. For example, at Claremont, Murdoch, Warnbro and Warwick stations, the centroid fell in the segment with the highest number of trips. For Greenwood and Cannington stations, it is within the segment with a relatively high number of trips, but with the highest spatial integrity. For Midland station, the centroid lies in the segment with a relatively higher number of trips, but with the highest road network density and average travel distances.

Table 5.4. The centroid location analysis

The rankings of variables at the segment containing centroid

Station	Segment no. containing centroid	No. of trips	Spatial Integrity	Road Density	Average Travel Distances	Population Density
Cannington	6	3	1	5	2	4
Claremont	6	1	2	1	11	2
Greenwood	4	3	1	2	3	2
Midland	2	4	10	1	1	9
Murdoch	9	1	5	5	7	7
Warnbro	7	1	2	4	2	2
Warwick	4	1	2	2	2	5

5.5 DISCUSSIONS

5.5.1 Implication of station centrality

The centrality of a station is an important and useful measure to assist transit planners and policy makers in understanding the effectiveness of a train station location with respect to the surrounding catchment area. A low value of station centrality indicates that train users access the station from certain directions more than others, suggesting that there may be locational disadvantages, i.e. there may be some spatial access inequity issues that need to be addressed. It may also indicate that relocating the station, where feasible, or building additional stations, may result in better access and therefore higher train patronage. Further investigation is necessary to identify where and why unequal access to a train station occurs as it could be due to a number of factors. For example, a station located just inside a fare zone could have locational advantage compared to an adjacent station in a higher fare zone, resulting in more users than would normally be expected from upstream areas.

In contrast, a station surrounded by low trip generating land uses, (such as parks), geographical features, (such as, lakes, rivers or the sea), would be likely to have a lower patronage level and potentially a “distorted” centrality value. Many strategies have been developed to address the locational disadvantage of a train station, including integration with other travel modes, e.g. park-and-ride (PnR), kiss-and-ride (KnR), feeder buses, walk and cycle access & facilities (Charles & Galiza, 2013; Vincent, 2007), improving and extending access to a train station (Brons, Givoni, & Rietveld, 2009), improving transit services and facilities (Olaru et al., 2014), and increasing surrounding density (Cervero & Kockelman, 1997). According to Vincent (2007), a parabolic shape is common for PnR catchment areas. However, based on this study, stations with multimodal facilities, (such as a bus-rail interchanges, e.g. Murdoch and Warwick station), good services (such as high frequency trains), and nearby attractors, (such as, large shopping centres or education institutions, e.g. Murdoch station), are likely to attract users from inner segments, i.e. downstream of their locations, (based on the primary direction of travel), which would lead to higher centrality values.

5.5.2 Centre of gravity, Location strategy

Location strategy is a vital factor in transport operation management. The centre of gravity indicates the effectiveness or the weaknesses and limitations of a location of a train station. A station located close to the centre of gravity could reduce the travel cost of train users and increase its patronage. This study has found some evidence to support the proposed theory of the centre of gravity. For example, the catchment area centroids were mainly located in or near to a segment with the highest number of trips. Murdoch train station has the highest station centrality with the station very close to the centre of gravity. It has the highest number of both boardings and bus-to-train transfers, (see Table 5.5). On the other hand, Claremont station, with relatively low centrality, has the lowest number of boardings among the seven train stations. The location strategy and centre of gravity measure can be used by planning and policy makers to assist in locating a station or improving infrastructure, such as bus services connected to train services due to higher demand from the region. For example, if the centre of gravity is located far from a station, more frequent bus-rail interchange could be introduced in the region where the centre of gravity locates for increasing the patronage of the station.

Table 5.5 The centroid location analysis

Station	Station boarding September 2011						
	Cannington	Claremont	Greenwood	Midland	Murdoch	Warnbro	Warwick
Total station boarding	3,165	1,967	2,143	3,899	7,898	2,735	5,867
Bus to rain transfers	1,129	227	4	1,211	4,430	736	2,480
PnR parking capacity	244	45	931	609	1152	790	978

5.5.3 Factors affecting upstream trips

In this study, we identified the statistically significant positive relationship between the number of trips and the factors of spatial integrity, average travel distance and population density for the trips within the inner segments, but not for trips within the outer segments. According to Vincent (2007) and Turnbull et al. (2004), people are more likely to come from outer segments than inner segments due to shorter total travel distances, but lack of parking at the downstream train stations can redirect them to the upstream station. In this study, we discovered that higher spatial integrity and population density around a train station can also result in increased use of the upstream stations. This means that people put more weight on easy access to a station or better spatial integrity than travel distance.

According to Turnbull et al. (2004), the greater the distance in relation to the total trip length, the less willing a PnR user is to travel to a station. The relationship between the average travel distance and number of trips in each diagram segment was measured and a statistically significant positive relationship between these two variables was discovered. This means that the average distance indicates the size of the catchment area of a train. The larger the catchment area of a station, the greater the number of trips to that station.

Shorter spacing between stations along a line was found to decrease the usage of a station due to competition. However, in this study, we discovered that this effect is also dependent upon the trip direction. The number of trips may reduce more along the directions of the train line and less along the directions perpendicular to the train line.

5.6 SUMMARY

This chapter has presented new spatial tools: station centrality and spatial integrity for exploring trip directions and factors affecting trip directions of a train station. From this study, we have discovered that trip frequency and its interaction with other factors vary with different directions. These findings can be useful in managing directional travel demand, accessibility to train stations, services and facilities of stations, infrastructure connected to train service and the integration of multimodal travel (Brons et al., 2009).

The next chapter will describe the third component of the exploratory data analysis, the elderly accessibility. The concepts and methods related to elderly accessibility will be discussed.

CHAPTER 6 ELDERLY ACCESSIBILITY ANALYSIS

6.1 INTRODUCTION

The previous chapter presented three new spatial methods, (trip frequency rose diagrams, station centrality and spatial integrity), for exploring trip directions and the factors affecting trip directions of a train station. It was found that the trip direction analysis provides another method to understand trip distribution and train directional accessibility. This chapter presents the third component of the exploratory data analysis which is the elderly accessibility analysis. A gravity based accessibility measure (composite measure) is used that combines all the relevant factors, with attractive factors have a positive contribution and resistant factors a negative contribution. Using the perceived accessibility identified from the intercept survey, the composite measure based accessibility was evaluated.

The chapter is organised as follows. Section 6.2 provides background to the issues relating to elderly accessibility. Section 6.3 focuses on the method used to measure of accessibility to a train station for the elderly. The results of a case study in Perth, Western Australia are presented and discussed in Section 6.4 and with a summary of findings, contributions and a discussion of limitations and areas of possible future research in Section 6.5.

6.2 RESEARCH CONTEXT

In Perth, Western Australia, approximately one-fifth of the population is aged 60 or older (Australian Bureau of Statistics, 2011a). It is reported that this aging population is unprecedented, ubiquitous and enduring. Projections suggest that this proportion will continue to increase as a result of a temporary, but significant, “baby boom” following the end of World War II. The cohort of individuals born between 1946 and 1964, (also known as the “baby boomer generation”), is wealthier, healthier and more involved in various activities than any previous generation of the same age. This is expected to lead to higher requirements for public transport access and therefore measures need to be established or improved to enable the mobility of the elderly.

Studies in Western Australia specific to accessibility to train stations for the elderly are limited, dated, and have tended to consider the elderly as akin to the disabled (e.g., Ashford (1981)). However, while improving accessibility for those with disabilities may translate into improvements for the some of the elderly, it is not a complete solution for all. Studies in different cities around the world have identified that the elderly tend to rely more on private car than on public transport and that land use plays a major role in shaping their travel patterns (Goulias et al., 2007; Rosenbloom, 2001; Schmöcker et al., 2008). However, many of the elderly will have to adjust their travel plans/arrangements due to their declining driving abilities and potential financial constraints, which are likely to become more restrictive the longer they are retired (Burkhardt, 1999). Therefore, public transport becomes a keystone for enabling mobility for this population group.

Improvements to the accessibility of train networks has been linked to increased usage (Schmöcker et al., 2008). Therefore, it is important to identify factors that are important for the elderly to ensure their needs are covered. When choosing a train station to board, the elderly may consider different factors compared to other age cohorts. For instance, walking distance when transferring to the train, seat availability at the train station and on the train, shelter availability and the presence of security staff may all be important to them. Therefore, these need to be properly quantified to best guide decision makers.

6.3 METHODOLOGY

Three steps of analysis were taken to understand accessibility for the elderly to a railway station (Figure 6.1). The first step aimed to identify the elderly respondents' most favoured and least favoured stations based on the rate of rail station patronage. Next, the variables affecting railway station patronage were investigated. Finally, based on these variables, accessibility indices were developed to measure and map their accessibility to train stations at a census district level for WnR, and PnR and at a street block level for BnR.

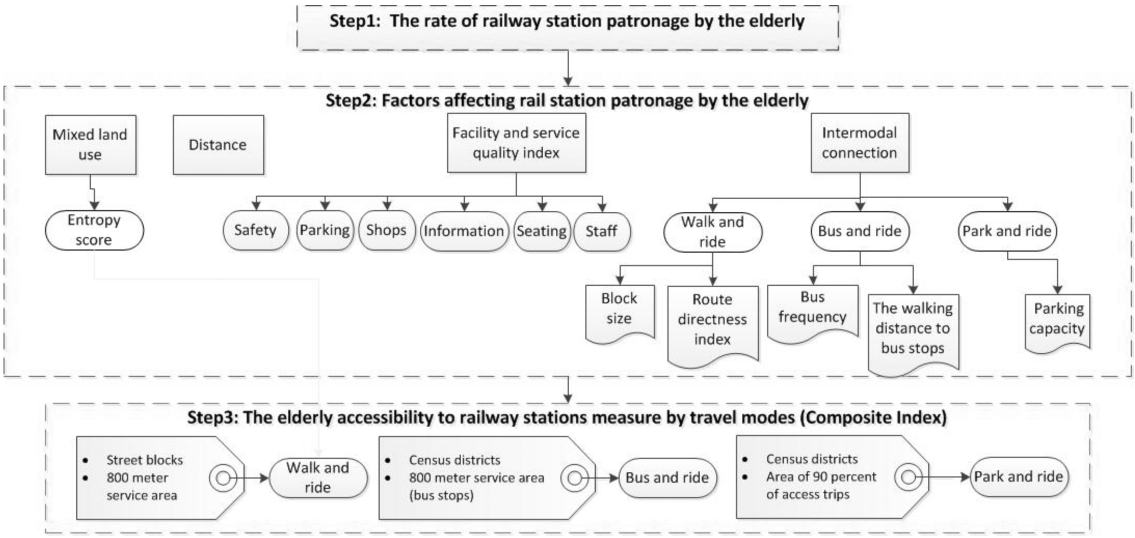

Figure 6.1. The Framework for Measuring Elderly Accessibility to Train Stations

6.3.1 Data used in the study

The data used in this study is from the first intercept survey that was conducted at seven train stations: Warwick, Greenwood, Murdoch, Warnbro, Midland, Cannington, and Claremont from 6:00AM to 6:00PM, July 31 and August 1, 2012. In total, 940 responses were collected, of which 122 were from elderly users. A further 43 responses from elderly users were obtained on the 6th and 15th of March, and 8th and 10th of May, 2013, at three stations (Murdoch, Greenwood and Midland), to supplement the original 122 observations. The surveys and the data are explained in detail Section 3.4.

6.3.2 Rate of elderly patronage

The first step of this study was to identify which stations potentially have a lower or higher rate of patronage compared to others, which can be defined as:

$$R_{pi} = \frac{P_{esi} / P_{tsi}}{P_{eci} / P_{tci}} \quad \text{6-1}$$

where

R_{pi} is the rate of the elderly's patronage at train station *i*;

P_{esi} is the number of the surveyed elderly at train station *i* ;

P_{tsi} is the total number of respondents at train station *i*;

P_{eci} is the number of elderly living inside of the catchment area of train station *i*; and

P_{tci} is the total population living inside the catchment area of train station *i*.

The numerator represents the percentage of surveyed elderly train users, whereas the denominator is the proportion of elderly residents in the catchment area. R_{pi} indicates whether the elderly could 'prefer' some stations more than others, i.e. the higher the value, the higher the patronage of the station. This ratio was used to target stations for study in order to focus close attention to one high use and one low use station. This calculation was based on the 2012 survey data only.

6.3.3 Factors affecting accessibility for the elderly

Accessibility to railway stations for the elderly was defined using the following indicators:

- Ease in reaching a railway station
  - a) Network connectivity - Route directness index (*d(r)*)
  - b) Distance (*D)*
  - c) Facility and service quality (*Q*)
- Adjacent opportunities or activities
  - a) Mixed land use within an 800m buffer around a railway station (*H*)
  - b) Intermodal connection
    - i. The number of trips per hour that use the stop on a weekday between 9:00am and 4:00pm (*F(b)*)
    - ii. PnR parking capacity at the station (*N(p)*)
    - iii. PnR parking capacity around the station (*NO(p)*)

The route directness *(d(r))*

The route directness index is the ratio of network distance to straight-line distance between two locations (Guerra et al., 2012). An index closer to 1 indicates a more direct route, in other words, the network is more directly connected. The route directness can reflect how easy it is for the elderly to reach a train station from the origin of their trip. This is particularly relevant for walking. The route directness index was calculated separately for WnR, PnR and BnR. For WnR, the route directness index was calculated based on the local street network within an 800m buffer; for PnR and BnR, the route directness is based on the road network. The catchment area for PnR and WnR were determined by the area of 90% of all access trips. Google Direction API and ArcGIS were used to perform the calculations.

Mixed land use *(H)*

Previous research has revealed that land-use diversity and density play an important role in determining trip rates (Kockelman, 1997). Commuters maximise the utility of their trip by making good use of opportunities around stations to improve their trip production rates (Ferdman, Shefer, & Bekhor, 2005; Rosenbloom, 2001). In this study, it has been assumed that the diversity of land use around a station can increase the accessibility to that station, which was measured by an entropy score, known as the mixed land-use index (Brown et al., 2009). Besides the diversity of mixed land-use, the relative proximity of mixed-use development, such as neighbourhood shops, can also encourage transit commuting (Rosenbloom, 2001). According to Cervero et al. (1995), *"If retail shops are within 300 feet, or several city blocks, from a dwelling unit, workers are more likely to commute by transit, foot or bicycle. Beyond this distance, however, mixed use activities appear to induce auto-commuting"*. This paper investigated how land-use, specifically the presence of retail, education and training, health care and social assistance, and art and recreation services, shape the elderly transit travel behaviour. These land use types were mapped in an 800 m circle around a train station.

The mixed land use index (H) used in the paper is defined as (Frank et al., 2006):

$$H = -A / (\ln(N)) \tag{6-2}$$

$$A = \sum_{i=1}^{4} (b_i / a) \times \ln(b_i / a) \tag{6-3}$$

where:

b_1 = $Area_{Education}$;

b_2 = $Area_{Entertainment/Recreational\ \&Cultural}$;

b_3 = $Area_{Health/Welfare\ \&\ Community\ Services}$;

b_4 = $Area_{CulturalShop/Retail}$;

a = total square metres of land for all four land uses present in the 800m buffer; and

N = number of the four land uses where area > 0 m^2.

Facility and service quality *(Q)*

The facility and service quality of a train station was measured by 12 surveyed items. The elderly were asked to rate these items and their importance, (weight), on a scale of 1 to 7, where 1 = Not at all important and 7 = Most important. A facility and service quality index Q_i was calculated using:

$$Q_i = \frac{\sum_{k=1}^{m}(\sum_{j=1}^{n}(q_{jki} \times w_{jki}))}{m \times n \times 7 \times 7} \qquad 6\text{-}4$$

where:

q_{jki} is the value of surveyed item *j* evaluated by the elderly respondent *k* at the station *i*;

w_{jki} is the weight of surveyed item *j* evaluated by the elderly respondent *k* at the station *i*;

m is the number of respondents *k* evaluating the item *j*;

n is the number of quality items; and

7 is the highest importance scale as well as the number of train stations where data was collected.

The higher the value of Q_i, the better the station is rated in terms of service quality.

Intermodal connection

Intermodal connection, also called "intermodality", is the connection between different transport modes or transport operators at a station (Akaike, 1974). Some common connections to railway stations are PnR, BnR, CnR, KnR and WnR. According to Shoup (1997), high levels of intermodal connections are associated with significant increases in railway station patronage. In this paper, the focus was on the intermodal connections of PnR and BnR. The effects of PnR services on enhancing accessibility to railway stations has been thoroughly researched in the past. In this study, only one aspect relating to PnR services, parking availability, was of interest. The elderly in Perth, are "*entitled to travel for free on all*

Transperth services between 9.00am and 3.30pm Monday to Friday, all day Saturday and Sunday, as well as public holidays" when using a SmartRider card (Transperth, n.d.). However, PnR parking lots are usually fully occupied before 7:30am in most stations which can have a negative impact on the accessibility to a railway station, if they use PnR services.

Yet, according to Young (2008) and Burns and Golob (1976), a higher number of different bus lines connected to a station positively influences the station usage. The information about the number of bus lines with service to a station, bus frequencies and their intermodal times (namely, the time to change from a bus to a train) were used to measure connections between bus and train.

These factors were all in different units and, in order to combine them into one index, were scaled into five levels to make them comparable, (see Table 6.1). The scaling strategy used was the equal interval and standard deviation. The PnR travel distance was converted into the cumulative probability of the travel distance because the travel distances for PnR users are different for different stations (see Figure 6.2). For example, Midland station has a much larger PnR catchment area than others, due to its location at the end of the line. The cumulative probability of the travel distance is consistent for all the stations and, therefore, more suitable for comparison purposes.

Table 6.1. The Standard for Scaling

	Land use mix	**Distance (WnR)**	**Distance (PnR cumulative probability)**	**Service quality**	**Route directness**
Very Good	0.8-1	0-200	0-20%	0.8-1	1-1.5
Good	0.6-0.8	201-400	20.1%-40%	0.6-0.8	1.51-2
Medium	0.4-0.6	401-600	40.1%-60%	0.4-0.6	2.01-2.5
Poor	0.2-0.4	601-800	60.1%-80%	0.2-0.4	2.51-3
Very Poor	0-0.2	>800	80.1%-100%	0-0.2	>3

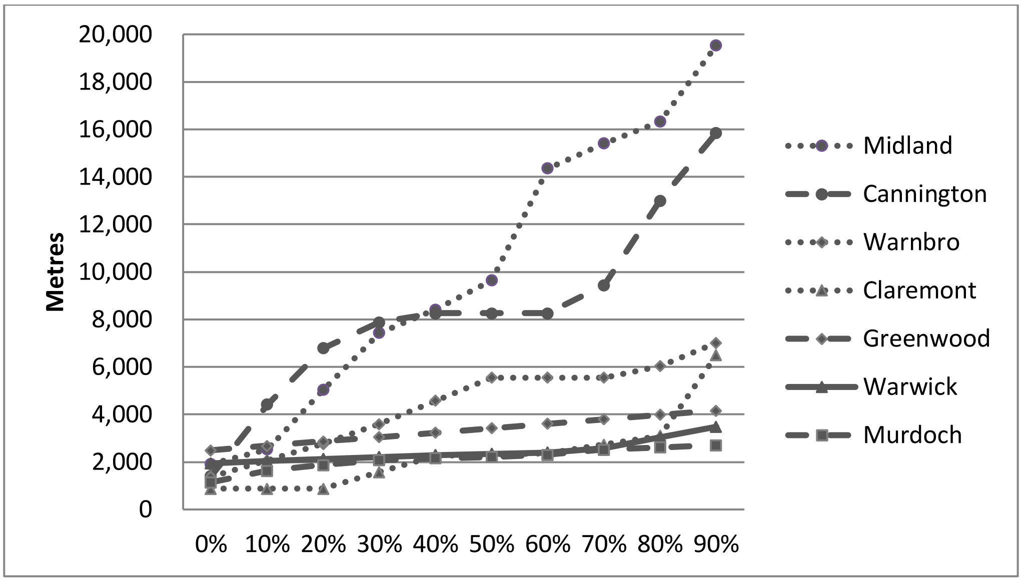

Figure 6.2 Cumulative Probability of the P&R Elderly's Travel Distances

Different variables may have differing importance with respect to measuring accessibility to train stations. The analytic hierarchy process (AHP) method was used to organise and analyse these influences (Saaty, 2008). The elderly users were asked to evaluate these influences as the weight of factors for each travel mode using the AHP method. As many elderly respondents had difficulties in understanding the AHP method, (mainly because it was administered during a short period of time while they were waiting for the train), the stated importance of variables, (from 1-not very important to 7-extremely important), was used to determine accessibility to the train station. Then the importance rating was converted into weights using the AHP method. The definition of other variables is provided in the Section 6.3.2.

- *Walk and Ride (WnR)*

Based on the literature, and supported by the survey data, the catchment area for WnR is around an 800m service area (Guerra et al., 2012). The catchment area was, then, subdivided into street blocks. The accessibility A_{ijwalk} to a train station j from each block i within the 800m buffer was estimated using the composite index:

$$A_{ijwalk} = W_{Q_{jwalk}} Q_{jwalk} + W_{H_j} H_j + W_{d(r)_{ij}} d(r)_{ij} + W_{D_{ij}} D_{ij} \quad \text{6-5}$$

where

Q_{jwalk} is calculated based on the all the items in the facility and service quality survey except factors related to parking; and

W represents weights of the four variables.

- *Park and Ride (PnR)*

The catchment area for PnR was delineated by capturing 90% of access trips to a station *j* by the PnR mode with census district boundaries (Cervero et al., 1995). The accessibility to a station *j* from each census district *i* within the catchment area by the elderly was estimated by:

$$A_{ijPnR} = W_{N(p)_j} N(p)_j + W_{NO(p)_j} NO(p)_j + W_{Q_{jPnR}} Q_{jPnR} + W_{H_j} H_j + W_{d(r)_{ij}} d(r)_{ij} + W_{D_{ij}} D_{ij} \quad 6\text{-}6$$

where

Q_{jPnR} is calculated based on the all the items in the facility and service quality survey.

- *Bus and Ride (BnR)*

The BnR catchment area was described by an 800 m service area buffer around bus stops, inside the area of 90% of access trips to a station *j* by the BnR mode. The accessibility to a station *j* from each census district *i* within the catchment area by the elderly A_{ijBnR} was estimated by:

$$A_{ijBnR} = W_{Q_{jBnR}} Q_{jBnR} + W_{H_j} H_j + W_{F(b)_{ij}} F(b)_{ij} + W_{D_{ikwalk}} D_{ikwalk} + W_{D_{kjbus}} D_{kjbus} \quad 6\text{-}7$$

where

Q_{jBnR} is calculated based on all the items in the facility and service quality survey except the items related to parking;

D_{ikWalk} is the distance between a census district *i* and a bus stop *k*; and

D_{kjWalk} is the distance between a bus stop *k* and a train station *j*.

6.4 RESULTS

Table 6.2 depicts the rate of rail station patronage by the elderly, based on the survey data. It shows that the Midland station has the highest patronage by elderly, while Greenwood station has the lowest. As Midland station is located at the end of the train line, it is reasonable to expect higher patronage at this station. For comparison purposes a mid-line station, Murdoch station, (which has the second highest patronage), was also selected, (Table 6.2). The three selected stations were compared from four perspectives: mixed land-use, distance, services/facilities of train station and inter-modal connection.

Table 6.2 The Rate of Train Station Patronage by the Elderly[1]

Station	P_{esi}	P_{tsi}	P_s(%)	P_{eci}	P_{tci}	$\mathbf{P_c}$(%)	R_{pi}	**Rank**
Cannington	17	130	13.08	263,309	1,081,166	24.35	0.54	*3*
Claremont	12	113	10.62	39,796	159,311	24.98	0.43	*4*
Greenwood	6	87	6.90	106,702	456,789	23.36	**0.30**	***7***
Midland	37	167	22.15	288,274	1,205,807	23.91	**0.93**	***1***
Murdoch	23	158	14.56	203,910	846,707	24.08	**0.60**	***2***
Warnbro	13	138	9.42	52,156	228,943	22.78	0.42	5
Warwick	14	147	9.52	127,812	544,566	23.47	0.41	6

[1]For the definitions of variables in Table 6.3, please see equation 6- 1.

6.4.1 Mixed land-use

The mixed land-use index was used to measure land-use diversity based on the four types of land uses, mentioned in Section 4.2, located in an 800m buffer of a train station. The dominant land-use type around Greenwood station is parks, including Fernwood Park, Newham Park and Kanangra Reserve. There is also a school nearby, St Stephen’s school. The calculated value of the mixed land-use was 0.37. At Midland, shopping, entertainment and health care, major activities for the elderly, are all located around the station. Its entropy level was 0.44. For Murdoch station, residential and health/welfare and community services dominate. In addition, there are a few shops and a recreation centre located in the residential area, leading to an index of 0.36. The land use maps of the three stations are shown in Figure 6.3.

6.4.2 Route directness index

The route directness varies considerably for the WnR mode (See Figure 6.3). A major issue for the accessibility via WnR is noted at the Greenwood station. Figure 6.3 shows an example of a street block near Greenwood. Its route directness is between 5 and 6, which means that a pedestrian has to walk five or six times more than the straight-line distance to access the station platform.

Figure 6.3 The Mixed Land-Use within 800m of Train Stations (left); Route Directness of a Train Station (right)

6.4.3 Facility and service quality of train stations

Service and facility quality was measured using Equation 6-4. The average value of each facility and services quality item at the train station is shown in Figure 6.4. Murdoch and Midland stations have higher overall values compared to Greenwood station. The major issue with Greenwood station is the inadequate provision of facilities, both basic, (staff, restrooms etc.), as well as seating or shops around the station. For Midland, safety and security are a major concern, especially secured parking facilities. For Murdoch, some elderly patrons complained about not enough seats on the platform and a lack of parking. The survey results supported the a priori assumption that insufficient parking capacity has a negative impact on accessibility to train stations for elderly PnR users. The facility and service quality indices for Greenwood, Midland and Murdoch train stations were 0.61, 0.68 and 0.68 respectively. When the parking items are excluded, the indices were 0.59, 0.69 and 0.71 respectively.

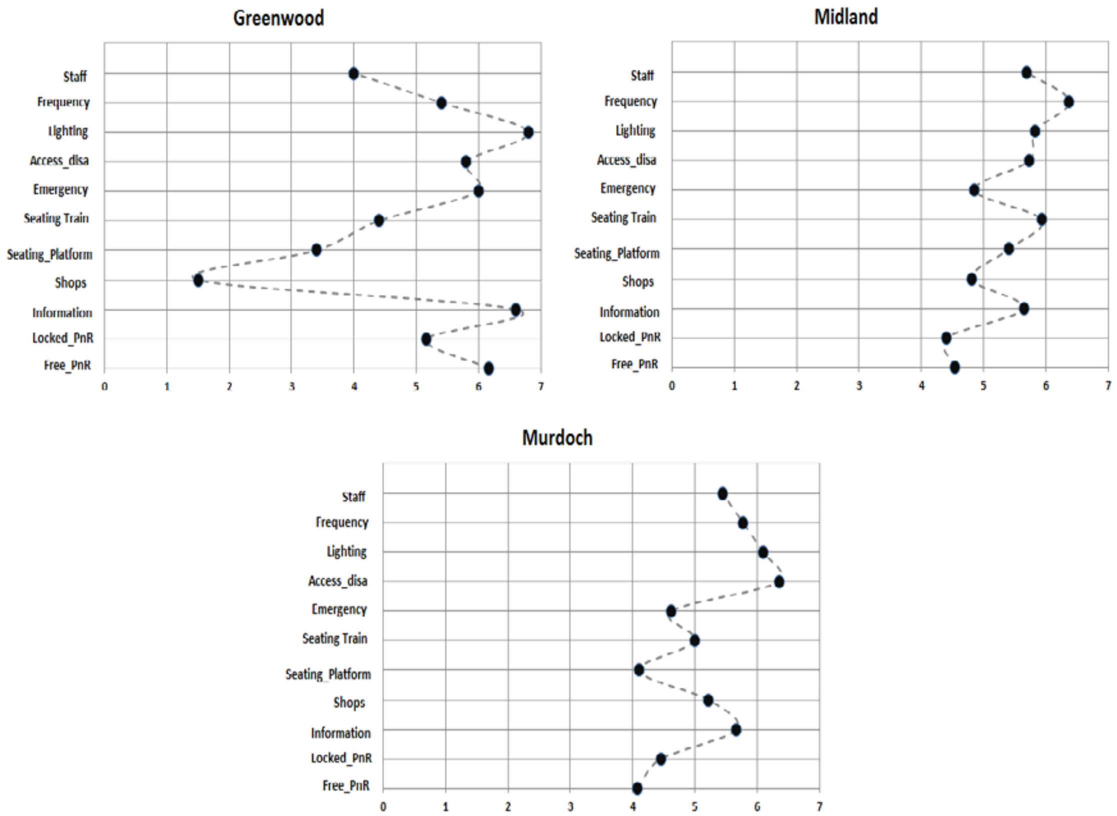

Figure 6.4 Service Quality of Train Stations

6.4.4 A composite accessibility index

Overall accessibility was measured for WnR, PnR and BnR separately using composite indices. The variables for measuring accessibility were scaled into five unified categories (see Table 6.3). The weights of these variables are shown in Table 6.3. The accessibility composite indices for WnR, BnR and PnR were calculated using relations 5-7 respectively (see Figure 6.5 and Table 6.4). Generally, the PnR and BnR elderly users considered mixed land-use less important. For WnR, the route directness was evaluated as the most important variable. However, it was less important for PnR users. For them, parking availability and facility and service quality were the key facilities.

Table 6.3. Weights of Various Factors of Accessibility

WnR	Weight	BnR	Weight	PnR	Weight
$W_{D_{ij}}$*	0.25	$W_{F(b)_{ij}}$	0.24	$W_{N(p)_j}$	0.2
$W_{d(r)_{ij}}$	0.3	$W_{D_{ikwalk}}$	0.23	$W_{NO(p)_j}$	0.2
W_{H_j}	0.24	$W_{D_{kjbus}}$	0.2	$W_{D_{ij}}$	0.15
W_{Q_j}	0.21	W_{H_j}	0.12	$W_{d(r)_{ij}}$	0.13
		W_{Q_j}	0.21	W_{H_j}	0.13
				W_{Q_j}	0.19

*The definition of the factors can be found at the beginning of the Section 4.2. The origin is *i*, the rail station is *j* and the bus stop is *k*.

Greenwood has more areas with poor or very poor walking accessibility to the train station than other stations. Midland station has a good accessibility from a PnR perspective. Murdoch station is in the middle, while Greenwood station again was found to have the poorest PnR provision. From a BnR viewpoint, Greenwood station has a much smaller catchment area than the other two stations. Its accessibility by BnR is from poor to average because there is just one bus service connected to the train station. For both the Midland and Murdoch stations, the areas around the stations have good accessibility by feeder buses. However, this decreases with distance from the station, which means that towards the edge of catchment areas there is low bus coverage. From Table 6.4, it can be observed that the average BnR accessibilities of Midland and Murdoch Stations are nearly the same, but the minimum values are quite different. The lowest bus accessibility to Midland train station is relatively lower (1.3) than Murdoch (1.8).

Table 6.4. The Overall Accessibility

Station	Average accessibility			BnR accessibility	
	WnR	BnR	PnR	Min	Max
Greenwood	2.38	2.36	2.38	1.7	3.06
Midland	3.1	2.55	3.63	1.3	4.22
Murdoch	2.7	2.55	2.61	1.8	4.22

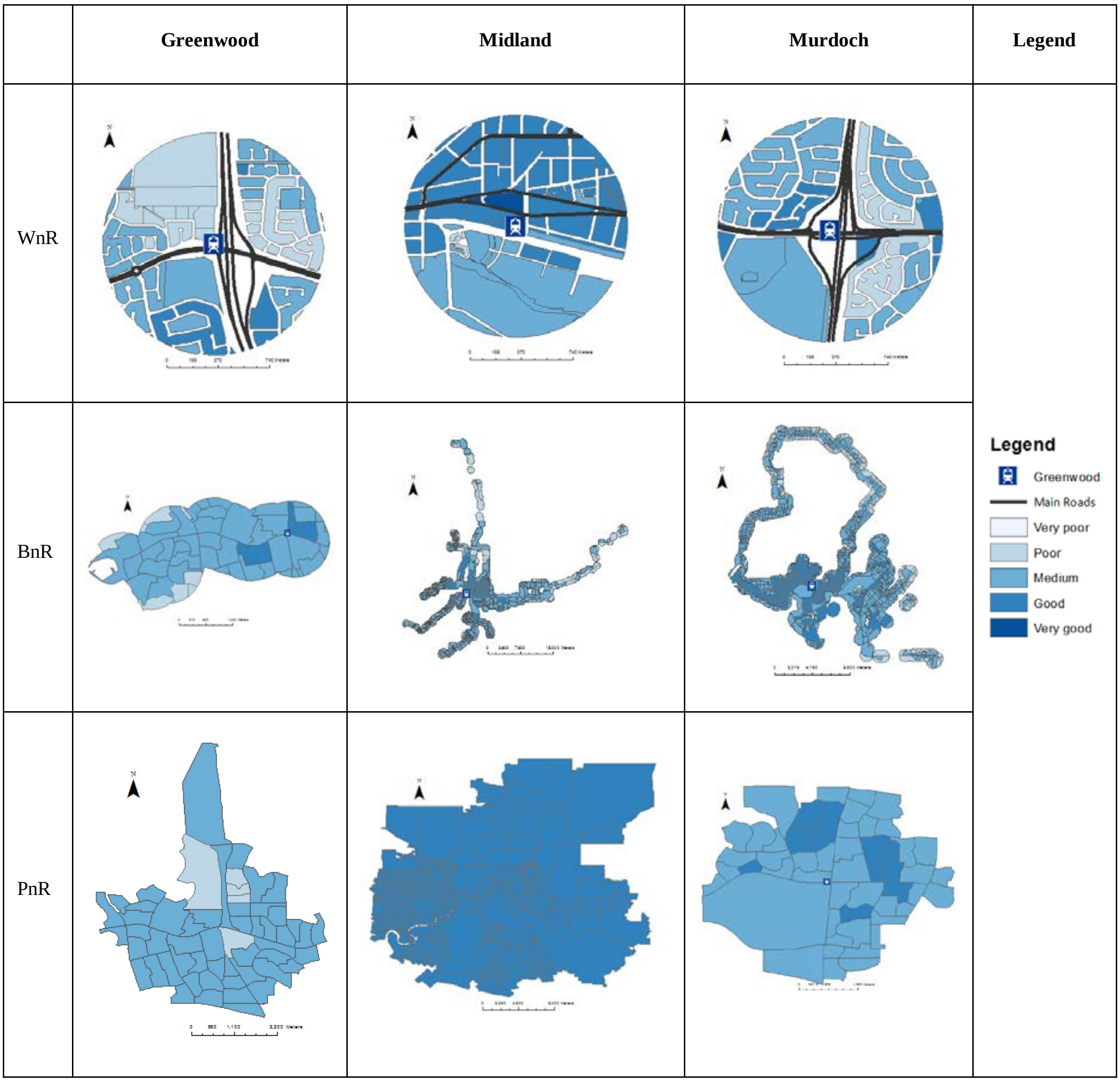

Figure 6.5 A map of access to and accessibility surrounding three train stations

In order to validate the composite index, the elderly were asked to evaluate the overall accessibility of each station. This was called their perceived accessibility and it was measured on a scale of 1 to 5 (Table 6.5). As there were only a limited number of responses from the elderly, the perceived accessibility was not categorised by the various access travel modes.

Table 6.5 shows that, except for Greenwood station, the perceived accessibility was evaluated relatively higher than the measured accessibility.

Table 6.5. A Comparison of Measured and Perceived Accessibility

Station	Accessibility											
	1		2		3		4		5		Average	
	M*	**P***	**M**	**P**	**M**	**P**	**M**	**P**	**M**	**P**	**M**	**P**
Greenwood			20%	40%	73%	60%	7%				2.37	2.33 (5#)
Midland			7%		29%	14%	62%	57%	2%	29%	2.96	3.84 (6#)
Murdoch			10%		70%		20%	63%		37%	2.75	4.33 (8#)

* *M* is measured accessibility and *P* is perceived accessibility.

Number of seniors interviewed at the train station, who provided the overall perceived accessibility.

6.5 SUMMARY

This chapter has introduced a measure of accessibility to train stations for the elderly population. This composite accessibility index distinguishes between the combined modes of WnR, PnR and BnR using spatial methods. This measure has been evaluated against the perceived levels of accessibility obtained from the intercept survey respondents. Although there are some slight differences between the measured accessibility and perceived accessibility, the gravity based composite measure has been shown to be a good method for measuring accessibility to a train station.

The next chapter will apply a modified Huff model to generate the catchment area for train station. The concepts and methods on catchment area modelling will be discussed.

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CHAPTER 7 CATCHMENT AREA MODELLING

7.1 INTRODUCTION

The previous three chapters thoroughly explored the intercept survey data from three different perspectives to understand the two main objectives of this research: catchment area and accessibility. Based on the insights from EDA, this chapter proposes a modified Huff model and uses it to automatically generate catchment areas for the train stations.

This chapter is structured as follows: Section 7.2 states the research context of this chapter. Section 7.3 focuses on the framework and methodology of estimating catchment areas. The results are explained, based on a case study of Perth, Western Australia, in Section 7.4. Section 7.5 evaluates the results by two different methods and Section 7.6 exemplifies the methodology using two scenarios. The chapter ends with conclusions in Section 7.7.

7.2 RESEARCH CONTEXT

A train station's catchment area refers to the areal extent from which the majority of users will typically be drawn (Dolega et al., 2016). It is a prerequisite for the calculation of several fundamental statistics including latent demand (potential customers) (Banister, 1980), market share (the portion of a market) (Lee & Masao, 1988, p. 17-19) and accessibility (ability to reach) (El-Geneidy & Levinson, 2006). There are numerous catchment area estimation methods that range greatly in sophistication. The choice between them largely depends on the complexity of the competitive forces and other attributes that can alter.

Proximity-only models include buffer rings and polygons depicting drive time along a network (i.e. service areas) from a point of interest (e.g. convenience store). Buffer rings are perhaps the simplest method to calculate but assume distance from origin to destination is Euclidean and omnidirectional, whereas catchment areas can have diverse shapes affected by natural features, property developments, zoning, parking capacity, location of train station, and surrounding land use (Cervero et al., 1995; Debrezion et al., 2009; Sanko & Shoji, 2009). Furthermore, they result in generalised and strictly binary decisions about maximum buffer distance (Upchurch et al., 2004). For example, 800 metres has been broadly accepted as a reasonable walking distance to a train station (Cervero, 2001; Cervero et al., 1995; El-Geneidy, Tetreault, & Surprenant-Legault, 2010; Zhao, Yan, & Gao, 2013). However, this distance varies spatially, with, for example, people living in the suburbs likely to accept larger distances than people living in the CBD (O'Sullivan & Morrall, 1996). Service area polygons are a more realistic way of delineating the catchment area and are valid where patrons are expected to use the closest facility (Dolega et al., 2016; Landex & Hansen, 2009). However, like buffer rings, they can be poor predictors of catchment area where proximity is not the only consideration for selecting a particular service.

Proximity to residence is not necessarily the only factor for choosing a train station, with factors such as service quality, facilities available at station, total travel time, access time, service frequency, generalised cost, access mode, road congestion, network connectivity, parking search time, carriage crowding, and demographics playing a key role in station choice (C. Chen et al., 2014; Z. Chen et al., 2014; Kastrenakes, 1988; Lin et al., 2014; Olaru et al., 2014; Ryan et al.,, 2016; Shao et al., 2015). For example, some users may choose a station nearer to their final destination in order to save travel costs, others may choose a station further away from their destination to secure a seat and improve the comfort of their travel. A study conducted by Debrezion et al. (2007) found that less than half, (only 47%), of the passengers in a Dutch railway survey chose their nearest train station. While this may be an extreme example, it does serve to illustrate that the size of a catchment area can differ depending on the interaction of travellers with facilities and services. This cannot be accounted for in proximity-only models. Another concept uses the convex hull of geocoded trip data, (origin to destination), after removal of outliers (Durr et al., 2010). This could better represent the actual catchment area but requires a substantial sample size, (both spatially and temporally), to be truly representative. In such cases, gravity models may be more appropriate as they include not only distance but attractiveness in their computation.

Research is needed to identify a method of defining train station catchment areas that can incorporate the plethora of reasons affecting their extent. In this study, the Huff Model has been used to define train station catchment boundaries using the railway in Perth, Western Australia as a test case. The Huff model is a probabilistic retail gravity model originally used to predict consumer behaviour among competing retail stores (Huff, 1963). Its major advantage over proximity-only models and more simplistic retail models (e.g. Reilly (1931)) is its ability to simultaneously estimate a customer's patronage probability for many centres (e.g. retail locations) (Joseph & Kuby, 2011). While originally developed for retail, the Huff model has been applied to many other areas including accessibility to health care (Luo, 2014) and healthy food (Kuai, 2015), and for choice based analysis including which university campus or movie theatre to attend (Bruno & Improta, 2008; De Beule, Van et al., 2014; Nakanishi & Cooper, 1974).

The aim of the chapter is to develop a methodology for deriving the spatial boundary of the PnR catchment area of train stations, by incorporating the Huff model and Geographic Information Systems (GIS) technologies. Four objectives for achieving this aim are to: a) adapt the Huff model by including additional factors that affect train station choice using Multiple Criteria Decision Analysis (MCDA); b) determine the probabilities for PnR commuters to choose a parking station from the nearest three train stations to their origins; c) derive the spatial boundary of the PnR catchment area of train stations; d) validate the model with observed license plate survey data.

7.3 METHODOLOGY

Starting with the Huff model, this section describes the steps required to model the catchment area of railway stations. The first step applied a modified Huff model to determine the probability of a station being chosen by PnR users. Linear referencing was used to calibrate the locations of the trip origins. Finally, the spatial boundary of the station catchment area was delineated, based on the adjusted points, using ArcGIS™ software. Perth, Western Australia, was selected as the case study location given the prominence of PnR in the public transport mode share and the local knowledge of the researchers. For simplicity, only morning commuting trips to the CBD were analysed, as they represent more than 60% of the total trips in the morning peak.

7.3.1 Data used in the study

The data used in this chapter includes all the data collected by the research team, as set out in Section 3.4. In particular, the license plate survey data were used in the catchment area evaluation. The licence plate survey provided the home addresses of the PnR users at the train stations, based on their number plate and vehicle registration information. The home location, (randomly shifted within a 50 m buffer in order to protect individual privacy), was then geocoded and mapped. Although this procedure aimed to ensure anonymity, it did introduce some locational errors but these were deemed small enough and within the range of confidence for model validation.

Information from the intercept surveys indicated that work and education represent the dominant trip purposes for the morning peak travel (over 80%) and one-third of train commuters use PnR (32.65%). In addition, results show that over 70% of the PnR travellers accessed stations from origins less than 8 km away, which corresponds to an average of three stations (see cumulative function Figure 7.1).

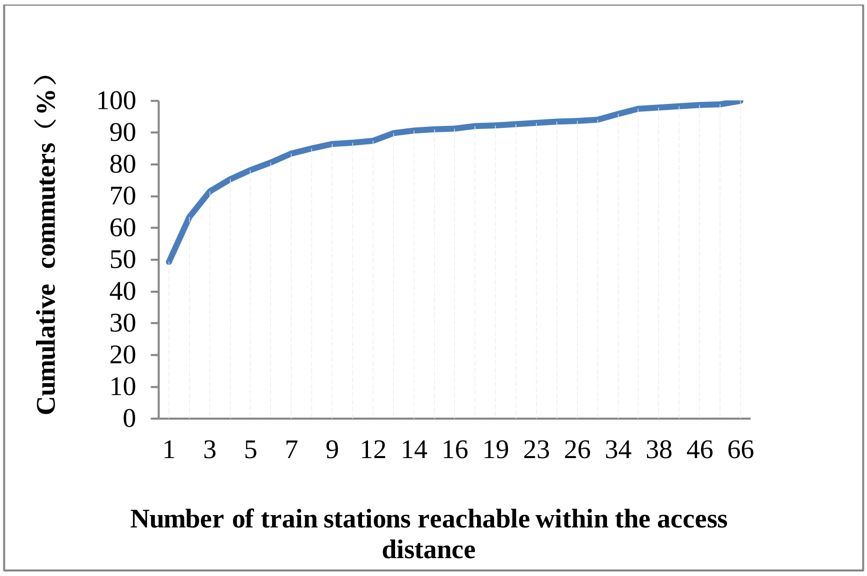

Figure 7.1 Cumulative distance function

7.3.2 Modified Huff model

The original Huff model was developed in 1963 (Huff, 1963) to understand the popularity of shopping centres based on a spatial interaction theory. It has endured for more than 50 years and has been widely used by business analysts and academicians all over the world (Huff & McCallum, 2008). For this study, the original Huff model was modified for application to choice of train station as follows through provided Equation 7-2 and Equation 7-3 regarding to how to define A_j and T_{ij}:

$$P_{ij} = \frac{\frac{Aj}{T_{ij}^{\lambda}}}{\sum_{j=1}^{n} \frac{Aj}{T_{ij}^{\lambda}}} \qquad 7\text{-}1$$

$$A_j = \omega_1 F_1 + \omega_2 F_2 + \ldots + \omega_l F_l \qquad 7\text{-}2$$

$$T_{ij} = TOT_{ij} + TTD_j \qquad 7\text{-}3$$

where:

P_{ij} is the probability of travelling from origin suburb *i* to Perth CBD, through train station *j*;

T_{ij} is network based travel time from origin suburb *i* to Perth CBD through train station *j*;

λ is a distance decay exponent, indicating the effect of travel time on station choice (here λ =2);

A_j is the attractiveness of train station *j*;

F_l is the factor *l* that contributes to the train station's attractiveness, such as parking availability index or land use diversity index;

W_l is the weight of the factor *l* that contributes to the train station's attractiveness;

TOT_{ij} is network based travel time from origin suburb *i* to train station *j* (access time)*;* and

TTD_j is travel time from train station *j* to Perth CBD (here it means in-vehicle time).

In the most recent form of the Huff model, the attractiveness was measured in a multiplicative form and the weight or parameter for the sensitivity of a choice associated with a factor was estimated and calibrated statistically using the actual shopping preference survey data (Huff & McCallum, 2008). In this study, rather than the multiplicative form, the additive form has been adopted to derive the weights by conducting an extra survey to understand policymakers' opinions on the importance of train station choice factors.

Dolega et al. (2016) reported that the distance decay parameter usually takes a value of between −1 and −2, depending on factors such as the types of retail centres or competition between centres. Dramowicz (2005) noted the distance decay parameter as having a value of 2. In transport, it is reported that 2 is usually used for the distance decay of a power function (National Cooperative Highway Research Program et al., 2012, p. 44). Based on the literature and the study model results, a distance decay value of 2 was adopted for the modified Huff model. The robustness of the model is thoroughly evaluated in Section 7.5.

As Perth's CBD is the largest employment centre and the largest destination, the analysis was simplified by only considering trips to the city. Therefore, the travel time includes access time from home to a station and travel time from the station to Perth's CBD, directly extracted from Transperth timetables (PTA, 2015b). As indicated, given the low density and longer travel distances in Perth, the station choice set for each PnR user was reduced from all 70 stations to the closest three stations to the home location. Therefore, instead of calculating the probability of accessing any of the 70 stations, only the nearest three stations to the centroid of a suburb were considered as candidate stations.

7.3.3 Attractiveness of a train station

The attractiveness of a station can be determined using either a multiplicative form (Huff, 2003) or an additive form (Haimes & Steuer, 2012, p. 333). This study adopted the additive form based on the MCDA model in order to incorporate the experts' opinions on the importance of factors affecting station choices. The attractiveness of a train station was measured using four indices:

- Parking capacity (the number of available parking bays at the train stations);
- Street parking availability (dummy variable, indicating whether street parking is available around a station 1 or not 0);
- Land use diversity index, and
- Service and facility quality index.

This research adopted the Walk Score for assessing land use diversity (Leslie et al., 2007), as it represents a good proxy for land use mix. Walk Score is calculated based on *"distance to 13 categories of amenities (e.g., grocery stores, coffee shops, restaurants, schools, parks, libraries); and each category was weighted equally and summarized scores were then normalized to yield a score of 0-100"* (Carr, Dunsiger, & Marcus, 2010). Finally, the train station service and facility quality index includes two components: facilities and frequency of services. Frequency was measured by the average number of trains serving the train station on a working day (using the Transperth timetables). The facilities index was calculated as a weighted sum of 12 facilities. Its components are shown in Figure 7.2.

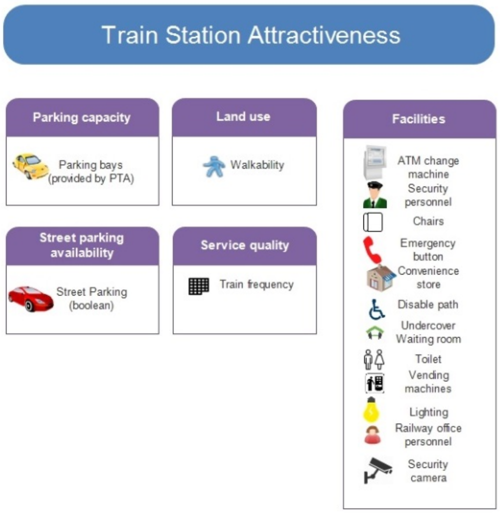

Figure 7.2 Components of a Train Station's attractiveness

These factors are measured in different units and, in order to combine them into one attractiveness index, were "standardised" using the score range (benefit criteria) method (Malczewski, 1999):

$$X'_{ij} = \frac{X_{ij} - X_j^{\min}}{X_j^{\max} - X_j^{\min}} \quad (7\text{-}4)$$

where:

X'_{ij} is the normalised value for item *i* in *j*th attribute;

$X_j^{\min}$ is the minimum score for the *j*th attribute;

$X_j^{\max}$ is the maximum score for the *j*th attribute; and

$X_j^{\max} - X_j^{\min}$ is the range of a given criterion.

Then, the overall attractiveness of a train station was calculated according to equation (2). These weights were determined through ranking the importance of factors from 1 to 7, with 7 the most important for policy makers. Seventeen officers from government agencies, (including DoP, PTA and DoT), were interviewed. The average of ranked values of each factor was calculated and rescaled into weights using a comparison weighting matrix. These weights, therefore, can be added up to one for deriving the attractiveness of a train station using the MCDA model (See Table 7.1). For the services and facilities quality index (SQI), there are two main components, frequency and facilities. However, these were not separated in the questionnaire. Based on research by Z. Chen et al. (2014), frequency is twice as important as facilities. The weight of SQI was re-distributed.

Table 7.1 The weights of factors that contribute to attractiveness of a train station

Factor	**Weights**		
Parking capacity	0.29		
Street parking availability	0.24		
Land use diversity index	0.23		
Services and facilities quality index	0.24	Facilities	0.16
		Frequency	0.08

7.3.4 Linear referencing and origin calibration for deriving spatial boundary of catchment area

The purpose of linear referencing and origin calibration is to define the spatial boundary of the catchment area of a train station. The modified Huff model outputs the probabilities of a station being chosen from a particular location, e.g. the centroid of a suburb (Figure 7.3). The suburb can then be allocated to three train stations with different probabilities. Once these probabilities have been calculated, the next step is to determine the spatial boundary of the catchment area for each train station. In order to make a fair allocation, the centroid of the suburb is relocated using the linear referencing method. The underlying principle is that the probability of a station being chosen is inversely proportional to the distance between a suburb and a station. If the probability of a station being chosen is lower, the centroid of a suburb will be moved closer to the station and vice versa. The lower the probability P_{ij}, the more the adjustment of the centroid of suburb i and the shorter the distance D'_{ij}. We call this process linear referencing and origin calibration. It can be formalised in the following.

$$D_{ij}^{'} = D_{ij} * \frac{P_{ij}}{P_i^{highest}} \qquad 7\text{-}5$$

where:

$D_{ij}^{'}$ is the adjusted distance from the centroid of a suburb (origin) i to station j which will determine the calibrated origin;

D_{ij} is the distance from the centroid of a suburb (origin) i to station j;

P_{ij} is the probability of choosing station *j* from the centroid of a suburb (origin) *i* to Perth CBD; and

$P_i^{highest}$ is the highest probability of a station being chosen from the centroid of a suburb (origin) *i* to Perth CBD.

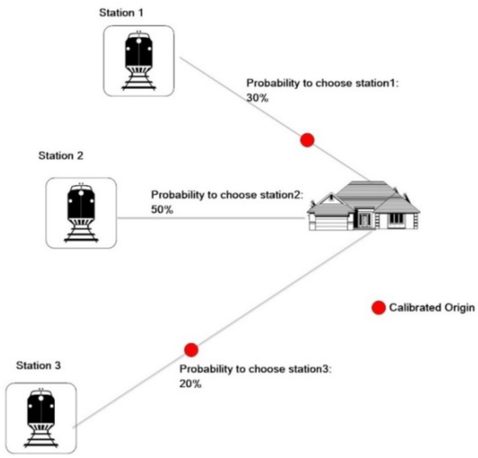

Figure 7.3 A diagrammatic sketch of calibrating origins for the nearest three train stations from the centroid of a suburb

The spatial boundary of the catchment area of a station was determined using the linear referencing method. As each calibrated origin point, (centroid), represented a suburb, the spatial boundary of a train station was drawn by selecting the intersected suburbs of a station and dissolving or aggregating the boundary of the selected suburb's polygons into one area of the station using the ArcGIS™ software. Figure 7.4 illustrates the process of how the boundaries were drawn using Model Builder™ in the ArcGIS™.

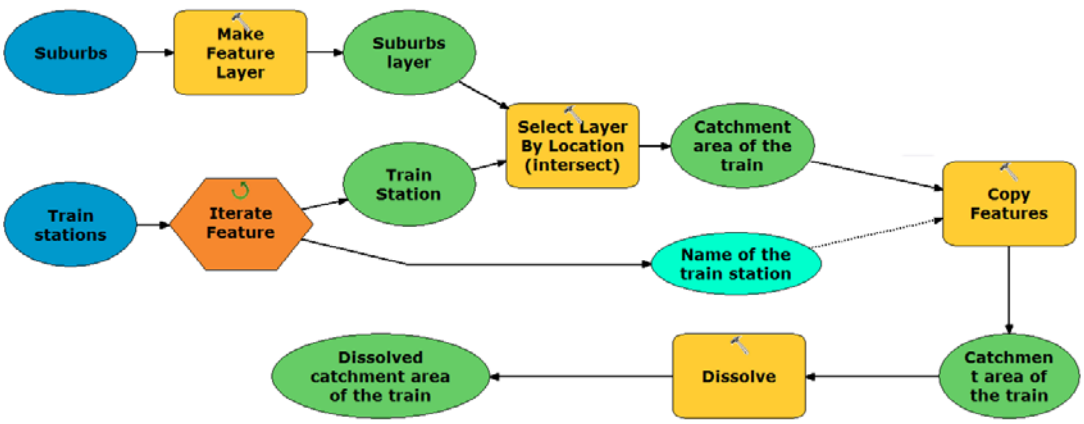

Figure 7.4 The process drawing a boundary in ArcGIS

7.4 RESULTS

7.4.1 The attractiveness of train stations

Figure 7.5a shows the Walk Score, which represents the land use diversity around the train stations. The two stations in the Perth CBD, Perth and Esplanade (now called Elizabeth Quay), have the highest Walk Score, with the Walk Score tending to reduce with distance from the CBD. Among the train lines, Fremantle and Midland have higher Walk Scores than the other train lines, as the surrounding areas are well-developed along these two train lines. Although Perth City station received the highest Walk Score, its attractiveness was not the highest when all factors were taken into account, (Figure 7.5b). This is mainly due to the limited parking capacity in the CBD area and it being primarily a destination station.

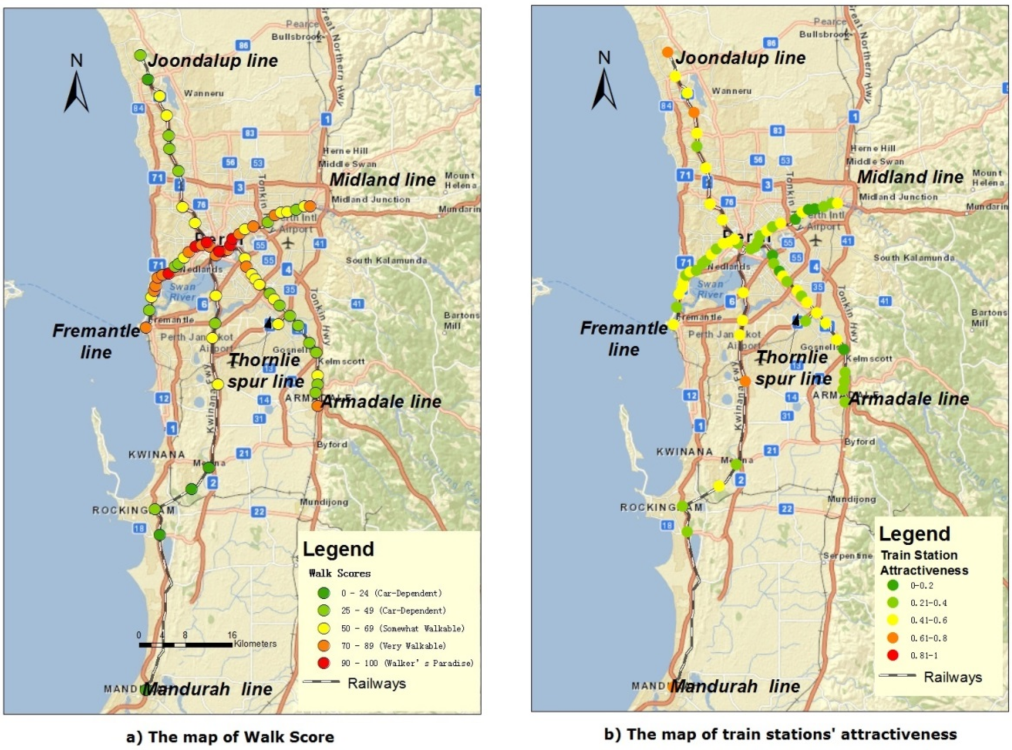

Figure 7.5 The map of Walk Scores of train stations and train station's attractiveness

7.4.2 Origin calibration

Figure 7.6 provides an example of output from the modified Huff model to illustrate how the method was applied. The suburb is Alexander Heights and the nearest three stations are Warwick, Greenwood and Whitfords, (see Figure 7.6). The probabilities of these three stations being chosen from the suburb are 0.41, 0.31 and 0.28 respectively. Warwick station has the highest probability; therefore, the centroid of Alexander Heights will remain unchanged on the line to the Warwick station. However, the centroid of the suburb will move towards the Greenwood and Whitfords stations by 1,882 m and 2,586 m respectively.

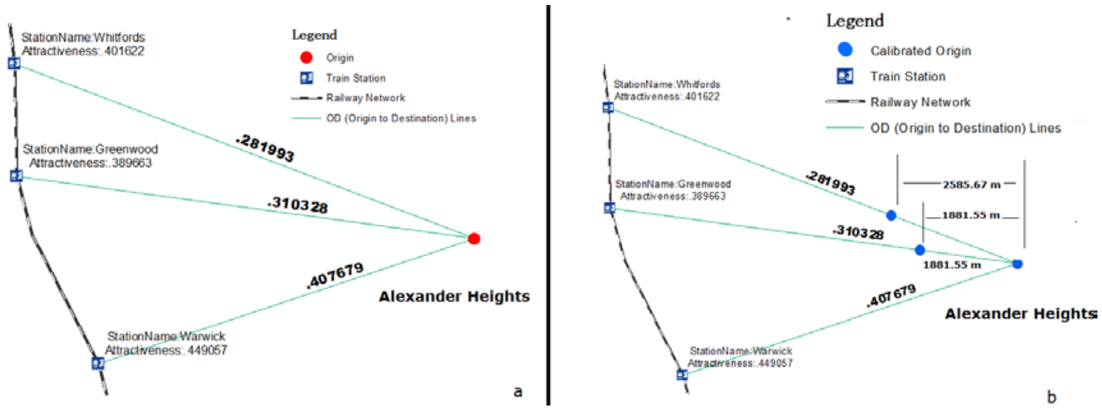

Figure 7.6 The outputs from the Modified Huff Model and origin calibration

7.5 EVALUATION OF THE METHODOLOGY

Two approaches were applied to assess the performance of the methodology: direct comparison and using the Kappa test. Both of them used the license plate survey data (section 7.3.1). The approximate home locations of PnR users were used to validate the accuracy of the derived spatial boundaries of the catchment areas as the licence plate survey is a good data source for understanding the train station catchment areas (see Figure 7.7). The yellow dots represent the approximate origins, (homes), of the PnR users. Buffer rings of 1, 3, 5, and 10 km were drawn around the train stations to illustrate the size of their catchment areas.

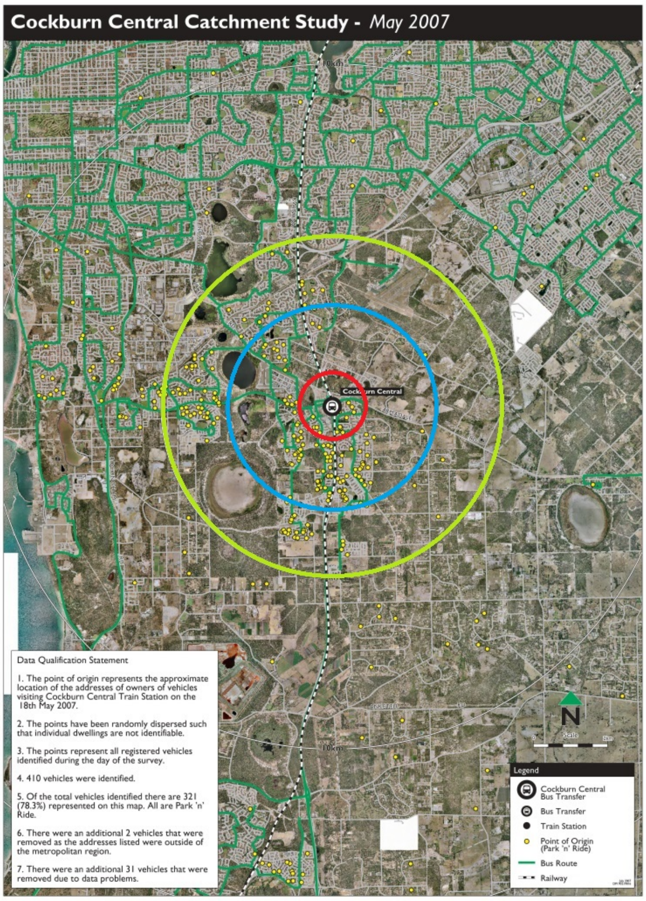

Figure 7.7 Cockburn central catchment area study based on 2007 plate survey data (DPI, 2007)

7.5.1 Direct evaluation

Direct evaluation was conducted by laying the catchment areas derived earlier over the observed PnR users' origins on a map and calculating the percentage of PnR users within the catchment area boundary. Table 7.2 shows the direct evaluation results for 22 train stations where the license plate survey was conducted. Overall, 73% of the surveyed patronage was captured and the accuracy of the model was considered satisfactory, especially given that the methodology considered only the nearest three train stations. Maylands, Cannington and Claremont stations, which are on heritage train lines, have a lower performance which is probably due to a combination of the small spacing between stations on these lines and the land use diversity around those stations, attracting commuters from beyond the three nearest stations. For example, Cannington station has 51% of its PnR patronage coming from outside the predicted catchment area, i.e. driving longer distances to board the train at the Cannington station. This is also consistent with the results in Shao's research that found that only 27% of commuters at Cannington station chose it because it was the nearest station. This means that

73% didn't choose the nearest station to their origin, choosing instead to drive a longer distance and board at Cannington station (Shao et al., 2015).

Table 7.2 Evaluation table using plate survey provided by PTA

Station Name	Percentage[1] (%)	Station Name	Percentage[1] (%)	Station Name	Percentage[1] (%)
Cannington	48.59	Maylands	58.18	Bassendean	60.55
Thornlie	66.73/70.892	Meltham	59.62	Midland	60.55
Armadale	76.34	Bayswater	60.83	Claremont	36.00
Fremantle	89.66	Stirling	62.45	Glendalough	74.92
Warwick	87.22	Greenwood	86.34	Whitfords	76.74
Edgewater	89.66	Currambine	85.38	Clarkson	85.64
Bull Creek	72.90	Murdoch	75.75	Cockburn Central	79.15
Mandurah	87.99			**Average**	**72.85**

1 Percentage of survey commuters covered by catchment area generation algorithm

2 PTA conducted two number plate surveys at the station

7.5.2 Kappa statistic test

Although the direct evaluation provided a simple way to assess the performance of the model, it only counted points of origin inside the catchment area. The Kappa statistic test can evaluate the performance by thoroughly considering origin locations both within and outside the boundaries of the station catchment areas – LOFI (little out from inside) and LIFO (little in from outside) (Huff & McCallum, 2008).

The Kappa test, introduced by Cohen (1960), is the most commonly used index for analysing agreement on a binary outcome between two observers or two classification methods (McLsaac and Cook, 2014). It is frequently used to test reliability.

Figure 7.8 illustrates how the Kappa coefficient was calculated. The colours denote three different train stations. The circles indicate the modelled catchment areas and the points indicate the origins of travel, (from observed data). In order to conduct the Kappa test for the blue station, the data from the adjacent, yellow and purple stations also need to be included. In the Kappa test, the records are grouped into four categories depending on the agreement between the catchment areas and the vehicle registration plate survey data: observed presence and modelled presence (PoPm), observed absence and modelled absence (AoAm), observed presence and modelled absence (PoAm), observed absence and modelled presence (AoPm). PoPm counts all the observed license plate points inside the modelled catchment area, (the four blue points inside the blue circle on Figure 7.8). AoAm counts all the observed points outside the modelled catchment area, (the 3 yellow and 3 purple points outside the blue circle on Figure 7.8). AoPm counts the yellow and purple dots inside the blue circle but outside their own colour circles. These locations are important because the catchment areas of the train stations can substantially overlap. Finally, PoAm counts for all blue points outside the blue circle. AoPm and PoAm indicate the errors of the model. Then the Kappa coefficient and the accuracy of the model can be determined as (Viera & Garrett, 2005) :

$$m_1 = P_o P_m + A_o P_m \quad 7\text{-}6$$

$$m_0 = P_o A_m + A_o A_m \quad 7\text{-}7$$

$$n_1 = P_o P_m + P_o A_m \quad 7\text{-}8$$

$$n_0 = A_o P_m + A_o A_m \quad 7\text{-}9$$

$$n = P_o P_m + A_o A_m + A_o P_m + P_o A_m \quad 7\text{-}10$$

$$AG_o = \frac{P_o P_m + A_o A_m}{n} \quad 7\text{-}11$$

$$AG_m = [\frac{n_1}{n} * \frac{m_1}{n}] + [\frac{n_0}{n} * \frac{m_0}{n}] \quad 7\text{-}12$$

$$K = \frac{AG_o - AG_m}{1 - AG_m} \quad 7\text{-}13$$

where:

AG_o represents the observed agreement;

AG_m = modelled agreement; and

K = Kappa index;

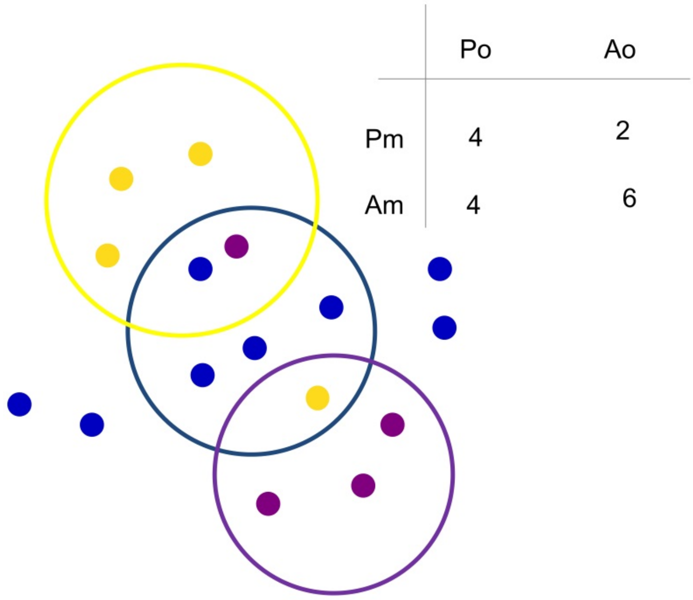

Figure 7.8 Illustration of the Kappa test

Like most correlation statistics, the Kappa can range from −1 to +1. Cohen suggested that the Kappa statistic could be interpreted as follows: values ≤ 0 indicate no agreement, 0.01–0.20 show weak/slight agreement, 0.21–0.40 fair agreement, 0.41–0.60 moderate, 0.61–0.80 substantial, and 0.81–1.00 as almost perfect agreement.

As described above, the Kappa calculation requires the presence of adjacent stations. Although 22 stations have car park license plate data, only six satisfied the criterion of three consecutive train stations available. The results for these six stations are shown in Table 7.3. The results from the Kappa index show that the overall accuracy of the model is satisfactory and the proportions are higher than in the direct evaluation method. The overall accuracy here refers to the proportion that is correctly modelled and is calculated by: (PoPm+ AoAm)/(PoPm+ AoAm+ PoAm+ AoPm).

Table 7.3 Kappa coefficient table

Station Name	**Kappa index**	**Overall Accuracy**	**Station Name**	**Kappa index**	**Overall Accuracy**
Meltham	0.70	0.91	Stirling	0.61	0.80
Warwick	0.86	0.95	Greenwood	0.84	0.92
Whitfords	0.78	0.89	Murdoch	0.62	0.83
Average	**0.74**	**0.88**			

7.6 IMPLEMENTATION OF THE METHODOLOGY AND POLICY IMPLICATIONS

Two case studies are presented next to understand the catchment area and the supply-demand relationships for Perth train stations.

7.6.1 Changes after Mandurah line expansion

Figure 7.9 and Table 7.4 show the variations in train station catchment areas after the opening of the Mandurah rail line. They indicate that it has had a significant impact on the Fremantle and Armadale lines. The largest catchment areas correspond to the stations located near to the end of the train line, such as Mandurah and Rockingham. At the same time, for the Fremantle and Armadale lines, most of the train stations had decreased catchment areas (Table 7.4). The large catchment area variations in Table 7.4 are because the study area included areas more than 20 km from Mandurah station. The reason for this was because, from the plate survey data, commuters were found to travel more than 20 km to board at Mandurah station (Figure 7.10). Another possible reason is the big station spacing along the Mandurah line. For example, the spacing between Warnbro and Mandurah stations is around 23.5 km. Figure 10b shows the substantial changes in the catchment area of Fremantle train station before and after the Mandurah line opened. The results are also due to some changes to the suburb boundaries that occurred between 2006 and 2011, (the Mandurah line started operation in December 2007). From the modelling results, the average rate of decrease in catchment area for stations along the Fremantle line was 127% while for the Armadale line, the average decrease rate was 91%.

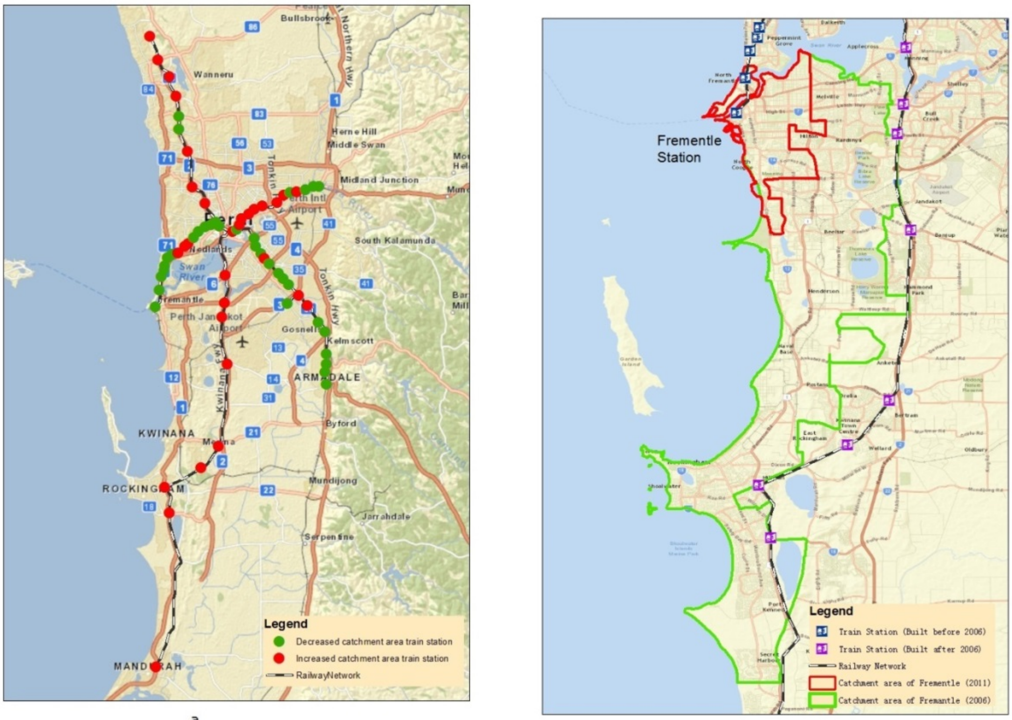

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Figure 7.9 Catchment area variation after Mandurah line expansion

Table 7.4 Catchment area variation rank table

Station Name	Catchment Area Variation – increased (km²)	Rank	Station Name	Catchment Area Variation - Decreased (km²)	Rank
Mandurah	2,129.99	1	Sherwood	-3,352.54	1
Rockingham	817.98	2	Armadale	-2,261.31	2
Warnbro	622.21	3	Challis	-924.21	3
Wellard	370.95	4	Seaforth	-486.57	4
Kwinana	315.47	5	Fremantle	-222.27	5

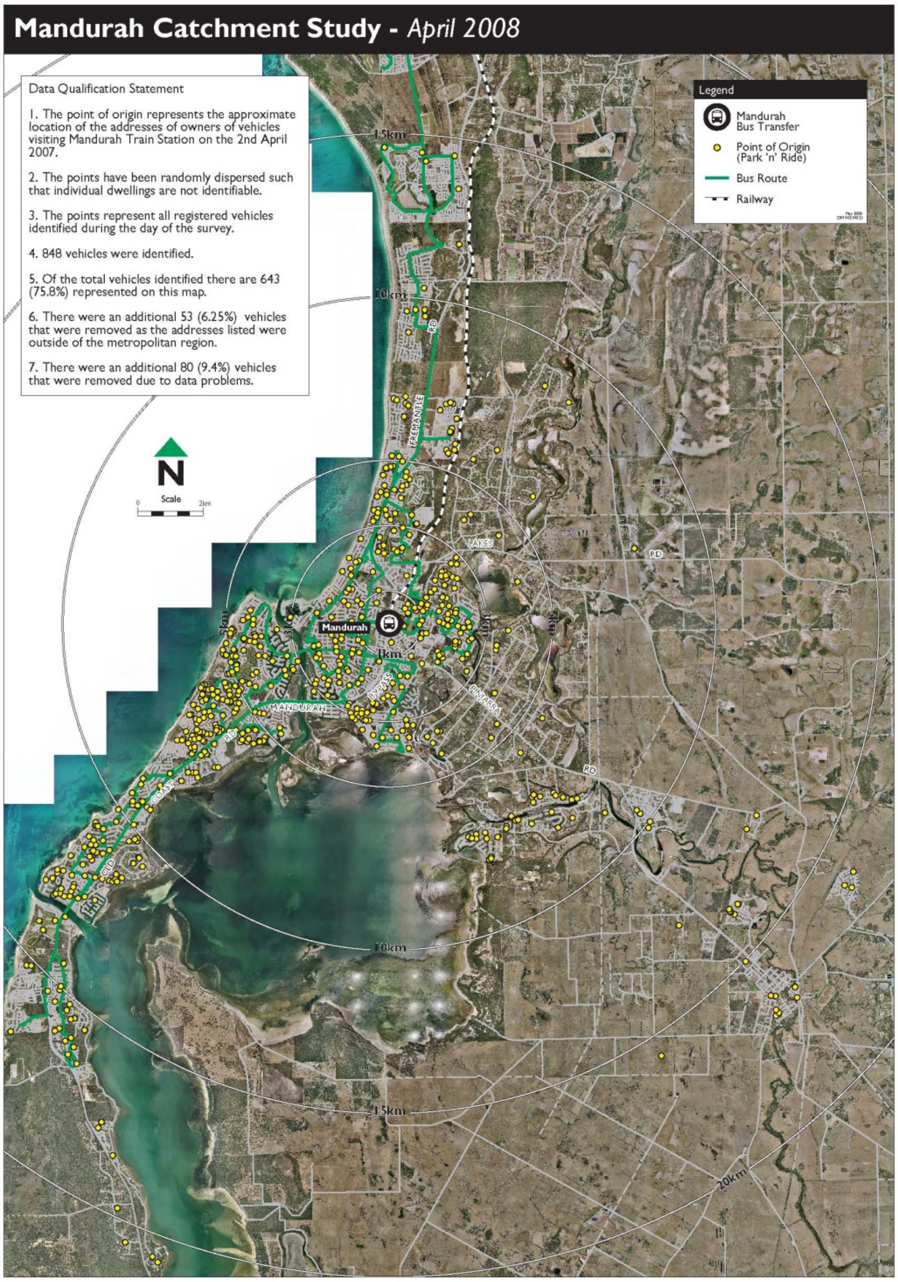

Figure 7.10 Mandurah catchment area study based on 2007 plate survey data (DPI, 2007)

7.6.2 Latent PnR demand and supply

In Perth, parking supply at train stations is an important determinant of the travel mode choice. As it delineates where travellers come from, the estimated catchment area of a train station can be used to estimate the parking demand, supporting parking supply decisions. The station car park survey undertaken in 2014 showed that most train stations had insufficient parking bays and most of them were full before 8:00am (Parliament of WA, 2014).

Combining this information with journey to work data from Census 2011 (Australian Bureau of Statistics, 2011b), Table 7.5 shows the estimated parking demand and the current parking supply, highlighting stations with high parking demand.

Table 7.5 Estimated PnR demand vs provided parking bays

Station Name	Estimated PnR Demand	Ranking by Demand	Long-term bays	Current Capacity Status
Edgewater	1,596	1	887	Full by 7:45 am
Joondalup	1,391	2	225	Full by 5:40 am
Murdoch	1,256	3	1,152	Full by 7:50 am
Greenwood	1,147	4	931	Full by 7:50 am
Whitfords	1,035	5	866	Full by 7:30 am

The highest PnR demand was found to be at train stations where there is already a high supply of parking bays but even at these stations demand exceeded supply. Indeed, at these higher capacity stations the parking areas tended to fill up earlier than at other train stations with lower supply, (according to the car park survey conducted in 2014). This is especially the case at Joondalup train station, where the car park was full before 5:40 am.

7.7 DISCUSSION

The method developed in this study has several advantages and benefits: 1) It is simple to calculate and provides not only the size of a catchment area, but also the spatial boundary (extent) of a catchment area of a transit station. Therefore, it can be easily used to communicate with decision makers (Dolega et al., 2016). 2) Using catchment areas can assist in better estimating and managing the latent demand of a transit station, accounting for competition between stations. 3) The tool is useful for both long-term and short-term planning. For example, catchment area can be used to test various infrastructure scenarios: the impact of adding a new station or even a new train line on the catchment area of the station or line itself, (local effect), or the catchment area of other stations and lines, (global effect) (Rietveld, 2010). Therefore, decision makers can plan in the long-term how to match the transport supply and demand. 4) This methodology can also be useful for a more operational and practical purpose, e.g. to understand the improvements to a train station's infrastructure or the quality of services offered, or to assess the impact of changing accessibility to train stations(Cervero et al., 1995). 5) Currently, this tool includes parking supply, a land use index and a services and facilities quality index. By adding new parking facilities or increasing the frequency of train services, the overall attractiveness of the station changes, which is expected to impact on the size and shape of the catchment area. 6) Although this tool was developed for understanding the catchment area of PnR users, the method can be transferred to estimate other travel mode catchment area, such as, walk and ride, bus and ride and bike and ride.

As with any research, there are limitations. Firstly, the modified Huff model was not calibrated to determine the distance decay parameter in a traditional manner. The widely accepted value was adopted. However, reliable benchmark data collected by PTA was used to validate the accuracy of the model. The overall accuracy was found to be 0.88. In the future, the model will be calibrated systematically in order to understand the impact of spatial variation, temporal variation and heterogeneity, (e.g. different transport modes), on the model accuracy. Secondly, although the method used in the research is a popular method for determining the weight of the factors, it could be subjective and may be difficult to translate directly to other studies. Other methods such as discrete choice modelling can help to understand how various station choice factors contribute to the station preference by various categories of travellers. Thirdly, the accuracy of the model could be improved if more stations were included in the "choice set" and then in the linear referencing. However, this would increase the complexity of the calculation. Fourthly, the modifiable areal unit problem (MAUP), a common problem in GIS analysis, may lead to varying solutions. In this study, the suburb was used as the spatial unit of analysis given the data availability, although it is not the smallest available unit. Adopting a smaller unit of analysis, (SA1 is the smallest spatial unit currently available in Australia), may be beneficial for the catchment area calculation but it is more computational intensive. In this research, in order to test the influence of the MAUP, eight train stations were selected to compare results by suburb and SA1. The catchment areas did change, but not considerably. Therefore, as a compromise between simplicity and accuracy, the suburb is considered a good unit for analysis.

7.8 SUMMARY

This chapter has reported on the development of a modelling tool to forecast the catchment area of a train station, which is useful for understanding the potential travel demand of transit stations. The developed model delineated the catchment area based on the attractiveness of the train station and the distribution of the origins. This is novel and enriches the existing catchment area measures. By combining an enhanced Huff model with linear referencing modelling, competition between train stations was better understood, as well as the role of train station attractiveness in the catchment areas.

The next chapter will improve the floating catchment area method to conduct macro accessibility modelling, which models the change in accessibility due to a major intervention. In this case the major intervention is the opening of the Mandurah train line. The macro accessibility concept and methodology will be discussed in the next chapter.

CHAPTER 8 MACRO ACCESSIBILITY MODELLING

8.1 INTRODUCTION

The previous chapter presented the spatial framework for modelling the catchment area of a train station based on the modified Huff model. This chapter applies the outputs from the modified Huff model and improves the existing FCA based accessibility models to examine the change in accessibility over time or either side of a major intervention. In this study the major intervention was the recent opening of the new Mandurah railway line. This chapter is organised as follows. Section 8.2 reviews the literature on the Floating Catchment Area (FCA) based accessibility measures and the distance decay function. Section 8.3 focuses on the methodology developed in this study to improve the FCA measure. The results are presented in Section 8.4, with a summary of findings, contributions and a discussion of limitations and possible further developments in Section 8.5.

8.2 RESEARCH CONTEXT

FCA is a special case of the gravity model that incorporates supply, demand, and distance decay (Delamater, 2013). Compared with the traditional gravity model, FCA is much more intuitive to interpret as its key output is supply to demand ratio (SDR).

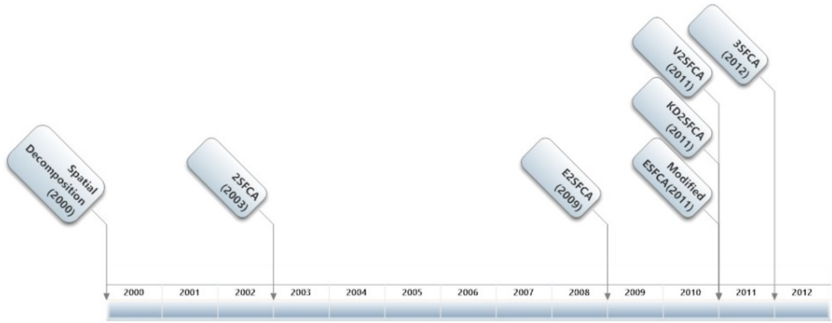

Figure 8.1 The development of FCA metrics

FCA was initially proposed by Wei Luo and Wang (2003) who were inspired by the spatial decomposition method (see Figure 8.1). Radke and Mu (2000) computed the ratio of suppliers to residents inside a service area based on the spatial decomposition method. Luo and Wang (2003) adopted the ratio idea, developed it as the two-step floating catchment area method (2SFCA), and applied it to measure spatial accessibility to health care. 2SFCA is so-named because it contains two steps. The first is to determine "supply availability" at supply locations as the ratio of supply to population within the supply catchment. The second sums up the ratios at each demand location within the demand catchment. Although 2SFCA has the advantage of being easy to interpret and produces meaningful results, some major limitations have been identified (Luo & Whippo, 2012; McGrail & Humphreys, 2009): 1) It is a dichotomous measure. It applies the cumulative distance decay function (see Figure 8.2). All locations inside catchment area get the value of 1 while the outside ones get 0; and 2) It uses a fixed catchment size for all locations which ignores the attractiveness of the facility itself and also the surrounding land use discrepancy. For example, it ignores the travel pattern of rural areas and urban areas. People in rural areas may be willing to or have to travel further distances to access to facilities than those in urban areas. Therefore, several efforts were made to improve this method. Luo and Qi (2009) enhanced 2SFCA by adopting a number of travel time zones, (e.g. 0-10 mins, 10-20 mins and 20-30 mins). Different weights were then applied to each of these zones in both the first step and the second step, to account for the distance decay (see Figure 8.2 simple buffer rings distance decay). This approach is called the

"Enhanced Two-step Floating Catchment Area" (E2SFCA) method. Langford (2011) further modified E2SFCA by using a distance decay function instead of simply weighting the different travel time zones. He suggests that linear decay, Gaussian decay and Butterworth filter decay are three decay functions that could be applied when conducting E2SFCA. The integration of distance decay into the E2SFCA was further advanced in the "Kernel Density Two-step Floating Catchment Area" method, (KD2SFCA), by assigning weights based on a continuous decay function(Dai & Wang, 2011). Luo (2011) proposed a variable catchment size method, called 2VSFCA, in response to the limitations imposed by fixed catchment sizes. It adopts an initial travel time (t_0) first and sums the population within this travel time of the facility. If the population is less than a pre-defined threshold, (usually from observation), the search radius time is increased by a series of small increments, (e.g. 2 mins), until the required population threshold is reached. Equally, if the population is more than the pre-defined threshold, the search radius time is decreased until the required population threshold is again reached. Wan et al. (2012) modified the E2SFCA by incorporating the potential for competition among facilities, i.e. it assumes that a local population's demand at a nearby service site is affected by the travel cost to that site as well as the travel costs to adjacent service sites. It therefore adds a step to calculate the competition effects, (selection weights). This modified approach is called "Three-step Floating Catchment Area" (3SFCA). Further, Luo (2014) integrated a Huff model to define the selection weights in the 2SFCA.

Although there have been many studies on the various FCA methods, the debate continues over which form of the distance function to choose, what proper methods to use to best define the catchment area and how to best define the selection weights. For example, in the literature, there is a number of different ways to populate the weights of the distance decay, e.g. distance rings based weights, the Kernel Density based continuous decay function and other popular distance decay functions such as Gaussian, Inverse power, and Exponential, (see Figure 8.2) (Delamater, 2013; Kwan, 1998; Luo & Qi, 2009).

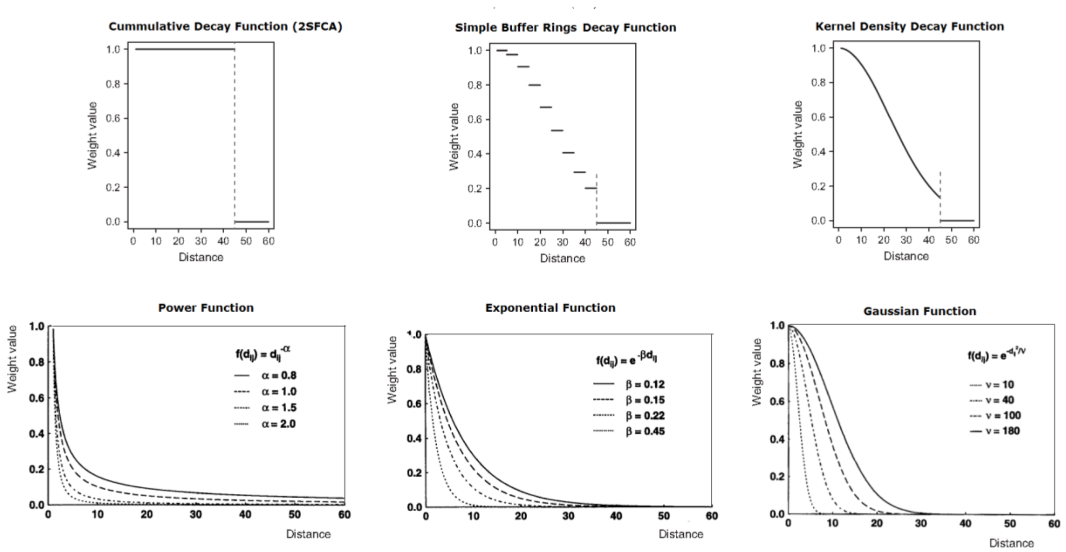

Figure 8.2 Popular distance decay functions (Delamater, 2013; M.-P. Kwan, 1998)

This chapter addresses two issues when applying FCA metrics to macro accessibility modelling. These are:

1) How to quantify the potential demand of the facilities more precisely?

Firstly, most of the existing FCA methods, (e.g. 2SFCA, E2SFCA, 3SFCA), use a single threshold to define the catchment area of all facilities and therefore the potential demand. Using a single threshold and applying it to all facilities may cause either underestimation or overestimation of demand at individual facilities, as the threshold should, in reality, vary according to the individual facility’s characteristics and also the characteristics of the surrounding area. Chapter 7 introduced the modified Huff model based catchment area generation framework as a potential solution to this problem as each facility would have its own catchment threshold. Secondly, most of the existing FCA methods do not consider the competition between facilities to distribute demand to accessible facilities or a simple single distance decay function to distribute the demand. In practice, the demand distribution should be based on the station choice probability. The results from modified Huff model could help with this as well.

2) How to improve the distance decay function?

Throughout the development history of the FCA method, many distance decay functions have been applied including the cumulative decay function, the simple buffer rings decay function and the kernel density decay function. Even in other fields outside the FCA metric, there is still a lot of discussion on, and disagreement over, the different impedance functions (Kwan, 1998). To date, there appears to be no general agreement on which is better, as distance decay is a complex issue determined by many factors. This study has derived a distance decay function using observed ABS census journey to work data from 2006 and 2011, and the distance from the centroid of each SA1/CD to its nearest train station.

An enhanced Three-Step Variable Floating Catchment Area (E3SVFCA) measure has been developed in this chapter. It used the Huff model to determine the probabilities of the station choice. These were then combined with a Linear Referencing System (LRS) method to delineate the catchment area of each facility, which varied from one facility to another based on their individual characteristics. Then the supply-demand ratio of each train station was derived based on the catchment area and station choice probability, from the previous step. Finally, the accessibility of each suburb to the train station was calculated based on attractiveness, (expressed as a parking supply- demand ratio), and distance from the station.

8.3 METHODOLOGY

8.3.1 E3SVFCA

As an extension to its predecessors, Enhanced Three-Step Variable Floating Catchment Area (E3SVFCA) improves the existing floating catchment area based method by integrating the Huff model. It required three steps:

***<u>Step1</u>:** the probability of choosing train station j (with selection weights) was calculated based on the Huff model (see Chapter 7 for details of this step).*

$$G_{kj} = \frac{\dfrac{A_j}{T_{kj}^{\lambda}}}{\sum_{j=1}^{n} \dfrac{A_j}{T_{kj}^{\lambda}}} \tag{8-1}$$

$$A_j = \omega_1 F_1 + \omega_2 F_2 + \ldots + \omega_k F_k \tag{8-2}$$

where

G_{kj} is the probability of suburb *k* choosing train station *j*;

n is the number of train stations (here, n=3);

T_{kj} is network based travel time from suburb *k* to train station *j*;

A_j is the attractiveness of train station *j*;

λ is a distance decay exponent, indicating the effect of travel time on station choice (here λ =2);

F_k is the factors and indices that contribute to the train station's attractiveness, such as parking availability index, land use diversity index;

ω_k is the weight of the factors that contribute to the train station's attractiveness;

Here, n=3 is because majority of PnR commuters chose the nearest three train stations according to the intercept survey data (see Figure 7.1); γ=2 because it is reported that 2 is usually used for the distance decay of a power function in transport (Cambridge Systematics et al., 2012, p. 44) .

Step2: *The supply-to-demand ratio* R_j *(No. of parking bays to No. of potential PnR users) is calculated for train station j.*

$$R_j = \frac{NP_j}{\sum_{k=1}^{m} NPnR_k G_{kj}} \quad \text{8-3}$$

where

R_j is the supply demand ratio for train station *j;*

NP_j is the number of parking bays at train station *j*;

m is the number of suburbs in the catchment area of station *j*;

G_{kj} is the probability of train users in suburb *k* using train station *j*; and

$NPnR_k$ is number of potential PnR train users in suburb *k*;

The number of potential PnR users is equal to total number of train users in the suburb, assuming that all train users could potentially use PnR if there were sufficient parking bays at station.

Step3*: The accessibility from suburb k to the stations is calculated.*

$$A_k = \sum_{j=1}^{n} R_j W_{kj} \qquad \text{8-4}$$

$$W_{kj} = f(\mathrm{d}) \qquad \text{8-5}$$

where

n is the number of train stations in the catchment area of suburb *k*;

W_{kj} is the accessibility distance decay weights of suburb *k* to train station *j* determined by distance decay function; and

d is the distance from suburb *k* to train station *j*.

8.3.2 Catchment areas

In the concept of E3SVFCA, there are two catchment areas. One is the catchment area of a train station and one is the catchment area of a suburb.

Catchment area of a train station

Obviously, the catchment area of a train station can be determined from the commuters' station choice. Train users do not necessarily choose the nearest station to their home (Shao et al., 2015). Some might choose a station nearer to their destination to reduce travel costs or choose a station further away from their destination to secure a seat. Therefore, the size and shape of a catchment area is influenced by the behavioural preferences of individual users and the facilities and services provided at each competing station.

The modified Huff model outputs the probabilities of a commuter from suburb *k* choosing each of a set of possible train stations. The probabilities were calculated based on the attractiveness of the train station and the travel cost (Equation 8-1). The Linear Referencing System (LRS) method was applied to get the adjusted points of origins based on the station choice probabilities. The catchment areas of the train station were then delineated by the adjusted points of origins. Details of the catchment area delineation process are provided in Chapter 7.

Catchment area of a suburb

The catchment area of a suburb defines the train station that the commuters in an area are able to reasonably access. This study used a threshold of the three nearest stations, (based on network distance), rather than the physical catchment boundary because:

- Using *number of nearest stations* satisfies the purpose of defining the potentially accessible facilities; and
- Using *number of nearest stations* avoids the drawbacks of using a single threshold.

It is recommended that the number of nearest train stations should be determined by the cumulative curve of the real data. Figure 7.1 indicates that the majority, (around 75%), of PnR user in Perth choose one of the three nearest train stations when making their station choice decision. Therefore, in this study, three was chosen.

8.3.3 Distance decay function

As discussed in Section 8.2, the most important contribution of E2SFCA is to account for the effect of distance decay by adding distance decay weights. In the literature, there are a few distance decay functions available, but there is no agreement on which distance decay function is best. This study therefore used observed data to derive, calibrate and validate the distance delay function, consistent with the observed distance decay pattern. Three steps were required to derive the function.

Step1: Calculate the network distance of SA1 centroid to the nearest train station;
Step2: Count the number of PnR users per unit area (are from ABS census journey to work data), inside each distance ring (e.g. 1 km-2 km, 2 km-3 km);
Step3: Determine the best distance decay function using the Matlab^{TM} curve fitting function.

8.3.4 Suburb distance to train station

In GIS for Transportation (GIS-T) studies, data is usually aggregated into geographic zones due to the unavailability of point data, (e.g. to maintain the privacy of individuals), and also to reduce calculation complexity. In this study, the suburb has been chosen as the spatial unit of analysis even though it is not the smallest unit in the ABS Basic Community Profile (BCP). The reasons for choosing a suburb level analysis are:

- The smallest unit in the ABS census changed from 'Census District' (CD) in 2006 to 'Statistical Area 1 (SA1)' in 2011 and CDs and SA1s are not consistent areas. The suburb is a relatively stable spatial unit over time and is available in both 2006 and 2011 ABS data.
- The calculation requires a small unit to calculate the weighted travel distance. Suburb is the second smallest unit in the BCP file, which fulfils this criterion.

The average distance from suburb to train station weighted by the PnR users inside each sub-area (CD in 2006 and SA1 in 2011), is calculated by the following equation:

$$d_{kj} = \frac{\sum_{i=1}^{m} NPnR_i * d_{ij}}{\sum_{i=1}^{m} NPnR_i} \quad \text{8-6}$$

where

d_{kj} is the average distance from suburb *k* to train station *j*;

m is the number of CDs(2006) or SA1s(2011) inside suburb *k*;

d_{ij} is the distance of CD(2006) or SA1(2011) *i* inside suburb *k* to the train station *j*; and

$NPnR_i$ is the number of PnR users of CD(2006) or SA1(2011) *i* inside suburb *k*.

8.4 RESULTS

8.4.1 Catchment area

Figure 8.3 shows the PnR catchment area boundaries for three adjacent train stations on the Mandurah line, determined using the modified Huff model. The size and shape of the catchment areas vary from station to station as they are a function of the train station characteristics, (e.g. the services and facilities provided by the train station itself), its surrounding land uses, parking availability and distances to potential origins. The derived catchment areas have been evaluated against the number plate survey data, (the dots in the Figure 8.3), and it is concluded that the defined catchment areas capture the majority of station users, (72.85%), (see Section 7.5 for details). This overcomes the shortfalls of the single threshold catchment area definition as it draws the boundary based on where the actual customers come from, which is a significant improvement for the FCA metric family.

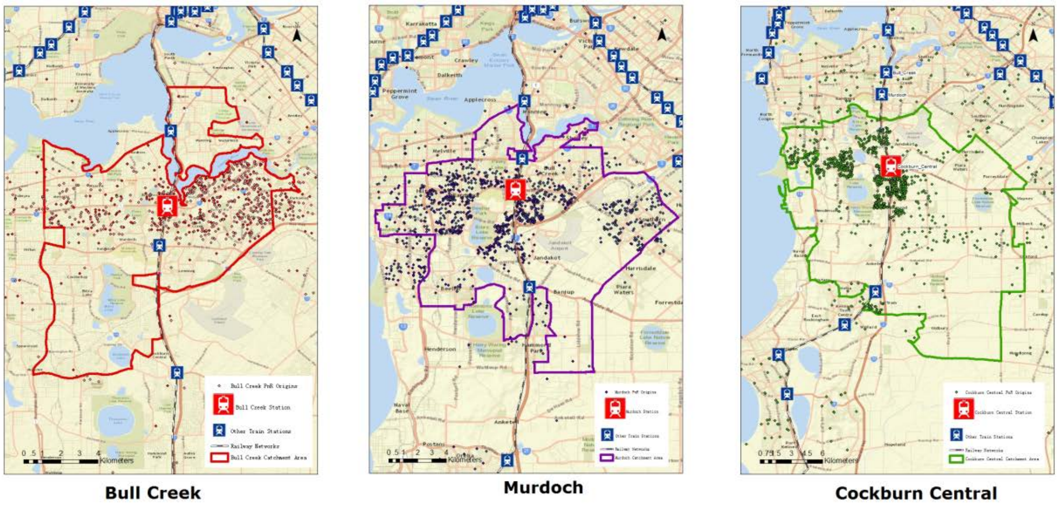

Figure 8.3 The PnR catchment area of the stations

8.4.2 Distance decay function

The network distance of each SA1 to the nearest train station was derived in accordance with Section 8.3.3. Figure 8.4 shows the relationship between the number of PnR trips and distance in 2006 and 2011. The number of PnR trip origins first increases and then decreases with distance from the station, in both 2006 and 2011. There are two possible reasons for this: (1) Travel mode choice. When people live very close, they might choose to walk to the train station rather than drive. (2) The area of each ring increases with distance from the station even though the distance increases are regular, i.e. 1 km increments. For example, the area of the 1 km-2 km ring is three times larger than the area of the 0-1 km ring.

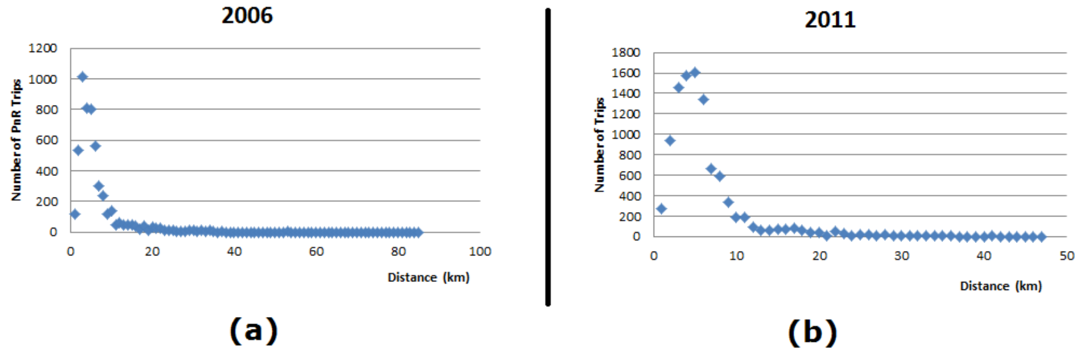

Figure 8.4 Decay of PnR trip origins with distance from station

Therefore, in this study, the number of PnR trips within a distance band, such as 0-1 km, was divided by the band area to provide the number of trips per unit area, rather than using the number of PnR users. With the areas standardised, those with more trip origins can be identified as areas from which more people are willing to travel to train station by PnR, i.e. are indicative of areas with higher accessibility. Although Figure 8.5 shows that the number of PnR users per unit increases first and then decreases, (i.e. the observed ABS data), the potential accessibility of PnR should, in theory, be consistently decreasing with increasing distance. People are unlikely to choose PnR as the travel mode when the distance is close to the train station because they can readily walk. It is also possible that they could catch a bus as the bus network is much denser when it is closer to train station. Therefore, the data to the left of the peak, i.e. for very short distances, were not used in the calculation of the distance decay function.

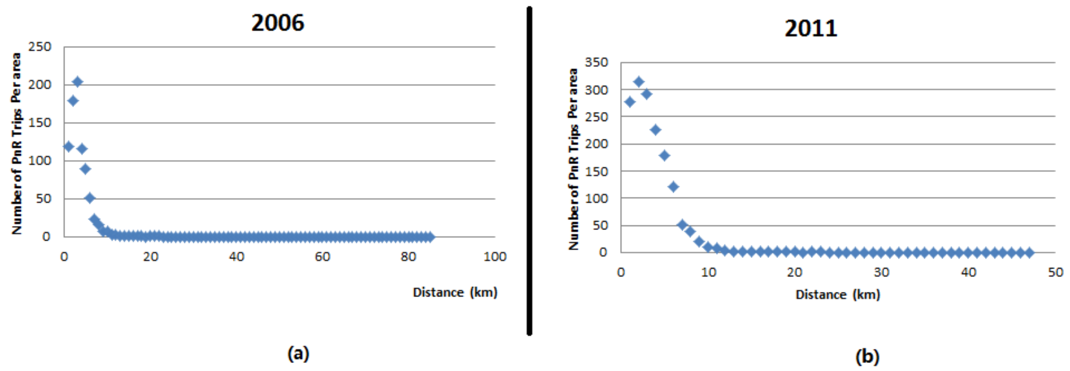

Figure 8.5 The number of PnR users per area by distance

As mentioned earlier, there are three popular standard distance decay functions in the literature: Gaussian, Inverse power, and Exponential. The 2006 data, the 2011 data and the combined 2006 & 2011 data were fitted using these functions. The results are shown in Table 8.1. The exponential function gave the best fit, (highest R-square value), for 2006 and the Gaussian function for 2011 and both years combined. As the change in accessibility from 2006 to 2011 was being measured, a consistent measure of accessibility was required, i.e. a consistent distance decay function needed to be used. Therefore, the combined 2006 and 2011 data were used to determine the best fitting function, i.e. the Gaussian function.

Table 8.1 Fitting results of distance decay function

Group	Decay function name	Decay function equation	R-square	Adjusted R-square
2006	**Exponential**	**exp(d*-0.4826)**	**0.9952**	0.9951
	Gaussian	$\exp(-d^2/18.9)$	0.9912	0.911
	Inverse power	$d^{-2.268}$	0.9812	0.981
2011	Exponential	exp(d*-0.298)	0.9696	0.9689
	Gaussian	**$\exp(-d^2/30.11)$**	**0.9948**	0.0047
	Inverse power	$d^{-1.359}$	0.8738	0.8709
Combined	Exponential	exp(d*-0.4001)	0.9914	0.9913
	Gaussian	**$\exp(-d^2/24.47)$**	**0.9965**	**0.9964**
	Inverse power	$d^{-2.018}$	0.9601	0.9596

8.4.3 Accessibility measure before and after opening of the Mandurah line

The main factors affecting accessibility determined using the Floating Catchment Area measures are supply, demand and distance decay. With regard to PnR user accessibility, these equate to, respectively, number of parking bays, number of potential PnR users and distance to the train station. Thus, the change in accessibility resulting from the opening of the Mandurah rail was explored using these factors.

Parking bays

The presence of an available parking bay is the key factor in determining PnR accessibility. Figure 8.6 shows the train station parking capacities (PC) in 2006 and 2011. The Perth Transport Authority, (PTA), has a train station car park expansion project (Public Transport Authority, 2008), that is steadily increasing the number of parking bays at train stations as the demand from a growing population also grows, especially along the newer Joondalup and Mandurah train lines. However, parking at some stations has decreased due to re-development of some of the land previously used for parking, e.g. at Warwick station. It is likely that further reductions in parking will occur at some stations as structure planning is taking place as a precursor to future development. For example, structure planning for the land around Murdoch station indicates that some current parking could be changed to commercial and residential mixed use in the near future (Department of Planning, 2014).

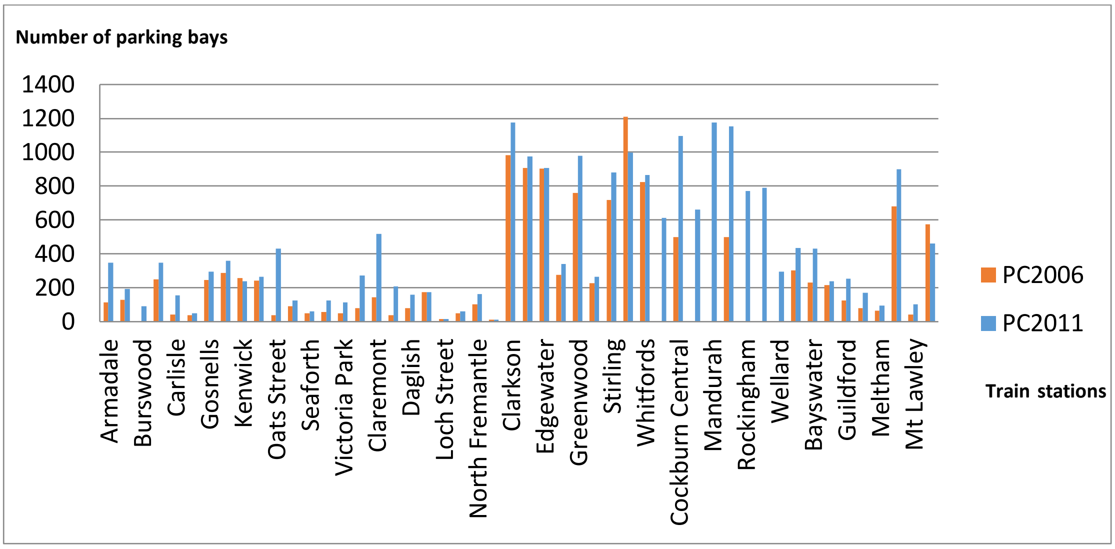

Figure 8.6 Parking bays in train station (2006 and 2011)

Potential PnR Demand

The number of train users in 2006 and 2011 were extracted from the ABS Census journey to work data (Australian Bureau of Statistics, 2011b) at the suburb level (the spatial unit of analysis in this study). For the purposes of this study, these have been assumed to be the potential, (maximum) PnR demand given unlimited parking supply at the stations. The home suburbs of these train users are plotted on Figure 8.7 for 2006 and 2011. The largest change in train use is, as one would expect, along the new Mandurah (southern) rail line, but growth in demand can also be seen along the other lines, especially the Joondalup (northern) rail line. These two corridors, north and south, are those that experienced the highest population growth between 2006 and 2011. Table 8.2 ranks the suburbs and train lines by the potential increase in PnR users. The five suburbs with the highest potential increase are all on the

Mandurah line, although some suburbs along the Joondalup and Armadale also were found to have high additional PnR demand.

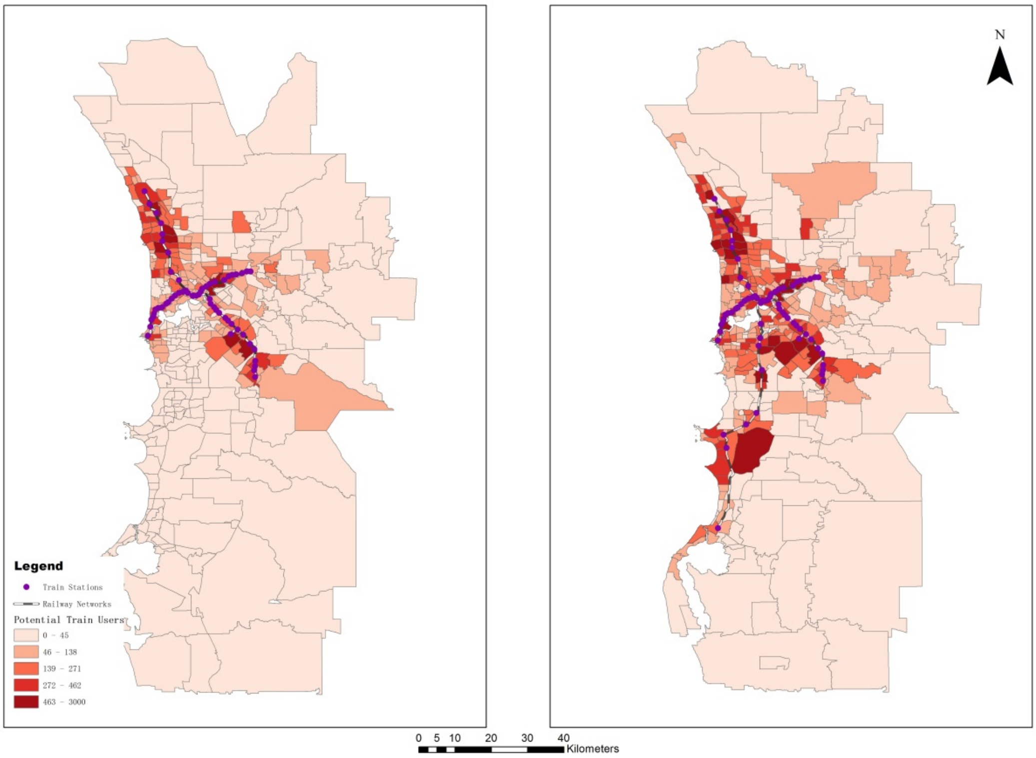

Figure 8.7 Potential PnR users by suburb in 2006 and 2011

Table 8.2 Suburb with highest potential PnR users

Suburb	Potential PnR users (2011)	Potential PnR users (2006)	Incensement	Rank
Canning Vale	1361	230	1131	1
Willetton	941	50	891	2
Leeming	613	15	598	3
Baldivis	589	0	589	4
Success	568	8	560	5
Train line	**Potential PnR users (2011)**	**Potential PnR users (2006)**	**Incensement**	**Rank**
Mandurah	14272	0	14272	1
Joondalup	19146	13126	6020	2
Armadale	10123	6226	3897	3
Midland	7146	4959	2187	4
Fremantle	5162	3543	1619	5

Supply to demand ratio (SDR)

The supply to demand ratio quantifies the relationship between supply and demand, the lower the SDR, the scarcer the resource. Values below 1 indicate that demand exceeds supply. Figure 8.7 shows that there is significant SDR change, (worsening), along three train lines, (Joondalup, Armadale and Mandurah), between 2006 and 2011, even though the number of parking bays also increased along those lines. The train stations located at the end of train lines, with the exception of Fremantle, had the highest SDRs, indicating less competition for parking bays. Fremantle station has a shortage of parking because it is in a well-developed area with high density and less land available for parking. Thornlie station has a large SDR change, possibly due to substantial residential development within its catchment area, in particular in the suburb of Canning Vale.

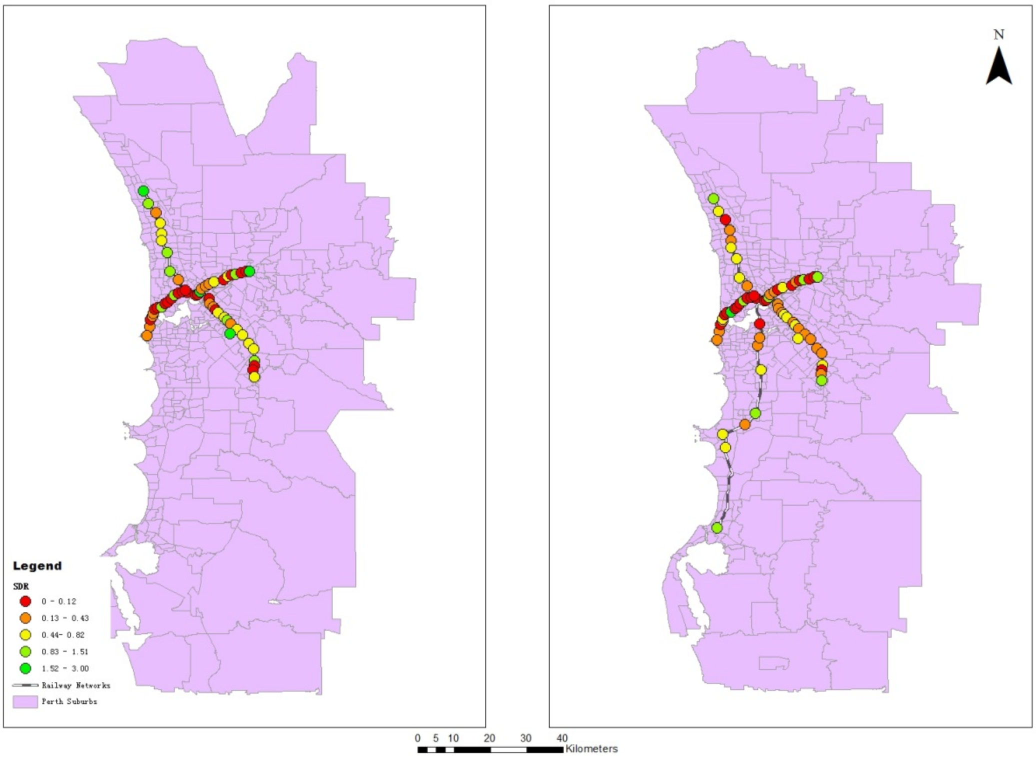

Figure 8.8 Train station parking supply-to-demand ratios (2006 and 2011)

Table 8.3 shows the changes in the average SDRs for the five different train lines. The change by line is an indicator of whether the line as a whole has a parking supply problem, i.e. whether there is spare capacity if commuters were prepared to drive long distances to access an available space somewhere along the line. The PnR accessibility of suburbs along the

Mandurah line is greatly improved, as would be expected, with the opening of the new line. The pressure for parking is also reduced on the Fremantle line as commuters who live in suburbs along the Mandurah line and used to broad on the Fremantle line could transfer to train stations on the Mandurah line. In theory, the opening of the Mandurah line should have also reduced the demand for parking along the Armadale line but due to the growth along the Armadale line corridor, the SDR did not change much.

Table 8.3 SDR changes by train line

Train line	**SDR (2011)**	**SDR (2006)**	**Change**	**Rank**
Mandurah	0.53	0	0.53	1
Fremantle	0.36	0.21	0.15	2
Armadale	0.4	0.38	0.02	3
Midland	0.41	0.4	-0.01	4
Joondalup	0.59	0.42	-0.17	2

Accessibility

Figure 8.8 shows the accessibility to train stations in 2006 and 2011. Figure 8.9 shows the variation between 2006 and 2011. As expected, the accessibility of the south- western areas was dramatically improved after the opening of the Mandurah train line. Accessibility for suburbs along the Joondalup and Armadale lines decreased due to substantial development in those areas producing a significant increase in demand. Along the heritage lines, (Midland and Fremantle), some suburbs experienced an improvement in accessibility. There are probably two reasons for this: (1) the opening of the Mandurah line reduced the demand on the Fremantle line; (2) an increase in the number of parking bays between 2006 and 2011. For example, at Claremont station, due to ongoing construction work on “Claremont on the Park”, a large area was opened up for parking that provided sufficient parking for PnR users. Similarly for the areas around Bayswater station in Midland line, accessibility improved because parking bays increased during this period (from 230 to 431). The colours on Figure 8.8 and Figure 8.9 clearly show that, although accessibility for the suburbs around Mandurah line have greatly improved, the improvements are not uniform. This is mainly due to the large train station spacing. For example, the spacing between Kwinana and Cockburn Central is 12.1km and the spacing between Mandurah and Warnbro is 23.5 km. Therefore, there is significant spatial accessibility inequality along the new line, especially for suburbs mid-way between the stations.

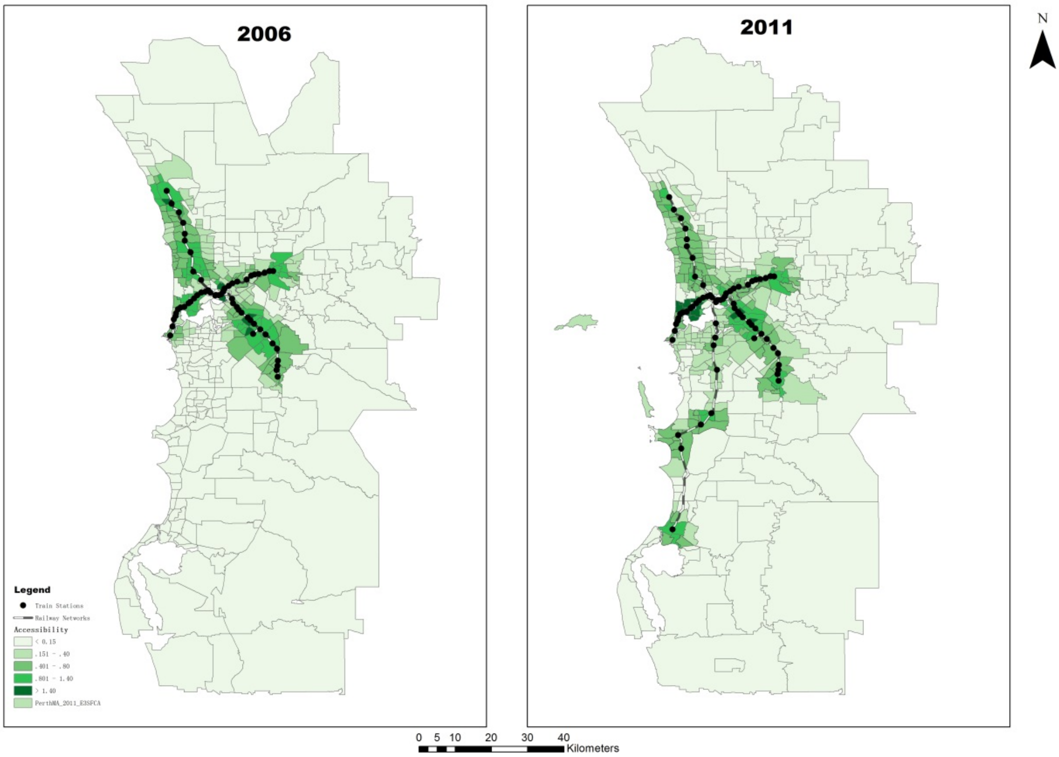

Figure 8.9 PnR Accessibility using E3VSFCA

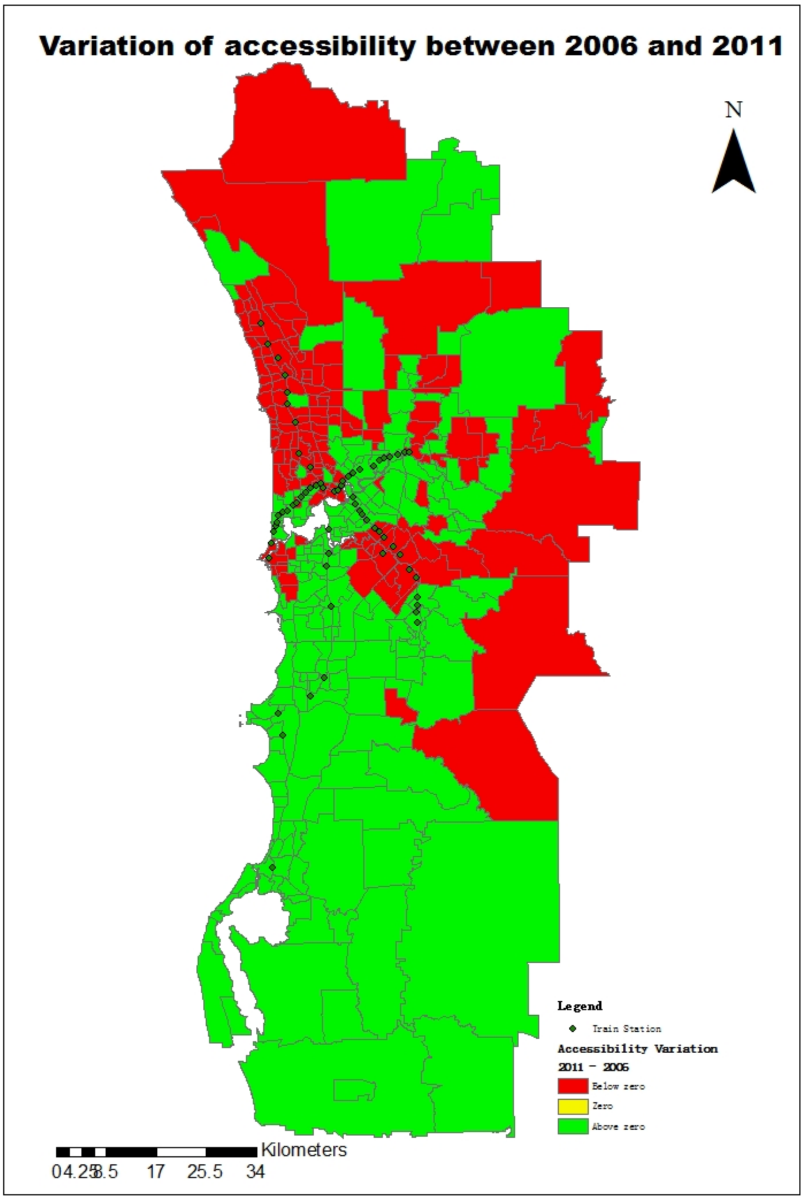

Figure 8.10 PnR accessibility variation using E3VSFCA (2011-2006)

Table 8.4 gives the top five and worst five suburbs in terms of change in accessibility between 2006 and 2011, ranked by the percentage of improvement in accessibility. This is used rather than the absolute value as the suburbs along the Mandurah line do not necessarily have the highest values but do have the greatest changes in PnR accessibility. For example, accessibility for the suburb of Success, near the Cockburn Central station, increased from 0.000002 to 0.38 with the opening of the train line, a huge improvement. Therefore, those areas with the greater improvements in accessibility are all suburbs in the new train line corridor. The suburbs with the largest decreases in accessibility are mainly around Thornlie and Clarkson stations because the number of resident workers increased significantly in these suburbs.

Table 8.4 Accessibility variation

Suburb	**Improvement in Accessibility Rank**	**Suburb**	**Reduction in Accessibility Rank**
Coodanup	1	Tamala Park	1
Mandurah	2	Thornlie	2
Bertram	3	Ferndale	3
Orelia	4	Kincross	4
Parmelia	5	Langford	5

8.5 DISCUSSION AND CONCLUSIONS

E3SVFCA was developed and adapted from previous FCA methods. This section presents a systematic comparison of the 2SFCA, E2SFCA and E3SVFCA methods using the Perth case study. The methodologies for 2SFCA, E2SFCA can be found in Luo and Wang (2003) and Luo and Qi (2009).

For 2SFCA and E2SFCA, the key is to define the catchment threshold for both train stations and suburb. It was decided that 10km was the threshold because, according to Figure 8.5, 10km seemed to be the distance at which the distance decay function flattened out.

Figure 8.11a illustrates the results for 2006 by 2SFCA. Generally, the 2006 PnR accessibility to train station for suburbs within 7 km of the Armadale, Midland and Joondalup train lines is relatively high. However, in 2011 (Figure 8.11b), a significant decrease in accessibility was found along the Armadale and Midland lines. Some reductions also occurred along the Joondalup line. As expected, the accessibility to train stations for people living in the southern suburbs of Perth significantly improved once the Mandurah line was opened. This revealed trend is similar to that of E3VSFCA. However, the main issue with the 2SFCA method is the homogeneity of accessibility for the inner city suburbs. The adoption of a uniform 10km distance threshold resulted in many inner city PnR users being able to reach up to 10 stations, especially those living along the heritage train lines. This caused accessibility to be overestimated in the second step. In reality, it is highly unlikely that PnR users in these inner suburbs would bypass nearer stations to use a station 10kms away. Another problem with 2SFCA occurs when train stations are further than 10 kilometres apart, as occurs on the southern section of the Mandurah line. As an example, Karnup is a suburb located between the Warnbro and Mandurah stations, which are around 23.5 kilometres apart. Karnup is further than 10km from both stations resulting in it being identified as having no access to a train station even though Karnup is located along the Mandurah line. Therefore, the homogeneous threshold distance used in 2SFCA becomes an issue.

Figure 8.12a illustrates the E2SFCA results for 2006. Although the general trend is similar to that of 2SFCA and E3VSFCA, E2SFCA overestimates the demand and therefore produces lower levels of accessibility compared to E3SVFCA. Compared with 2SFCA, as it is integrated with the distance decay function, the value from E2SFCA is also smaller than 2SFCA.

E3SVFCA solves the problems with 2SFCA and 3SFCA identified above. The catchment area modelling, based on the characteristics of each train station, allows the actual catchment areas to be used instead of a uniform 10 km road network catchment area. The probability of choosing a train station is then calculated using station choice modelling rather than using a simple calculation from distance decay. This research presents a further development of the floating catchment area accessibility method by incorporating a modified Huff model and a distance decay function derived from observed data. The results show that the improved floating catchment area measure is a robust and reliable model. For example, the SDR ratios obtained showing PnR demand higher than supply are consistent with the full-parking time survey by Parliament of WA (2014). The lower the SDR value, the quicker a parking area will fill up. For example along the Midland line, East Perth station, with a higher SDR, (green colour), was 90% full by 8:45am, while Bassendean station, with a lower SDR, (orange colour), was full by 7:30am.

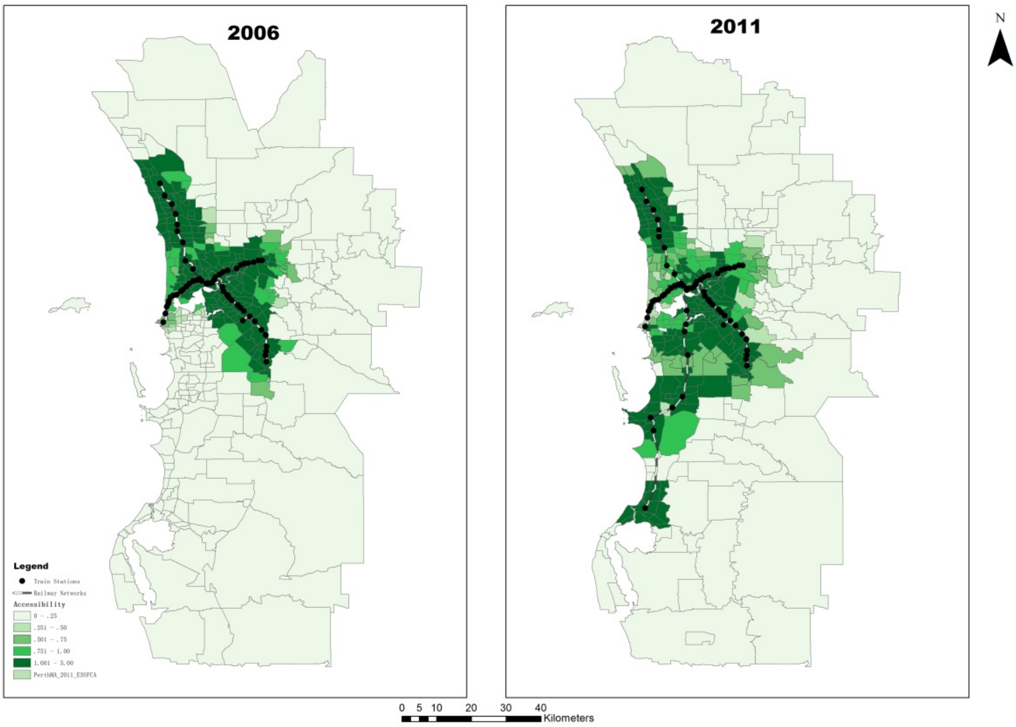

Figure 8.11 PnR Accessibility using 2SFCA (left:2006 and right:2011)

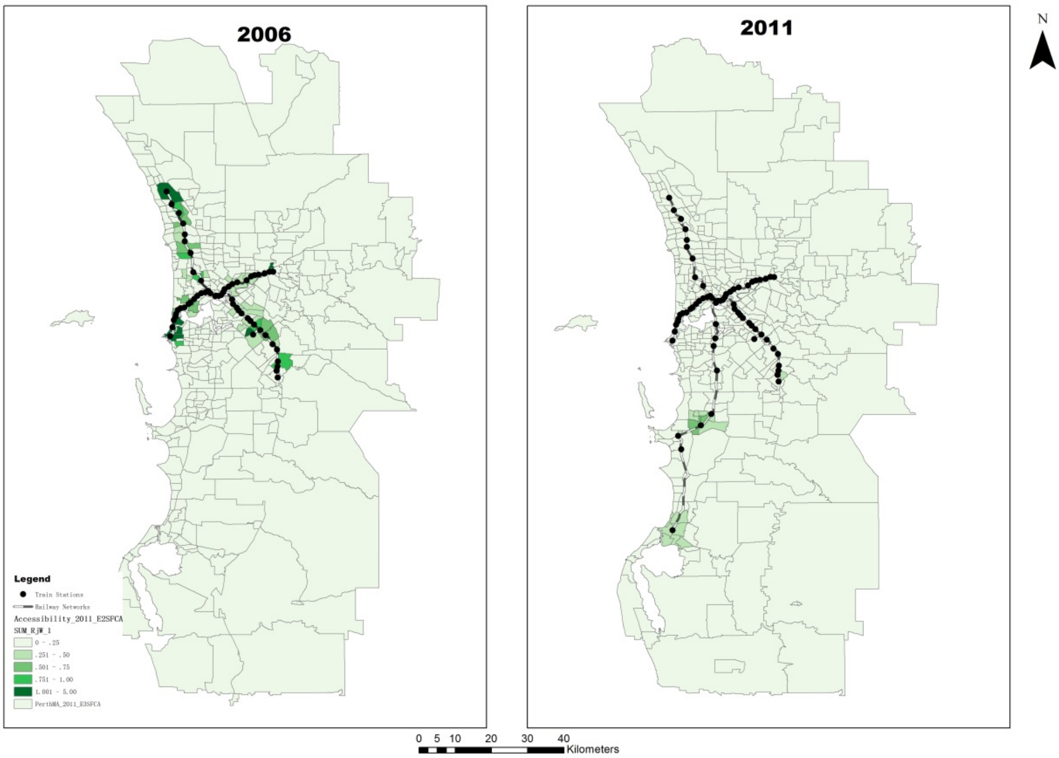

Figure 8.12 PnR Accessibility using E2SFCA (left:2006 and right:2011)

8.6 SUMMARY

This chapter has developed the E3VSFCA method to measure accessibility to train stations before and after the opening of the new Mandurah line. It improved the existing floating catchment area method by quantifying the potential demand of the facilities more precisely and calibrating the distance decay function. Through the E3VSCA method, the demand and supply and its relationship to accessibility can be measured and quantified, which is helpful for understanding the effects of the new train line. It was found that the accessibility to train stations for suburbs along the Mandurah line has greatly improved. However, the accessibility to train stations for suburbs along with Armadale and Joondalup line has decreased due to the significant increase in the working population in those suburbs.

The next chapter will apply space-time continuum theory to examine dynamic accessibility variation in the dynamic road network. The concepts and methods on dynamic accessibility will be discussed.

CHAPTER 9 MICRO ACCESSIBILITY

9.1 INTRODUCTION

The previous chapter presented the macro accessibility modelling through E3VSFCA. This chapter develops a space-time accessibility continuum model to evaluate train station accessibility at the micro (short time scale) level, using TomTom® live traffic time data. The space-time accessibility continuum model can be used to identify accessibility at any point in time or space (location). This chapter is organised as follows. Section 9.2 focuses on the research background and space-time theory and section 9.3 presents the methodology. The results are explained in Section 9.4, with a summary of findings, contributions and a discussion on the limitations and possible further developments in Section 9.5.

9.2 RESEARCH CONTEXT

As outlined above, a space-time continuum model of train station accessibility has been built using dynamic road network travel times extracted from the TomTom® travel time database.

This section reviews the available literature on space-time continuum models with particular reference to those with dynamic road network/travel time components.

9.2.1 Live road traffic data collection method overview

Many organisations and government agencies are interested in live traffic data. Transportation departments (at the local, state and federal levels), require reliable and timely traffic data to improve the daily management of traffic, (e.g. through variable message signing and interactive traffic signal control), and to manage incidents such as traffic crashes and breakdowns. The general public is also interested in real time travel information as it provides them with advice on where and when to travel, e.g. to avoid a traffic jam due to a crash. There are many ways to obtain the traffic data (BITRE, 2014; Leduc, 2008) which can essentially be categorised into one of two types. The first is the conventional "in-situ" method that collects traffic data from detectors, e.g. pneumatic tube counters, at fixed locations, although many of these can be moved to other locations if required. The second type is the floating car method that collects data from vehicles equipped with moving sensors such as GPS devices or mobile phones. These data include the location, speed, and direction of travel of each vehicle, recorded at regular and frequent time intervals or set locations on the network. Every vehicle with GPS devices/mobile phones acts as a sensor for the road network for constructing intelligent transportation systems (ITS). It empowers the traffic flow identification, travel times calculation, and rapid traffic reports generation.

Currently, in Western Australia, there are no detectors located along the major roads to provide congestion data, although Main Roads WA is considering their installation. At the time of this study, the only available traffic congestion data source from government was the floating car survey by Main Roads WA. The method involves driving a vehicle in the traffic flow along a selected route and measuring the times at known points along the path. The disadvantages of this method are the limited network coverage, (only 11 routes in Perth), limited time periods and the data are always historical, i.e. record what traffic conditions were like not what they are like now.

There are a number of online APIs providing accesses to historical and live traffic information, such as Google® Maps Direction API, Yahoo® API, Map Quest®, InRIX® and also

TomTom® Online Routing API. The main two are Google® Maps Directions API and TomTom® Online Routing API, both of which have very good coverage. Google® Maps Direction API with live traffic information is only available at a cost, while TomTom® Online Routing API is free. Therefore, the live traffic data from TomTom® API has been used in this study.

As one of the world's largest suppliers of GPS navigation devices, TomTom® has a significant floating car database. It uses a wide range of GPS probe data from fleets, portable navigation devices (PNDs), smartphones, in-dash system and other data sources to generate precise real-time traffic information (Figure 9.1). Fontaine and Smith (2007) suggested that GPS-equipped cell phones will become more attractive and realistic alternatives for traffic monitoring as this technique can provide more accurate locational information and, thus, more accurate traffic data including speeds and travel times. As well as the standard datasets, instantaneous velocity, acceleration, and direction of travel can also be captured. TomTom® has a large database of traffic movements that is utilised for congestion level benchmarking and travel time analysis. It has made over 12 trillion anonymous GPS measurements since 2007 and adds 7 billion new GPS measurements every day.

Figure 9.1. How TomTom® collects its traffic data (TomTom, 2015)

9.2.2 Space-time continuum

Space-time geography is an approach used in a number of disciplines to understand dynamic processes that take place in the dimensions of space and time. The path of a moving object is defined by a series of positions in space at a series of given times, i.e. a series of simultaneous space-time coordinates. Many models have been developed to measure the space-time characteristics of moving objects. Two of the most popular models are the space-time path model and space-time prism model, both established by Hägerstrand in 1970 (see Section 2.4.4). Both capture individual behaviours within continuous space and time. However, they measure accessibility more from individual freedom in limited time budget perspective.

Space contains three dimensions and time is one dimension. Therefore, space-time has four dimensions. According to a mathematician, Hermann Minkowski, who gave a famous speech about space-time emphasising it geometric qualities in 1906 (Minkowski, 1952, p 75):

> *"The views of space and time which I wish to lay before you have sprung from the soil of experimental physics, and therein lies their strength. They are radical. Henceforth, space by itself, and time by itself, are doomed to fade away into mere shadows, and only a kind of union of the two will preserve an independent reality."*

The union of space and time is considered as a continuum, which means continuous space without missing points and continuous time without missing instants. Space and time can be subdivided without breaking the property of continuum (*continuous*). Space-time can be sliced at specific locations and times to investigate a particular feature of space, e.g. travel time (*ubiquitous*). The space-time is also transferable, which means that once the space-time has been built mathematically, features can be aggregated into any higher level of scale spatially and temporally (*transferable*) with an assumption of the property of homogeneity. It can be a useful tool to understand the past, present and future of the space and its features. However, there is limited research on the use of a space-time continuum to measure accessibility.

There are two fundamental theories in the space-time continuum (Figure 9.2). One is the First Law of Geography. The First Law of Geography, according to Waldo Tobler, is "*everything is* *related to everything else, but near things are more related than distant things*." (Tobler, 1970). The First Law of Geography can be seen everywhere when implementing the space-time continuum theory, e.g. when creating a Thiessen proximity polygon to represent an area that has similar accessibility inside the area or developing the local Kriging interpolation algorithm. The second theory is called "Accessibility Dichotomy". In the literature, accessibility is a flexible notion and concept; it could be complex or simple, depending on the specific application scenario. Accessibility Dichotomy theory describes this intrinsic feature of accessibility and simplify travel time as accessibility measure indicator in this study. Hence, based on the "spatial correlation upon the distance" and "travel cost as representation of accessibility", the space-time continuum for accessibility is developed.

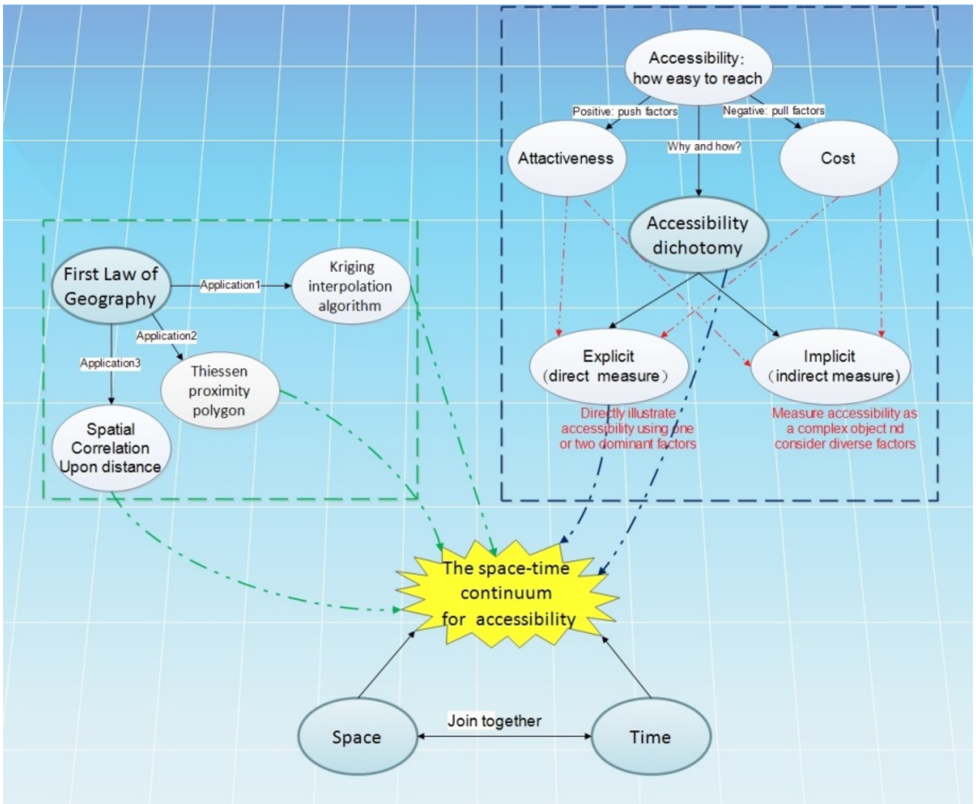

Figure 9.2. Space-time continuum

9.3 METHODOLOGY

9.3.1 Framework

Three steps of analysis were undertaken to construct the space-time continuum and to understand dynamic accessibility (Figure 9.3). The first step determined which live data source to use, based on the above literature review (see Section 9.2), and which station to choose as the experimental station. Next, the space-time continuum was constructed by, initially, building a space continuum and a time continuum separately and then combining them. Finally, based on the space-time continuum model, accessibility was presented through 3D and 4D environments to simulate the variations in accessibility by location, (i.e. in space), and time of day.

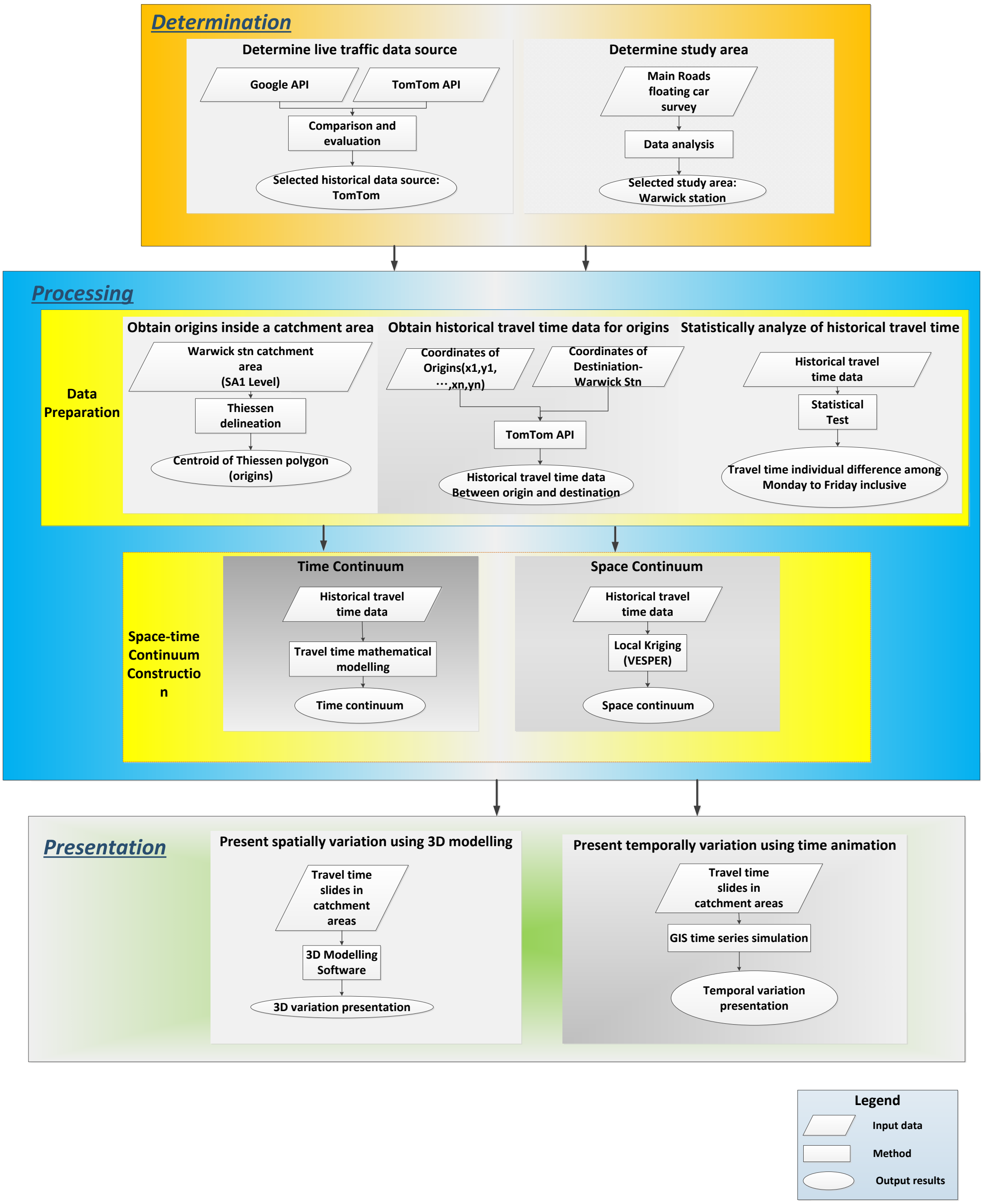

Figure 9.3. Framework of micro accessibility modelling

9.3.2 Space continuum

Thiessen polygons, (also known as Voronoi polygons or Voronoi diagrams), are used extensively for conducting proximity and neighbourhood analysis. Thiessen polygons define a boundary inside which all points are closer to a specific feature point, e.g. train station or hospital, than to any adjacent similar feature points, (in two dimensions). The First Law of Geography can be used to allocate all points to their nearest feature point and thus develop these Thiessen polygons, although it is a rough estimation.

Kriging interpolation can overcome the shortcomings of the Thiessen proximity polygon method by estimating the feature or value of unknown points according to sampled values at known locations. It was developed in the 1960s by the French mathematician Georges Matheron (Matheron, 1963; Krige, 1951). A semivariogram graph was developed to model the difference between a value at one location and the value at another location in terms of the distance and direction between them. The basic form of Kriging (ordinary Kriging) is a weighted average of neighbouring samples, which is defined as (Bailey & Gatrell, 1995):

$$\widehat{Y}_0 = \sum_{i=1}^{n} w_i y_i = [w_1 \cdots w_n] \begin{bmatrix} y_1 \\ \vdots \\ y_2 \end{bmatrix} = w_1' y \qquad 9\text{-}1$$

Where $\widehat{Y}_0$ is the estimated value; w_i is Kriging weights depends only on locations and covariance function C, $\boldsymbol{y_i}$ is a known value at location *i*; *i*= 1, …, *n*. over w $w_1,\ldots, w_n$, subject to

$$\sum_{i=1}^{n} w_i = 1 \qquad 9\text{-}2$$

The Kriging weights w_j that minimize MSE are (Cressie, 1990):

$$MSE = E\lfloor Y_0 - \widehat{Y}_0 \rfloor = \gamma'\mathbf{T}^{-1}\gamma - (1-\gamma'\mathbf{T}^{-1}\mathbf{1})(\mathbf{1}'\mathbf{T}^{-1}\mathbf{1})^{-1} \qquad 9\text{-}3$$

where

$\mathbf{1}$ is an $n*1$ vector of 1s; $\mathbf{T}$ is an $n*\text{n}$ matrix whose (*i,j*)th element is $\gamma(S_i, S_j)$;

$\gamma \equiv (\gamma(S_0, S_1),\ldots,\gamma(S_0, S_n))'$; and

$$2\gamma(S_0, S_n) \equiv \mathrm{C}(S_i, S_i) + \mathrm{C}(S_j, S_j) - \mathrm{S}(S_i, S_j) \qquad 9\text{-}4$$

where 2 $\gamma(S_0, S_n)$ is called the variogram, while $\gamma(S_0, S_n)$ is called the semivariogram. Semivariogram is used to determine the weights of Kriging.

In Kriging spatial interpolation, there are two Kriging interpolation methods: global Kriging and local Kriging. Global Kriging calculates the whole area's variogram whilst local Kriging estimates the variogram only from the neighbourhood (Minasny et al., 2005). In order to consider the spatial heterogeneity， local Kriging was applied in the study using Variogram Estimation and Spatial Prediction Plus Error (VESPER), a PC program developed by the Australian Centre for Precision Agriculture (ACPA).

9.3.3 Time continuum

Time continuum means that time is continuous without any breaks or intervals. For example, when travel time is measured from location *i* to location *j* using travel mode *k*, the measure should be able to estimate the travel time at any instant *t*. Time series models have been developed and applied extensively to predict the future and to understand the past. As with the First Law of Geography, system evolution also follows three rules:

- Observations closer together in time will be more related than observations further apart in time.
- Evolution must be derived from regularities in the past, which can be learnt or understood from the observed behaviour.
- Irregularity resulting from short-term fluctuations is not predictable. It must be estimated and removed.

These basic rules guide time series analysis and modelling to achieve goals such as forecasting (short-term evolution of system), modelling (long-term evolution of system), and characterisation (fundamental properties of an evolving system, e.g. degree of freedom and amount of randomness). To date, three major streams of theoretical framework have been developed to achieve these goals:

- Autoregressive technique (Yule, 1927): the next value can be estimated based on the weighted sum of previous observations of the series from a linear system;

- State-space reconstruction by time-delay embedding (Kennel, Brown, & Abarbanel, 1992): a nonlinear technique to derive deterministic governing equations based on the dynamic system and differential topology principal for capturing internal structure of an evolving system;
- Machine learning, such as neural network: complex algorithms developed to learn the patterns from the historic time series data and predict values at future time instants.

Many techniques have been developed based on these theories to analyse or model a time series. Below is one method to produce a continuum of travel time from location *i* to location *j* using travel mode *k* at start time *t*. (1) Capture historical and real time travel time using TomTom® GPS data at discrete 15 minute intervals; (2) Interpolate between 15 minute times to estimate unknown travel times from known travel time to build a continuous travel time approximating function, using techniques such as trigonometric polynomial periodic functions. With respect to the variations in travel time to a train station, the equation could be formulized as:

$$\begin{cases} y = mean(x_t)\ \mathrm{t}_0 \le t < t_1 \\ y = \sum_{j=1}^{n} a_i Sin(\mathrm{b}_i\ x_{t,} + C_i)\ \mathrm{t}_1 \le t < t_2 \\ y = mean(x_t)\ \mathrm{t}_2 \le t < t_3 \end{cases} \tag{9-5}$$

where

x_t is known travel time and y is unknown travel time.

9.3.4 Hot Spot analysis

By looking at each feature within the context of neighbouring features, the Hot Spot Analysis tells where features with either high or low values cluster spatially. A feature with a high value is interesting but may not be a statistically significant hot spot. A statistically significant hot spot would have a high value and be surrounded by other features with high values. The Getis-Ord Gi* statistic applied by Hot Spot Analysis can be used to identify these.

The Getis-ord local statistic is given as (Ord & Getis, 1995):

$$G_i^* = \frac{\sum_{j=1}^{n} w_{i,j} x_j - \bar{X} \sum_{j=1}^{n} w_{i,j}}{S \sqrt{\frac{[n \sum_{j=1}^{n} w_{i,j}{}^2 - (\sum_{j=1}^{n} w_{i,j})^2]}{n-1}}} \quad 9\text{-}6$$

$$\bar{X} = \frac{\sum_{j=1}^{n} x_j}{n} \quad 9\text{-}7$$

$$S = \sqrt{\frac{\sum_{j=1}^{n} x_j^2}{n} - (\bar{X})^2} \quad 9\text{-}8$$

where:

x_j is the attribute value for feature *j*;

w_{ij} is the spatial weight between feature *i* and *j*;

n is the total number of the feature.

9.4 RESULTS

9.4.1 Floating car survey analysis

The 2013-2014 floating car survey was used for micro accessibility modelling to find out the experiment station. Although the floating car survey covers 11 routes in Perth, only some routes have travel time data for the AM Peak, Off Peak and PM Peak periods. Main Roads Western Australia’s (MRWA) definitions of these three periods are shown in Table 9.1. The variations in the travel times of the 11 routes for the three periods are plotted in Figure 9.4a. Route 25 inbound and route 49 inbound have the largest variations between AM Peak and Off Peak travel times. For route 49, the largest variations are for segments 7 to 9, (Figure 9.4b), which is inside the Warwick station catchment area. Therefore, Warwick station was chosen as the study station.

Table 9.1. The definition of AM Peak, Off Peak and PM Peak (MRWA)

AM/PM	Time period
AM(Morning) Peak	7:30am – 9:00am
Off Peak	10:00am-12:00 noon
PM (Afternoon) Peak	4:30pm – 6:00pm

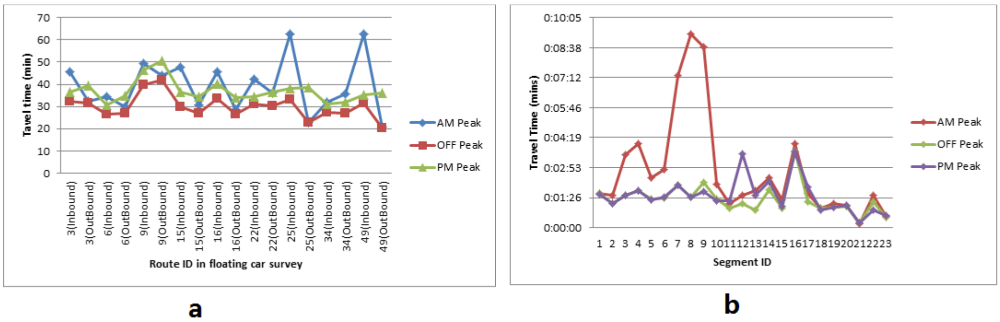

Figure 9.4. Floating car survey

9.4.2 Statistical analysis of historical travel time using TomTom® GPS data

Voronoi polygons were generated for Warwick train station in accordance with the processes set out in the framework of micro accessibility modelling, (Figure 9.3). There were 401 trip origins within the Warwick train station catchment area from which 401 Voronoi polygons were generated. Each origin had a travel time for 96 times time slices, as data were collected every 15mins from 0:00am to 11:45pm. Therefore, each day 38,496 records were captured. Travel time data were collected for five days, (Monday to Friday), resulting in a total of 192,480, (38,496*5), travel time records for use in the micro accessibility modelling and analysis.

Travel time descriptive statistics

Descriptive statistics summarising the main features of the collected data are presented in Tables 9.2 and 9.3, Thursday was the most congested day for travel to Warwick train station as it had the largest mean and median travel times and the largest standard deviation. Kurtosis is a measure of the "peakedness" of the distribution and heaviness of its tail. A high kurtosis distribution has a sharper peak and fatter tails, while a low kurtosis distribution has a more rounded peak and thinner tails. Skewness is a measure of the asymmetry. Thursday also had the lowest kurtosis and skewness values among the five workdays, which means that the travel time was more evenly distributed over the catchment area compared to the other workdays. When combined with the results for the mean, median and standard deviation, it was concluded that Thursday was the most congested day for Warwick train station. Using the same criteria, Monday seemed to be the least congested day.

Table 9.2 Descriptive statistics of travel time to Warwick station from all origins inside Warwick station catchment area by day of the week

Monday		**Tuesday**		**Wednesday**	
Mean (secs)	882.68	Mean	884.07	Mean	884.61
Median (secs)	893	Median	894	Median	894
Mode (secs)	937	Mode	994	Mode	953
Standard Deviation	181.37	Standard Deviation	182.11	Standard Deviation	182.42
Sample Variance	32892.24	Sample Variance	33165.24	Sample Variance	33276.23
Kurtosis	5.52	Kurtosis	5.42	Kurtosis	5.36
Skewness	0.82	Skewness	0.82	Skewness	0.81
Confidence Level (95.0%)	1.81	Confidence Level (95.0%)	1.82	Confidence Level (95.0%)	1.82

Thursday		Friday	
Mean	887.50	Mean	884.01
Median	897	Median	894
Mode	904	Mode	894
Standard Deviation	184.05	Standard Deviation	181.78
Sample Variance	33874.84	Sample Variance	33043.24
Kurtosis	5.05	Kurtosis	5.46
Skewness	0.77	Skewness	0.81
Confidence Level (95.0%)	1.84	Confidence Level (95.0%)	1.82

Table 9.3 presents the maximum and minimum travel times and the range for ten origins for Monday and Thursday. The records are sorted by the Thursday travel time range. Only the origins with the five largest and five smallest ranges are listed. ID is the identity number of the trip origin in the system. Min and Max refer to the minimum and maximum travel times from the specific ID to Warwick station in seconds. The Range is the difference between the minimum and maximum travel times. ID 94 has the largest range in travel times at 217 seconds, or around 4 minutes. This means that travel from Location ID 94 to Warwick station in the peak hour takes nearly 4 minutes longer than travelling in the off-peak. However, for location ID 271, there is no difference in travel times between peak and off-peak.

Table 9.3 Descriptive statistics of travel time for 10 origins (Monday and Thursday)

ID	Monday			Thursday			
	Min (s)	**Max(s)**	**Range(s)**	**Min(s)**	**Max(s)**	**Range(s)(↓)**	**rank**
94	945	1026	81	945	1162	217	1
95	953	1035	82	953	1162	209	2
101	994	1082	88	994	1202	208	3
102	1158	1260	102	1158	1334	176	4
92	953	1030	77	953	1125	172	5
…	…	…	…	…	…	…	
277	485	498	13	485	499	14	397
202	493	509	16	493	506	13	398
206	441	456	15	441	454	13	399
201	505	516	11	505	515	10	400
271	436	436	0	436	436	0	401

ANOVA Test

The purpose of an ANOVA (Analysis of Variance) test is to determine whether there is a statistically significant difference among several means. One-way ANOVA is the simplest type of ANOVA. It is a technique used to compare means of three or more samples, (using the F distribution). ANOVA testing relies on the F ratio.

In the study, SPSS was applied to calculate the one-way ANOVA. It outputs the significant value which helps to determine whether there is a significant difference or not. Table 9.4 shows the results of the ANOVA test. The number in the DayofWeek column indicates the specific day of the week, i.e. 1 means Monday, 2 means Tuesday, etc. The results show that the only significant difference is between Monday and Thursday (see the bold in Table 9.4), which is consistent with the results of the descriptive statistics analysis. Although there were significant differences between these two days, there were no significant differences between Tuesday and Monday, Tuesday and Thursday, Wednesday and Thursday or Wednesday and Monday. Monday and Thursday were simply the two most extreme scenarios (see the asterisks in Table 9.4), i.e. the days where travel was the most and least congested respectively. Therefore, it is decided that only one model would be sufficient, rather than a separate model for each day.

Table 9.4 Results of ANOVA test

(I) DayofWeek	(J) DayofWeek	Mean Difference (I-J)	Std. Error	Sig.	95% Confidence Interval	
					Lower Bound	Upper Bound
1	2	-1.381	1.3143	0.832	-4.966	2.2
	3	-1.9219	1.3143	0.587	-5.507	1.66
	4	-4.8104*	1.3143	**0.002**	-8.396	-1.2
	5	-1.3276	1.3143	0.851	-4.913	2.26
2	1	1.381	1.3143	0.832	-2.204	4.97
	3	-0.5409	1.3143	0.994	-4.126	3.04
	4	-3.4294	1.3143	0.069	-7.015	0.16
	5	0.0534	1.3143	1	-3.532	3.64
3	1	1.9219	1.3143	0.587	-1.663	5.51
	2	0.5409	1.3143	0.994	-3.044	4.13
	4	-2.8885	1.3143	0.18	-6.474	0.7
	5	0.5943	1.3143	0.991	-2.991	4.18
4	1	4.8104*	1.3143	**0.002**	1.225	8.4
	2	3.4294	1.3143	0.069	-0.156	7.02
	3	2.8885	1.3143	0.18	-0.697	6.47
	5	3.4828	1.3143	0.062	-0.102	7.07
5	1	1.3276	1.3143	0.851	-2.258	4.91
	2	-0.0534	1.3143	1	-3.639	3.53
	3	-0.5943	1.3143	0.991	-4.18	2.99
	4	-3.4828	1.3143	0.062	-7.068	0.1

Travel time curve characterisation

Figure 9.5 shows the travel time variation curves for six randomly selected sample origins. As it was decided not to model the temporal information by different days, all collected data have been plotted on the figure to get the generalized, (averaged over 5 days), distribution. It is found that overall they have very similar trends. Travel times from the origin to the train station were stable until around 4 am and then rose sharply to peak at around 8 am, with a second peak around 6 pm. Some origins had longer travel times in the AM Peak, whilst others in the PM Peak, probably depending upon whether or not the trip to the station was in the peak or non-peak direction for general traffic. After 10 pm, the travel times became stable again, indicating free flow conditions.

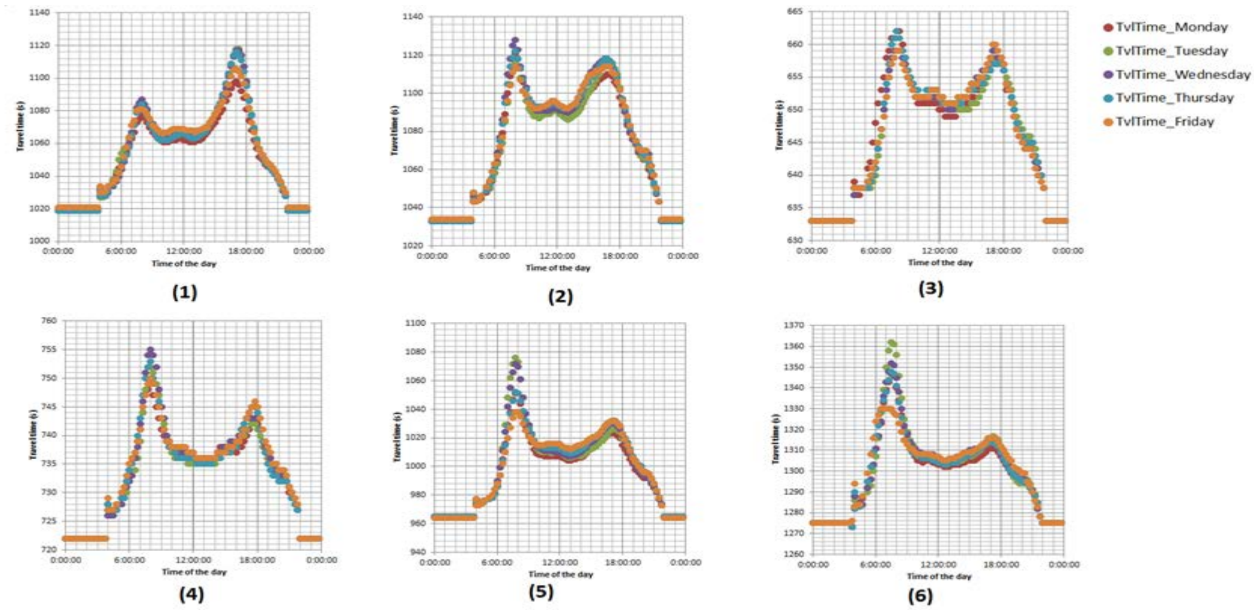

Figure 9.5. Travel time curve for six origins

Travel Time Hot Spot Analysis

A Hot Spot Analysis indicates where either high or low travel time clusters locate spatially, by comparing travel times for individual origins with neighbouring origin travel times. The range data of Thursday (Table 9.4) were used for the Hot Spot Analysis and the results are shown in Figure 9.6. The hot spots, (red dots), were found to cluster at the southwest of Warwick station, which is consistent with the Floating Car Survey results, i.e. a separate analysis using a different data source. The red spots are mainly distributed among those segments.

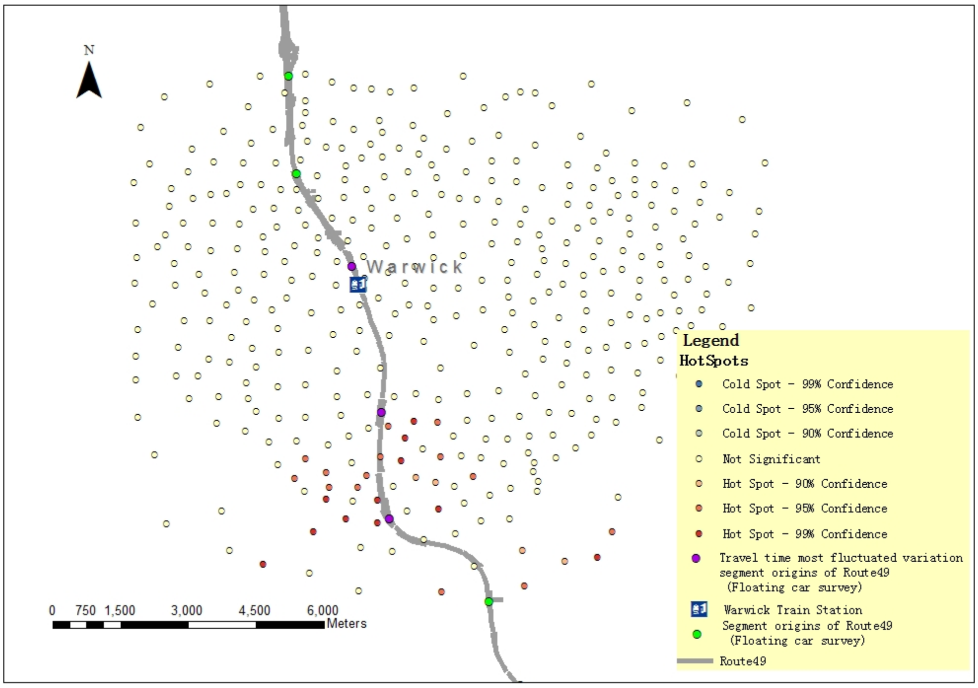

Figure 9.6. Results of the Hot Spot Analysis

9.4.3 Space-time continuum

The space-time continuum was developed in accordance with Section 3.3. Figure 9.7 shows the variations in travel times to Warwick Station over 24 hours. The green colours indicate shorter travel times and red colours longer travel times. During the peak hours, e.g. 7:00 am to 8:00 am, the size of green area reduces significantly. The southern central part of map, which was identified as the hot spot in Figure 9.6, also changes significantly. In the peak hours most of the areas are coloured red. However, outside the peak hours, they turn green or yellow. Another interesting finding for the southern central part of map is that the travel times in this area also change during the off peak hours.

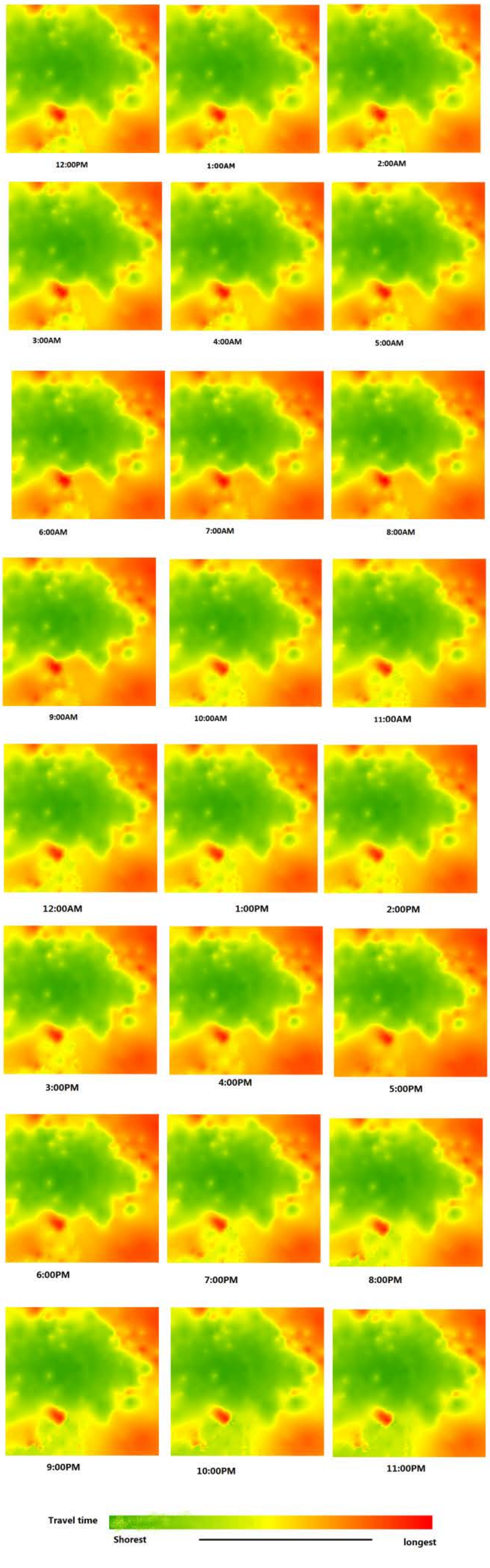

Figure 9.7 Travel time variations for Warwick train station

Figure 9.8 shows the travel time differences of that time comparing with the ideal travel time during the morning and afternoon peak (the ideal travel time here means the minimum travel time from the origin to the train station). Red dots means longer travel time to the Warwick train station compared with the ideal travel time. It is found that 8:00 am in the morning got the larger area of red dots which is consistent with Figure 9.7. In the afternoon, 5:00 pm seems to be the hour has the most of red dots.

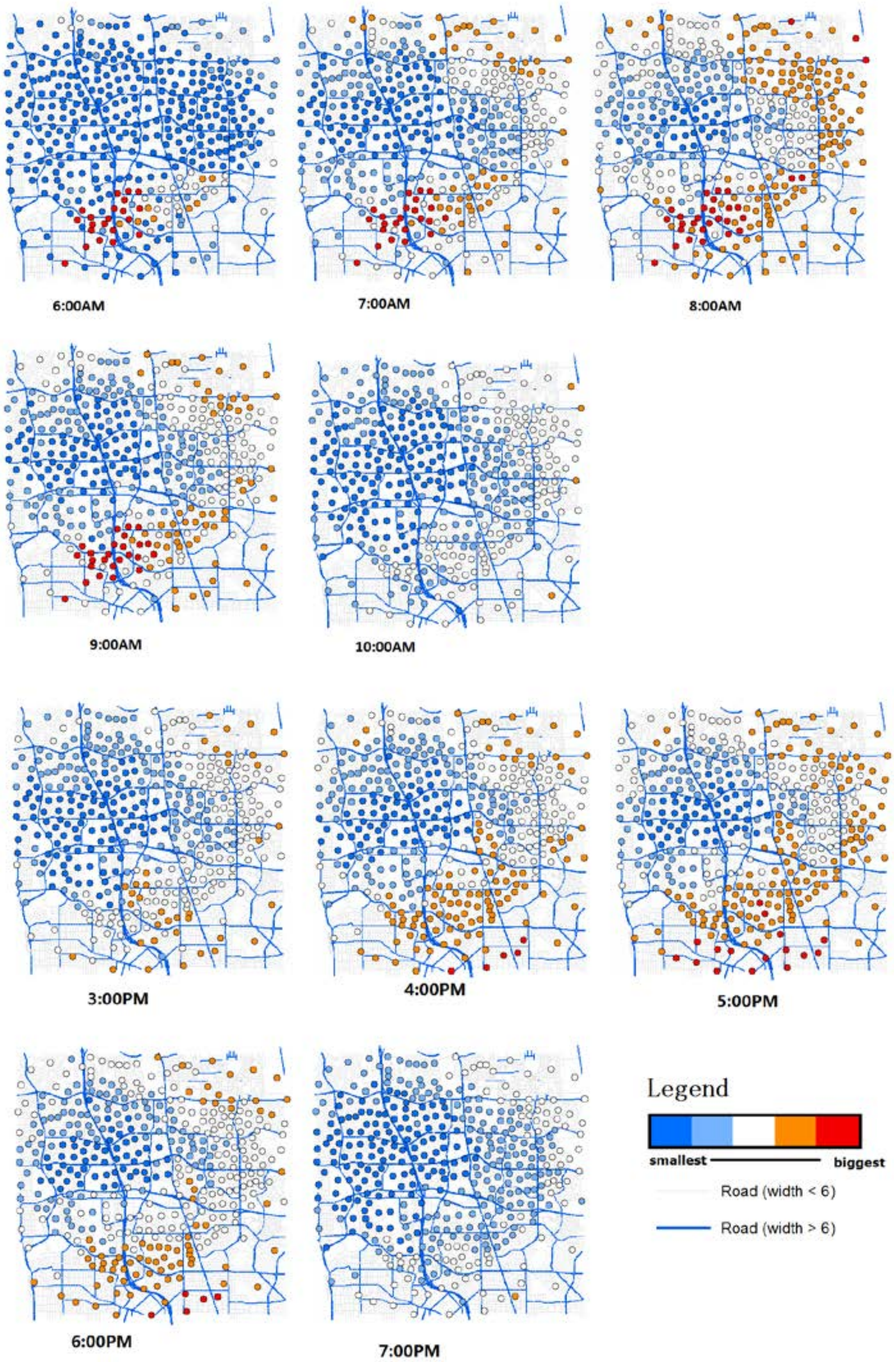

Figure 9.8 Travel time variations for Warwick train station

9.5 DISCUSSION AND CONCLUSIONS

This study has developed a framework using TomTom® APIs to estimate the travel times between a set of origins and a set of destinations, which is essential in transport related spatial analysis, including accessibility analysis. Through the interrogation of an online live traffic service, this data collection method overcame the deficiencies of a commercial GIS package including extra data support, knowledge and license of the software. Analysis of the collected data has proven that they were robust and consistent with the data obtained from the more traditional floating car survey method.

Another contribution of this research is to expand the space-time continuum theory to model accessibility. It is a novel model that can estimate accessibility to a train station from any location at any time. The model developed for the Warwick train station catchment area, as a case study, demonstrates the usefulness of the approach in assessing how accessibility to the train station changed over time, in terms of travel time. The 3D and animation presentations would give the policy maker a more intuitive understanding of the variations in accessibility over time. The modelling result is consistent with the floating car survey result, proving the space-time continuum model to be a robust model.

In this research, only travel time has been considered when measuring accessibility, in order to reduce the model complexity. In the future, the model could be expanded to include additional factors, including variations in available parking supply at the station over time, and factor weighting. This model could also be adapted to assess the accessibility of other travel modes, such as Bus and Ride (BnR).

9.6 SUMMARY

This chapter used TomTom® APIs to collect travel time data at 15 minute intervals, from which a framework for measuring dynamic accessibility was developed using space-time accessibility continuum theory. From this model, travel time to the train station can be estimated for any location at any point in time. It would provide travellers with a better understanding of the variability in travel times and also assist traffic engineers and policy makers in monitoring traffic congestion and developing effective mitigation strategies.

The next chapter will summarise the major findings and key achievements of this research, discuss the limitations of the methods, their implications and also recommendations for improvements and directions for the future research.

CHAPTER 10 EVALUATION AND CONCLUSIONS

10.1 INTRODUCTION

When faced with the challenge of improving train station accessibility, planners need a wealth of information on the status quo to make effective decisions. Chapters 4 to 9 presented and implemented a methodology to better understand and evaluate PnR user accessibility to train stations over space and time, and a detailed analysis, using Perth train stations as a case study, to demonstrate and validate a methodology for deriving this information. This chapter summarises the major findings and key achievements of this research. It discusses the limitations of the methods and their implications, and also gives recommendations for improvements and directions for the future research. The research objectives and research questions set out for this thesis are reiterated to show how these have been achieved.

10.2 SUMMARY OF RESEARCH FINDINGS

Through a systematic review of the existing accessibility metrics in the literature, seven types of accessibility measures were identified. These were spatial separation measures, network measures, contour measures, random utility measures, competition measures and place rank measures. Gravity based models were chosen for the research, (although with different kinds of transformation), due to their flexibility and suitability to the adopted methodology, ability to satisfy the research objectives and the data availability. It was found that the gravity model aligned with Tobler's First Law of Geography and was easy to implement using GIS technology. Apart from that, the gravity model can have a lot of transforms and the factors can readily be added or removed depending on the situation being assessed. Additionally, the analysis unit of a gravity model can be very flexible, e.g. the unit can be the individual or a group of individuals with similar characteristics, (a cohort). Gravity models are also very flexible with respect to the geographic boundaries being considered and can relate directly to real scenarios.

Although many accessibility measures have been developed in the literature, few consider directional accessibility and address the accessibility by different user groups, i.e. few measure the difference in accessibility by direction and elderly accessibility. Within the existing gravity model based FCA measures, debate continues on how to better quantify potential demand and what the best distance decay function is. Another example is space-time accessibility modelling. Although it has advanced Time-Geography theory, it focuses on individual freedom in the temporal constraints. There is a lack of theory/framework and limited research examining the ease of access to a valuable destination over time and especially a lack of a continuum theory that would be able to identify accessibility at any time at any location.

This project has been conducted to address these research gaps. It began with the exploratory data analysis, as the first step in order to achieve two major research objectives, which are to more accurately and reliably define train station catchment areas and to determine the variations in accessibility to train station by location and over time. In the second step, the train station catchment areas were modelled using a modified Huff model. The third step was to evaluate the accessibility improvements after the opening of the Mandurah train line (macro accessibility modelling). The final step was to determine the short-term variations in accessibility through an analysis of the dynamic road network (micro accessibility modelling).

10.2.1 Catchment area characteristics

Chapter 4 examined train station catchment characteristics mainly from a spatial perspective with two indices: catchment area and shape. The size of catchment area was found to be greatly affected by the train station location, its surrounding geographical constraints and the distance to adjacent train stations. The diverse land uses around a train station can also contribute to the size of the catchment area as they can attract more people to use the train station by providing opportunities for catching the train to be combined with other activities, e.g. shopping or eating a meal.

The shape of a catchment area, as measured by its compactness, was found to be similarly affected by these factors affecting the size of catchment area. Compactness was found to have a positive relationship with train station ridership. The compactness of a catchment area was also found to be a good indicator of potential station accessibility problems for certain user groups. For example, although Warwick station generally has good accessibility by most user groups, the elderly mainly access the station from a narrow area to the southwest. This could be due to physical barriers hindering elderly access from the other directions. Additionally, a spatial segmentation analysis framework was devised to identify the main market share, (user groups), of a train station. Two indices were developed (area ratio and composite ratio) that successfully determined the spatially dominant market segments for each train station. The results were consistent with the data clustering results of the EM algorithm.

The research also investigated the relationship between catchment area characteristics and train station characteristics using statistical analysis. An integrated transport system was found to be the key factor with a higher number of bus services, and higher frequencies, at a train station encouraging train users to come from diverse travel directions. Parking capacity was found consistently to be directly proportional to the compactness of the catchment area across different types of catchment areas, although it was not significant. Competition between adjacent train stations was another important factor. The overall conclusion was that, to model catchment areas reliably and accurately, these important factors need to be considered.

10.2.2 Trip direction analysis

Trip direction can be considered to be an indicator of the integration of transport and land use. A good integration should see train users coming from diverse directions to access a train station. Two new spatial methods (centrality and spatial integrity of land use types) were developed for understanding train trip directions and the relevant factors influencing these trip directions. A theory of centre of gravity was developed, based on station centrality, to help locate a train station and better integrate it within its surrounding land uses. A station located closer to the centre of trip gravity was found to potentially result in better integration of transport and land use. A statistically significant positive relationship was identified between trip frequency and spatial integrity, and average travel distance and population density, respectively, for the trips to upstream stations. No similar relationships were found for trips to downstream stations.

10.2.3 Elderly accessibility analysis

Elderly accessibility analysis was undertaken to understand accessibility to a railway station for this important cohort in Western Australia. A gravity based accessibility measure (composite measure) was used that combines all the relevant factors, with attractive factors have a positive contribution and resistant factors a negative contribution. This composite accessibility index distinguishes among the combined modes of WnR, PnR and BnR using spatial methods. Seven train stations (Cannington, Claremont, Greenwood, Midland, Murdoch, Warwick, and Warnbro) were investigated. Greenwood station had the lowest elderly patronage and accessibility for all three travel modes. Shopping opportunities around the station, seat availability on the platform, intermodal connectivity and network connectivity or route directness and street parking need to be improved if elderly use of the Greenwood station is to be increased. Another interesting finding of this study was the way in which the elderly respondents evaluated the importance of variables for measuring accessibility. The composite measure is a transform of the gravity model as the attractive influence increases accessibility whilst the resistant factor, (such as distance), reduces the overall accessibility. The measured accessibility has been thoroughly evaluated against the perceived accessibility (from the intercept survey) and the results show consistency between measured and perceived accessibility, which indicates that the gravity based model is suitable for the measurement of accessibility to a train station.

10.2.4 Catchment Area Delineation

The catchment area delineation (Chapter 7) developed a framework for deriving a spatial boundary of a Park and Ride (PnR) catchment area by incorporating the Huff model and Geographic Information Systems (GIS) technologies. It incorporated, in one model, all the key factors found in the EDA process, including parking, land use diversity, service quality and distance. The model outputs were evaluated against the licence plate survey data. The resulting Kappa coefficient (0.74) and overall accuracy (0.88) statistics suggested that the model was robust for the train station catchment area delineation and was transferrable to other catchment area generation studies. The methodology was implemented in two scenarios in Perth: expansion of the train network research and latent demand analysis. The opening of the new train line to Mandurah resulted, as would be expected, in a reduction in the size of the catchment areas of existing stations on the adjacent lines. The average decrease in size of the catchment areas of the Armadale line stations was about 91%, and for 127% for Fremantle line. The results of the assessment of latent PnR demand show the robustness of the model as the estimated demand was consistent with that determined from the station car park occupancy surveys.

10.2.5 Macro accessibility modelling

Macro accessibility modelling was used to explore the change in PnR user accessibility to train stations after the opening of the Mandurah train line. E3SVFCA was developed to investigate these changes. It improved its floating catchment areas by incorporating a modified Huff model and a distance decay function derived from observed data. By applying the catchment areas from the modelling results based on the characteristics of each train station (Chapter 7), the actual catchment area of each train station for 2006 and 2011 was used instead of single threshold. It also distributed the demand based on the station choice probability. E3VSFCA indicated that there had been a significant accessibility improvement for suburbs along the new train line but that the supply-demand ratios of many of the train stations along the existing train lines had still decreased, due to rapid demand growth in their corridors. For example, the suburb of Success, near Cockburn Central station, saw its accessibility increase from 0.000002 to 0.38 with the opening of the Mandurah line. The average supply-demand ratio of train stations along the Joondalup line decreased from 0.59 in 2006 to 0.42 in 2011. The overall results indicate that the improved floating catchment area measure is a good model for evaluating accessibility for new train line expansion with reliable and meaningful results.

10.2.6 Micro accessibility modelling

Micro accessibility modelling endeavoured to explore the variations in PnR accessibility to a train station over 24 hours and to construct a space-time accessibility continuum. It is a novel model that can estimate accessibility to a train station from any location at any time. The model, developed for the Warwick train station catchment area as a case study, demonstrated the usefulness of the approach in assessing how accessibility to the train station (in terms of travel time) changed over time. The research extracted real-time travel data for trips to Warwick train station through the TomTom® real time traffic API and conducted a thorough data analysis of the collected data. Thursday was identified as the most congested day while Monday was the least congested. The plotting of travel times showed that the daily travel time variations followed the same pattern on each weekday although there were some slight differences between days, at certain times of the day. The modelling results were presented in 3D and 4D animation. The space-time accessibility continuum could be a useful tool to understand the past, present and future of the space and its features. It could assist transport managers in assessing and developing proposals to increase PnR accessibility and efficiency. The results have been proven to be useful in understanding and improving the accessibility of PnR users to train stations in Perth.

10.3 LIMITATIONS OF THE RESEARCH

This section looks at the limitations of the methods for modelling the spatio-temporal accessibility of PnR users to train stations. Limitations regarding survey design and implementation are also discussed.

10.3.1 Limitations of the survey design and implementation

Two large intercept surveys were conducted from 31/07/2012 to 1/8/2012 (6:00AM - 4:00PM) and 19/09/2013 to 20/09/2013 (7:00AM-12:30PM) at seven train stations in Perth. Although the seven train stations were proposed by business partners and experts from the relevant agencies, met the study's selection criteria, and were representative, the survey still didn't cover the opinions of train users at the other train stations in the Perth train network.

Another limitation of the data collection is the sampling time. Both surveys were conducted during the daytime, which covered the majority of train users. Train services are available in Perth from 4:50am to 1:00am the next day. Therefore, the opinions of early morning and night time train users have not been collected. Their opinions on the weights of factors could be very different as security might be the most important factor for those commuters travelling in the dark. For the elderly commuters, the survey was conducted at Greenwood, Murdoch and Midland stations on 8-10/05/2013 (9:00AM – 3:30PM). This survey didn't collect the opinions of the elderly who still work and may travel before 9:00am and after 3:30pm. Their opinions on accessibility could be very different to those elderly who don't work and travel in the inter-peak period.

The final limitation is in the wording of the questionnaire itself. One question was: “Where and when did you start that trip?” Some respondents considered their trip origin as their place of residence, while others their location immediately before the train trip, e.g. a school if they had just dropped their children there. Clearer wording of this question, such as “Where and what was your last activity (e.g. home, work, education, shopping) immediately before heading to the train station?” could be used in subsequent surveys. Those would help to eliminate those outliers such as one commuter in Greenwood station who filled in Joondalup as his origin.

10.3.2 Limitations of the modelling methods

- Huff model based catchment area generation

As with any research, there are limitations. Firstly, the modified Huff model wasn’t calibrated to determine the distance decay parameter in a traditional manner. The widely accepted value was adopted in the paper. However, reliable benchmark data collected by PTA were used to validate the model. Its overall accuracy was found to be 0.88. In the future, the model will be calibrated systematically in order to understand the impact of spatial variation, temporal variation and heterogeneity (e.g. different transport modes) on the model’s accuracy. Secondly, although Multiple Criteria Decision Analysis (MCDA) method used in the research is a popular method for determining the weight of the factors, it could be subjective. Other methods, such as discrete choice modelling, can help to understand how various station choice factors contribute to the station preference by various categories of travellers. Thirdly, the accuracy of the model could be further improved if more stations were included in the “choice set” and then in the linear referencing. However, this would increase the complexity of the calculations. Fourthly, the modifiable areal unit problem (MAUP), a common problem in the GIS analysis, may lead to different solutions. In this study, the suburb was used as the spatial unit of analysis given the data availability, even though it was not the smallest available areal unit. Adopting a smaller unit of analysis, (SA1 is the smallest spatial unit currently available in Australia), may be beneficial for determining the catchment area but would be more computationally intensive. In this research, to test the influence of the MAUP, eight train stations were selected and the suburb versus SA1 results compared. Only minor catchment area change was observed. Therefore, as a compromise between simplicity and accuracy, the suburb is considered a reasonable container for aggregation and analysis.

- E3VSFCA based macro spatio-temporal accessibility modelling

The main limitation of the E3SVFCA method is the distance decay function. In the research, only one distance decay function was developed from the census data and then applied to all PnR users in Perth WA. This approach ignored the differences in distance decay between the train stations. A future research question is therefore how to include these individual train discrepancies but also make the results comparable.

- Space-time continuum based micro spatio-temporal accessibility modelling

In this research, the space-time accessibility continuum is constructed based only on the travel time, in accordance with the "Accessibility Dichotomy" theory. Although travel time is a good measure for accessibility, there are other factors that affect accessibility to a train station when considering variations over 24 hours, including the service quality and train frequency that might be worth investigating further in the future.

10.4 FUTURE RESEARCH DIRECTIONS

10.4.1 EDA analysis

For future exploratory data analysis, further research could be explored. For example, how to define, collect and interpret perceived accessibility to achieve a better understanding of the gaps between perceived and measured or actual accessibility. Another research direction is to investigate how a grid pattern or curvilinear street layout can influence accessibility to train stations and how to create liveable neighbourhoods around train stations. For the elderly accessibility analysis, it would be worthwhile to compare accessibility to stations in different age groups (e.g., 60-69, 70-79 and 80+) as they are likely to have different needs, levels of mobility and attitudes towards various facilities and services. This approach is likely to provide further insights into the links between personal mobility and the provision of transport services but will require a three-fold increase in survey time and effort.

10.4.2 House hold survey and Huff model parameter calibration

As described in the Huff model based catchment area generation, the widely accepted value of 2 was adopted although reliable benchmark data collected by PTA was used to validate the accuracy of the model. However, in the future, it may be beneficial to collect household survey data, including commuter's opinions on station choice, to calibrate these parameters, leading to a potential improvement in model accuracy.

10.4.3 Integrated space-time accessibility continuum

For the space-time accessibility continuum, more factors might be integrated into the accessibility continuum, e.g., the train frequency, the street parking availability, the parking variation inside the train station or the crime rate around the train station, (especially for those who travel in the dark). PTA WA has recently introduced parking machines to manage the payment of parking fees at the train stations. It would be worth exploring these data to determine the availability of parking bays over time during the morning peak. This information could then be provided to commuters, e.g. via a smart phone app, to advise on whether there was parking available. Finally, this research has developed a prototype model using a limited number of train stations in Perth as the case study. It would be interesting to apply these methods to different regions and at larger spatial and longer temporal scales.

10.5 DID THE STUDY MEET ITS OBJECTIVES?

Research in this thesis has dealt with the development of modelling PnR users' accessibility to train stations over space and time. Seven objectives were established at the beginning of the research (Chapter 1). These objectives were achieved by a number of successive steps. A clear explanation of the term accessibility, its definition and measures, was presented in Chapter 2. Chapter 3 provided an outline of the research methodology for spatio-temporal modelling of PnR users' accessibility to train stations. The questions regarding the factors affecting catchment area modelling and train ridership were answered in Chapters 4, 5 and 6 respectively, through exploratory data analysis. Chapter 7 addressed the research question of developing a model delineating the catchment areas of PnR users for the train stations. To achieve this goal, the modified Huff model and the linear referencing method were adopted. Chapters 8 and 9 assessed accessibility to train stations for PnR users at two time scales. The first was macro spatio-temporal modelling of accessibility with the ability to explore the accessibility improvement before and after the opening of a new train line, in terms of demand and supply changes over time and travel impedance improvements. The second was micro spatio-temporal modelling of accessibility with the aim of constructing accessibility to train station continuum in terms of travel time, which has ability to explore accessibility at any location at any time.

10.6 SUMMARY

This thesis has established the framework and methodology for the spatio-temporal modelling of PnR users' accessibility to train stations. A case study undertaken in Perth, Western Australia was used to apply and evaluate the innovative approaches and enhanced models. The study has proposed some new data analysis approaches and indices, including the spatial segmentation analysis approach to identify the main market share and the innovative centrality index, with the ability to evaluate the location of a train station from an equal spatial accessibility perspective, instead of the traditional node influence centrality indices. The study also established the framework for generating the catchment area based on the modified Huff model, a framework that could readily be applied to other industries. From a spatio-temporal modelling of PnR users' accessibility to train stations perspective, this thesis investigated the accessibility from two time scales: a longer time scale (called macro spatio-temporal modelling) that examined accessibility improvements before and after the opening of the Mandurah train line, and a shorter time scale, that focused on the variations in accessibility over 24 hours, (called micro spatio-temporal modelling). The macro spatio-temporal model adopted the floating catchment area metrics but, by enhancing the existing method, fully resolved the two main issues within the existing methods. The micro spatio-temporal accessibility proposed a space-time continuum theory with the ability to evaluate accessibility to a train station at any location at any time.

Understanding and improving accessibility is a key aim for transport planning and policy making worldwide. In Perth, PnR has become a key factor in generating a high volume public transport train ridership. The methodology developed in this thesis can assist commuters to choose their PnR train station. It can also assist policy makers to address the potential accessibility issues and provide suggestions for accessibility improvements and future development.

The established methodology could also be readily applied to other industries. For example, the catchment area delineation method could be applied to other human geography areas, such as hospital catchment area or shopping centre catchment areas. The E3SFCA method could also be used to evaluate accessibility to the health services.

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Appendix A Information Sheet

Request to Participate in Research

Dear Passenger,

My name is Ting (Grace) Lin and I am a Doctor of Philosophy student of Curtin University in the Department of Spatial Sciences. My Supervisor is Dr Jianhong (Cecilia) Xia who is a Senior Lecturer in the same department. We are currently undertaking a joint project, which is named 'Modelling and evaluating the joint access mode and train station choice', with The University of Western Australia (UWA), The Department of Transport (DoT), The Public Transport Authority (PTA) and The Department of Planning (DoP). Our study, ***'Spatial and Temporal Modelling of PnR Users Accessibility to Train Station'***, forms part of it**.**

Your participation in this research will involve filling in a questionnaire designed to ascertain basic data to expand our understanding on people's attitudes towards train stations' facilities and services provided. It is very important to our study since facilities and services are considered as one of vital factors affecting travellers' accessibility. The questionnaire will take no longer than 15 minutes of your time.

All information collected will be kept strictly confidential and will be used for this study only. The survey is completely anonymous, thus information collected from the survey will not include names or other characteristics that can potentially identify you. You will be free at any time to withdraw consent to further participation without prejudice in any way. In such cases, any records of your participation in the interview will be destroyed unless you agree otherwise.

This study has been approved by the Curtin University Human Research Ethics Committee (Approval Number xxxx). The Committee is comprised of members of the public, academics, lawyers, doctors and pastoral carers. If needed, verification of approval can be obtained either by writing to the Curtin University Human Research Ethics Committee, c/- Office of Research and Development, Curtin University, GPO Box U1987, Perth 6845 or by telephoning 9266 9223 or by emailing hrec@curtin.edu.au.

If you have any queries regarding the survey, please do not hesitate to contact us at C.Xia@curtin.edu.au or zju.grace@gmail.com or on 92667563.

We look forward to your participation in this study and thank you for your co-operation.

Yours sincerely,

Jianhong (Cecilia) Xia

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Ting (Grace) Lin (16304219)

Ph.D. Student
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Appendix B Ethic Approval

Curtin University

Memorandum

To	Ting (Grace) Lin, Spatial Science
From	Dr Paul Copland, Manager, Research Ethics
Subject	Protocol Approval **RD-02-13**
Date	24 January 2013
Copy	Dr Cecilia Xia, Spatial Science

Office of Research and Development
Human Research Ethics Committee

TELEPHONE 9266 2784
FACSIMILE 9266 3793
EMAIL hrec@curtin.edu.au

Thank you for your "Form C Application for Approval of Research with Low Risk (Ethical Requirements)" for the project titled *"Spatial and Temporal Modelling of Transit Accessibility to Departure Train Station"*. On behalf of the Human Research Ethics Committee I am authorised to inform you that the project is **approved** subject to the following condition detailed below:

1. **Final version of the survey questionnaire will be supplied prior to commencement of data collection.**

Approval of this project is for a period of twelve months **24-01-13** to **24-01-14**.

The approval number for your project is **RD-02-13**. *Please quote this number in any future correspondence*. If at any time during the twelve months changes/amendments occur, or if a serious or unexpected adverse event occurs, please advise me immediately.

Yours sincerely,

Dr Paul Copland
Manager, Research Ethics

Please Note: The following standard statement must be included in the information sheet to participants:
*This study has been approved under Curtin University's process for low-risk Studies (Approval Number **RD-02-13**). This process complies with the National Statement on Ethical Conduct in Human Research (paragraph 5.1.7 and paragraphs 5.1.18-5.1.21). For further information on this study contact the researchers named above or the Curtin University Human Research Ethics Committee. c/- Office of Research and Development, Curtin University, GPO Box U1987, Perth 6845 or by telephoning 9266 9223 or by emailing hrec@curtin.edu.au.*

CRICOS Provider Code 00301J

Standard conditions of ethics approval

These standard conditions apply to all research approved via the Curtin University's process for low risk studies. It is the responsibility of each researcher named on the application to ensure these conditions are met.

1. **Compliance.** Conduct your research in accordance with the application as it has been approved and keep appropriate records.
2. **Adverse events.** Consider what might constitute an adverse event and what actions may be needed if an adverse event occurs. Follow the procedures for reporting and addressing adverse events (http://research.curtin.edu.au/guides/adverse.cfm).Where appropriate, provide an adverse events protocol. The following are examples of adverse events:
    a. Complaints
    b. Harm to participants. This includes physical, emotional, psychological, economic, legal, social and cultural harm (NS Section 2)
    c. Loss of data or breaches of data security
    d. Legal challenges to the research
3. **Standard forms.** Use the standard forms for the following
    a. **Monitoring**. Assist the Committee to monitor the conduct of the approved research by completing promptly and returning all project review forms that are sent to you.
    b. **Annual report**. Submit an annual report on or before the anniversary of the approval.
    c. **Extensions.** If you are likely to need more time to conduct your research than is already approved, complete an application for extension four weeks before the current approval expires.
    d. **Changes to protocol**. Any changes to the protocol are to be approved by the Committee before being implemented.
    e. **Changes to researcher details**. Advise the Committee of any changes in the details of researchers involved in the approved study.
    f. **Discontinuation.** You must inform the Committee, giving reasons, if the research is not conducted or is discontinued before the expected completion date.
    g. **Closure**. Submit a final report when the research is completed. Include details of when data are to be destroyed, and how, or if any future use is planned for the data
4. **Data management plan.** Have a Data Management Plan consistent with the University's recordkeeping policy. This will include such things as how the data are to be stored, for how long, and who has authorised access.
5. **Publication.** Where practicable, ensure the results of the research are made available to participants in a way that is timely and clear (NS 1.5). Unless prohibited from doing so by contractual obligations, ensure the results of the research are published in a manner that will allow public scrutiny (NS 1.3, d). Inform the Committee of any constraints on publication.
6. **Police checks and other clearances.** All necessary clearances, such as Working with Children Checks, first aid certificates and vaccination certificates, must be obtained before entering a site to conduct research.
7. **Participant information.** All information for participants must be approved by the HREC before being given to the participants or made available to the public.
    a. **University logo**. All participant information and consent forms must contain the Curtin University logo and University contact details for the researchers. Private contact details should not be used.
    b. **Standard statement**. All participant information forms must contain the HREC standard statement.
    c. **Plain language.** All participant information must be in plain language that will be easily understood by the participants.

Please direct all communication through the Research Ethics Office

Curtin University

Curtin HREC Form B

PROGRESS REPORT
or APPLICATION FOR RENEWAL

The Form B is to be completed and returned to *the Secretary, Human Research Ethics Committee, c/- Office of Research & Development.*

If any of the points below apply prior to the expiry date, this form should be submitted to the Committee at that time. An application for renewal may be made with a **Form B three years** running, after which a 'new' application form, providing comprehensive details, must be submitted.

Approval Number:	RD-02-13	**Expiry Date** 22-01-14	
PROJECT TITLE:	Spatial and Temporal Modelling of Transit Accessibility to Departure Train Station		

1A	Has this project been completed?	YES☐	NO☐
1B	OR Do you wish to apply for a renewal of the project?	YES☐	NO☐
If YES please state the expected completion date.			
If NO please state why, eg abandoned/withdrawn/no funding etc.			
2	Has this project been modified or changed in any manner that varies from the approved proposal?	YES☐	NO☐
If yes, please provide details______ *(Attach additional comments on a separate sheet of paper if necessary)*			
3	Have any ethically related issues emerged in regard to this project since you received Ethics' Committee approval? (e.g. breach of confidentiality, harm caused, inadequate consent or disputes on these).	YES☐	NO☐
If yes, please provide details *(Attach additional comments on a separate sheet of paper if necessary)*			
4	Have any ethically related issues in regard to this project been brought to your attention by others? (i.e. study respondents, organisations that have given consent, colleagues, the general community etc).	YES☐	NO☐
If yes, please provide details ______ *(Attach additional comments on a separate sheet of paper if necessary)*			

Investigator:	Ting (Grace) Lin	Signature:	
Co-Investigator/s Supervisor:	Dr Cecilia Xia	Signature:	
School/Department:	Spatial Science		
Head of Enrolling Area:		Signature:	
Date:			

Office Use Only
APPROVED: ______________________________ DATE: ____/____/____
Chair HREC/Executive Officer

Appendix C Permission from Co-authors

Ting Lin <zju.grace@gmail.com> 2016/11/24
发送至 Cecilia、Todd、Doina、John、Brett、Renlong、Buyang、rick.church、Rick、Konstadinos

Dear Coauthors,

I am going to put two of our published papers into my PhD thesis as two chapters (chapter 6 and chapter 7) which is going to submit soon. Can I please get your permission here to put them into my thesis. Those two are:

Lin, T., Xia, J., Robinson, T.P., Olaru, D., Smith, B., Taplin, J., Cao, B., 2016. Enhanced Huff model for estimating Park and Ride (PnR) catchment areas in Perth, WA. Journal of Transport Geography 54, 336-348.

Lin, T., Xia, J., Robinson, T. P., Goulias, K. G., Church, R. L., Olaru, D., Han, R. (2014). Spatial analysis of access to and accessibility surrounding train stations: a case study of accessibility for the elderly in Perth, Western Australia. Journal of Transport Geography, 39(0), 111-120.

If you agree, could you please reply this email and I can print it out to attached to my thesis as an appendix. Thanks so much for your help.

Cheers,
Ting(Grace)LIN

Doina Olaru 2016/11/24
发送至 我

Dear Grace,

Yes, that is absolutely fine.
Congratulations for your work.

Best regards,
Doina

Konstadinos Goulias 2016/11/24
发送至 我、Cecilia、Todd、Doina、John、Brett、Renlong、Buyang、rick.church、Rick

Yes, of course!

Konstadinos (Kostas) Goulias,
Professor of Transportation,
Department of Geography,
University of California Santa Barbara,
Santa Barbara, CA 93117-4060, USA

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Rick Church 2016/11/24
发送至 我、Cecilia、Todd、Doina、John、Brett、Renlong、Buyang、Konstadinos

Grace,

That is fine with me.

Brett Smith 2016/11/24
发送至 我、Rick、Cecilia、Todd、Doina、John、Renlong、Buyang、Konstadinos

All good for me.

Brett

Han, Renlong 2016/11/24
发送至 我、Cecilia、Todd、Doina、John、Buyang、Konstadinos、Brett、Rick

It is fine with me.

Dr Renlong Han
Team Leader Transport Modelling | Integrated Transport Planning | Department of Transport
140 William Street, Perth WA 6000
Tel: (08) (08) 6551 6610 Fax: (08) 6551 6942
Email: Renlong.Han@transport.wa.gov.au | Web: www.transport.wa.gov.au

John Taplin 2016/11/24

发送至 我

Dear Ting Lin

You certainly have earned the right to put them in your PhD thesis. Excellent work in both of them. They are your studies and you are certainly entitled to claim them.

Regards John T

Emeritus Professor John H E Taplin
Senior Honorary Research Fellow
Transport and Logistics
Business School M261
The University of Western Australia
Crawley 6009 Australia
Email: john.taplin@uwa.edu.au
Phone: +61 8 6488 2081
UWA: CRICOS Provider No 00126G

Ting Lin 2016/11/24

发送至 Todd

Great! Thanks Todd.

...

2016-11-24 8:46 GMT+08:00 Todd Robinson <T.Robinson@curtin.edu.au>:

> I think you're safe with the manuscript.
>
> Cheers
>
> Todd.

Appendix D Permission from Journals and Conference

Your Question 收件箱 x

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发送至 我

Dear PhD Candidate Ting Lin,

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Best regards,

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Pringle, Chris (ELS-OXF) <c.pringle@elsevier.com> 6月5日 (2天前)
发送至 Frank、 我、 Kevin

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Chris

Chris Pringle, MILT
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Appendix E Intercept Survey Questionnaire 1

(31/07/ 2012- 1/8/2012 (6:00AM - 4:00PM))

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Department of Transport

Public Transport Authority

Planning Western Australia

Train Station Survey *(Example completed)*

Project title: Modelling and Evaluating the Joint Access - Mode and Train Station Choice **(LP110201150).** *This research has the UWA Human Research Ethics Office approval number RA/4/1/5370 from May 2012.*

Project description: *We are interested in the way people get to the train station.*

The survey will be completed on paper while waiting on the platform (ensure 3 min before train). Select (circle) the appropriate option.

Trips today from: Warwick, **Greenwood**, Bull Creek, Kwinana, Midland, Beckenham, or Claremont; Time: **8:10am**

Q1. How did you travel to the train station? **Car PnR**, Car kiss-and-ride, Bus, Walking, Cycling, Other (please specify) *taxi*

Q2. Where did you start that trip (street, suburb, landmark)? **Glencarry St., Padbury, 6015**

Is that: **Home**, Work, School, Shop, Gym, Pub, Other (please specify)?

Q3. What is the destination of this trip: **St George's Tce, Perth CBD**

Q4. What is the purpose of your travel *(open question)*? **dentist**

For those who used PnR:

Q5. Why did you choose the PnR today? *(open question?)* **lack of parking in the city**

(*some pointers: no parking at destination, costly parking at destination, traffic congestion, convenience of riding the train, other activities on the return trip, environmentally responsible*)

Q6. Did you easily find parking available when you arrived? Yes/**No**

6b. If No, please specify how long were you searching (min): **5**

Q7. Where did you park? Free parking bays, paid parking bays, residential streets, shopping centre parking, other (please specify)

Q8. How much would you pay to secure a parking bay? **$ 3.00**

Q9. If you could not find an available parking bay at this station, what would you do? Arrive earlier, Use the bus, Get dropped-off, **Travel to other PnR stations**, Drive to your destination, Other (please specify)

9a. If considering changing the PnR station, please specify which ones: **Stirling**

Perception and attitudinal questions

Q10. What are the most important features/facilities for you at a train station? Please rate them on a scale 1 to 7, where: 1 = Not at all important at all to 7 = Utmost important

Facilities available at a train station:	1	2	3	4	5	6	7
Free park-and-ride bays					☑		

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Facilities available at a train station:	1	2	3	4		6	7
Secure/locked car park					☑		
Secure/locked bike storage				☑			
Information on Transperth's timetables and communication of changes							☑
Shops *(convenience stores)*					☑		
Vending machines						☑	
Seating available while waiting for the train					☑		
Seating on the train *(in the carriage)*				☑			
Emergency services							☑
Easy access to the platform for people with disabilities						☑	
Lighting					☑		
Other (please specify):							

Q11. Could you please rate the facilities at this train station? 1 = Very poor to 7 = Excellent

The quality of facilities available and services at this train station is:	1	2	3	4	5	6	7
Free park-and-ride bays						☑	
Secure/locked car park						☑	
Secure/locked bike storage						☑	
Information on Transperth's timetables and communication of changes							☑
Shops *(convenience stores)*			☑				
Vending machines				☑			
Seating available while waiting for the train					☑		
Seating on the train (in the carriage)				☑			
Emergency services						☑	
Easy access to the platform for people with disabilities						☑	
Lighting							☑
Train frequency at present						☑	
Service provided by train station staff					☑		
Arriving according to the timetable						☑	
Other (please specify)							

Thank you for your time.

Gender *(to be recorded by interviewer after the survey)*: **M**/F

Age group *(to be recorded by interviewer after the survey)*: Young adult, **Middle aged**, Senior

Interviewer code: **13** Signature interviewer: Questionnaire ID: 0001

Appendix F Intercept Survey Questionnaire 2

(8-10/05/2013 (9:00AM – 3:30PM))

Train Station Survey Directed at Seniors Card Holders *(Example completed)*

Project title: Modelling and Evaluating the Joint Access - Mode and Train Station Choice **(LP110201150).** *This research has the UWA Human Research Ethics Office approval number RA/4/1/5370 from May 2012.*

Project description: *We are interested the opinion of seniors on the accessibility of this train station*

Survey Time: [ ] Home (Suburb name or postcode):

Q1. How did you travel to the train station? Car PnR, Car kiss-and-ride, Bus, Walking, Cycling, Other (please specify) [ ]

Q2. Is this the usual/regular mode you get to the station? Yes/No

2b. If not, how do you travel regularly to the train station? [ ]

Q3. Where and when did you just depart from before heading to this train station (the last stop of this trip before taking this train)?

When: | Where (street, suburb):

Q4. What is the purpose of your trip today? Home, Work, Education, Shop, Gym, Pub, Health, Other (please specify)? [ ]

Q5. Are there any other activities related to your travel on the way to the train station?

[ ]

Q6.Where is your destination of this trip by this train?

(Street, suburb):

Q7. Is it easy to find parking around this train station? Yes/No/Unable to judge

Q7b. How many minutes did it take you to find parking? [ ]

Q8. How would you rate the overall accessibility of this train station for older people? (Check one that applies.)

( ) It is so inaccessible that I cannot use it
( ) It is not very accessible at all
( ) It is usable but needs work
( ) It is pretty accessible
( ) It is extremely accessible
( ) Don't know

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Q9. What is the maximum acceptable walking distance to the train station for you? (Check one that applies.)

( ) 0 – 400 metre ( ) 401 – 800 metre ( ) 801 – 1200 metre

( ) Other, please specify

Q10. What barriers have you encountered in using this train service in the last 12 months? (Check all that apply.)

( ) Personal mobility
( ) Step on the bus
( ) Gap at the platform
( ) Difficultly managing climate conditions (too hot, cold or wet)
( ) Crossing busy streets
( ) Difficult to access the station
( ) The alighting station is too far away from my final destination
( ) Too far from my origin to reach transit stations
( ) Infrequent service at night or on weekends
( ) Unreliable PT system
( ) Inappropriate attitude towards older people from staff
( ) Don't feel safe travelling here
( ) I have encountered no barriers
( ) Other ________________________

Q11. How often do you use the train monthly? (Check one that applies.)

( ) <4times ( ) 4-8 times ( ) >8 times

Perception and attitudinal questions

Q12. What are the most important features/facilities for you at a train station? Please rate them on a scale 1 to 7, where: 1 = Not at all important at all to 7 = Utmost important

How do you rate them at this train station? 1 = Very poor to 7 = Excellent

Facilities available at a train station:	Importance	*At this station*	N/A
Free park-and-ride bays			
Secure/locked car park			
Information on Transperth's timetables and communication of changes			
Shops *(convenience stores)*			
Seating available while waiting for the train			
Shelter available when waiting for train station			
Seating on the train *(in the carriage)*			
Emergency services			
Easy access to the platform			
Lighting			
Train frequency			
Service provided by train station staff			
Other (please specify):			

Q13. Please rate the importance of the following factors when you are evaluating the accessibility level to train station? Please rate them on a scale 1 to 10, where: 1 = Not at all important at all to 10 = Utmost important.

Mark a cross (╳) in the gradient ramp according to your rating.

- Walk

Factors	Not at all important → Utmost Importance 1 --→ 10
Distance (from home to train station) Network Directness (the degree of routes' detour) Land Use (the shopping centre, medical centre or park around the stations) Service and Facility Quality (at the station)	

- Park and Ride

Factors	Not at all important → Utmost Importance 1 --→ 10
Parking Capacity (Parking bays available at the station) Parking on the Streets Car Ownership Distance (from home to train station)	

Network Directness (the degree of routes' detour)	
Land Use (the shopping centre, medical centre or park around the stations)	
Service and Facility Quality (at the station)	

- Bus

Factors	Not at all important → Utmost Importance 1 --→ 10
Bus Frequency to train station	
Walking Distance (from home to bus stop)	
Bus Distance (from bus stop to train station)	
Land Use (the shopping centre, medical centre or park around the stations)	
Service and Facility Quality (at the station)	

Gender: M/F

Age group: 60-69 ☐ 70-79 ☐ 80+ ☐

Household income: (optional)

( ) <$25,000
( ) $25,000 - $50,000
( ) $50,000 - $75,000
( ) $75,000 - $100,000
( ) $100,000+
( ) I choose not to answer

End of the questionnaire

Thank you very much for your time!

Appendix G Intercept Survey Questionnaire 3

(19-20/ 09/ 2013 (7:00AM-12:30PM))

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Train Station Access Survey

Project title: Modelling and Evaluating the Joint Access - Mode and Train Station Choice **(LP110201150).** *This research has the UWA Human Research Ethics Office approval number RA/4/1/5370 and Curtin Human Research Ethic office approval number RD-002-13.*

Project description: *We are interested in your opinion on the accessibility of this train station*

Survey **Date and Time**: ____

Gender:	( )M	( )F				
Age group:	( )18-24	( )25-29	( )30-34	( )35-39	( )40-44	( )45-49
	( )50-54	( )55-59	( )60-69	()70-79	( ) >80	

Q1. What is the nearest station to your home? ____

Q2. When and where was your last activity (e.g. home, work, education, shopping) immediately before heading to this train station?

When: ____ Where (landmark, nearest corner, suburb): ____

Q3. How did you travel to the train station? Car Park-and-ride, Car Kiss-and-ride, Bus, Walking, Cycling, Other ____

Q3b. If Park-and-ride, how long did it take you to find a parking bay? ____ mins

Q4. Is this your normal/regular mode you use to get to this station? Yes/No

Q4b. If not, how do you normally travel to the train station? ____

Q5. What is the purpose of your trip today? Home, Work, Education, Shopping, Leisure, Health/Medical, Holiday, Other (please specify)? ____

Q6. What other activities have you conducted during this trip? (Shopping or Seeing a doctor or dropping off the kids to school on the way to the train station)

____

Q7. What types of facilities around train stations have you used? *(Please select all that apply)*

() None ( ) Shop/Retail ( )Education ( )Health/Welfare & Community Services
( )Residential ( ) Office/Business ( ) Entertainment, culture & recreation

( ) Other, please specify ____

Q8. What is the destination of this trip? (landmark, nearest corner, suburb): ____

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Q9. What is the maximum acceptable walking distance to the train station for you?

( ) 0 – 400 m ( ) 401 – 800 m ( ) 801 – 1,200 m

( ) Other, please specify

Q10. Each week how often do you take the train (return journey = 2 times)?

( ) <=4 times ( ) 5-10 times ( ) >10times

Q11. How would you rate the overall access to this train station in consideration of your travel mode?

( ) It is so inaccessible that I cannot use it
( ) It is not very accessible at all
( ) It is usable but needs work
( ) It is pretty accessible
( ) It is extremely accessible
( ) Don't know

Perception and attitudinal questions

Q12. What do you think of the importance of the following facilities and services available at or around your regular train station? Mark a cross (☒) in the table according to your rating.

	Not at all Important	Very Unimportant	Somewhat Unimportant	Neither Important nor Unimportant	Somewhat Important	Very Important	Extremely Important	N/A
Free park-and-ride bays	○	○	○	○	○	○	○	○
Secure/locked car park	○	○	○	○	○	○	○	○
Information on Transperth's timetables/ fares/ communication of changes	○	○	○	○	○	○	○	○
Shops (convenience stores)	○	○	○	○	○	○	○	○
Seating available while waiting for the train	○	○	○	○	○	○	○	○
Seating on the train (in the carriage)	○	○	○	○	○	○	○	○
Emergency services	○	○	○	○	○	○	○	○
Easy access to the platform	○	○	○	○	○	○	○	○
Lighting	○	○	○	○	○	○	○	○
Train frequency	○	○	○	○	○	○	○	○
Service provided by train station staff	○	○	○	○	○	○	○	○
Shelter available when waiting for train station	○	○	○	○	○	○	○	○
Security on the train	○	○	○	○	○	○	○	○
Security around the station	○	○	○	○	○	○	○	○
Other (please specify):	○	○	○	○	○	○	○	○

At your regular station, how satisfied are you with these facilities and services. Please rate these items. Mark a cross (⨉) in the table according to your rating. Please note that safety means your perception of risk or an accident and personal security means your perception to become a victim of unlawful and/or violent action

	Poorest	Very Poor	Somewhat Poor	Neither Poor nor Good	Somewhat Good	Very Good	Excellent	N/A
Free park-and-ride bays	○	○	○	○	○	○	○	○
Secure/locked car park	○	○	○	○	○	○	○	○
Information on Transperth's timetables/ fares/ communication of changes	○	○	○	○	○	○	○	○
Shops (convenience stores)	○	○	○	○	○	○	○	○
Seating available while waiting for the train	○	○	○	○	○	○	○	○
Seating on the train (in the carriage)	○	○	○	○	○	○	○	○
Emergency services	○	○	○	○	○	○	○	○
Easy access to the platform	○	○	○	○	○	○	○	○
Lighting	○	○	○	○	○	○	○	○
Train frequency	○	○	○	○	○	○	○	○
Service provided by train station staff	○	○	○	○	○	○	○	○
Shelter available when waiting for train station	○	○	○	○	○	○	○	○
Security on the train	○	○	○	○	○	○	○	○
Security around the station	○	○	○	○	○	○	○	○
Other (please specify):	○	○	○	○	○	○	○	○

Q13. Please rate the importance of the following factors when you make a decision about the train station choice? Please rate them on a scale 1 to 7, where: 1 = Not at all important at all to 7 = extremely important. Mark a cross (⨉) in the table according to your rating.
Please fill the table according to your travel mode today.

- Walking and cycling to the train station

	Not at all Important	Very Unimportant	Somewhat Unimportant	Neither Important nor Unimportant	Somewhat Important	Very Important	Extremely Important
Distance (from home to train station)	○	○	○	○	○	○	○
Path directness (shortest route)	○	○	○	○	○	○	○
Land use (e.g.shopping center, medical center or park around the stations)	○	○	○	○	○	○	○
Service and Facility Quality (at the station)	○	○	○	○	○	○	○
Safety during the walk	○	○	○	○	○	○	○
Security during the walk	○	○	○	○	○	○	○

- Driving to the train station

	Not at all Important	Very Unimportant	Somewhat Unimportant	Neither Important nor Unimportant	Somewhat Important	Very Important	Extremely Important
Parking capacity (Parking bays available at the station)	○	○	○	○	○	○	○
Parking on the streets	○	○	○	○	○	○	○
Distance (from home to train station)	○	○	○	○	○	○	○
Path directness (shortest route)	○	○	○	○	○	○	○
Land use (e.g.shopping center, medical center or park around the stations)	○	○	○	○	○	○	○
Service and Facility Quality (at the station)	○	○	○	○	○	○	○
Safety from parking lots to the station	○	○	○	○	○	○	○
Security from parking lots to the station	○	○	○	○	○	○	○

- Taking bus to the train station

	Not at all Important	Very Unimportant	Somewhat Unimportant	Neither Important nor Unimportant	Somewhat Important	Very Important	Extremely Important
Bus frequency	○	○	○	○	○	○	○
Walking distance (from home to bus stop)	○	○	○	○	○	○	○
Bus Distance (from bus stop to train station)	○	○	○	○	○	○	○
Land use (shopping center, medical center or park around the stations)	○	○	○	○	○	○	○
Service and Facility Quality (at the station)	○	○	○	○	○	○	○
Safety on the bus	○	○	○	○	○	○	○
Security on the bus	○	○	○	○	○	○	○
Safety at the bus stops around the station	○	○	○	○	○	○	○
Security at the bus stop around the station	○	○	○	○	○	○	○

End of the questionnaire

Thank you very much for your time!

If you wish to go into the draw for one of three double movie passes please fill in your e-mail address in the survey winners will be contacted by e-mail. *Email:*

Surveyor Initials:	**Station**: (Surveyor please record station)

Appendix H Facilities Survey (2012)

Number	Name of station	Platform																Parking and Ride		Biking 'n'Ride			Bus	Rail
		Ticket machine	Ticket checking machine	emergency	lighting	Public telephone	information	chairs		Undercover waiting room	Toilet	office	Security personal	cleaner	Disable path/lift	Convenience store	Water foundation	unlocked	Locked	Have/not	Room(*)	number		
								Have/not	number															
1	Perth																							
2	McIver																							
3	Claserbrook																						√	√
4	East perth	√	√	√	√	√	√	√	16*2=32	√	√	√	√	√	√	√		√						√
5	Mount Lawley	√	√	√	√		√	√	Under construction	√					√			√						
6	Maryland	√	√	√	√	√	√	√	10	√		√			√	√		√		√	√(4)	9		
7	Meltham	√	√	√	√		√			√					√			√		√	√(2)	4	√	
8	Bayswater	√	√	√	√		√			√			√		√			√	√	√	√(4)	9+3	√	
9	Ashfield	√	√	√	√		√	√	8	√					√			√		√	√(4)	0+4	√	
10	Bassendean	√	√	√	√	√	√	√	30	√		√	√		√			√		√		8+6		
11	Success Hill	√	√	√	√		√	√	8	√					√					√	√(4)			
12	Guildford	√	√	√	√		√	√	8	√					√			√		√		8+4		
13	East Guildford	√	√	√	√		√	√	8*2=16	√					√					√	√(4)			
14	Woodbridge	√	√	√	√		√	√	7	√					√					√		0+7		
15	Midland	√	√	√	√		√	√	32*2=64	√	√	√	√		√	√		√	√	√	√(16)	9+12	√	√