School of Earth and Planetary Sciences

Evaluating spatial efficiency and equity in urban structure: An accessibility study

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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.

Signature:______________

Date: 13/03/2020.

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RELATED PUBLICATIONS

Published peer-reviewed journal papers:

Kelobonye, K., Xia, J. C., Swapan, M. S. H., McCarney, G., & Zhou, H. (2019) . Drivers of Change in Urban Growth Patterns: A Transport Perspective from Perth, Western Australia. *Urban Science*, 3(2), 40. doi: https://doi.org/10.3390/urbansci3020040

Kelobonye, K., Mao, F., Xia, J., Swapan, M. S. H., & McCarney, G. (2019). The Impact of Employment Self-Sufficiency Measures on Commuting Time: Case Study of Perth, Australia. *Sustainability*, 11(5), 1488. doi: https://doi.org/10.3390/su11051488

Kelobonye, K., McCarney, G., Xia, J., Swapan, M. S. H., Mao, F., & Zhou, H. (2019). Relative accessibility analysis for key land uses: A spatial equity perspective. *Journal of Transport Geography*, 75, 82-93. doi:https://doi.org/10.1016/j.jtrangeo.2019.01.015

Kelobonye, K., Zhou, H., McCarney, G., & Xia, J. (2020). Measuring the accessibility and spatial equity of urban services under competition using the cumulative opportunities measure. *Journal of Transport Geography.* 85, 102706. https://doi.org/10.1016/j.jtrangeo.2020.102706

Kelobonye, K., Xia, J., Zhou, H., & McCarney, G. (2020). Assessing the Potential of an Effective Density-Based Measure for Evaluation and Prioritisation of Activity Centres: A Case Study of the Perth Metropolitan Region. *Manuscript under review in Applied Geography*.

Refereed conference papers:

Kelobonye, K., Xia, J. C., Swapan, M. S. H., McCarney, G., & Zhou, H. (2019). Analysis and Optimisation Strategy of Employment Decentralisation in Perth through Density and Accessibility Indicators. Paper presented at the *State of Australian Cities National Conference*, Perth, Western Australia, Australia. 3 – 5 December 2019.

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ABS	Australian Bureau of Statistic
AC	Activity Centre
CBD	Central Business District
COM	Cumulative Opportunities Measure
DoP	Department of Planning
DoT	Department of Transport
EJD	Effective Job Density
ELD	Effective Labour Density
ESC	Employment Self-Containment
ESRI	Environment Systems Research Institute
ESS	Employment Self-Sufficiency
GIS	Geographic Information System(s)
GPS	Global Positioning System(s)
JHB	Job-Housing Balance
JWB	Job-Worker Balance
MAUP	Modifiable Areal Unit Problem
MRS	Metropolitan Region Scheme
PMR	Perth Metropolitan Region
PT	Public Transport
PTA	Public Transport Authority
SDR	Supply Demand Ratio
STEM	Strategic Transport Evaluation Model
TAZ	Traffic Analysis Zone
TOD	Transit Oriented Development
USA	United States of America
WA	Western Australia

ABSTRACT

Cities are living organisms; they are born, they grow and eventually die. During their growth, cities often must manoeuvre numerous challenges not only to survive, but also to thrive. The spatial arrangement of land uses within a city and the quality of networks connecting them can be the difference between a struggling city and a thriving one. Thus, urban spatial structure has an enormous influence on a city's day-to-day performance and overall sustainability. Urban spatial structure can be defined and measured from a static/morphological perspective or a dynamic/functional perspective. The evolution of an urban spatial structure, however, is a slow and complex process – which makes it difficult to 'create' a desired urban structure or, even more so, to change an existing structure. Therefore, while urban spatial structure and the functioning of a city as a system have been extensively studied, efforts to develop comprehensive urban spatial structural solutions have been limited. More specifically, there is a lack of a methodological framework to understand and evaluate the spatial efficiency of an urban structure from both morphological and functional viewpoints, and the spatial equity at a detailed and nuanced level.

Perth, the state capital of Western Australia, is the epitome of a sprawling city, characterised by low population density and high private vehicle usage. In most cases, sprawling cities are associated with serious functionality and sustainability challenges including inefficient use of resources such as land, energy and time and high carbon emissions. While the planning framework for Perth has for a long time promoted suburbanisation and private car usage, the 21st century planning agenda has brought a complete paradigm shift that emphasises limiting greenfield developments and promoting compact, high density developments, land use diversity and use of sustainable travel modes. However, despite this clear policy direction, research addressing the urban spatial structure question in Perth is lacking, and what there is, is ad hoc and fragmentary.

To improve our contemporary understanding of Perth's urban spatial structure and address the aforementioned issues, this thesis develops a robust and comprehensive framework for evaluating the urban spatial structure, particularly from the perspectives of spatial efficiency and spatial equity. A suite of existing and new indicators and strategies are explored for practical evaluation and/or enhancement of urban spatial efficiency and spatial *equity, including urban expansion, employment self-sufficiency and self-containment, job and labour density, employment decentralisation, and service accessibility.*

The investigation starts with evaluating Perth's urban structure from a morphological perspective. This involves chronicling the urban form evolution in relation to planning policy framework, transport and economic drivers since establishment of the Swan River Colony (present day Perth) in 1829. As it turns out, transport was a major driver of the shape and direction of Perth's urban form up until the late 20th century. Since then, the urban footprint has expanded well beyond the major transport links. Despite the rate of urban expansion having diminished dramatically since the beginning of the 21st century, transport developments – particularly in the form of railways – are still yet to catch up.

On the dynamic/functional perspective, the thesis utilises trip data to evaluate the levels of job-worker balance (JWB), employment self-sufficiency (ESS) and employment self-containment (ESC), and their impact on commuting times. The thesis discovers poor levels of JWB, ESS and ESC as well as weak correlations between these measures and commuting time. The weak correlation is ascribed to the measures' failure to fully account for the exogenous component of the trip. Poor JWB, ESS and ESC levels imply a mismatch between jobs and residential locations across the metropolitan area. The Western Australian government has invested robust efforts in developing a decentralisation policy to address these imbalances and improve the overall travel efficiency and service access equity. The thesis proceeds in an evaluation of Perth's decentralisation policy using density and accessibility indicators, and an effective density-based measure is proposed for optimising employment decentralisation. The city's employment targets for strategic suburban centres are found to be insufficient and causing little to no change in the current urban spatial structure.

A cumulative opportunities accessibility measure is employed to assess the spatial equity of jobs, education, shopping and health care services by car and public transport. This measure is simple, practical and easy to interpret, which makes it favourable to policy makers. Finally, a modified cumulative opportunities accessibility measure is proposed. The proposed measure incorporates a competition or demand component into the traditional cumulative opportunities measure, in order to more accurately reflect demand-supply imbalances and spatial equity implications. Incorporating a competition component in the *cumulative opportunities measure produced significantly different accessibility patterns to what has been widely reported by accessibility studies in Perth. Nonetheless, in both approaches (with and without competition) the various urban services studied showed various levels and patterns of spatial equity, suggesting that contrary to the approach of some urban structure studies, no single one of them can be fully representative of the city's urban spatial structure. Lastly, public transport was found to be markedly limited when compared to the private car in providing access to all services.*

Finally, the thesis recommends a consolidated 'spatial efficiency-spatial equity' framework. A consideration of both efficiency and equity indicators is necessary to fully and accurately understand the performance of an urban structure. Efficiency is not efficient without equity, and, of course, spatial equity alone does not imply any form of efficiency. Results of this thesis are both informative and instructive to urban policy makers and practitioners seeking to evaluate and improve the spatial efficiency and spatial equity of the modern city and enhance its overall sustainability.

CHAPTER 1 INTRODUCTION AND OUTLINE

1.1 INTRODUCTION TO THESIS

Cities are complex, dynamic structures which evolve slowly over a long period of time, shaped by a range of multifaceted factors. Geographical constraints, government policy and market influences, all have a great influence on the type of urban spatial structure that emerges in a city (Lan, Da, Wen, & Wang, 2019; Nankervis, 1992; Z. Wang & Lu, 2018). It is, therefore, difficult to 'create' a desired urban structure – a possible explanation for the limited attempts to analyse spatial structure and understand how it influences the quality of life of urban residents. However, a deficient urban structure can negatively affect the sustainability of a city (Anas, 1998). In fact, many of the problems faced by modern time communities can be ascribed to the spatial structure of urban areas. Even though it is an issue that is limited in the mainstream debate, our inefficient and/or inequitable use of land is conceivably the raison d'être of climate change, obesity, unemployment, foreclosures and the many other pressing environmental, social, health and economic challenges that we face today (Lopez, 2004;

Nakagome, 1989; P. W. G. Newman & Kenworthy, 1989; Zenou & Smith, 1995). On the other hand, a well-planned city can bring about efficient usage of a wide range of resources such as land, energy and time, and can reduce emission of greenhouse gases and waste generation.

Rising suburbanisation has been a major problem facing cities around the world in recent decades. Extensive outward growth has led to a rise in car dependence at the expense of non-motorised transportation and public transport; owing to the car's spatial and temporal flexibility (Steg, 2005). While there has been extensive investment in public transport, this has not been followed by a reduction in car usage, particularly in the USA and Australian cities (G. Giuliano & Hanson, 2017; Peter Newman, 1996). Thus, many big cities in Australia and around the world have in recent decades been pursuing efforts to reduce suburbanisation through compacting most new developments within the existing urban footprints. Perth, the State Capital of Western Australia, has experienced one of the highest rates of suburbanisation in the world since its establishment as a British colonial town two centuries ago (in 1829) (T. Adams, 2010; Demographia, 2017). This rapid outward expansion was characterised by low population density and high car ownership and usage. Up until the late 20th century, Perth's transportation strategy assumed that private vehicle usage would deliver efficient mobility (Curtis, 2012; Curtis & Mellor, 2011a). Curtis and Mellor (2011a) reported Perth to have the highest level of car ownership in Australia. Promoting private vehicle usage has led to serious transport challenges in Perth including traffic congestion, increasing transport costs and inequitable access to jobs and services (Lin, 2017).

The government of Western Australia has responded to this unsustainable trend by developing policies aimed at curbing suburbanisation and improving travel efficiency within the Perth metropolitan area. Since the beginning of the 21st century, Perth's planning strategy has reflected a paradigm shift that emphasises compact, high density developments and promotes the use of sustainable travel modes. The current planning efforts defined in the *Perth and Peel @ 3.5 Million* planning document also emphasise the development of several suburban Activity Centres to reduce the CBD dominance. The activity centres will be hubs of economic development hosting a high density and diversity of activities/services including jobs, housing, shopping, education and recreation, and will be well-connected by PT (Western Australian Planning Commission, 2015). The overarching goal of this policy is to optimise land use and travel efficiency, and minimise negative impacts on the environment. Successful development of activity centres would be marked by, among other things, less excess commuting and a more spatially equitable distribution of and access to services.

This thesis seeks to contribute to the empirical and theoretical knowledge that informs the evaluation and implementation of the ongoing policy agenda. It focuses on investigating the changing urban spatial structure and the associated (or potential) improvements pertaining to spatial efficiency (e.g. urban footprint expansion, employment self-sufficiency/self-containment and accessibility) and spatial equity (defined by an even distribution of access to services). Accessibility is increasingly being used around the world as a performance indicator for urban structure, particularly in operationalising the integration of transport and land use planning (Boisjoly & El-Geneidy, 2017; Deboosere & El-Geneidy, 2018). Although suburbanisation, employment distribution and service accessibility have each been assessed by previous studies (K.T. Geurs & Ritsema van Eck, 2001; Hansen, 1959; Lawler et al., 2014; Moniruzzaman, Olaru, & Biermann, 2017; Osman, Divigalpitiya, & Arima, 2016; Owen, Murphy, & Levinson, 2017), albeit separately, research at a detailed and nuanced level into the urban spatial structure is limited, particularly from spatial efficiency and spatial equity perspectives. Thus, this study develops a comprehensive and robust framework for understanding the urban spatial structure in Perth, starting from a simple analysis of its evolution to more advanced and critical spatial analyses of its efficiency, equity as well as development targets. Spatial efficiency is evaluated from multiple approaches including rate of urban expansion, employment distribution and patterns of commuting. Spatial equity is evaluated based on the level of access to opportunities. The research also argues for a consideration of both spatial efficiency and spatial equity in a complementary manner when evaluating urban structural performance.

1.2 RESEARCH OBJECTIVES

The aim of this research is to investigate and augment the ways in which urban spatial structure can be exploited to enhance the sustainable growth of modern cities using accessibility and other spatial efficiency and equity indicators. This broad aim is to be achieved through the following specific objectives:

1. To investigate the spatial efficiency of urban structure from an urban form evolution perspective. The study examines the chronology of Perth's development milestones from the colonial era to the 21st century. More closely, it examines the influence of transport developments and planning policy framework on urban expansion, and quantifies changes in the urban footprint over the last five decades.

2. To investigate the spatial efficiency of urban structure from a functional perspective (travel efficiency). Here the study applies novel trip data to determine the levels of job-worker balance, employment self-sufficiency and employment self-containment in the Perth Metropolitan Region (PMR), and investigates their impact on commuting time. Using transport and land use data and models, prospective spatial efficiency is also investigated through a critical

analysis of Perth's employment decentralisation agenda, and estimating its potential impact on the spatial pattern of job accessibility.

3. To critically and thoroughly evaluate the spatial equity of the PMR using an accessibility approach. In this context, the accessibility of various key urban services/destinations is investigated based on private and public transport travel. Spatial equity implications are drawn from the accessibility results, while also highlighting the value of addressing competition effects in accessibility measures – particularly within the spatial equity context. The spatial equity of various services are compared.

4. To establish a link between spatial efficiency and spatial equity of urban structure and make recommendations regarding their nature as often-competing priorities.

1.3 SIGNIFICANCE OF THE STUDY

A well-planned city can promote efficient use of resources such as land, energy and water, and reduce emission of greenhouse gases and waste generation (Commonwealth of Australia, 2010). The thesis makes empirical and methodological contributions on evaluating the urban spatial structure, from spatial efficiency and spatial equity perspectives. Spatial structure is defined using morphological/physical characteristics (e.g. urban footprint and transport infrastructure) and dynamic or functional characteristics (e.g. trip patterns and travel times). On the morphological aspect, this research provides a systematic enquiry of the pattern of evolution of the urban footprint in relation [or perhaps, in response] to transport developments and the planning policy framework, and how it has changed over the past two centuries in the case of Perth metropolitan region (chapter 4).

The study also provides systematic evaluations of existing methods and practices for determining:

a) urban spatial efficiency, such as:

   i. the effectiveness of job-worker balance (JWB), employment self-sufficiency (ESS) and employment self-containment (ESC) targets in reducing commuting times (chapter 5); and

   ii. the reliability of accessibility measures in evaluation and prioritisation of activity centres for purposes of employment decentralisation (chapters 6 and 7).

   iii. the sufficiency of the employment decentralisation targets for activity centres in Perth to be achieved by 2050.

b) urban spatial equity, such as:

   i. the validity of sampling a single urban service (such as employment distribution or accessibility) to represent the overall spatial equity of an urban spatial structure (chapter 8), and

   i. the accuracy of the cumulative-opportunities accessibility measure in drawing spatial equity implications for various key urban services (chapter 9).

The research contribution of this thesis includes making empirically supported recommendations for improving existing practices for measuring spatial efficiency and spatial equity.

More significantly, this study proposes methods for:

a) more accurately measuring urban spatial efficiency, particularly with regards to evaluation and prioritisation of decentralised activity centres (effective density-based measure – chapter 7); and

b) incorporating demand and competition into the widely favoured cumulative-opportunities accessibility measure to measure spatial equity of various urban services/amenities in Perth (chapter 9).

This study will help urban planners, public transport planners and developers understand how planning framework and transport development influence urban expansion, particularly in the Perth context. It will help decision makers come up with effective ways to promote and evaluate efficiency and sustainability of the urban spatial structure.

1.4 RESEARCH METHODOLOGY

The study implements both existing and new rigorous, practical and easily computed methods for modelling and evaluating the performance of urban spatial structure in the Perth Metropolitan Region from spatial efficiency and spatial equity perspectives. Initially, the historical evolution of Perth's urban form evolution is studied based on secondary sources, mainly to understand the influence of transport infrastructure developments, but also to determine its alignment with planning policy framework. Then, trip data were used to investigate the levels of job-worker balance, employment self-sufficiency and employment self-containment in the individual traffic analysis zones (TAZs) (or Strategic Transport Evaluation Model (STEM) zones, as they are referred to in Perth), and determine their effect on commuting time using statistical correlation. Next, the city's employment decentralisation policy was critically evaluated using accessibility and density indicators – focusing first on the sufficiency of the employment targets for activity centres, and then applying an effective density-based model to determine ideal locations for activity centres. For the equity aspect, the study uses a cumulative opportunities accessibility measure to evaluate the spatial equity of various services in the metropolitan region. Thus, spatial equity is represented by the spatial variations in the accessibility of services. Finally, a modified cumulative opportunities measure of accessibility is developed, which incorporates a competition component into the method to more accurately reflect service supply-demand imbalances.

1.5 THESIS STRUCTURE

A graphical illustration of the thesis structure is presented in Figure 1.1. The thesis contains a total of ten chapters to address its objectives. Different colour codes are used to indicate chapters with a spatial efficiency focus (yellow) and those with a spatial equity focus (pale red).

The thesis also contains some results from the author's peer reviewed publications conducted during the candidacy period (2016 – 2020). A list of these publications, their respective chapters in the thesis, and the thesis objective(s) they address are shown in Table 1.1. The full bibliography of the publications has been provided in the 'related publications' section above.

Table 1.1: Peer reviewed publications of the author's research conducted during the candidature.

Paper	Chapter	Thesis objective	Reference	Journal
Paper 1	4	1	(Kelobonye, Xia, Swapan, McCarney, & Zhou, 2019b)	Urban Sci.
Paper 2	5	2	Kelobonye, Mao, Xia, Swapan, and McCarney	Sustainability

			(2019)	
Paper 3	6	2/3	Kelobonye, Xia, Swapan, McCarney, and Zhou (2019a)	SOAC2019 (refereed conference)
Paper 4	7	2	Kelobonye, Xia, Swapan, Zhou, and McCarney (2020)	Under review: Applied Geography.
Paper 5	8	3	Kelobonye, McCarney, et al. (2019)	J. Transp. Geogr.
Paper 6	9	3	Kelobonye, Zhou, McCarney, and Xia (2020)	J. Transp. Geogr.

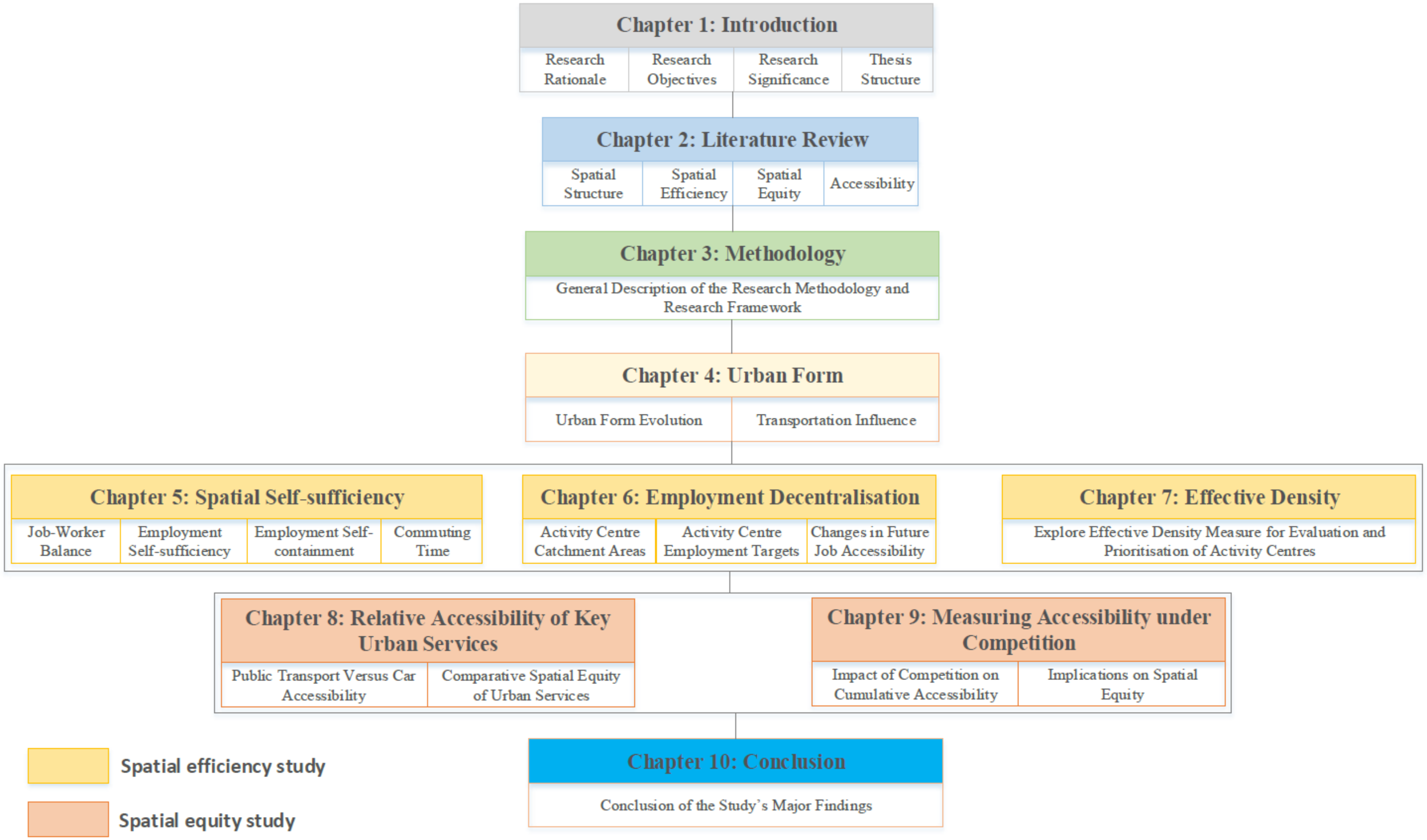


Figure 1.1: Research structure and relationship to the chapters of this thesis

Chapter 2 reviews the relevant literature on urban spatial structure, spatial efficiency and spatial equity. Some key indicators used for evaluating urban spatial efficiency and spatial equity are discussed. Existing studies on job-worker balance, accessibility and effective density measures are explored, and the limitations or research gaps relating to these indicators are identified.

Chapter 3 presents a discussion of the study area and data used in the study. A theoretical framework for urban spatial structure efficiency and equity modelling is established and presented. An overview of the methodology for urban structure analysis, spatial efficiency and spatial equity assessments are briefly discussed. The chapter also includes a brief discussion of the software used in implementing the methodology.

Chapter 4 develops a timeline for exploring the developmental milestones of Perth since being founded as a British colony in 1829. The milestones are broken down into transport, planning policy framework, economic and land developments. The chapter goes further to deconstruct these timelines, interrelating their cross effects on each other. Finally, it provides a detailed discussion of the transport developments and their role in driving the ensuing urban form. Objective 1 is addressed in this chapter.

Chapter 5 investigates the impact of self-sufficiency indicators on commuting. It presents the level of job-worker balance, employment self-sufficiency and employment self-containment for each of the region’s TAZs, and applies statistical correlation to determine relation with each zone’s average commuting time. Objective II is addressed in this chapter.

Chapter 6 critically examines the employment decentralisation agenda for the Perth Metropolitan Region using density and accessibility measures. Firstly, it investigates the spatial patterns of labour and job densities and their ability to support suburban activity centres (ACs). Secondly, it investigates changes (potential improvements) in the level of job accessibility in and around ACs, which would result if the employment targets are achieved. Finally, it identifies a suitable location for developing a primary AC (second tier after the CBD), which is currently missing in the AC policy. Objective II is addressed in this chapter (and partly, objective III).

Chapter 7 develops an effective density-based model to evaluate performance and potential of activity centres. The developed measure is implemented alongside a commonly used accessibility measure, and each activity centre is assigned an accessibility score and an effective density score. The activity centres are then ranked based on these scores, and the results from each measure are compared. Objective II is addressed in this chapter.

Chapter 8 employs a ‘cumulative opportunities’ measure to understand the relative accessibility and spatial equity of various urban services or land uses in Perth. Comparisons are drawn between the accessibility of different land uses, as well as between access by private car and public transport, the two major travel modes in the Perth metropolitan region. Objective III is addressed in this chapter.

Chapter 9 develops a modified cumulative opportunities accessibility measure to investigate the ‘effective’ accessibility of different services, and more accurately understand the spatial equity implications. The developed effective accessibility measure incorporates a competition component that relates services supply (or available opportunities) with demand (people seeking the opportunities). A detailed discussion compares the results of this method with previous results to deduce the implications on spatial equity of the services. Objective III is addressed in this chapter.

Chapter 10 concludes the thesis by presenting a summary of the major findings and research contributions. Recommendations of a consolidated ‘spatial efficiency-spatial equity’ framework are made in this chapter, which addresses objective IV of the thesis. Study limitations as well as directions for the future research are also presented in this chapter.

1.6 SUMMARY

This chapter has established the rationale for and defined objectives of the research on urban spatial structure and its influence on urban performance i.e. spatial efficiency and spatial equity. The chapter has also set out the key tasks of the research and stated the outline of the thesis structure. The next chapter will review the relevant literature in this area, focusing on defining the key terms and establishing existing methods for evaluating urban spatial structure.

CHAPTER 2 LITERATURE REVIEW

2.1 INTRODUCTION

This chapter reviews previous research related to urban spatial structure and its efficiency and equity measurement. This review provides a background to the existing body of knowledge around some of the major indicators used to measure the performance of urban structure, including density, accessibility and equity measures. Consequently, some gaps in the literature are identified that will be addressed by this research. The chapter begins with a definition of urban spatial structure. Next, relevant research into the performance indicators of urban spatial structure is discussed, including their definitions, significance, related factors and modelling methods. The chapter ends with a summary of the gaps identified in the literature, within which locates the purpose of this research.

2.2 URBAN SPATIAL STRUCTURE

There are divergent views on the set of elements that defines urban spatial structure (Anas, 1998; Horton & Reynolds, 1971). Even though it is more comprehensive, the term 'urban spatial structure' is at times used interchangeably with 'urban form' or 'morphology', which more precisely refers to the physical pattern/layout of a city. Because it is such a broad concept, urban spatial structure is often defined operationally – within the context in which it is being used. For example, in his study to assess how spatial structure affects residents' recreational travel behaviour, S.-I. Kim (1988) defined it as the spatial arrangement of recreational facilities and the distances between them, as well as between the facilities and users' origins.

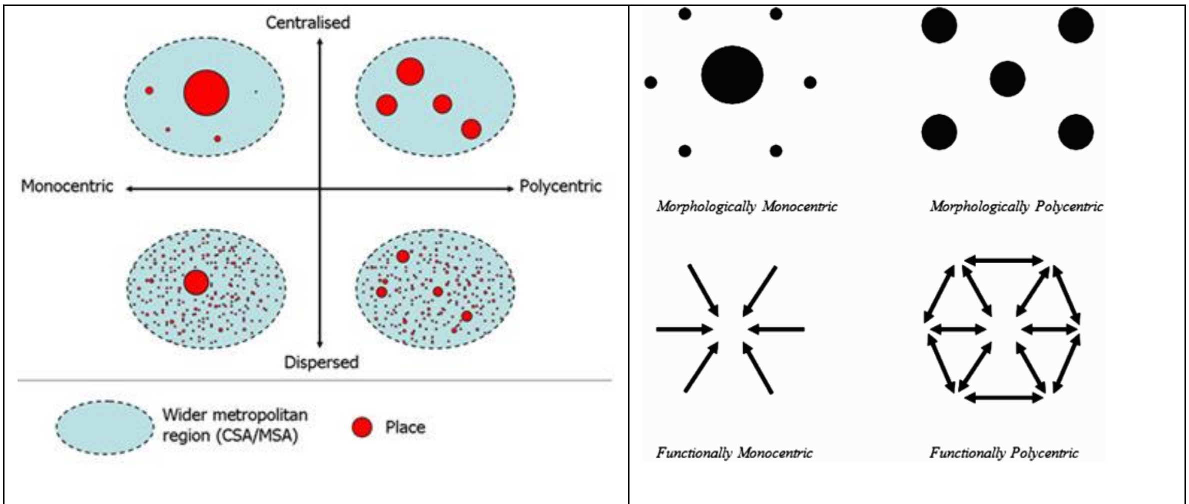
Despite the extensiveness of the concept and, consequentially, the versatility of its application, most researchers seem to agree that the basic definition of urban spatial structure describes the morphological (or geometric) character of a city/town/metro and its internal physical and functional linkages (M. Burger & Meijers, 2012; Gordon, Kumar, & Richardson, 1989; Horton & Reynolds, 1971; Evert J Meijers & Burger, 2010; Næss, 2006; Zhong et al., 2015). It entails three characteristic elements; the urban form, the urban/human interactions, and the rationale/principles of how people and the urban form relate to and interact with each other (Anderson, Kanaroglou, & Miller, 1996; Mindali, Raveh, & Salomon, 2004). For this project, the working definition of urban spatial structure is adopted from the works of (Bertaud, 2002b), which focus on the patterns of spatial distribution of people and their movement within and around the built-up area. Thus, urban spatial structure herein has two aspects; (1) static or physical aspect (urban footprint) and (2) dynamic/functional aspect (e.g. travel patterns).

2.2.1 Why 'spatial' structure?

Human settlements exist over space, and the level of interaction within/between them depends on relative positions. Space is essentially the cause for travel in that people travel to reach certain things at different spatial locations. This means the level of travel depends on the distances between (or relative locations of) places/facilities. Hence, manipulating the urban form over space through land use and transport planning can influence urban functionality both directly and indirectly.

2.2.2 Types of urban spatial structure

Two main types of urban spatial structure are conspicuously evident from the literature: monocentric structure and polycentric structure. Each of these can be further divided into subtypes. Applying my working definition of spatial structure, these two types emerge when; i) one central point exists surrounded by sparsely dense residential developments and attracting virtually all commute – monocentric; or ii) multiple, similarly sized/functioning centres exist in a metro area, attracting a comparable share of commute and other trips within the region. Of course, different patterns may emerge when applying different sets of measures and/or indicators to determine the type of spatial structure. This is particularly common when defining 'polycentricity'. For instance, an urban area may be considered to be polycentric if there is a balance or similarity in the size and distribution of its centres – morphological polycentricity (M. Burger & Meijers, 2012; Evert J Meijers & Burger, 2010). However, by another definition, there has to be a set of reciprocal linkages between the centres for an area to be considered polycentric – functional polycentricity (M. J. Burger, van der Knaap, & Wall, 2014). See Figure 2.1.



Source: Evert J Meijers and Burger (2010)

Source: M. J. Burger et al. (2014)

Figure 2.1: Monocentric and polycentric structures

Travel patterns within the city area can reveal the type of spatial structure it has. This is so in the functional definition of spatial structure. This implies that there can be physical ‘centres’ that may not be reflected in the travel patterns. For this reason, travel patterns can be a good measure of the performance of centres, particularly those ‘designed’ in the suburbs to ease pressure on the CBD. People do not just travel for the sake of it, they do so because they need to reach a particular place or perform a certain activity. This provides a great opportunity for assessment of the revealed ‘attractiveness’ of destinations. According to Bertaud (2001), four main different patterns emerge from the movement/trips of people across a city (Figure 2.2). First, the classical monocentric model, which has a strong high-density centre with jobs and amenities, and trips are in a radial pattern towards to centre. Second, the ‘urban village’ model, which is the planners’ ideal polycentric structure in which people live close to their jobs and walk or cycle to work. Third, a polycentric model can display a random pattern of trips across the sub-centres that are also distributed across the region. Last is the more realistic composite (mono-polycentric) model. This model has a dominant centre that attracts most of the trips, but there are also sub-centres distributed across the region which attract trips from people in a random pattern.

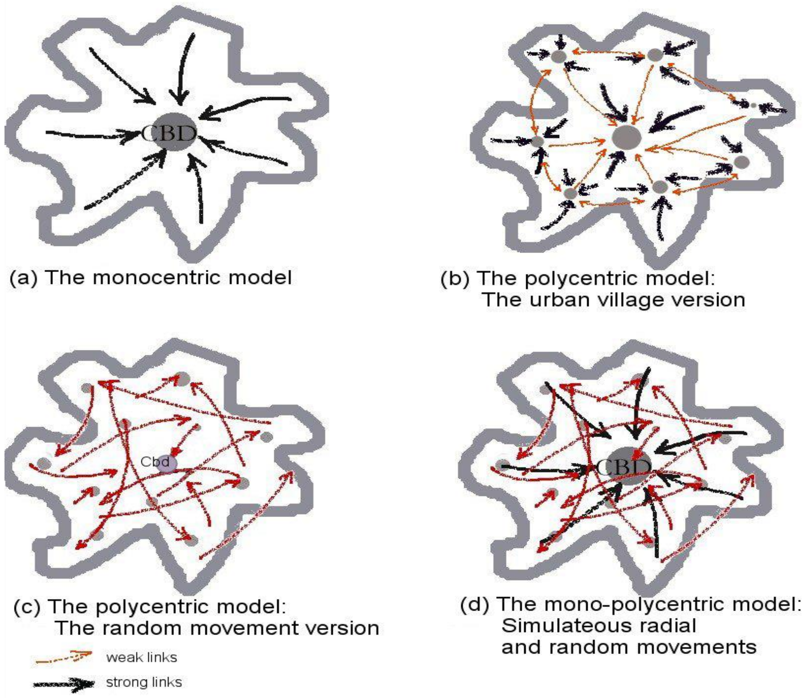


Figure 2.2: Schematic representation of most common urban spatial structures. Source: Bertaud (2001).

2.3 SPATIAL EFFICIENCY

Urban spatial structure has an enormous impact on the quality of life and should be monitored for human health and urban and environmental sustainability. An efficient means of interaction between people and businesses in various locations is necessary for a city's economic sustainability (Bertaud, 2002a; Morrill, 1974). Efficiency, in its traditional conception, pertains to the ability to achieve a task with minimum amount of time and effort, avoiding any wastage on materials, money or any form of cost. Spatial efficiency, therefore, refers to "the ease with which economic activities are geographically organized and transacted within a region" (Sarzynski & Levy, 2010, p. 2). From these definitions, it becomes immediately apparent that efficiency is not an outcome in and of itself, but rather it refers to the relationship between the input and 'desired output' (Reidpath, Olafsdottir, Pokhrel, & Allotey, 2012).

Definitions and measurement criteria of spatial efficiency vary according to the specific objectives desired from an urban spatial structure. These objectives often lie within the frameworks of the Location Theory (Hoover, 1937; North, 1955) and the Central Place Theory (Berry & Garrison, 1958; King, 1985). Both theories aim to minimise transport and land costs, with the latter focusing attention on the interaction between the dispersed consumers and producers, and the centrally located businesses (Morrill, 1974). The major consideration of urban development efficiency has traditionally been economic. However, since the issue of sustainable development has arisen, the consideration of urban development efficiency has begun to be more environmentally oriented (Kuo & Tsou, 2012).

At a metropolitan scale, spatial efficiency is dependent on the spatial arrangement of land uses and infrastructure; the distances, and the quality of transport and communication infrastructure between people and places (Bertaud, 2002a; Morrill, 1974; Sarzynski & Levy, 2010). These factors influence travel, energy, communication and public service needs within the metropolitan region (Sarzynski & Levy, 2010). Longer distances between places fragment people and land uses, and escalate capital and operating costs of infrastructure networks. Longer travel times also imply a loss of productivity. The encroachment of sprawling cities into pristine areas and rising automobile emissions degrade the environment.

Fisher and Rushton (1979, p. 84) defined the term spatial efficiency as "the access or distribution costs associated with a given locational arrangement of a service in comparison with those costs associated with the best-known alternative arrangement. Maximum spatial efficiency is achieved when both costs are the same." A key aspect of this definition involves defining the "best-known alternative arrangement" which should precede operationalisation of the concept. This means the objectives that need to be achieved by the ideal locational pattern must be specified. Objectives to define optimum locational patterns of services often include to (Fisher & Rushton, 1979):

- minimise aggregate [average] distance (time or cost) of all service users in the area;

- minimise average distance subject to a maximum distance constraint;
- minimise distribution cost subject to variable capacity limitations;
- minimise distribution cost subject to service area populations achieving a threshold size.

Sarzynski and Levy (2010) defined spatial efficiency as the geographic organisation of residences, businesses and infrastructure that minimises the cost (effort, time etc.) required for performing economic activities for the whole metropolitan district. Their definition considers economic activity in three classes: business-to-consumer; business-to-worker; and business-to-business interactions. This definition informs, more directly, the methodology for modelling spatial efficiency in this thesis. Thus, on the static/morphological aspect, spatial efficiency is achieved by managing urban expansion and greenfield developments. On the dynamic/functional aspect, shorter travel distances and times for the majority of the population are deemed more efficient.

2.4 SPATIAL EQUITY

Sustainable development is underpinned fundamentally on the concept of equity (Beder, 1996). In fact, the basis of the popular definition of sustainable development by the Brundtland Commission is intergenerational equity (Beder, 2000; Spijkers, 2018); "development which meets the needs of the present without compromising the ability of future generations to meet their own needs" (World Commission on Environment and Development, 1987, p. 43). Since the publication of the Brundtland report, many governments have incorporated equity into their development policy frameworks.

"Equity derives from a concept of social justice. It represents a belief that […] burdens and rewards should not be spread too divergently across the community, and that policy should be directed with impartiality, fairness and justice towards these ends." (Falk, Commonwealth Environment Protection Agency, University of Wollongong. Technological

Change, & Environmental Strategies Group, 1993, p. 2).

The phrase ‘spatial equity’, therefore, in a general sense means the provision of benefits at a level that is consistent or fair throughout a geographical space (Tsou, Hung, & Chang, 2005). More specific definitions vary with priorities, but three general categories or frameworks of equity are evident from the literature; horizontal equity, vertical equity with regards to income and social class, and vertical equity with regards to mobility need and ability (T Litman, 2007; Ricciardi, Xia, & Currie, 2015). Horizontal equity, which is the most commonly used approach, seeks for a fair and equal distribution across all groups throughout the space. This framework derives from a philosophical approach of egalitarianism – equality and fairness for all individuals. It considers all people as equal and deserving of the same level of supply regardless of their ability, social class or need. The other framework, vertical equity, specifically identifies disadvantaged members of the community and prioritises service supply to them to compensate for the overall inequalities in the society (Delbosc & Currie, 2011; T Litman, 2007). The priority incorporated to the under-privileged groups could be either with regard to income and social class, or mobility need and ability (T Litman, 2007; Ricciardi et al., 2015). In the transport planning agenda, these two frameworks bring contrasting perspectives; transporting highest numbers of people (horizontal equity) to ease congestion versus proving access to those in highest need such as no-car households, low-income or elderly (vertical equity framework) Delbosc and Currie (2011). Therefore, a proper assessment of equity lies in its proper definition, and the way in which equity is defined will highly influence the priorities and/or objectives for service supply (T Litman, 2007).

Spatial equity assesses the geographical distribution of service and facility supply relative to that of the consumers/users. With growing interest in spatial equity research in recent decades, a range of approaches and methods have been proposed and/or applied by researchers in this area. Truelove (1993) indicates that spatial equity measures can be classified into four categories;

- *Mapping areas beyond the defined range of existing facilities:* a service range is defined, and areas lying outside the service range are considered unserved. No consideration of need, i.e. it is assumed to be equally distributed.

- *Service-to-need ratio:* each region's equity is calculated by a ratio contrasting service and need levels e.g. number of day-care centre spaces per thousand pre-school children.

- *Correlation analysis:* measures the relation between the distribution of service provision and need. Higher correlation indicates more equity e.g. if a strong negative correlation exists between the number of subsidised day-care spaces per district and family income per district. However, Truelove highlights the difficulty that comes with deciding on the appropriate level of spatial aggregation, since this affects the value of correlation coefficients.

- *Indices*: several other indices that can be used to measure spatial equity that vary according to the type of data and definition of equity, among many other factors. Most common example is the Gini index (Gastwirth, 1972; Rogerson, 2013).

Sometimes referred to as distributional equity, spatial equity is often measured by the level of accessibility to opportunities by members of the population living in various locations. Talen and Anselin (1998) argued that accessibility and equity are the primary building blocks in assessing spatial distribution of public services. A highly prominent trend in spatial equity literature is that studies tend to pick a single service and assess it outside of the holistic system of an urban spatial structure. E.g. employment (Cheng & Bertolini, 2013; Kawabata & Shen, 2007; Shen, 1998), recreation (J. W. Kim, 2015; S. I. Kim & Fesenmaier, 1990; Nicholls, 2001; Talen & Anselin, 1998), or health care (Apparicio, Abdelmajid, Riva, & Shearmur, 2008; Kinman, 1999; Rosero-Bixby, 2004).

There are only a few exceptions in the literature where the accessibility and/or spatial equity of two or more services was considered. For example, Delmelle and Casas (2012), in their study evaluating accessibility of bus rapid transit, examined the accessibility in relation to three services of libraries, hospitals and recreation sites. A recent study by Guzman, Oviedo, and Rivera (2017) considered transport equity to work and study. Nonetheless, there is no clear evidence to support the inference of spatial equity results across urban services within the urban spatial structure. In this study, a more holistic investigation of spatial equity within an urban structure will be conducted. Multiple urban services will be examined, and their spatial equity patterns compared. A conclusion will be made on the reliability of a single service to reflect overall spatial equity of the urban structure.

2.5 JOB-WORKER BALANCE

2.5.1 Defining job-worker balance and/or job-housing balance

The idea of co-locating jobs and housing units is not new; it goes as far back as 1898 to the utopian idea of 'Garden City' envisioned by Ebenezer Howard (Levine, 1998). Margolis (1957) was the first to translate job-housing balance (JHB) as a concept into planning practice (Q. Wu, Zhang, & Yang, 2015). JHB is defined as "the distribution of employment relative to the distribution of workers in a given geographic area" (Genevieve Giuliano, 1991, p. 305) (p. 305). In this definition housing is taken to represent workers – their population and/or distribution. While some studies have used household data (e.g. P. Zhao, Lu, and Linden (2009) and S.-m. Li and Liu (2016)), many directly use worker or trip (journey-to-work) data, with a focus on commuting patterns, and put little reference to housing (e.g. Cervero (1989b); Genevieve Giuliano and Small (1993); (M. Horner & Murray, 2003); (P. Zhao, Lü, & Roo, 2011); (Geyer & Molayi, 2017)). Job-housing balance, therefore, is a perpetuated misnomer for a concept that is more appropriately termed *job-worker balance*. Nonetheless, the term job-worker balance is much less used in the literature. It is noted that studies in the field of urban planning tend to use housing or household data while those in the transport field often use worker and trip data (Q. Wu et al., 2015). Genevieve Giuliano (1991) rightly observes that "the central concern of jobs-housing balance as it relates to transportation policy is the journey to work" (p. 305). Using household-based data to draw transport implications is susceptible to gross errors emanating from the variation in household structures/sizes and participation in the labour force.

2.5.2 Benefits and challenges of achieving job-worker balance

The argument for job-worker balance is based on the premise of reducing distances of commuter trips, and consequently reducing traffic congestion and improving overall traffic conditions. Previous studies have found that a better balance between jobs and workers results in reduced average commuting distances and times (Gordon et al., 1989; Mark W Horner & Mefford, 2007; Ta, Chai, Zhang, & Sun, 2017). Moreover, decentralising jobs to achieve a balance between the number of local jobs and worker residences increases job opportunities near the people, and many are inclined to take that opportunity to minimize disutility (Geyer & Molayi, 2017). This also encourages the use of active modes (e.g. walking and cycling) as proximity to work lessens the need for motorized vehicles (Ewing & Cervero, 2010). Shorter commuting distances and less car dependence can have several environmental and health benefits such as less air pollution and an improved quality of life (Ta et al., 2017). Cervero (1989b) also noted that a localized parity between jobs and workers might create localized commuter traffic zones segregated from regional traffic, thus easing the pressure on regional traffic streams.

In the ongoing discussion of job-worker balance, a controversial issue has been whether it is the appropriate approach to transportation problems. While its good intentions are undisputed, arguments against its suitability have ranged from wrongly premised, misdiagnosis of the commuting problems, to outright infeasible. One study that has received a lot of attention, by Genevieve Giuliano (1991), critically investigated this issue and concluded that job-worker balance is not an effective solution to ameliorate commuting and associated challenges. Quigley (1985) indicates that a complex range of factors influence residential location choices, including quality of neighbourhood, quality of schools, amenities and racial mix, which makes job-worker balance (JWB) an infeasible target.

Even those who advocate balance admit that it does not suffice as a solution. Cervero (1991) states that "jobs-housing ratio only indicates the potential for balance" (p. 12). Also, its relationship with self-containment has been found to be weak (Cervero, 1996), meaning that living close to jobs does not necessarily result in people working locally (job/skill mismatches). A proper functional balance can be realised by promoting two local community objectives that are less vague and more direct; maximising local capture of the labour force - "self-containment", and maximising local employment opportunities – "self-sufficiency" (SGS Economics and Planning Pty. Ltd., 2005). Self-containment measures the proportion of residents that work locally, and self-sufficiency measures the proportion of jobs filled by residents (S Biermann & Martinus, 2013). Over and above a numerical parity, self-sufficiency and self-containment promote spatial 'matches' between jobs and workers, which can bring down commuting times. However, the impact of self-sufficiency and self-containment on commuting time has rarely been examined.

2.5.3 Measuring job-worker balance

The measurement of JWB is generally classified into two categories. The first one compares the number of jobs and housing units in a given area. This approach uses housing units as a proxy for workers, to circumvent data limitations. The rule of thumb is to set a threshold range that constitute a balance e.g. if the jobs-housing ratio lies between 0.75 and 1.25 (Margolis, 1957). Anything outside this range is considered 'unbalanced', with the lower end of the range indicating residence dominance and the higher end indicating job dominance. When taking into account the households with two or more workers, fewer houses may be needed and the threshold ceiling may be brought up (Cervero, 1989b). Alternatively, and perhaps more accurately, actual worker numbers may be used instead of residential dwelling units. Each worker is assumed to have one job, hence a much smaller ‘balance’ range is appropriate.

The second approach seeks balance between ‘matching’ jobs and workers i.e. workers should live in the same area as their workplace. While the former approach only evaluates ‘potential’ for balance, this one determines the actual balance in a locality. Thus, it can also give an indication of the match between jobs and skills in the labour force, housing affordability for local workers, or interest of workers pertaining to living in the area (SGS Economics and Planning Pty. Ltd., 2005). With this approach it is also possible to determine the level of inter-regional commuting. It, therefore, enables an evaluation of the levels of local employment – self-sufficiency, and local capture of employment – self-containment (S Biermann & Martinus, 2013; SGS Economics and Planning Pty. Ltd., 2005). Employment self-sufficiency indicates the level of inward commuting and employment self-containment indicates the level of outward commuting. When there is no inward commuting the area is considered to be fully self-sufficient, and no outward commuting signifies full self-containment (S Biermann & Martinus, 2013).

2.5.4 The link between JWB and commuting behaviour

There prevails a long-standing debate in the literature on city spatial structure and how/whether it affects commuting patterns, or even travel behaviour in general. Some scholars have argued that spatial structure has little, if any, effect on commuting patterns and policies based on this link are wasteful and futile (Genevieve Giuliano, 1991; Genevieve Giuliano & Small, 1993; Gordon & Richardson, 1989). Peng (1997) contends that vehicle-miles travelled (VMT) is only marginally linked to changes in job-housing ratios. In his study conducted in the Portland, Oregon, metropolitan area, Peng demonstrates that VMT responds to JWB only in extremely imbalanced (very job-rich or very job-poor) areas. He therefore concludes that since most areas are roughly balanced, policies targeting JWB will only affect a small portion of the city, and thus have very little impact on overall commuting in the region.

A number of researchers have highlighted the relationship between proximity to jobs and commuting time. For example, Cervero (1989b) found that job-housing balance was significantly inversely related to commuting time in 40 major suburban employments centres in the United Stated. Another study by P. Zhao et al. (2009) also found a significant negative relationship between home-based job proximity and mean commuting time in Beijing (China). The same study revealed that job proximity could explain an overwhelming 68% of the commuting time changes. An increasing number of studies over the past three decades have reiterated not only the existence of this relationship, but also the necessity of its uptake into land use planning policies (Bento, Cropper, Mobarak, & Vinha, 2005; Geyer & Molayi, 2017; M. Horner & Murray, 2003; Levine, 1998; P. W. G. Newman & Kenworthy, 1989; Pan & Ge, 2014; Stoker & Ewing, 2014). These studies attest and contribute to the value of co-located and/or proximate jobs and residences in reducing average commuting times, as well as addressing other important issues including congestion, efficiency and sustainability within metropolitan settings.

Similarly, an increasing number of planning authorities in cities around the world are incorporating job-worker ratio targets in their land-use policies. Many cities around the world, in both developed and developing countries, are in desperate pursuit of congestion solutions. Since congestion happens during the peak times when people are commuting to/from work (Redmond & Mokhtarian, 2001), it is reasonable to expect that better balances of job-worker ratios in local sub-regions would create potential for reduced overall commuting. With better Employment Self-Sufficiency (ESS) and Employment Self-Containment (ESC) – which maximize local job opportunities and local labour capture, respectively – this potential for balance can be realized.

2.6 ACCESSIBILITY

2.6.1 Definition of accessibility

Gould (1969) is popularly quoted: "*Accessibility… is a slippery notion… one of those common terms that everyone uses until faced with the problem of defining and measuring it*" (P. 64).

Researchers have presented different understandings and interpretations of the idea of accessibility (L. Li et al., 2017). The concept of accessibility was first put forward by Hansen (1959) and was defined as the opportunity for interaction and overcoming spatial separation. This definition emphasises not just the ease of interaction but the potential for or possibility of interaction between different places. A more recent definition by K.T. Geurs and Ritsema van Eck (2001) and K. T. Geurs and van Wee (2004) refers to the extent to which people or goods can reach destinations by a given travel mode within the land use-transport system. Here the emphasis is on the spatial dimension and the intricate linking of accessibility to land use and transport patterns (Curtis & Scheurer, 2007). Another important component of accessibility that is less emphasised in the aforementioned definitions is time. This obviously pertains to the time it takes to reach a place from another, but it can further include the constraints experienced by users by virtue of their time/day/week/month of travel such as availability of opportunities or peak-hour congestion. The needs and abilities of transport users are also increasingly being considered in defining accessibility, directing focus to the demographic and socio-economic differences of individuals and communities (K.T. Geurs & Ritsema van Eck, 2001). Therefore, at its simplest, accessibility can be defined as the ease with which important destinations can be reached from residences, subject to spatial separation, travel mode and time (e.g. morning or afternoon) of travel. It is an indication of both the availability of an activity (such as work, education, shopping, health care or recreation) and the ease with which the location where such an activity occurs can be reached from a given origin, usually a residential place.

2.6.2 An overview of accessibility analysis

There are several methods that have been developed for measuring accessibility within urban structures. The methods base on various definitions and/or approaches of the concept of accessibility, and they have various (levels of) data requirement and complexity. Four major categories of accessibility measurement can be identified in the literature (K. T. Geurs & van Wee, 2004; J. Lee & Miller, 2018; S. Liu & Zhu, 2004). The first category is gravity-type measures, which utilise a distance/time decay function to normalise the cost of travel between origin (residence) and destination (activity location). It follows the Gravity Model's assumption that the interaction between activities is directly proportional to their size and inversely proportional to the distance/cost of travelling between them (Hansen, 1959). A gravity-type measure is greatly dependent on the weighting system (decay function) used and it produces indices which are often hard to interpret and/or understand. The selection of a weighting function can also bring subjectivity into the model, especially when dealing with different kinds of destinations. For example, convenience shopping has a higher travel impedance than comparison shopping (Handy, 1992), and people may be willing to travel further for work than other activities (K.T. Geurs & Ritsema van Eck, 2001).

The second category is utility-based measures, which estimate the value of opportunities based on the assumption that users of a transport system/consumers seek to maximise the utility of their behavioural choices. It is a cross-disciplinary approach utilising economic, social, land use and transport data input, and is still considered an emerging model requiring significant research and development (Curtis & Scheurer, 2010; K.T. Geurs & Ritsema van Eck, 2001). Third is the time-space approach, which adds the dimension of individuals' time constraints. People have a limited time budget within which to perform activities and the accessibility of an activity decreases as the travel time to reach it increases. Time constraints include capability constraints, (human body limits, e.g. how far one can reasonably walk), coupling constraints, (commitments, e.g. work times) and authority constraints, (movement-inhibiting regulations e.g. parking limits/fees or service operation times) (Bhat et al., 2000; K. T. Geurs & van Wee, 2004).

Last, but by no means least, is the opportunity-based approach which is concerned with the total opportunities that can be reached within a specified travel cost, or the total cost (e.g. time) required to reach a specified number of opportunities (K. T. Geurs & van Wee, 2004). An opportunity-based measure could entail simply finding the nearest opportunities and calculating their distances from the origin, which S. Liu and Zhu (2004) term as 'catchment profile analysis', or it could be a 'cumulative-opportunities measure' whereby the number of opportunities available within a specified travel time/distance from an origin is determined (S. Liu & Zhu, 2004; Wachs & Kumagai, 1973). The cumulative-opportunities approach is extensively applied in planning practice (Cheng & Bertolini, 2013; Merlin & Hu, 2017; Owen et al., 2017), and is the one on which the gist of this study is founded. For a more detailed discussion of accessibility measures readers are referred to, inter alia, these authors; Bhat et al. (2000); K.T. Geurs and Ritsema van Eck (2001); K. T. Geurs and van Wee (2004) and Curtis and Scheurer (2007).

2.6.3 Opportunity-based measures of accessibility

The most widely used approach in accessibility measurement is the cumulative-opportunities measure. A simple cumulative opportunities measure of accessibility takes the form (Equation 2.1):

$$A_i = \sum E_j c \qquad (2.1)$$

where A_i is the total opportunities available to zone i, E_j is the number of opportunities in zone j, and c is a constant with a value of 1 for zones within a given cost threshold from i to j, and 0 otherwise.

This method is widely embraced by transportation and urban planners or policy makers as it is easy to compute and interpret and thus can enable a range of scenarios and policy options to be explored (Bhat et al., 2000; Cheng & Bertolini, 2013). Other advantages of the cumulative opportunities measure include modest data requirements and repeatability which enables direct inter-city comparisons (Merlin & Hu, 2017; Owen et al., 2017). Opportunity-based measures quantify accessibility by the number/proportion of opportunities that can be reached from a location within a given travel time or distance. All opportunities within the selected time or distance threshold are deemed to have equal accessibility. It takes no greater account of, (i.e. gives no greater weight to), opportunities that are very close compared to those that are right at the time threshold. While a weighting system or gravity-based method could be applied, as other accessibility measures have done (e.g. (Fayyaz, Liu, & Porter, 2017); K. T. Geurs and van Wee (2004); L. Li et al. (2017); van Wee, Hagoort, and Annema (2001)), this introduces a degree of subjectivity in selecting the weights and can result in accessibility indices that may be less easy to interpret and understand. For example, this method may produce an index of 5 for one zone and a 6 for another. How do we interpret these and is the difference significant? The simple cumulative measure makes the understanding and comparison much easier. For example, 30,000 jobs can be reached from this zone and 40,000 from that is very easy to understand and compare. The biggest weakness of this approach is low accuracy, which stems from among other factors, its reliance on an arbitrary, binary threshold to define what is and what is not accessible, and its disregard for competition effects. The threshold within which the opportunities are counted is, therefore, a critical part of opportunity-based measures which greatly influences the results.

There is, however, no clear consensus on the appropriate access time thresholds for the various land uses that exist within an urban spatial structure. Zahavi (1979) and Marchetti (1994) demonstrated that people have traditionally adjusted their residential locations and travel modes such that the average daily work commute remains around half an hour in each direction. This notion is supported by many studies and is often adopted to inform land use and transport policy objectives. Appropriate thresholds for non-work trips are far more fuzzy and under-researched. Adler and Ben-Akiva (1976) allocated 40 minutes for a total shopping round-trip, further arguing closer destinations are generally preferred to those that are more remote. This time possibly translates to 10 – 15 minutes one way, accounting for the time spent shopping. Another study investigating retail travel behaviour in Brisbane, Australia found that almost all districts could reach a small centre by car within 15 minutes, but medium-sized centres required 30 minutes for the same level of accessibility (Nejad & Maryam, 2016). With PT, Nejad and Maryam (2016) found that only 11% of districts could reach small centres within 15 minutes, while 30 minutes allowed access to 51% of the districts. In another empirical study that analysed trip data in the Daegu Metropolitan Area in South Korea, I. Kim, Han, Kim, and Jung (2013) found the threshold travel time for shopping trips to be as high as 41.5 minutes, and 'other' trip purposes were 45 minutes one way.

Health trips also show varying evidence of recorded or desired travel times. Matthew Richard McGrail, Humphreys, and Ward (2015) found that rural residents in Australia (Victoria and New South Wales) travelled about 10 minutes farther for primary health care than urban residents (26.3 vs 16.9 min), and were prepared to travel 22.2 min farther (54.1 vs 31.9 min). However, studies have suggested that living farther from health services may lead to poor health outcomes (Kelly, Hulme, Farragher, & Clarke, 2016). Kelly et al.'s (2016) review further found that more people lived closer to the healthcare facilities that they were attending. Education trips make up about 20% of the morning peak traffic (Bureau of Infrastructure Transport and Regional Economics (BITRE), 2016). However, a good proportion of education trips to universities and TAFEs are made outside of peak times. Travel time requirements for these trips vary between basic education and technical/tertiary education – with primary & secondary education trips being shorter and tertiary education being generally longer.

Another critical factor to be considered in this measure is the fact that travel time fluctuates throughout the day. One way to account for this is to calculate accessibility measures at different times throughout the day (Farber & Fu, 2017). Some studies then compute a weighted average of accessibility from these various times e.g. Fan, Guthrie, and Levinson (2012). Others have employed a unified ratio that captures both spatial and temporal variations of PT services throughout the day e.g. Fayyaz et al. (2017). This brings a complex temporal dimension which makes interpreting the results challenging. In the current study, specific times of day when majority of trips for given purposes are made, will be selected to evaluate their accessibility. This requires the use of travel times at specific periods of the day (peak or off-peak) which is both easy to interpret and is a truer indication of accessibility for the majority of users of the respective services.

2.6.4 Accessibility and equity

Spatial equity in the field of transportation and land use planning is often defined and measured by the level of accessibility. The gaps in accessibility help to identify spatial, vertical, temporal, and intergenerational inequities (Martens, Golub, & Robinson, 2012). Equity and social inclusion have increasingly been considered as integral parts of PT planning in recent decades (Kaplan, Popoks, Prato, & Ceder, 2014). However, there is still no clear definition nor standard measures of what constitutes fair transport benefit distribution and how success or progress can be measured (Martens et al., 2012). Existing literature also shows that much less attention has been given to the match between need and provision of transit services (Welch, 2013). Additionally, diverse opinions exist on the best ways to improve transport equity. Some scholars have suggested mixed land uses, transit-oriented developments and more transit investment to improve accessibility especially for minority groups (e.g. Duncan (2010), Loo, Chen, and Chan (2010), Delmelle and Casas (2012), H. Kim and Sultana (2015), Poticha and Wood (2016) and Peter Newman (2016)) while others have advocated that private car ownership for the disadvantaged communities can improve access equity (e.g. Ong and Miller (2005) and Grengs (2010)).

However, the latter argument goes against urban sustainability objectives of reducing traffic congestion and carbon emissions. From a land use transport integration perspective, the focus is more on reducing the spatial separation between residences and services/destinations (jobs, schools, shops, hospitals and recreation facilities). Nonetheless, methodological and empirical research on equitable distribution (equitable accessibility) of major urban destinations/services is still limited.

2.6.5 Competition in accessibility measurement

When opportunities are limited, there is bound to be competition between those seeking the opportunities. More competition reduces the actual value of an opportunity that can be reached by an individual, since the chances of claiming that opportunity are reduced. Hence, the actual accessibility of an opportunity depends not only on it being reachable but also on the number of other seekers (competitors) that can reach it (Bunel & Tovar, 2014). This competition could occur either on the demand side (e.g. between job seekers) or on the supply side (e.g. between employers) (K. T. Geurs & van Wee, 2004). In issues of accessibility, competition on the demand side is more common than competition on the supply side (Cheng & Bertolini, 2013). Therefore, in this research, the interest is on competition on the demand side.

Researchers are increasingly advocating a consideration of competition in accessibility measures. In their widely cited paper, Shen (1998) warns that when competition effects are not accounted for in an accessibility measure, the results may be inaccurate or even misleading. K. T. Geurs and van Wee (2004) developed a checklist of five criteria by which any accessibility measure should behave, among which is the need to relate accessibility to the changes in demand: “If the demand for opportunities for an activity with certain capacity restrictions increases (decreases), accessibility to that activity should decrease (increase)” (p. 130). While there is increasing advocacy by researchers for accessibility measures to account for competition, planners and policy makers continue to opt for measures that are relatively simple, most commonly the cumulative opportunities measure (Bertolini, le Clercq, & Kapoen, 2005). Accessibility measures that account for competition tend to be complex and difficult to implement and/or interpret, and consequently, are less favoured by policy makers (Merlin & Hu, 2017). Notwithstanding its wide application in planning practice, the cumulative opportunities measure does not account for the spatial distribution of demand for the opportunities and is, therefore, not realistic insofar as competition for opportunities is concerned.

A delicate balance needs to be found in improving the accuracy of the cumulative opportunities measure without deterring its real-world application. One critical way in which this balance can be achieved is by ensuring that the model outputs remain easy to interpret – which is a major strength of the cumulative opportunities measure. Many accessibility measures that fail to influence policy decisions, while more realistic (e.g. gravity measures), give index values that have no clear-cut meaning and are difficult to relate to geographical reality (Geertman & Ritsema Van Eck, 1995). Addressing competition in the cumulative opportunities measure is a good opportunity for finding this balance since the method is widely understood and favoured by metropolitan planning authorities.

Despite being widely adopted in accessibility studies and planning policies, only a limited number of studies have made efforts to address competition in its application. For example, Cheng and Bertolini (2013) incorporated a competition component, combined with diversity and distance decay, in a modified version of a cumulative opportunities measure. However, the introduction of diversity and decay functions bring in a fair amount of complexity and subjectivity which could hamper both application and interpretation. This becomes even more challenging (and potentially increases complexity and subjectivity) when analysing and comparing two or more different services. This study will seek to modify the cumulative opportunities measure to address competition effects while preserving the objectivity of the measure, and with minimal increase in complexity (chapter 9). The paramount concern, while seeking to achieve better accuracy, was to not contaminate the ease of interpretation of results i.e. keep results in meaningful units (such as number of jobs or school vacancies).

2.6.6 Accessibility of distinct urban services

Accessibility literature often samples one service type to draw conclusions about the spatial structure of a city. Job accessibility is the most widely studied and linked to urban form (e.g. Black and Conroy (1977); Cheng and Bertolini (2013); Mark W. Horner (2004); Kawabata and Shen (2006, 2007); Merlin and Hu (2017); Shen (1998); van Wee et al. (2001)), but other urban services have also been considered such as recreational parks (J. W. Kim, 2015; S. I. Kim & Fesenmaier, 1990; Omer, 2006; Talen & Anselin, 1998) and health facilities (Luo & Wang, 2003; Oppong & Hodgson, 1994; Vadrevu & Kanjilal, 2016). Notwithstanding the foregoing, accessibility results that are based on only one type of urban service cannot reveal the whole picture about the urban spatial structure, and the spatial equity of services may be misrepresented (Tsou et al., 2005). In a rare accessibility study covering multiple urban service, Tsou et al. (2005) developed and applied an accessibility-based measure to examine the spatial distributions of 12 types of public facilities in the Taiwan city of Ren-De. This study will attempt to fill this research gap by examining the relative accessibility of five urban services (jobs, health services, shopping, primary/secondary education and tertiary education – chapter 8) using the cumulative opportunities measure. Additionally, the study will propose a modified cumulative opportunities measure that accounts for competition effects, and test it in a case study of three difference urban services (jobs, primary/secondary education and shopping).

2.7 EFFECTIVE DENSITY

Firms/businesses often cluster in central locations to tap the agglomeration externalities, which outweigh the disadvantages of congestion and higher rent. These agglomeration benefits can range from access to a wider customer base and skilled labour, increased productivity, complementary services, to transfer of knowledge and technology updates (Graham, 2007; Hensher, Truong, Mulley, & Ellison, 2012; Venables, 2007). The agglomeration benefits are not just available through co-location but can also be enjoyed some short distances away from the dense area, permited by transport infrastructure and services. Advances in transport and communication technology have reduced the need to cluster in high density areas, as it becomes increasingly possible for businesses to enjoy the 'agglomeration' benefits while located in less congested areas outside the urban core (Nurlaela, Xia, Tuladhar, Lin, & Lie, 2018; Venables, 2007). However, these agglomeration benefits are not equally accessible everywhere within the metropolitan area (Garcia-López & Muñiz, 2010). Therefore, employment decentralisation could affect the availability of agglomeration benefits to firms locating in the outer subregions. "Effective density" is a concept that makes use of the scale of economic activity and the proximity between those activities to portray economic agglomeration or 'market potential' available to a given geographic unit (Graham, 2007; Venables, 2007).

Graham (2007) developed an effective density-based model to represent agglomeration economies available to a specific area with an implicit transport dimension (Equation 2.2). The model measures the effective density (*ED*) of employment accessible to a firm located in ward a;

$$ED_a = \frac{E_a}{\sqrt{(\frac{A_a}{\pi})}} + \sum_{b}^{a \neq b} \frac{E_b}{d_{ab}} \tag{2.2}$$

where E_a is the total number of jobs in ward a, A_a is the area of ward a, E_b is number of jobs in ward b, and d_{ab} is the distance between a and b. In Graham's model, the implicit transport dimension is provided by Pythagoras distance between ward centroids. For the density effect arising within the ward a proxy for average ward radius is used based on the assumption that the wards are circular-shaped (Graham, 2007). Nurlaela (2016) proposed an adjustment to this model by replacing travel distance with travel time. However, this adjustment excluded the density effect that arises from within the geographic unit.

In this research, further adjustments were made to the transport dimension of Graham's model by using travel time for both travel between and within geographic units, and applying it to weigh the actual employment or worker density i.e. the actual area of geographic units is used to determine employment and worker density (shown in Chapter 7, Equations 7.3 and 7.4) , executed in a GIS environment. Travel time is a more explicit measure of accessibility that can more accurately reflect 'changes' in relative positions of business activity due to improvements in transport systems (Graham & Melo, 2010).

2.8 CHAPTER SUMMARY

This chapter reviewed existing literature on urban spatial structure. It defined the term urban spatial structure and established its various types, as well as the two different perspectives from which it can be defined. Research on spatial efficiency and spatial equity was discussed, and the existing methods for measuring these were explored – which included job-worker balance, employment self-sufficiency and accessibility. Consequently, research gaps identified in the literature that are addressed in this work are:

- limited attempts to analyse spatial structure and its drivers, as well as to understand how it evolves and influences the quality of life of urban residents;
- lack of a thorough examination on the impact of job-worker balance, employment self-sufficiency and employment self-containment measures on reducing commuting time;
- lack of a holistic spatial structure approach that incorporates diverse urban services in the evaluation of urban spatial equity;
- inconsistency of the effective density model concerning its transport dimension i.e.

use of travel time to account for the density effect between geographic units while distance is still used for the density effect that arises from within the geographic unit. Furthermore, no existing applications of the effective density model for prior evaluation and prioritisation of potential activity centre locations;

- lack of consideration of demand and competition in the cumulative opportunities measure – and consequently, its low accuracy, as one of the most widely applied accessibility measures in planning practice;

The next chapter will establish the theoretical framework for the study and provide an overview of the research methodology. The study area and data used for the case study will be discussed, and research workflow outlined.

CHAPTER 3 RESEARCH FRAMEWORK

3.1 INTRODUCTION

The previous chapter identified some existing literature and definitions of key terms in the area of urban spatial structure. Some gaps in the literature were identified including limited research into the measurement of spatial efficiency and spatial equity, and the lack of empirical evidence to guide and support policies that seek to change the overall urban spatial structure, particularly in the Western Australian context. A comprehensive and robust methodology for understanding, measuring and evaluating urban spatial structure is needed among both the industry and research communities. This chapter presents the research framework and an overview of the methodology employed in this research to contribute towards addressing this gap.

3.2 STUDY AREA

The study area for this research is the Perth Metropolitan Region (PMR) and the Peel Region in Western Australia (see figure 3.1). While the Perth and Peel regions are often considered together in planning policy documents, the Peel region, by default, still does not belong in the PMR. However, for the purposes of this research, PMR refers to and includes both the Perth and Peel regions. Perth is the State Capital of Western Australia, which is the biggest state in the country by land mass (about a third of the total). Save for the Indian Ocean on the west, escarpments on the east and some areas of shallow ground water, little stands on the way of the city's expansion. On the north-south dimension, the PMR spans over a 100km along the coast, and the city's longest train lines followed the land expansion along this direction. Altogether, Perth has five passenger train lines which all terminate at the city centre: Joondalup Line, Mandurah Line, Fremantle Line, Midland Line and Armadale Line (plus one spur from the Armadale Line, being the Thornlie Line). Figure 3.1 also shows the PMR, divided into seven subregions. The smaller divisions within the subregions show the delineation of the zones within the Department of Transport's transport model, (STEM). The locations of strategic and specialised activity centres are also indicated.

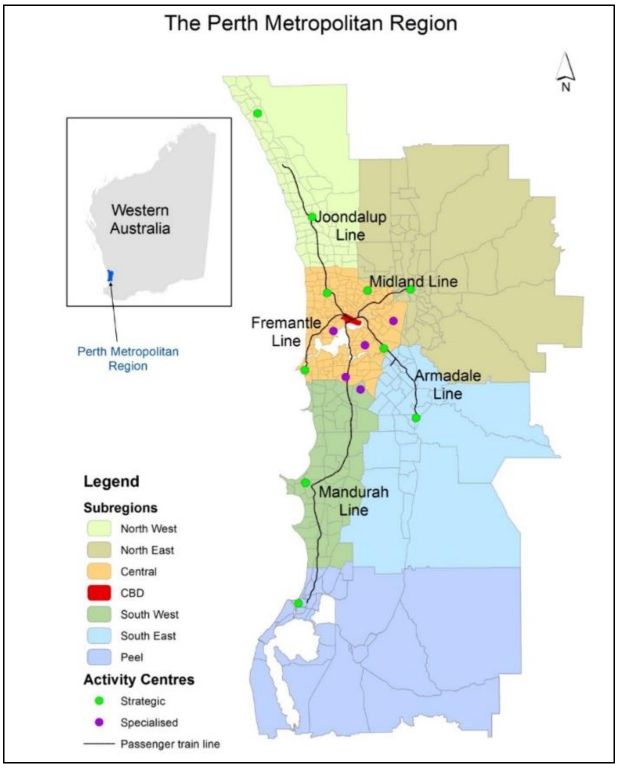


Figure 3.1: The Perth Metropolitan Region.

Perth is the fourth largest city in Australia. It is characterised by a low population density (Holt, 2013) within an expansive spatial coverage – the Mandurah strategic metropolitan centre (farthest south) is over 60 km from the CBD and the proposed centre at Yanchep (farthest north) will be over 50 km from the CBD. It also has a high car ownership of 723 vehicles per 1,000 people (Australian Bureau of Statistics, 2012-2013). Perth has experienced the fastest population growth in the country in recent years, with majority of the growth occurring at the fringe areas (Australian Bureau of Statistics, 2016; Weller, 2009). Despite being a relatively young city, Perth's spatial expansion has surpassed that of many older and much more populated cities around the world. It has about 2 million people over an area of 1,566 km^2, while, for example, Hong Kong has 7.3 million people in a 285 km^2 area, Madrid 6.2 million people over 1,321 km^2 and Istanbul 13.8 million over 1,360 km^2 (Demographia, 2017).

On the other hand, jobs and other services have remained concentrated in the CBD and central subregion. It is estimated that the Central subregion hosts about 64% of all jobs in the metropolitan area (Western Australian Planning Commission, 2018), while a lower 43% of workers reside here, according to data provided by the Department of Planning. The CBD and its immediate surrounds host a job share of around 15%, while only 2% of the workforce live here (Western Australian Planning Commission, 2018). Forty percent of the people that work in the CBD and surrounds live outside the Central sub-region (Western Australian Planning Commission, 2018). These imbalances make the central sub-region the primary importer of labour from other sub-regions, which results in excess commuting and traffic congestion. The low population density is a challenge to the self-sustenance of public transport (PT) due to low patronage. The Public Transport Authority, therefore, requires yearly grants and subsidies from the government to sustain the running of PT services (Public Transport Authority, 2016, 2017), the majority of which are in the inner city area.

It is projected that Perth's population will reach 3.5 million by 2050, adding almost 1.5 million to the current population (Western Australian Planning Commission, 2018). The long-term planning objective seeks to concentrate employment in activity centres (ACs) which are distributed across the metropolitan region to improve job accessibility in the suburbs (Western Australian Planning Commission, 2010b). The ACs will also be targeted for intensive mixed-use developments – with sub-regional and local catchments, and good public transport links.

Therefore, the growth patterns, challenges and policy directions discussed above make Perth a suitable case for studying the urban spatial structure. A combination of these factors presents a good opportunity to implement existing and new performance indicators to evaluate the urban spatial structure and forecast potential improvements from the planning policy objectives.

3.3 THEORETICAL FRAMEWORK

This research falls under the broader theoretical framework of 'urban spatial structure', focusing more specifically on investigating its spatial efficiency and spatial equity. Urban spatial structure is defined from two perspectives: static, morphological (or geometric) perspective; and dynamic, functional perspective. The former can also be referred to as urban form or urban footprint, while the latter concerns itself with the urban/human interactions and internal functional linkages (Anderson et al., 1996; Mindali et al., 2004). The underlying measure of spatial efficiency and spatial equity that is employed in this study is accessibility. An illustration of the theoretical framework guiding this research is presented in Figure 3.2.

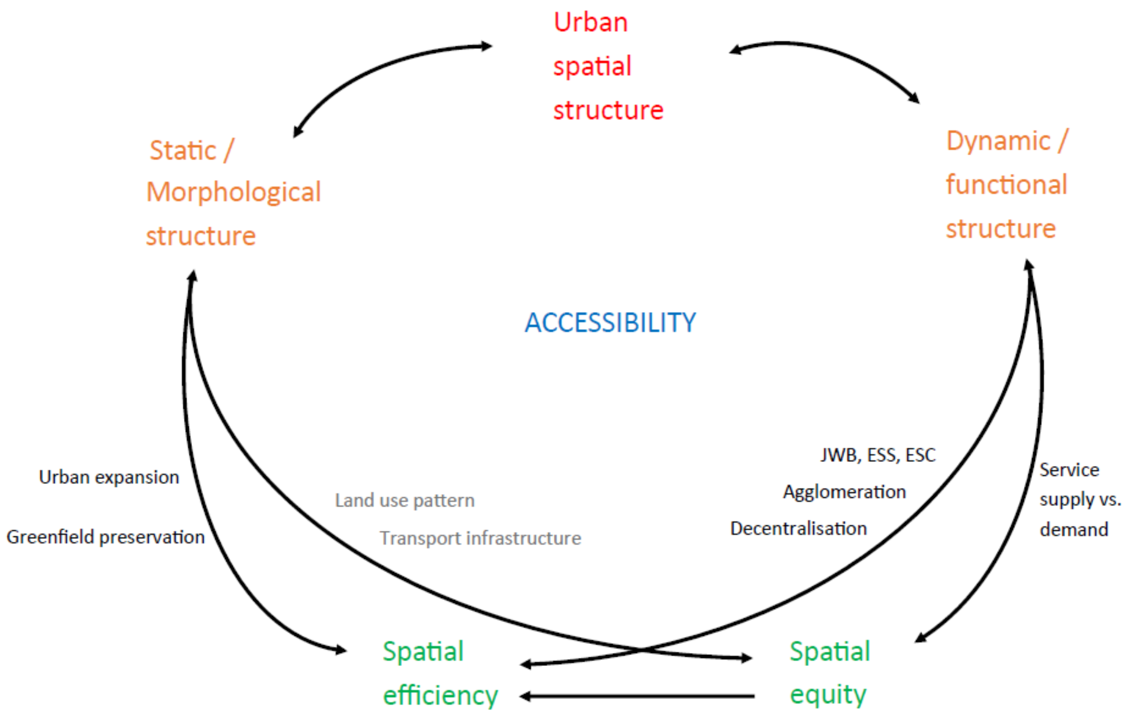


Figure 3.2: Theoretical framework of the study

The spatial efficiency of an urban structure, from a morphological perspective, can be determined through the rate of urban expansion and greenfield developments, with more compact brownfield developments constituting better spatial efficiency. From a functional perspective, spatial efficiency is determined mainly through the extent of land use separations and associated levels/patterns of travel between them. It is measured through indicators such as job-worker balance, employment self-sufficiency (proportion of jobs taken by local residents), employment self-containment (proportion of workers occupying local jobs), accessibility and the potential for agglomeration benefits for new firm locations in the decentralisation process.

While this study does not focus on spatial equity from a morphological perspective, this could be defined and/or achieved through an even balance of land use mix across the metropolitan area, and a fair coverage of transport and other infrastructure supply. Nonetheless, spatial equity in this thesis is discussed from a functional perspective, and it is measured through the patterns of service accessibility and service demand-supply ratios. A fair/even spatial distribution of accessibility constitutes better spatial equity.

3.4 RESEARCH WORKFLOW AND OVERVIEW OF METHODS

The research methodology for assessing the impact of spatial structure on urban development comprises several steps that were carried in sequence. These steps are outlined in Figure 3.3

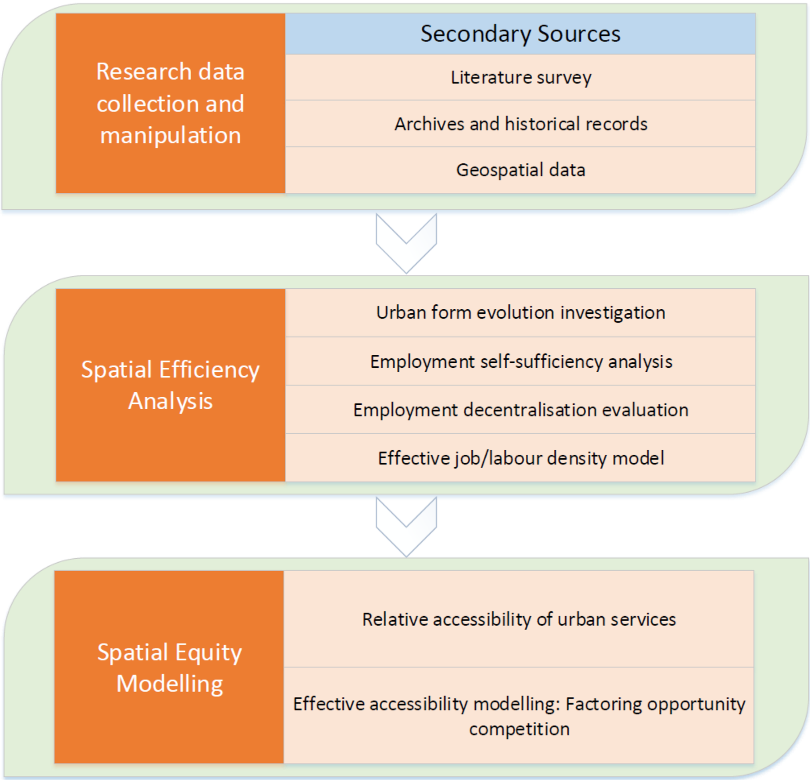


Figure 3.3: Research workflow

- Research data collection and collation

The first step in carrying out this research entailed a search and collection of the relevant data from various sources. The study made use of secondary data from state records and literature, planning reports and model data for transport and land use planning. Full details of the research data relied upon in this research are provided next in section 3.5.

- Spatial efficiency analysis

The spatial efficiency analysis aimed to evaluate the urban spatial structure with respect to urban footprint management (morphological perspective) and day-to-day performance or functionality based on travel patterns (functional perspective). Functional spatial efficiency was determined under three categories: employment self-sufficiency indices, projected employment distribution (decentralisation policy) and using a modified effective density-based measure (estimating potential agglomeration externalities). Details of the spatial efficiency analysis can be found in section 3.6 and chapters 4 to 7.

- Spatial equity modelling

Spatial equity modelling aims to determine the differences between supply levels of various services within an urban spatial structure. An accessibility measure is used to determine the relative spatial equity for each urban service, determined firstly, based primarily on the spatial variations and then with an addition of a competition component. A total of five urban services are investigated for relative spatial equity. Details of the spatial equity modelling are provided in section 3.7 and chapters 8 and 9.

3.5 RESEARCH DATA

3.5.1 Strategic transport evaluation model (STEM) data

A major component of the data used in this research is the trip and travel time data extracted from the Strategic Transport Evaluation Model (STEM) (Department of Transport, 2011). STEM is a macroscopic/strategic level multi-modal model of Perth's land use and transport systems developed and run by the Department of Transport. The model was developed based on trip data from the 2006 Perth and Regions Travel Survey, but has been updated to 2011 using the census journey-to-work data collected by the Australian Bureau of Statistics (Australian Bureau of Statistics). It divides the metropolitan region into 472 zones (marked by the small line divisions in Figure 3.1), and estimates the number of trips between these zones for various purposes (e.g. work, education, shopping) and by different travel modes (e.g. PT, car, walk, cycle). Model outputs include average travel times between each origin-destination zone pair by public transport and by car at four time periods: morning peak, daytime between the peaks (or off-peak), PM/afternoon peak and evening/night-time period. PT times include walking to the stop/station, waiting and transfer times. Car times include a park and walk component.

In this research, it is assumed that trips to work and school are made in the morning, and trips to other services such as shopping and health care are made in the daytime after the morning peak period. Therefore, morning peak travel times are used for all analysis focusing on employment and education, and daytime travel times are used for other travel purposes. Other elements of the data that are relevant to this research are, for each zone, number of residents, people in the labour force and school age children, number of jobs by industry type and number of enrolments in primary, secondary and tertiary education institutions. The number of opportunities available to each zone were determined based on the following. Total employment numbers were used to represent job opportunities and number of enrolments to represent education opportunities at the various levels. For health this research used the number of health jobs as a proxy for health care facilities/services/opportunities, and for shopping, retail jobs were used as a proxy for shopping facilities.

The competition for respective services was derived from the number of people constituting the demand demographic for each service i.e. the demand/competition for jobs was represented by the labour force – consisting employed and unemployed people, demand for primary/secondary education was represented by number of school-age children (5 – 18 years), while the total population was used as demand for shopping opportunities.

- Validity and reliability of STEM data

The STEM model is a multi million dollar model that has been developed over a period of more than 20 years. It has been used extensively to plan and assess major land use policies including Future Perth , Directions 2031 and Perth and Peel @ 3.5 Million. It has also been used to plan, design and assess major public transport proposals including the Mandurah rail line, the MAX light rail and the airport railway. Output from STEM was used to undertake the economic assessment of these projects and to develop their business cases for presentation to state and federal government for approval and funding. Therefore, the STEM model is considered to be fit for purpose for this research, and especially appropriate at the scale of the assessment.

3.5.2 Perth and Peel @ 3.5 Million

Perth and Peel @ 3.5 million is a spatial plan for the PMR that will guide development towards accommodating a population of 3.5 million people. The nominal year by which this landmark is estimated to be achieved is 2050. The plan seeks to accommodate this population through a balance between greenfield and infill developments to consolidate the urban form and attain a sustainable growth approach. To achieve this, it makes projections for population, housing and employment, and indicates how these will be distributed across the subregions. It also sets specific targets for the number of jobs to be located at the various ACs by the end of the plan period. This research uses the plan's current and projected/target employment numbers for the ACs and their respective subregions to investigate potential improvements in job accessibility, spatial equity and travel patterns.

3.6 SPATIAL EFFICIENCY ASSESSMENT

Spatial efficiency was defined in chapter 2 as the geographic organisation of residences, businesses and infrastructure that minimises the cost (distance, effort, time etc.) required for performing economic activities for the whole metropolitan district. Thus, the first step is managing urban footprint expansion – to keep maximum travel distances low and minimise environmental impact particularly in the form of forest land conversion to urban uses. More elaborate ways of measuring and enhancing urban spatial efficiency can also be explored from a functional perspective, pertaining to the interaction of land uses and ease of movement between them. Thus, spatial efficiency in this thesis was addressed in four chapters (4-7); chapter 4 addressed the morphological perspective, chapter 5 focused on self-sufficiency and self-containment of geographic units at a local level, and chapters 6 and 7 dealt with the employment decentralisation to optimise job and labour accessibility and potential for economic agglomeration externalities in the suburbs.

3.6.1 Urban form analysis

Urban form was analysed through investigating the urban footprint evolution since the establishment of Perth as a British colony in 1829. The investigation focused on three key aspects in sequential steps:

Step 1: Developing and deconstructing the timeline

A timeline of development milestones was built up under the themes of planning policy framework, transport developments, economic developments and land/other infrastructure developments. The timeline was deconstructed with the main focus on understanding how the major transport milestones – amid the influence of economic development and planning regulation – impacted on the land use development of Perth. Thus, transport developments were further divided into two timelines of road and rail developments. The deconstruction of the timelines provides a cross-section inspection of the timelines to deduce influences on land developments i.e. how transport development, economic development and planning regulations influenced the pattern of urban expansion.

Step 2: Tracking the milestones of transport evolution

As a key focus of the study, transport development was further explored based on the evolution of key transport modes in Perth and the greater state of Western Australia. The evolution of major travel modes that had a significant impact on the phases of urban expansion involved passenger trams, railway and private cars – in that order. The impact of each of these on the pattern of urban growth was analysed.

Step 3: Assessing the pattern of urban form evolution

While the time scope of study started from the point of the colony's establishment in the early 19th century, the footprint was studied only from the beginning of the 20th century (1901) due to data limitations. Urban footprint maps for the first half of the century (1901, 1915 and 1945) were sourced and analysed from the city's first ever regional plan (i.e. G. Stephenson and J. A. Hepburn (1955)). From the latter half of the 20th century onwards, the Metropolitan Region Scheme (MRS) provided a rich source of information of not only the urban footprint, but all the various land use categories within the entire metropolitan area. This rich history enabled a further analysis of the land use changes during the MRS years (1963, 1971, 1992, 2002, 2012 and 2016), which were discussed under the categories of urban land, industrial, parks/recreational, rural and state forest land. The amount and rate of change were determined in quantitative terms.

3.6.2 Employment self-sufficiency analysis

The employment self-sufficiency analysis evaluates spatial efficiency through three related employment indices: job-worker balance (JWB), employment self-sufficiency (ESS) and employment self-containment (ESC), and their impact on commuting time. The level of each index was determined at a zonal level, and their influence on commuting time was determined using statistical correlation tests.

The indices were computed using trip data generated from the Department of Transport's strategic transport model (STEM). Since a key emphasise of the employment self-sufficiency indices is on the relation between job and residence locations, the focus for this analysis was directed to home-based work trips i.e. only trips made from home to work were considered (STEM has various trips purposes such as education, shopping and health care). The AM peak period origin-destination (OD) trip matrix from STEM was used with the assumption that the origin represented the home end and the destination the work end. In practice, some workers, e.g. nightshift workers, would be returning home from work in the AM peak and the trip "origin" would in those cases be the work end and the "destination" the home end. Nevertheless, the vast majority of AM work trips would be home to work and the resulting indices should be broadly representative of the actual commuting patterns. The process of computing the indices and their relationship with travel time is described next.

- **Job-worker balance**

JWB evaluates the numerical balance between the number of jobs in a zone and the number of workers that live in that zone (its resident workers). It was determined by the total of all work trips coming into a zone (inflow) plus the intrazonal trips (intra) divided by the total of all trips leaving a zone (outflow) plus intrazonal trips (intra). The sum of inflow and intra trips (the numerator) represents the number of jobs located in the target zone, while the sum of outflow and intra trips (the denominator) represents the number of workers residing in the zone. If the JWB index is more than 1, the zone is job-dominated. If the JWB is less than 1, the zone is residence-dominated. This means a balanced zone should have a JWB index of 1. In this study, balanced was deemed to be in the range of 0.8 – 1.2, less than 0.8 was considered residential dominance and more than 1.2 job dominance.

- **Employment self-sufficiency**

Employment self-sufficiency evaluates the proportion of jobs filled by local residents, and reflects the level of inward commuting. It was computed by dividing the number of internal zone work trips (intra) by the sum of inflow work trips and intra trips. A higher ESS ratio means more work travel within the zone and less travel from outside into the zone. For example, an ESS measure of 85% means that 85% of jobs are filled locally, and the remaining 15% are filled by non-resident workers who then have to commute into the area.

- **Employment self-containment**

Employment self-containment focuses on the workers (as opposed to jobs) and measures the proportion of workers that work within the zone. It is the appropriate measure for cases or zones where the objective is to reduce outward travel. In this study, it was determined by computing the ratio of internal trips to the sum of outflow and internal trips. Thus, the higher the ESC ratio the more zone residents work locally – and as such, fewer outbound work trips.

Relationship with travel time

The three indices discussed above are dependent solely on the number of trips crossing a zone boundary, and take no account of the length of such trips. A high number of trips crossing the zone boundary would result in a poor/low index even if the majority of those trips are actually shorter than many internal trips. This can make the commuting situation look worse than it actually is. This issue is also directly related to the Modifiable Areal Unit Problem (MAUP), as changing the zone sizes, or selecting a different zone system, could significantly influence the results, even though the underlying spatial pattern of resident workers and jobs remains unchanged.

The sufficiency of the indices was tested through comparison with modelled travel times between the zones across the metropolitan area. Average work trip travel times from STEM, aggregated by all travel modes, were computed for each zone – both inflow and outflow travel times. The inflow travel time of a zone was determined by averaging the work travel times from all zones within the metropolitan region into that zone. Outflow travel time was determined by the average travel times from a given zone to all other zones within the metropolitan region. Then, a statistical correlation test was performed between each index and the averaged travel times. Note that JWB relates to both inflow and outflow travel times, but ESS has a bearing on inflow travel time only while ESC only relates to outflow travel time. Thus, the correlation test was performed between JWB and both inflow and outflow travel times, between ESS and inflow travel time, and between ESC and outflow travel time.

3.6.3 Employment decentralisation evaluation

Perth is currently in the middle of an employment decentralisation agenda, where the objective is to increase the number of jobs located in suburban activity centres (ACs) to reduce long commuting, particularly into the city centre. A hierarchy of ACs has been developed, but interestingly, no primary centre(s) – which is the next tier below the central business district – has been identified among either existing or future ACs. The plan only states that some strategic centres are expected to develop into primary centres. It, therefore, remains unclear how these centres will be identified and/or prioritised for development into the higher primary centre tier. Thus, this study evaluated strategic centres for their potential and suitability to develop into the level of primary AC, and established their relative ranks to aid prioritisation/order of their development in the short-to-medium term.

This evaluation was performed using two indicators: density and accessibility. The task was performed using two slightly different approaches, presented in chapters 6 and 7. Chapter 6 identified the catchment areas of selected strategic ACs and determined their worker densities. It also investigated potential job accessibility improvements from policy employment targets, and as such, the sufficiency of the targets. Chapter 7 proposed an effective density-based measure to replace accessibility measures in evaluating ACs for development prioritisation.

Density and accessibility for optimising employment decentralisation

It could be argued that in many cases, high density is a sign of good accessibility, as more people are attracted to places with good transport connections. However, even though density can be a factor of accessibility, they are not always correlated. There are some areas that have high accessibility but low density, while others may have high density but low accessibility. Identifying these discrepancies is important to planners, and the coincidence of high accessibility and high density presents good potential for AC location/development (Figure 3.4). On the other hand, high accessibility with low density shows opportunity for densification, and high density with low accessibility shows that transport improvements are needed. Therefore, both density and accessibility are important indicators of a potential

AC location.

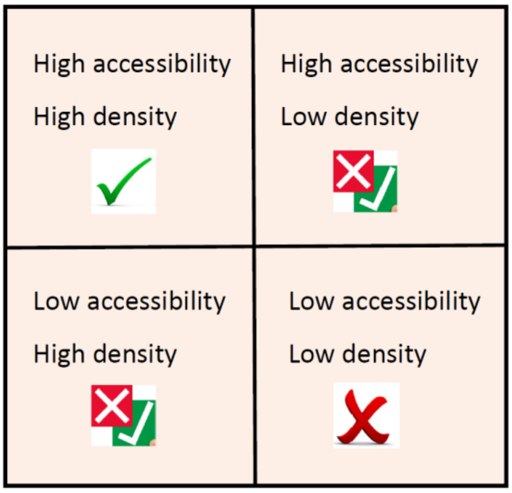


Figure 3.4: Accessibility-density framework for guiding employment decentralisation

This task was performed in three major steps:

<u>Step 1:</u> Activity centre selection

A pre-analysis assessment of the ACs was undertaken and a selection of four centres were identified based on their locational characteristics. The selection criteria included being:

- outside the central subregion
- distant from the city centre (CBD)
- connected to the rail network
- evenly distributed: two centres were north of CBD and the other two were south. Two were along the north-south transport corridor, while other two were on the city's eastern edge.

<u>Step 2:</u> Catchment area delineation

A catchment area of an AC denotes the area in which the centre can be reached within a given travel time threshold. Catchment areas of the selected centres were determined based on public transport and car travel times. For car travel, the catchment area was set within a travel time threshold of 30 min. This means all zones from which the AC could be reached within 30 min by car were considered to be within the catchment area. For public transport travel, the threshold was set higher at 45 min. The reason for a higher public transport threshold is that there were hardly any zones within a 30-min public transport catchment. The catchment areas for each of the four selected centres, by both car and public transport, were visualised in maps produced in ArcGIS.

Step 3: Worker density calculation

Once the catchment areas were delineated, the density of workers within each catchment area was calculated. The number of workers residing in each zone was obtained from the model (STEM), and the area of zones (and the catchment areas) were computed using ArcGIS.

Step 4: Job accessibility analysis

Job accessibility – defined as the number of job opportunities that can be reached within a given travel time threshold – was calculated for all zones in the metropolitan region. Then, the employment targets for all ACs were added to the existing job numbers, and job accessibility was recalculated. This provides an indication of the level and pattern of job accessibility (and the improvements) that can be expected in 2050 (the nominal year of the plan). The travel time threshold of 30 min was used, and since the main interest was on comparing current and future accessibility, the analysis was only based on car travel times (the most efficient mode of travel in the Perth metropolitan region). Both results (current and future) were mapped to enable visual interpretation and comparison.

Once job accessibility for the whole metropolitan area was determined, the strategic ACs were extracted into an ordered table, based on their relative accessibility levels. The job accessibility of ACs is important because they are planned to host a high number (and high density) of residents, alongside the high number of jobs and a diversity of other services. Thus, it is important to understand the level of job accessibility for those people living in the ACs. The strategic centres were compared based on their current and future/expected job accessibility levels, with a particular focus on the four selected centres.

Effective density analysis of activity centres

An effective density-based measure was compared with and proposed over the cumulative opportunities accessibility measure in evaluating and deciding prioritisation of ACs. In this task, labour/worker accessibility was included in the analysis, in addition to the job accessibility as described above. Likewise, labour accessibility was defined as the number of workers that can reach a given zone, from their home zone, within the specified travel time threshold. Both private car and public transport modes were considered, and their thresholds were again set as 30 min and 45 min, respectively. All the ten strategic centres in the metropolitan region were ranked according to their accessibility scores. The rankings were divided into four categories: job accessibility by both car and PT, and labour accessibility by car and PT.

The next step was to develop an effective density-based measure to perform a similar ranking to the above, and compare the results to the accessibility rankings. The effective density-based measure was based on Graham's (2007) effective density model, and is used to estimate the potential for agglomeration benefits available at any given business location. It combines a proximity/transport component, (accounted for in the accessibility measure), and a scale/size component, (not accounted for in the accessibility measure). In this study, the effective density measure was modified by replacing distance with network travel times, weighted by a gravity-like decay function. Travel time was applied both for travel between the zones as well as for internal travel within a zone – based on STEM's estimation of intrazonal travel times. The scale component was also more accurately determined by the calculation of job/worker densities using the actual area of a zone. Effective density results were produced for the whole metropolitan region and mapped for visual interpretation. Strategic centres were extracted from the results into ordered/ranked tables, from highest to lowest effective density. Results were categorised into a) effective job density by car, b) by PT, c) effective labour density by car, and d) by PT. Finally, results were compared to respective categories in the accessibility rankings to establish any consistencies, or lack thereof.

3.7 SPATIAL EQUITY ANALYSIS

The spatial equity analysis in this thesis was conducted using a measure of accessibility, or the ease of reaching destinations. Accessibility is increasingly used in transport and land use planning to operationalise integration of the two concepts, and as an indicator of their performance (Boisjoly & El-Geneidy, 2017; Deboosere & El-Geneidy, 2018). It has also been employed in metropolitan plans either as an independent objective, or as part of an equity assessment (New South Wales Government, 2013; SEAGRIFF, 2007; Western Australian Planning Commission, 2018). As a measure of the interaction between land use and transportation (Susan L Handy & Debbie A Niemeier, 1997), accessibility can indicate the ability of people to participate in various activities coming from different locations (spatial (horizontal) equity) or socio-economic groups (vertical equity) (Deboosere & El-Geneidy, 2018).

In this thesis, the cumulative opportunities measure of accessibility (COM) was used as a measure of spatial equity. The COM determines accessibility by summing up the number of all opportunities that can be reached from a zone within a specified travel time threshold. The measure makes two important assumptions: (i) people prefer to have as wide a choice of opportunities as possible (Doi & Kii, 2012), and (ii) travel time limits the extent to which this can be achieved. Thus, spatial equity was interpreted based on the spatial variations in the level of accessibility to urban services, by a given travel mode. Two major approaches were employed: 1) a standard cumulative opportunities measure was applied to a list of five urban services (jobs, primary/secondary education, tertiary education, shopping and health care), and their accessibility levels and spatial patterns were compared. Comparisons were made between the services, and between car and PT for the accessibility of each service (chapter 8). 2) a competition component was incorporated into the cumulative opportunities measure, and the accessibility of three key services was analysed and compared (jobs, primary/secondary education and shopping) (chapter 9).

- **Relative accessibility analysis using the cumulative opportunities measure**

The spatial equity of five urban services was determined based on the number of opportunities that could be reached from each zone within a specified travel time threshold. Job opportunities were represented by the total number of jobs in each zone, number of school enrolments was used to represent education opportunities, number of retail jobs was used as a proxy for shopping opportunities and health jobs as a proxy for health services. It was assumed that all work and education trips were made in the morning, thus average morning/AM peak travel times were used for job, primary/secondary education and tertiary education accessibility. Shopping and health care trips were assumed to be made later, i.e. after the morning peak, so day-time off-peak travel times were used for these two services. In terms of travel time thresholds, 30 min was used for jobs and tertiary education, informed by both literature and relevant policy objectives. Primary/secondary education, shopping and health care were assumed to be more local services, and hence a lower threshold of 15 min was applied to them.

- **Analysing the effect of competition in the cumulative opportunities measure**

While the cumulative opportunities measure is widely used across the policy and research communities, it is often criticised for its relatively limited accuracy compared to other more complex accessibility measures. One of these limitations is the lack of consideration of the impact of competition on the availability of the reachable opportunities. On the other hand, evidence from the literature has shown that accessibility measures that are simpler and easier to interpret are more likely to be adopted and applied in practice by planners and policy makers. Indeed, this is the major reason behind the popularity of the cumulative opportunities measure. In this part of the research, the aim was to investigate spatial equity using a cumulative opportunities measure that incorporates a competition component in order to improve the accuracy of the measure while keeping it simple and easy to interpret.

The process for calculating accessibility at each zone can be summed up in a few steps:

- Find all the zones that can be reached from zone *i* within the threshold time (zones *j*),
- For each zone *j*, divide the total opportunities in it by the sum of people that can reach it within the threshold time (people coming from other competing zones, *k*).
- Sum the results to find the accessibility of zone *i*.

The analysis was performed based on car travel, PT travel, and a combination of both modes. This assumes that, for car travel, all people have access to and use a car for accessing the opportunities, meaning they face competition only from people also travelling by car. Likewise, for PT it was assumed that everyone travels by PT and face competition only from other PT users. The main results, and indeed the most realistic, combined the travel modes allowing for opportunities to be accessed either by car or PT. Similarly, the competition for opportunities was from other people travelling by either car or PT. This means the opportunities were deemed accessible if they can be reached by either of the two travel modes. Results of this task were compared to those obtained without considering competition in the cumulative opportunities measure, and implications on spatial equity were discussed.

3.8 SOFTWARE

3.8.1 GIS software

The main software used for the data processing, spatial data analysis and map design was ArcGIS 10.4 (Esri, 2016). The spatial data was stored in Esri geodatabases and shapefiles.

3.8.2 Programming software

Python programming language was used to prepare, analyse and run computations on the big data (STEM data) used in this research.

3.9 CHAPTER SUMMARY

This chapter established the research framework and presented an overview of the methodology for the evaluation of spatial efficiency and spatial equity of urban spatial structure. The chapter started with providing a description of the study area, on which the developed research framework was implemented. The theoretical framework guiding the research was also described. The research workflow entailed a detailed description of the data, and a systematic description of the key steps and methods employed to achieve the research's individual tasks. The chapter ended with a brief description of the software used in the research.

The next chapter will present the first set of results addressing the project's first objective. It will present and deconstruct a timeline of development milestones in Perth since being established as a British colony in 1829. The influence of transport developments on the evolution of Perth's urban form over the last two centuries is looked at more closely, and urban footprint changes over the last five decades are quantified.

CHAPTER 4 URBAN FORM EVOLUTION

This chapter consists of research that has been published in Kelobonye, Xia, et al. (2019b).

4.1 INTRODUCTION

The previous chapter presented the methodological framework for the investigation and evaluation of urban spatial structure. An essential part of understanding urban spatial structure is to understand its historical evolution. Therefore, this chapter provides a historical review and background of Perth Metropolitan Region. It focuses on understanding spatial efficiency from a morphological perspective, and investigates the urban form evolution of Perth and its response to key developmental milestones in transportation, economy and planning policy framework. The chapter investigates, more closely, the role played by transport developments in the expansion of Perth's urban footprint.

The analysis starts by developing and deconstructing a timeline of the key developmental milestones. An overview of the eras of transport evolution is provided, and the pattern of urban form changes as they relate to these transport advancements are discussed. The chapter ends by mapping and quantifying changes in Perth's urban land over the past five decades.

4.2 RESEARCH CONTEXT

Low-density suburbanisation has been the dominant trend of urban growth in major cities in the US, Canada and Australia since the end of WWII (Glaeser & Kahn, 2003; Goetz, 2013). In addition to a general world population increase, urban areas in particular are expected to house about two thirds (66%) of the world's population by 2050 (United Nations Department of Economic and Social Affairs Population Division, 2014). The effects of urbanisation on the environment around the world have become a major concern (Osman et al., 2016). Urban expansion is one of the major causes of natural ecosystem degradation (Lawler et al., 2014) as it displaces natural land cover and destroys natural habitats (Sumarga & Hein, 2014; Swetnam et al., 2011). By removing vegetation, these changes reduce the rate of atmospheric carbon dioxide sequestration (Metzger, Rounsevell, Acosta-Michlik, Leemans, & Schröter, 2006) and the cooling effect provided by vegetation to the atmosphere, resulting in the urban heat island effect (Wong & Yu, 2005; H. Wu, Ye, Shi, & Clarke, 2014), among other problems. In many cases, urban expansion has exacerbated spatial inequalities as amenities often remain concentrated in the central areas. It results in job-worker imbalances which are a significant contributor to long commuting distances and reliance on unsustainable travel modes (Cervero, Rood, & Appleyard, 1999; Levinson, 1998).

The pace and trajectory of urban expansion is driven by many external factors, which can either constrain the expansion or facilitate it into urban sprawl. Urban sprawl is often the physical outcome of urbanisation, and is usually the term used to denote unsustainable urban expansion (Osman et al., 2016). The phenomenon of urban sprawl/expansion has been discussed extensively in the literature. Several studies have also investigated forces that affect urban growth and shape the urban form, however, this is neither uniform nor constant. Catalán, Saurí, and Serra (2008) assert that the study of urban form "must be approached and understood taking into account specific geographical and historical contexts in which particular urban forms shape cities" (p. 174). A polarisation of case studies on North American urban expansion and transitional urban patterns of some European cities (e.g. Barcelona and Athens) is noted in the literature. An overwhelming amount of studies ascribes sprawling largely to increasing automobile usage and road network expansions (Bhatta, 2010; Ewing, Tian, & Lyons, 2018; Knaap, Song, Ewing, & Clifton, 2005; Rubiera Morollón, González Marroquin, & Pérez Rivero, 2016; P. Zhao, 2010). Also evident in the literature is the wealth of theoretical discussion highlighting the debate between compact and dispersed urban forms. There is limited study on the evolution of dispersed urban form in different contexts outside these trends. Studies of urban growth drivers interwoven along the trajectory of city development are imperative.

Perth presents a good opportunity to study the pattern of expansion in post-colonial cities. The evolutionary journey of Perth from a small colonial town of 1829 to a modern metropolis has attracted the interest of urban scientists due to its rapid and dispersed suburbanisation that made it one of the most sprawling cities in the world (see, among others, Alexander and McManus (1992); Alexander, Greive, and Hedgcock (2010); Falconer, Newman, and Giles-Corti (2010) Curtis and Mellor (2011b) and Troy (2012)). In 1970, the Perth Metropolitan Region (PMR) contained 0.7 million people in about 500 km^2 of area. While the population was twice as much in 2005, the footprint area, on the other hand, had more than doubled (T. Adams, 2010). In 2015, the population within the PMR was 2.04 million, which amounted to 79% of the total Western Australian population. The highest population growth in the state happened in Perth's outer suburbs (Australian Bureau of Statistics, 2016). The metropolitan area of Perth now spans more than 100 km from north to south. The city recorded a maximum density of just 3600 people per km^2 in 2015 (Holt, 2013). Today, Perth (with just about 2 million people) has a larger area (1566 km^2) than some of the older and most populated cities in the world including Hong Kong (285 km^2 for 7.3 million people), Madrid (1321 km^2 for 6.2 million people) and Istanbul (1360 km^2 for 13.8 million over) (Demographia, 2017).

Studies have identified transport as a major driver of urban growth (Antrop, 2000; Bhatta, 2010; Tan et al., 2014; H. Wu et al., 2014). In Perth, the state government has invested significantly in transport infrastructure over the years. As Alexander and McManus (1992) describe it, “Perth laid out freeways like red carpet to welcome the automobile” (p. 6). The city has also, to date, invested in about 180 km of heavy rail across five passenger lines—plus one currently under construction to the airport, all of which run electric trains. These investments facilitated the city’s expansion, as they alleviated the effects of living further from the city centre (Curtis & Mellor, 2011b). Undoubtedly, economic development also plays a fundamental role in driving urban expansion (Bhatta, 2010; L.-c. Zhang, Zhu, & Yao, 2005; Q. Zhang & Su, 2016; T. Zhang, Sun, & Li, 2017). In addition to making transport investments possible, the associated improving quality of life enables families to cope with longer distance commutes. These infrastructure (and other urban development) expansions occur under a system of planning regulations that evolves over time. As it rezones and releases land for development, the planning framework directly influences the pattern (shape, direction and pace) of how the urban form evolves. The planning framework in Perth has applied different philosophies over the years. At one point expansion from the city centre was encouraged (Culpeffer-Cooke, Gunzburg, Pleydell, Brown, & Society, 2010) and now the policies are advocating limiting future expansion outside the current urban footprint for a compact urban form (Western Australian Planning Commission, 2018).

This chapter investigates the role of transport developments in driving urban form change in the PMR. Given that transport is also influenced by other factors, and the importance of the combinations of these factors (Q. Zhang & Su, 2016), the analysis starts by relating past transport developments to economic milestones and planning framework. Thus, the study identifies the major milestones under the broad themes of transport, economic development and planning framework that happened in the state since British colonisation, and develops and deconstructs their timelines in relation to land development. The analysis advances into a focus on the interaction between transport and urban growth. The chapter ends by mapping and quantifying changes in urban land over the past five decades.

Data

A large part of the information in this chapter is a product of reviewing historical literature on Perth and the state of Western Australia (WA). Government publications, museum archives, population data and academic articles have been reviewed and analysed to understand and examine the growth of Perth and develop a timeline of milestones. The WA Department of Planning provided copies of the PMR statutory plans and historic Metropolitan Region Scheme (MRS) data for the years 1963, 1971, 1992, 2002, 2012 and 2016 (the MRS is a statutory plan of broad land zones for future development in Perth).

Study Area

The study areas for this research was described in detail in section 3.2. In this chapter, however, there are some key mining towns and railway lines which were instrumental in the development of Perth but outside its metropolitan area. These are presented in Figure 4.1, along with geographical location of Perth – which happens to be the nation’s most isolated city. The metropolitan region of Perth consists of 30 Local Government Areas (LGAs) – depicted by the subdivision lines within the PMR map – that roll out detailed planning within their areas in conformity with the MRS zoning.

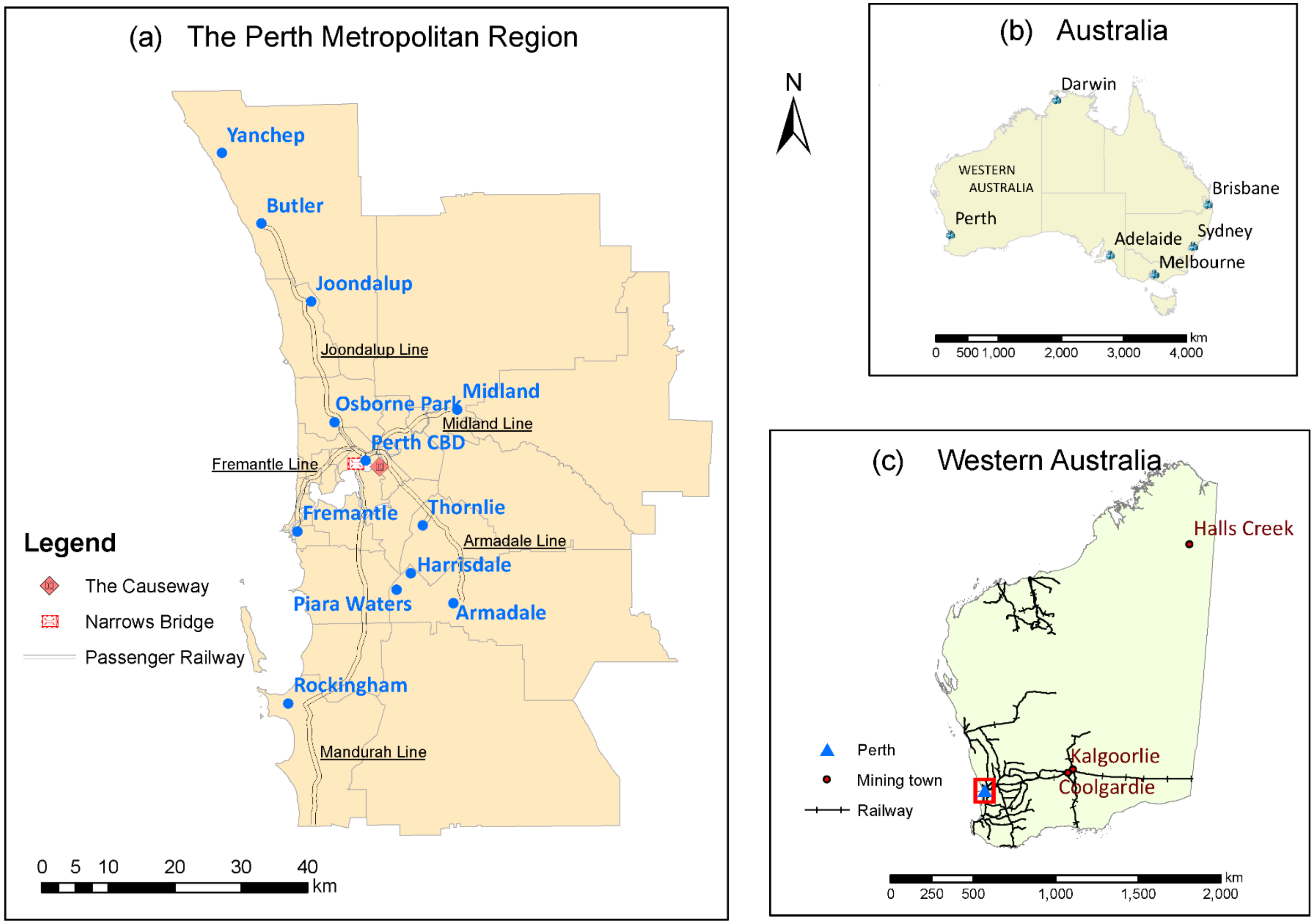


Figure 4.1: (a) The Perth Metropolitan Region. (b) Geographic location of Australia's major cities. (c) Locations of key mining towns in Western Australia.

4.3 DECONSTRUCTING THE TIMELINES OF CITY DEVELOPMENT

Perth is a relatively young city that was founded under two centuries ago, in 1829. From its inception, Perth was a miniscule colony of two small settlement points, one at the mouth of the Swan River in Fremantle and the other on the northern bank of the river about 15 kilometres upstream at the present-day Perth Central Business District (CBD) (see Figure 4.1a). In its earlier years, the colony had limited planning regulation that mainly provided for current needs with little projection inputs. From the 1950s, planners sought "to accommodate economic growth and the Australian suburban dream of home and car ownership" (Martinus & Biermann, 2016a, p. 1). Perth is ranked among the least dense cities in the world, having an urban footprint that has become larger than many bigger (by population) cities within a much shorter period (Demographia, 2017). With its metropolitan population expected to increase by an additional one million people within the next two decades (Australian Bureau of Statistics (ABS), 2013), it is necessary to understand the region-specific factors that will influence Perth's future urban form.

In this regard, the study proposes to deconstruct city development milestones from 1829 (when Perth was founded as a British colony) up to 2016. It borrows the definition of 'deconstruction' from Dear (1986), who refers to it as historicising the growth of a city looking through physical factors including transport and other infrastructural development, economic shifts and land use planning. This study contends that a timeline analysis can be effectively utilised to understand how the major transport milestones – amid the influence of economic development and planning regulation – impacted on land use development of Perth. Figure 4.2 presents a timeline of developments under four themes, viz. planning framework, transport developments, economic milestones (in the State) and the resultant land use developments. Transport developments, as a focus of the study, are divided into two timelines to distinguish between rail and road developments. A State population graph is also superimposed across the timelines, which enables for a cross-comparison of the milestones against population growth.

It is important to note that given the breadth of the period, it would be impossible to include all events in the timeline. While the study attempts to identify the most prominent events within the theoretical scope of this study, Dear (1986) warns that such historical interpretations are often shaped by idiosyncrasies of the observer and the observed.

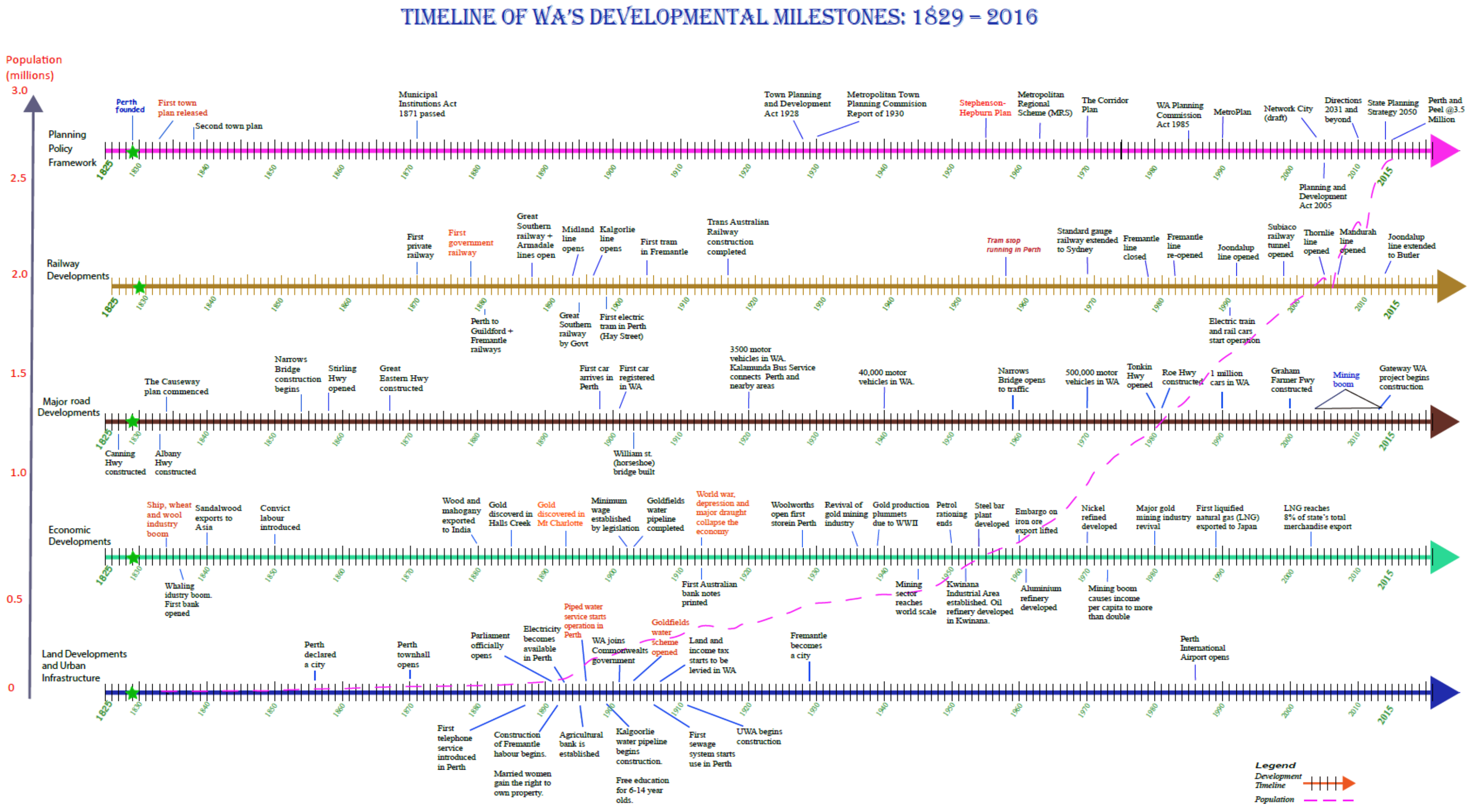


Figure 4.2: Timelines of major events/developments in the history of Perth. Source: Made by author.

The first timeline tracks the evolution of the planning framework by highlighting the release of key planning documents. The two transport timelines trace the introduction of major roads and railways connecting areas within WA and other states across the country. Economic developments denote major economic activities in the colony/state impacting on general development such as industrial boom, mineral discovery or flagship policies for major economic restructuring. The last timeline shows major land and other infrastructure developments which ensued from the influence of transport developments, economic milestones and/or planning regulations.

A cross-section inspection of the timelines reveals that the construction of transport infrastructure significantly contributed to urban land development. The trend was spread out through the spectrum of time, with some of the most significant highways constructed in the early to mid-nineteenth century (1827–1858), while the recent constructions were in the late twentieth century (from the 1980s). Nonetheless, the period between the late 1800s and early 1900s was rather dormant in terms of major road/highway construction. Ironically this is the period during which the private automobile arrived and multiplied in numbers in the state. According to the Revolutions Transport Museum, the number of motor vehicles on the state roads grew from 3500 in the 1920s to 500,000 in the 1970s. This number had doubled just 20 years later, reaching the million mark in the 1990s. This trend is consistent with the high rate of urban expansion in the late twentieth century, which is reflective of easier commuting ability between suburbs and the city centre.

The first major roads of the state predated railway lines, the first of which was only constructed in the latter half of the nineteenth century (1871). This railway was constructed by a private company, out of timber. Interestingly, the trough of dormancy in the major roads timeline coincides with an upsurge of railway constructions. Some of the key rail links with surrounding urban centres and major towns were established in the late nineteenth century. The trains were mixed (freight and passengers), with passenger trains mainly within the urban areas. The railway construction industry, too, had a dormant period. In 1992, the opening of Joondalup Line connecting the northern suburbs to the city centre appeared as a breakthrough after almost 100 years. This somewhat marked the resurrection of rail in the state, as the southeast suburbs were connected through Thornlie Line just 12 years later. About three years after that, a major urban centre in the south was linked through Mandurah Line at the end of 2007. In 2014 the Joondalup line was extended along the northern coast to follow the prolonged suburban sprawl- the Butler extension.

The early stage of railway development was enabled by the state's economic boom. From its establishment, the state had a shaky economy that could not propel a steady development. The discovery of gold in Halls Creek, Coolgardie and Mt Charlotte (in 1885, 1892 and 1893 respectively), commonly referred to as the gold rush, changed the fate of the state forever (GoldOz, 2017). It transformed it from a poor, sparsely populated desert colony to a mineral-rich economy. The gold era is credited for being the major enabler of the first '*railway construction period*' in the state. It certainly played a large part in the growth of household incomes, to which the rise of motor vehicle numbers can be ascribed. A lot of other land use and planned developments also came after the gold rush. This is despite the fact that Perth was declared a city in 1856, 30 years before the Halls Creek gold discovery.

Impacts from the First World War, Great (economic) Depression (1929–1930) and drought are also evident across the timelines. The war led to a collapse of the economy, and no new infrastructural projects were undertaken during the war and immediate post-war period. As a result, all major land use developments were halted.

The juxtaposed timelines clearly demonstrate the resulting impacts of organised planning efforts, transport infrastructure and economic developments on urban expansion during the city's history. There were very few planning interventions observed in the early years. The colony's establishment in 1829 followed Sir James Stirling's (first Governor of WA) survey two years prior, and his consequent persistence and exaggerated description of the soil fertility in the area (State Library of Western Australia, 2010). The beauty of the landscape, freshwater springs, fertile soils and availability of building materials proclaimed by Stirling (and supported by gardener and colonial botanist, Charles Frazer) were some of the factors that led to the colony's establishment, and attracted people to the area. No prior arrangement had been made to establish a colony, so the settlement was laid out hastily upon arrival of the first settlers (Crowley, 1967). Despite the expedited establishment, growth thereafter was very slow due to low population growth and highly limited public investment.

With the introduction of convict labour in 1850, a few road and land developments occurred. Later, the gold rush triggered the need, and provided the means, to invest in port development (e.g., Fremantle harbour) and establish rail networks between key economic centres. The resource boom also brought other land development measures and urban services (e.g., piped water supply and sewage system) to support the increasing population. The city experienced a slow and steady population growth, resulting in expansion of the urban footprint. This growth justified investment in tram transport which led to the introduction of electric trams in Perth (1899) and the first tram operating in Fremantle (1905) to facilitate travel particularly for the outlying suburb residents commuting to the city centre.

The first official regional plan for the PMR was released in 1955, which was followed by gazetting statutory land use zones in 1963, known as the Metropolitan Region Scheme (MRS). Subsequent regional plans followed in 1970 (the *Corridor Plan*) and 1990 (*MetroPlan*). It is important to note that while the direction of development generally adhered to these statutory documents, a significant amount of development still happened outside of the identified growth areas. For instance, T. Adams (2010) noted that by 1990 "urban zoned land had indeed spread into these corridors [of the 1970 Corridor Plan]; as well as into many other areas which had not been identified for urban growth potential" (p. 39).

The state population graph communicates another interesting piece of information when juxtaposed against the timelines (Figure 4.2). A population growth rate of 27% was recorded between 1849 and 1850, the same year in which convict labour was introduced in the colony. The population trend line shows that a significant leap occurred between the late 1880s and early 1890s. A spikes check (Trewin, 2012) revealed that a more than 20% yearly growth was recorded between 1894 and 1896. It is evident that the gold rush significantly contributed in population growth during this period. The availability of electricity, piped water supply and improved links with mining towns are equally considered to have attracted more people in the city in the early 1890s. The growing trend was, however, disrupted in the early 1910s, causing a declining trend until the end of the decade roughly due to the WWI. The recent mining boom of the twenty-first century (2003/04-2013/14) also had a big effect in the state's population growth. The highest growth was seen during this period, albeit with some fluctuations.

4.4 MILESTONES OF TRANSPORT EVOLUTION IN PERTH

4.4.1 Passenger Trams

Tramways are an integral component of the beginnings of the public transport era in Perth, having serviced the people for a period of nearly 60 years. Tram lines allowed Perth to grow from a small riverside colony into an urban centre surrounded by expanding residential suburbs; people could live further from the centre as the trams allowed them to commute further and more quickly. The worldwide trend was that as cities grew larger the options to live close to the centre diminished, forcing more and more people to live further away.

Since city centres were the largest employment areas, there was a dire need for a cheap and fast way to travel between homes and work on a daily basis. These developments happened during an era when railway construction was at a peak, and so it is no surprise that the mainline railway emerged as the first solution. The train, however, had several disadvantages, which included high level of investment, distance from residential streets, as well as spacing between stations, which meant that it could only serve a portion of the population. Other public transport systems that could provide more flexible travel within the suburban streets and the city were needed. Horse-drawn buses and trams had horse-related disadvantages such as their maintenance and the unpleasant excretions they left on the streets. Steam trams provided a more powerful alternative and solution to the horse-based systems, but they were noisy, smoky and steamy, thus incompatible with residential houses – or even other road traffic. Cable trams posed solutions, while, just as the other systems, introducing new problems of their own; they had high installation and maintenance costs, plus several operational limitations.

The electric tram provided a solution to the limitations of the cable tram, enabling it to spread and become popular in many big cities across the world. Sydney, Melbourne and Adelaide had well developed steam tramways, cable tramways and horse tramways respectively. Perth, on the other hand, started right off with the electric tram; the electric tram was becoming popular at about the same time as Perth was starting to invest in improving public transport. This was also during a period when the state's population was rapidly expanding due to the 'pull factor' of gold discovery. Tram routes became synonymous with places of residence. While the tram lines were laid along existing house-lined streets, some lines were laid in advance of residential developments in order to influence the direction of suburban growth (Culpeffer-Cooke et al., 2010). Trams were able to directly influence urban growth due to their relatively rigid network and popularity as a major mode of transport of their era, which required people to live fairly close to them.

4.4.2 Railways

The first Government railway was a 53km Geraldton-Northampton link of a copper mine and the port, whose construction started in 1874, and was officially opened in 1879 (State Record Office of Western Australia, 2017). Since then several railway developments occurred, consisting of local metro lines, numerous intra-state tracks and an interstate standard gauge link.

The construction of many of these railways was inspired by the industrial needs (e.g., transportation of agricultural products, iron ore and gold), so trains outside the metro area were mainly mixed and slow for passengers. Passenger trains had a higher significance in the metro area, and this trend has continued into the modern years. The past three decades, for instance, saw high investment in metropolitan rail transport, consisting of the introduction of electric train and rail cars, and the construction of Joondalup Line, Subiaco tunnel (on the Fremantle line), Thornlie and Mandurah Lines (Figure 4.1a). Suburban trains not only provided an important connection with the city centre, they also enabled people to live in the suburbs and enjoy a smoother commute.

4.4.3 Private Cars

Private car usage has increased rapidly and constantly since cars came into the scene in the early twentieth century. The car introduced unprecedented flexibility and convenience in travel, allowing for an extensive urban footprint expansion (Alexander & McManus, 1992). At the same time, the urban expansion reinforced car dependence as driving became the most viable option for travel, particularly the work commute.

The rise in car usage brought along unique challenges that have evolved over the years. Planners were already dealing with traffic problems as early as the early twentieth century. The Metropolitan Town Planning Commission Report of 1930 (*Report of the Metropolitan Town Planning Commission*, 1931) acknowledged two main traffic problems to which it recommended that planning efforts should be directed. These were the provision of greater facilities for crossing both the river and the railway.

The report pointed out that at peak periods the Causeway, which was the sole entrance to the city for the southern and south-eastern suburbs, had approximately as much traffic as the two busiest bridges in Melbourne. While there were calls to divert traffic elsewhere, it was not until about 30 years later that the Narrows Bridge was built (1959), providing an alternative route to the city centre for the southern suburbs. Today, private car is the most dominant mode of transport in Perth and travel times are significantly longer due to congestion (Commonwealth of Australia, 2015). Hence, the general policy objective has gone in the direction of seeking and encouraging alternative travel modes that are more efficient, environmentally friendly and sustainable.

4.5 INTRA-URBAN TRANSPORT AND URBAN GROWTH

Advances in transport have played a major role in shaping the spatial structure of modern cities (Anas, 1998). In the earlier decades of the nineteenth century, cities were closer to canals, rivers and harbours which were the main ways of transportation. Inland, intra-urban transport modes were foot, camel, horse and wagon. These modes were much slower which prompted dwellers to live closer to the city, thus forming a rather confined footprint of developments. The advents of trams and trains (which were much faster and more reliable) in the second half of the nineteenth century allowed for an expansion of the urban form along the tramways and railways.

Even though trains and trams were faster and reliable, they were rigid in timetables, and even more restricting in geographical coverage. This gave the automobile an upper hand when it sprung into the scene in the early twentieth century. The automobile rapidly gained popularity among households, particularly due to its great flexibility and convenience. It changed the patterns of travel to random intra-urban trips. People increasingly started travelling to places out of the city centre and further from tram/train zones, and for purposes other than work such as recreation. Urban expansion, particularly in the form of residential developments, soon became possible as people could live in the outer suburban areas further from the city centre and tramways/railways. Highways and freeways determined the urban form as the car became the dominant mode of transport. The eras of intra-urban transport and urban growth were aptly illustrated by J. S. Adams (1970) for US cities.

The development of Perth followed a similar trend to the eras described above, save for the geographical constraints such as the river and ocean. Earlier developments took place along the Swan River, with most of the settlement being around Perth City, the Fremantle harbour and along the river between the two. The expansion then followed the spine of transport in the form of tramways in the latter and early years of the nineteenth and twentieth centuries, respectively, and freeways in the mid–late twentieth century. This proved a successful influence of growth direction by planners as they laid the backbone of transport infrastructure in areas to which they wished for the city to expand (Culpeffer-Cooke et al., 2010).

4.6 THE PATTERN OF PERTH'S URBAN FORM EVOLUTION

Using information from G Stephenson and J.A Hepburn (1955), Figure 4.3 presents snapshots of Perth's urban footprint in 1901, 1915 and 1942. It is worth noting that the PMR boundary did not, at the time, exist as depicted in the figure, but is provided for purposes of illustration only. Stephenson and Hepburn's efforts were further updated using the MRS zones from 1963 to 2016 in Figure 4.4 (next section). The two figures give us a time series from which we can observe the growth pattern over the last century. Figure 4.3 confirms the confinement of growth to areas around the river in the early years, leading to a jointure of the formerly dis-contiguous colonial centres of Perth and Fremantle. It is also clear that land development (contiguous) was relatively faster on the northern side of the river than on the southern side. It is highly plausible that since the CBD was on the northern side, the river was an access barrier for people on the south, making the northern suburbs more desirable, until the Narrows Bridge was opened in 1959, as there was only one way to access the CBD from southern suburbs i.e. via the Causeway (see Figure 4.1.a).

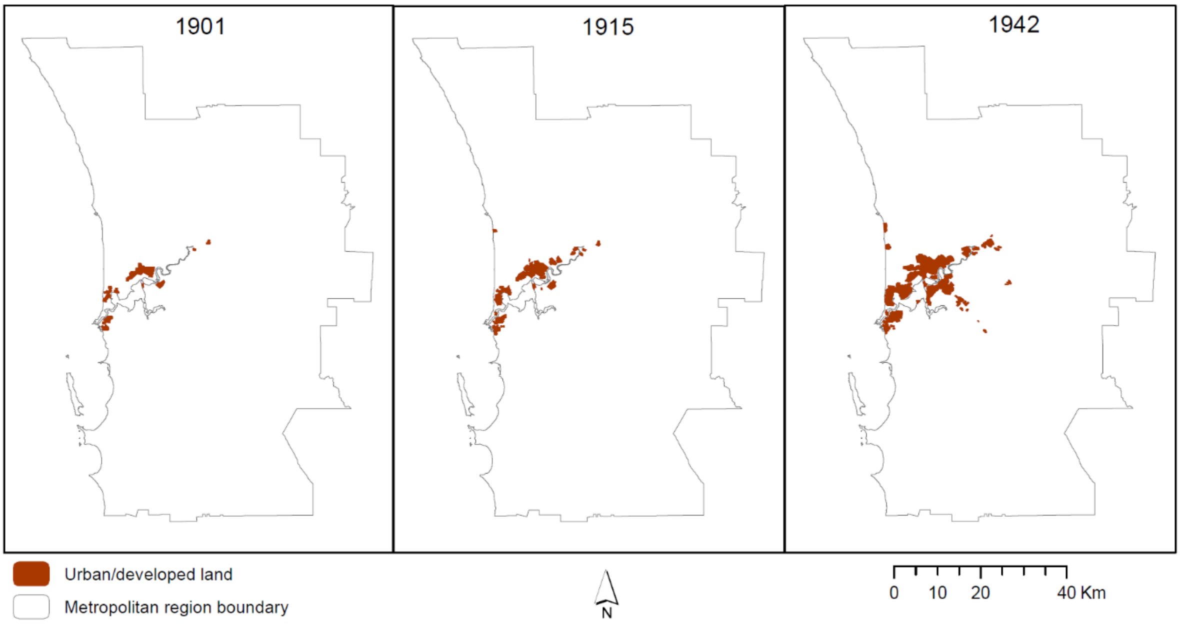


Figure 4.3: Footprints of Perth's urban expansion between 1901 and 1942. Source: Made by author.

A linear expansion deviating from the river in the south-eastern direction became visible from 1942. This shows how residences followed the railway line (Armadale) going farther from the city centre (explained further in the next section).

In recent years (2000–2016), urban expansion has been marked by reduced outward growth, as confirmed by the footprint mapping exercise in Figure 4.4. During this period, growth was more interstitial as the state government sought to restrain sprawl and move towards greater density through infill and mixed-use developments. During this period, the government produced three strategic planning documents; *Directions 2031 and Beyond* (Western Australian Planning Commission (WAPC), 2010), *State Planning Strategy 2050* (Western Australian Planning Commission (WAPC), 2014) and *Perth and Peel @ 3.5 million* (Western Australian Planning Commission (WAPC), 2015). At the core of each of these documents is advocacy for less outward expansion and more densification for accommodating current and future population demands. As a matter of fact, the total urban land increased by 2.75% between 1992 and 2002, but only increased by 0.59% from 2002 to 2012, and by 1.26% over a longer period of 2002 to 2016 (see Table 4.1).

Overall, the expansion of Perth's urban footprint imitated a triangular shape, delimited by the ocean on the base and following the Swan River at the triangle's peak (see Figure 4.4). The CBD lies in the centre of the triangle, as the centre of gravity or driving force of development. As Perth expanded towards the north and south, the shape of the triangle gradually changed from *acute triangle* with all angles less than 90 degrees to an *obtuse triangle* with one angle at the peak larger than 90 degrees. This may signify urban sprawl along the coast which led to Perth overtaking some of the world's biggest cities in its footprint expansion. Coastal developments, also termed as 'sea change', have been a common phenomenon in Australia for several decades (Bohnet & Pert, 2010; Gurran & Blakely, 2007; Gurran, Squires, & Blakely, 2005). Sea change migrants move to coastal areas for lifestyle reasons (Bohnet & Pert, 2010; Burnley, 2005) since "coastal views and short travel times to the sea [are] perceived as valuable amenities, and hence the growth of coastal suburbs" (Z. Liu & Robinson, 2016, p. 184). Some other factors also contributed to this growth pattern, such as geographical terrain, e.g., escarpments on the east confined expansion closer to and along the coast where land is more developable.

4.7 TRANSPORT AND URBAN FORM INTERACTION

The extent of urban land use zones in the MRS over the last five decades are analysed in Figure 4.4. An urban land in this case consists of residential, commercial, recreational and industrial zones. Also shown in the figure are the freeways and passenger railways that existed at the respective years. As indicated in the previous sections, transport infrastructure was a strong determinant of the urban form in the early years of Perth's evolution. Tramlines attracted residential settlements in the late nineteenth century, and the connection of built-up land between Perth CBD and Fremantle along the Swan River also happened to follow the Fremantle railway line. The southerly expansion, while it started with dispersed settlements on the coast, later compacted and expanded towards and along the freeway.

Three railway lines (Fremantle, Midland and Armadale) were present at the first MRS (1963), from the great 'railway era' of the late nineteenth century. These lines formed the backbone of urban expansion, leading to visible concentration of developments in the north-eastern and south-eastern directions. However, these lines have not been extended and the rapid urban growth has now sprawled beyond (in the case of Armadale and Midland) and away from them. It is a similar situation, if not worse, with the longer north and south lines where some of the furthest developments from the CBD have occurred. When the Joondalup Line was constructed in 1992 after almost a century of railway construction dormancy, it did not go the full extent of the urban expansion. And despite the urban development expansion southward, it was not until 2007 that the Mandurah line was opened.

The 7.5 km extension of the Joondalup Line (to Butler) in 2014 is the latest addition to Perth's railways, and it still fell behind the rather linear urban land expansion along the coast. The 2016 MRS shows that urban land has gone beyond each of the terminals and some lines may require extension. From this information, it is evident that the MRS has been availing land for urban development well ahead of transit development. This is a deviation from the earlier trend of urban expansion following transport links. This has led to a prominent level of dependence on the automobile in Perth (Alexander & McManus, 1992; P. Newman & Kenworthy, 1999), as it is the most accessible transport mode particularly for the outlying residents where transit option are limited.

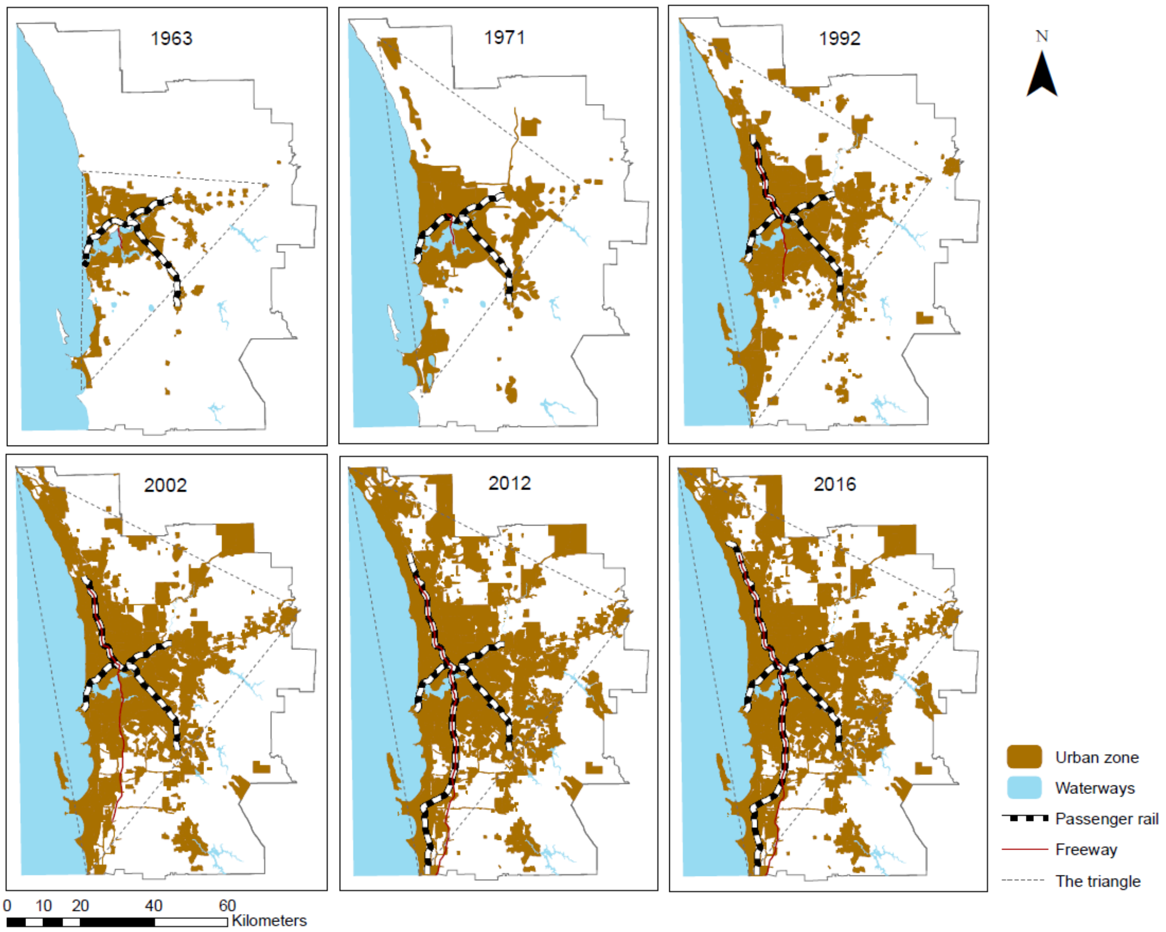


Figure 4.4: Metropolitan Region Scheme (MRS) urban land footprints changes between 1963 and 2016 (Note: Industrial and parks & recreation are also considered to be urban land). Source: Made by author.

4.8 URBAN FOOTPRINT CHANGES BETWEEN 1963 AND 2016

Using a GIS, the digitised MRS data were used to calculate land areas for different land use categories in each of the six years (1963, 1970, 1992, 2002, 2012 and 2016). Calculating the areas enables for a quantitative measure of change for each land use category. Together, these areas define the total changes in Perth's urban form. Although the MRS data merely shows planning zones (as opposed to existing developments), it does provide a valuable impression of the trend and pattern of change of the urban form.

The results confirmed that land areas in various land use categories experienced significant changes, albeit in varying degrees. Figure 4.5 presents an analysis of the data for five land uses from 1963 (first MRS) to 2016, which shows that the areas of state land and rural land within the PMR boundary have decreased quite significantly during this period. On the other hand, urban and parks and recreation land areas increased, encroaching into formerly forest and rural land. Specifically, urban land increased from 7.41% of the total MRS area to 20.64% during this period. Rural land decreased from 56.56% to 33.49% (see Table 4.1 for the detailed land area changes). However, the rate of increase in urban land area (as well as the rate of decrease in rural land) has significantly reduced in recent years. These trends highlight the restricted urban growth of the twenty-first century by the state government.

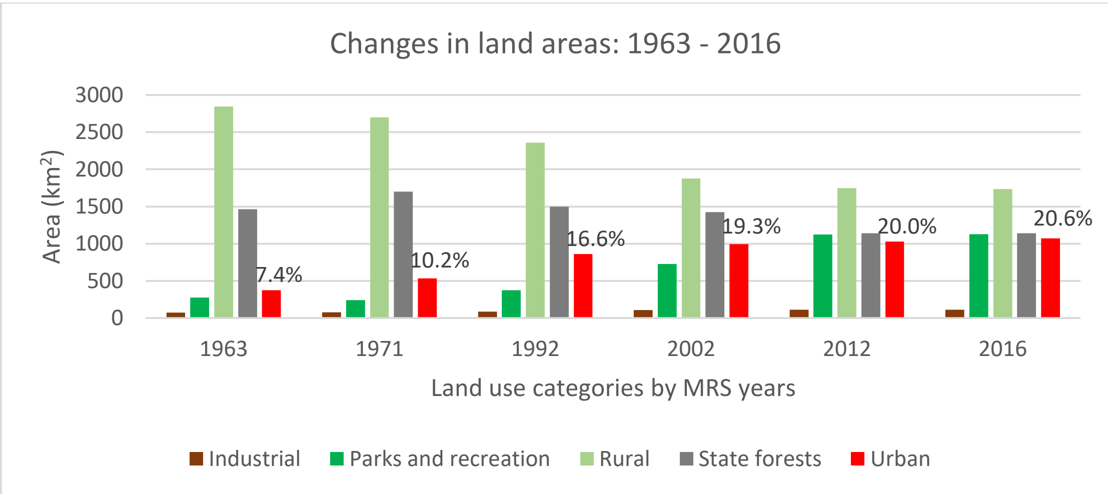


Figure 4.5: Areal land use changes between 1963 and 2016. (Percentages signify the proportion of urban land in the PMR). Source: Made by author.

Table 4.1: MRS land areas between 1963 and 2016.

Land use	Area (km^2) by Year of MRS					
	1963	**1971**	**1992**	**2002**	**2012**	**2016**
Industrial	73.29	78.27	86.18	104.57	110.43	112.33
Parks and Recreation	273.33	239.59	373.38	728.73	1124.50	1125.49
Urban	372.79	533.52	861.35	994.10	1029.34	1069.63
Rural	2844.14	2697.80	2361.40	1879.09	1749.58	1736.02
State forest	1464.81	1699.87	1498.09	1422.94	1139.47	1139.47
Total	5028.36	5249.05	5180.40	5129.43	5153.31	5182.94
Percentage of Total MRS area						
Industrial	1.46%	1.49%	1.66%	2.04%	2.14%	2.17%
Parks and Recreation	5.44%	4.56%	7.21%	14.21%	21.82%	21.72%
Urban	7.41%	10.16%	16.63%	19.38%	19.97%	20.64%
Rural	56.56%	51.40%	45.58%	36.63%	33.95%	33.49%
State Forests	29.13%	32.38%	28.92%	27.74%	22.11%	21.98%
TOTAL	100.00%	100.00%	100.00%	100.00%	100.00%	100.00%

Note: The total areas differ between the years due to some other land use categories not being included such and roads and water bodies, which also underwent some changes.

4.9 SUMMARY AND CONCLUSION

This chapter investigated urban spatial structure from a morphological perspective. It presented a timeline of developmental milestones in WA since the founding of the Swan River colony by the British Government. Following the three themes, it demonstrated how the transport developments, planning regulations and economic milestones, contributed to the evolution of urban form in Perth. The discussion advanced into a focus on transport evolution and how it informed the fashion in which the urban form evolved over the last century, and particularly during the era of the MRSs.

A deconstruction of the timelines showed that planning regulation was limited in the early years of the colony, as were land developments. However, as the population increased, it became imperative to not only regulate current developments but also plan for future growth. Economically, the state struggled for the better part of the nineteenth century. Agriculture, as the major industry driving the economy, did not allow for much investment in development. The discovery of gold in the late nineteenth century was a turning point for the state, allowing more investment in infrastructure (e.g. railways, electric trams and piped water). The population also increased rapidly due to interstate and overseas immigration. Many of these people settled in Perth and created a land demand that propelled urban expansion.

The city's transformation to car dependence could also be ascribed to the flourishing economy, as car ownership grew with commuting distances to newer outer suburbs. The transport developments – which were also enabled by the economic growth, and provided for by the planning regulations – supported or encouraged the sprawling urban footprint. In fact, the urban footprint evolved around transport corridors such as the river and railways. The railways were, however, overtaken by urban expansion from the late twentieth century, and newer ones were built to catch up in already developed areas. This was a deviation from the olden trend where urban expansion was heralded and shaped by transport infrastructure developments, and particularly railway developments in the case of Perth.

With coastal developments stretching further north and south, and radial expansion around the spine of the Swan River, Perth's footprint developed into a triangular shape. As the triangle grew, its shape changed from acute to obtuse triangle (with reference to the angle inland). Nonetheless, the expansion has slowed down in the twenty-first century. This reflects the government's efforts to limit sprawl and densify developments.

Overall, the general trend has been an increase in population and urban expansion in the PMR despite some challenges such as the world war, Great Depression and droughts. Considering the mining boom that just ended, and indeed all those that have happened since the advent of the goldfields, it is clear that the state will always have a 'boom and bust' economy. As such, planning in Perth needs to incorporate this dimension, and anticipate depressions as a fabric of a mining-based economy. This chapter provides a historical benchmark of the city's performance, which can help planners and policy makers in managing urban expansion in the metropolitan area.

An important insight from this chapter is that public transport in the form of trams and trains had great influence on the pattern of urban growth. These findings indicate that modern and future cities could leverage the same kind of influence from similar transport modes such as heavy and light rail transit. Sustainable growth could be induced by promoting higher density and mixed developments in their catchment areas (further discussed in Chapter 6). A major challenge lies in increasing the competitiveness of public transport against the car, particularly in the suburban areas where public transport is hugely uncompetitive. This could be done through appropriate improvements to public transport efficiency including wider geographic coverage and higher service frequency to reduce walking, waiting and transfer times.

For its relatively small population size, Perth has some of the longest distances between the city centre and its suburbs particularly on the north–-south dimension. This pattern is a product of a combination of factors including escarpments which curtail easterly expansion, 'sea change' or coastal migration, and transport related factors such as the passenger train, freeways and high car dependence and ownership. Together, these factors created a unique set of circumstances that have given metropolitan Perth an elongated urban footprint. This study has shown that the city spread more widely as mobility became easier and more flexible. As a city that is now so reliant on the ubiquitous and highly flexible automobile, strategies to mitigate unsustainable urban expansion are particularly imperative. While new technological revolutions in transportation such as the autonomous vehicle could continue to increase the ease of mobility, they also present a unique opportunity for city authorities to introduce nuanced, powerful policies with which they could induce sustainable urban growth.

The next three chapters will explore the spatial efficiency of urban structure from a functional perspective. In the next chapter, the second component of spatial efficiency analysis – and the first from a functional perspective, will be presented. The effectiveness of employment self-sufficiency measures on reducing the level of commuting will be examined.

CHAPTER 5 EMPLOYMENT SELF-SUFFICIENCY MEASURES AND COMMUTING

This chapter consists of research that has been published in Kelobonye, Mao, et al. (2019).

5.1 INTRODUCTION

The previous chapter adopted a morphological perspective to defining urban spatial structure and understanding its spatial efficiency. This chapter presents the first component of analysing urban spatial structure from a functional perspective. The chapter contributes significantly to research in spatial efficiency, through a robust investigation of job-worker ratios in the PMR and their effect on reducing commuting in general.

Recent research has come out in support of land use policies that promote balancing the numbers of employment opportunities and residents in local geographical units to reduce excess commuting. However, research on the effectiveness of these measures is still limited, particularly in the PMR. This chapter investigates the impact of job-worker balance, employment self-sufficiency and employment self-containment on commuting times in the PRM. Using novel trip data, the level and spatial pattern of each of the three measures is investigated and mapped, respectively, and their effects on average commuting time are tested through statistical correlation tests.

5.2 RESEARCH CONTEXT

The traditional city structures were monocentric, with jobs located in the central prime land and residences in the suburbs. As cities got bigger, efforts were directed towards decentralising jobs and bringing them closer to the people as a way to reduce commuting and its related problems. Studies have reported a steady migration of jobs to the suburbs over the past several decades (Cervero, 1989b). These developments changed the conventional city structure, shifting it from the traditional monocentric to some degree of polycentricity (M. Burger & Meijers, 2012; Evert J Meijers & Burger, 2010). As a result, many suburbs are no longer just dormitories for centrally located jobs but have become destinations in their own right.

Despite these efforts, and material changes thereof, studies have shown that commuting distances have continued to get longer (Cervero, 1989b). Additionally, traffic congestion has reached unprecedented levels in major metropolitan areas. P. W. G. Newman and Kenworthy (1989) and (Cervero, 1989b) contend that part of the reason is job-worker imbalances. They argue that despite the decentralisation, more people now live farther from their jobs (Cervero, 1989a, 1989b). This shows that balance does not necessarily result in people working near to where they live. While it is reasonable to expect that increasing job opportunities nearby will increase the chances of people working nearby, there is a complex range of factors at play, including skills match and housing affordability among others. As a result, there has been growing research interest going towards unravelling urban mobility and developing methodologies for measuring it. Recent research efforts have ranged from urban data preparation and improvement (Freire, 2016; Martino, Read, Elvira, & Louzada, 2017) to development of new indices and models for understanding urban movements (Seabra, 2013; Song & You, 2018). The advances in big data analytics are also enabling researchers to examine the complex patterns of urban mobility such as temporal trends in trips to various destinations within cities (e.g. see K. Zhao, Chinnasamy, and Tarkoma (2015)). Some researchers have taken the perspective of accessibility, evaluating access equity across cities through specific travel time thresholds for jobs and other urban services (Cui, Boisjoly, El-Geneidy, & Levinson, 2019). Others have aligned with the notion of job-worker balance and suggested more nuanced measures which take into account the skills match between jobs and workers. Beyond the numerical balance, interest is increasingly moving towards self-sufficiency (maximising local employment opportunities) and self-containment (maximising local capture of the labour force) within sub-regional units of major cities (S Biermann & Martinus, 2013; Martinus & Biermann, 2018).In Australia, over 60% of the population lives in the five largest cities. These cities are also experiencing the most growth in population and travel demands. Perth had the highest growth rate since 2004, at 30 per cent (Commonwealth of Australia, 2015). Most of this growth occurred at and beyond the fringes (Weller, 2009; Western Australian Planning Commission, 2018) with no corresponding job supply to match it (Moniruzzaman et al., 2017). The Perth Central Business District (CBD) and its surrounds remains the biggest centre of employment, with around 20% of the Perth metropolitan total. The high number of commuters from around the metropolitan region into the CBD creates unpleasant traffic conditions during peak hours. The current policy objective seeks to curb urban expansion, create more suburban jobs at decentralised activity centres and encourage local employment, to reduce the long commutes (Western Australian Planning Commission, 2010b, 2018).

Since the 1950s, Perth's strategic plans have advocated a balanced regional growth and job distribution to reduce the impact of commuting (Curtis & Olaru, 2007; Martinus & Biermann, 2018). The Australian "suburban dream" and the associated higher car ownership levels have consistently led to rising commuting between the CBD and suburbs. As indicated by Martinus and Biermann (2016b, p. 1) "commuting has continued to challenge the liveability and infrastructure efficiency of Perth and Peel" (p. 1). In parallel to the academic literature (Cervero, 2001; Forster, 2006; Mark W Horner & Mefford, 2007; Yigitcanlar, Dodson, Gleeson, & Sipe, 2007), recent strategic plans, such as *Direction 2031* and *Perth and Peel@3.5 Million*, have also emphasized employment self-sufficiency and self-containment as tools to determine the equity of job distribution and the reduction in commuting flows (Western Australian Planning Commission, 2018).

While a significant body of literature expounds upon job-worker balance (JWB), less attention has been given to self-sufficiency and self-containment. Moreover, the effectiveness of these measures in reducing commuting within metropolitan areas remains largely untested and contentious. Previous research by S Biermann and Martinus (2013) and Martinus and Biermann (2018) has examined these policy targets and suggested strategies by which they might be achieved in the Perth sub-regions. The former study explored three employment targets of self-sufficiency, self-containment and job-housing balance with particular focus on Perth's Central and North West sub-regions. The latter explored employment self-containment in the North West sub-region by performing a nuanced disaggregation of commute data by industry and occupation. These studies provide great insight into the [relationship between] employment and commuting patterns in general, and in Perth's North West sub-region in particular. However, there remains a need to understand commuting patterns in the metro region as a whole, and how they relate to each of the three different employment self-sufficiency measures mentioned above. This study sought to empirically test the effectiveness of job-worker balance (JWB), employment self-sufficiency (ESS) and employment self-containment (ESC) using the case study of Perth Metropolitan Region (PMR), Australia. It investigates both the levels and spatial patterns, of JWB, ESS, and ESC using trip data. It then compares the results with the modelled average travel times in the region to test their statistical correlations.

In the next section a discussion of existing literature on this subject is presented, followed by a description of the methods engaged in the study. Then, the results of the study are presented, which are followed by a section of their discussion, and finally the conclusion.

5.3 METHODOLOGY

5.3.1 Indices for Job-Worker Balance (JWB), Employment Self-Sufficiency and Employment Self-Containment (ESC)

The work trip data were used to define and measure indices for JWB, ESS and ESC. The JWB index used in this study is a refinement of the conventional JHB index, based on actual home-based work trips committed. Trip origins represent residences while destinations represent jobs. JWB is, therefore, defined as the total of inflow trips from other zones within the PMR to a target zone and intrazonal (internal) trips within the target zone divided by the number of outflow trips from the targeted zone to other zones in PMR plus intrazonal trips within the target zone (see Equation 5.1). The numerator represents the number of jobs in the target zone (occupied by both residents and non-residents), while the denominator is the total workers living in that zone.

$$JWB_i = \frac{\sum_{j}^{n} inflow_{ji} + intra_i}{\sum_{j}^{n} outflow_{ij} + intra_i} \tag{5.1}$$

where, JWB_i represents the job-worker balance index of zone i, $inflow_{ji}$ is the number of incoming work trips from zone j to zone i, n is the number of zones in PMR except the zone i, $intra_i$ is the number of internal work trips within zone i, and $outflow_{ij}$ is the number of outgoing trips from zone i to zone j.

A JWB index of more than 1 means the zone is job-dominated – more inflow of work trips than outflow. An index of less than 1 means the zone is residence-dominated – more outflow of work trips, and 1 is balanced. In this study, values between 0.8 and 1.2 are considered to denote a balance of jobs and workers in a zone, less than 0.8 means residential dominance and more than 1.2 job dominance.

In addition to comparing the numerical balance between jobs and resident workers, interest was also in understanding the match between local jobs and resident workers. Inter-zonal commuting is inherently a factor of the proportion of local jobs filled by local residents (Equation 5.2), and the proportion of resident workers who work in local jobs (Equation 5.3).

$$ESS_i = \frac{intra_i}{\sum_j^n inflow_{ji} + intra_i} \tag{5.2}$$

$$ESC_i = \frac{intra_i}{\sum_{j}^{n} outflow_{ij} + intra_i} \tag{5.3}$$

ESS indicates the level of inward travel, and the higher the ESS ratio the less the travel into the area e.g. an ESS measure of 85% means that 15% of local jobs are filled by non-resident workers who then have to commute into the area. ESC indicates the level of outward travel, and a high ratio of ESC means fewer people have to travel out of the local area for work (S Biermann & Martinus, 2013). ESC can also be alternatively defined as the proportion of internal trips to the total trips made by residents of a particular locality (Cervero, 1996; O'Connor & Healy, 2002). For those zones in which reducing outward travel is the objective, ESC is an appropriate index to measure their performance.

For analysis in this study, GIS aggregation tools were used to determine the number of intra, inflow and outflow trips for each zone and visualized JWB, ESS and ESC using thematic mapping methods. Spatial and statistical relationships between travel time and JWB, ESS and ESC were also analysed, with the aim to determine how these indices impact on commuting time, using cross-tabulation methods. The hypothesis was that balanced, self-sufficient and self-contained zones would have shorter commuting times.

5.3.2 Dealing with issues of geographic scale

A key question in measuring JWB ratios is determining the geographic scale at which jobs and workers should be measured/balanced. Typically "the larger the size, the more likely the balance - at the extreme, planet earth has a perfect balance of jobs and employed residents" (Cervero, 1996, p. 495) (p. 495). Likewise, the entire metropolitan area will inherently have a match between jobs and workers (Stoker & Ewing, 2014). Metropolitan sub-regions are demarcated by arbitrary boundaries which often differ depending on their purpose and across authorities. For example, census region classification is different from suburb boundaries or planning sub-regions. The sizes of these established tracts/sub-regions often have large variations e.g. census tracts are often smaller in downtown areas and much larger in low-density suburbs and exurbs (Stoker & Ewing, 2014). These differences (between sub-regional classification systems) and variations (in size between sub-regions of the same system) can have a great influence on the results, known as the Modifiable Areal Unit Problem (MAUP).

Various approaches have been recommended for dealing with the MAUP. Some scholars recommend using a minimum average commute to define the geographic units. Some have used a 'potential opportunities' approach to measure the proximity of jobs to households, while others used floating catchment areas of traffic analysis zones and measure job-housing ratios within them (e.g. see Peng (1997)), or circular catchment areas of a given radius e.g. (Cervero, 1989a; F. Wang, 2000). Nonetheless, some researchers are still using the pre-defined administrative sub-regions for JWB and commuting behaviour analysis (e.g. Geyer and Molayi (2017).

In the current study, the analysis is based on the STEM zones. STEM zones were built from the Australian Bureau of Statistics (Australian Bureau of Statistics) census collector districts which focus on households and seek to have a similar number in each. Hence, in denser areas they tend to be smaller and in more rural areas, larger. The zones also tend to split up different land use types, especially residential and non-residential uses. This can mean that residences adjacent to employment may well be in two separate zones, giving a low JWB for one and a high JWB for the other. Were the zone boundaries to be drawn differently, or the two zones combined, the JWB, ESS and ESC values would be very different, although the spatial distribution of workers and jobs is identical - the MAUP issue.

While STEM zones are susceptible to the MAUP issues described above, they contain adequate data for the current analysis, and also form an important part of the basis for transport and land use planning policies in the PMR. Using the same scale as the model, and indeed the policies, enables direct comparison and application of the indicators to the zones so defined, and a closer reflection of the improvement made in the target areas. The scale problem is alleviated by conducting a commuting time analysis. Analysing inward and outward commuting times appears to be one way to reduce the potential distortion due to MAUP. For example, a zone may have a poor job-worker balance, but if it has short or ideal average commuting time that means the trips made to/from such a zone are not too long, and therefore such a zone is sufficiently accessible for workers. Thus, the travel times enable a more contextualised interpretation of the JWB values.

5.4 RESULTS

5.4.1 Benchmarking Job Distribution and Commuting Patterns in STEM Zones

- Spatial distribution of JWB

Figure 5.1 shows the spatial distribution of JWB in the PMR. Since many zones fall outside of the balanced range, the ‘residence-dominated’ and ‘job-dominated’ categories were further divided into two sub-categories each. Thus, zones with JWB ratios in the range 0.8-1.2 are balanced, 0-0.4 is high residential dominance and 0.4-0.8 is low residential dominance while 1.2-2 is low job dominance and greater than 2 is high job dominance.

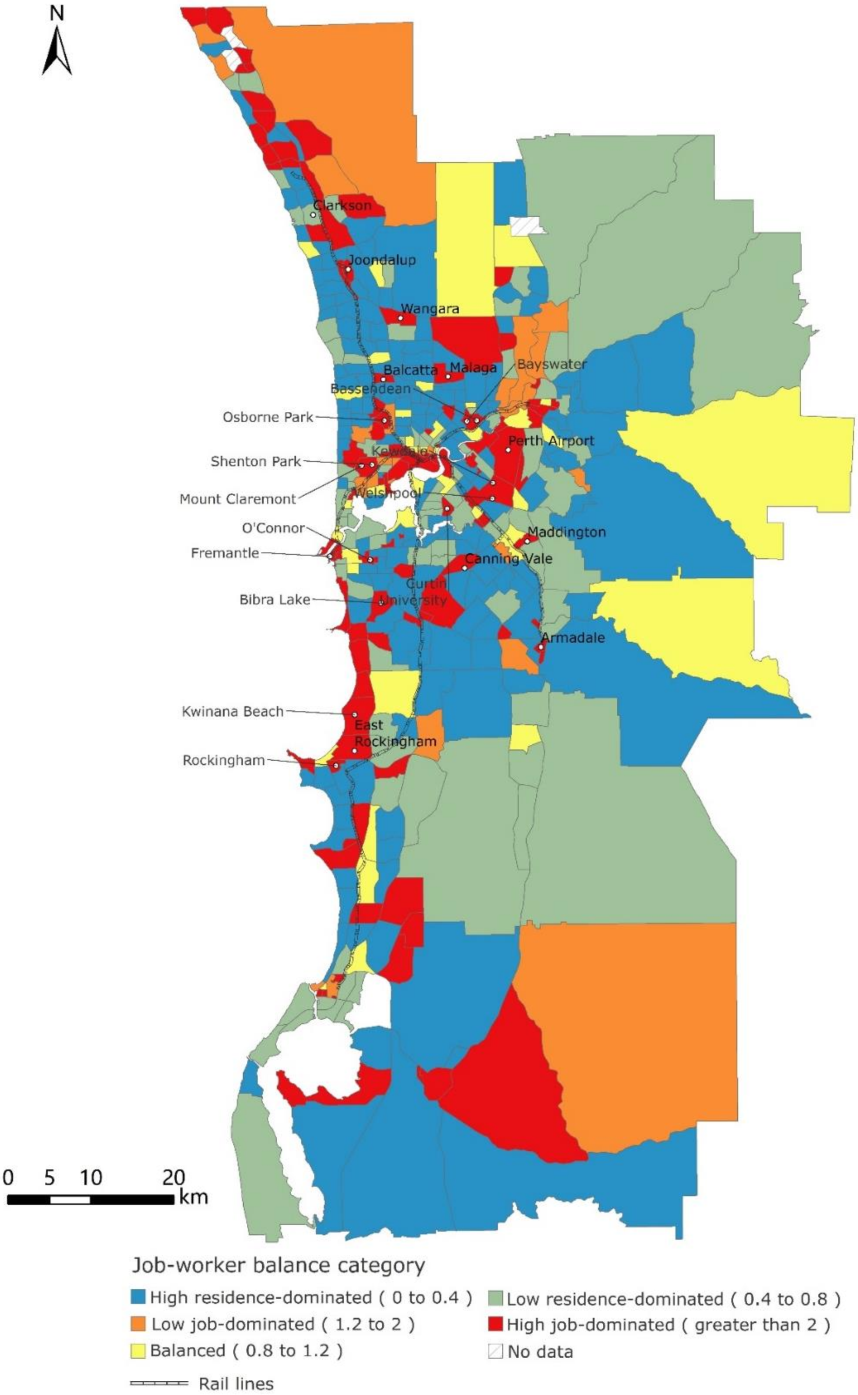


Figure 5.1: Spatial distribution of JWB within STEM zones

Out of the total of 472 zones in the PMR, 436 had sufficient data for JWB calculations. The majority of these zones are in the categories of 0-0.4 (40% of zones and 15.3% of trips) and >2 (25% of zones and 61.1% of trips). According to the current classification, these zones are either highly residence-dominated or highly job-dominated with a very small portion of mixed land use. Only 9% of the zones (6.3% of trips) are in the balanced range. Further, the spatial distribution of JWB was checked in accordance with the city's broader land use pattern. Residential dominated areas are identified along transport corridors and rivers (Swan and Canning). The major job concentrations occur in the City of Perth (CBD), which provides 17% of the total employment (BIRTE, 2010). Sharon Biermann and Martinus (2016, p. 390) ascertain that Perth CBD has “an excess of job opportunities in relation to the local resident labour force” (p. 390).

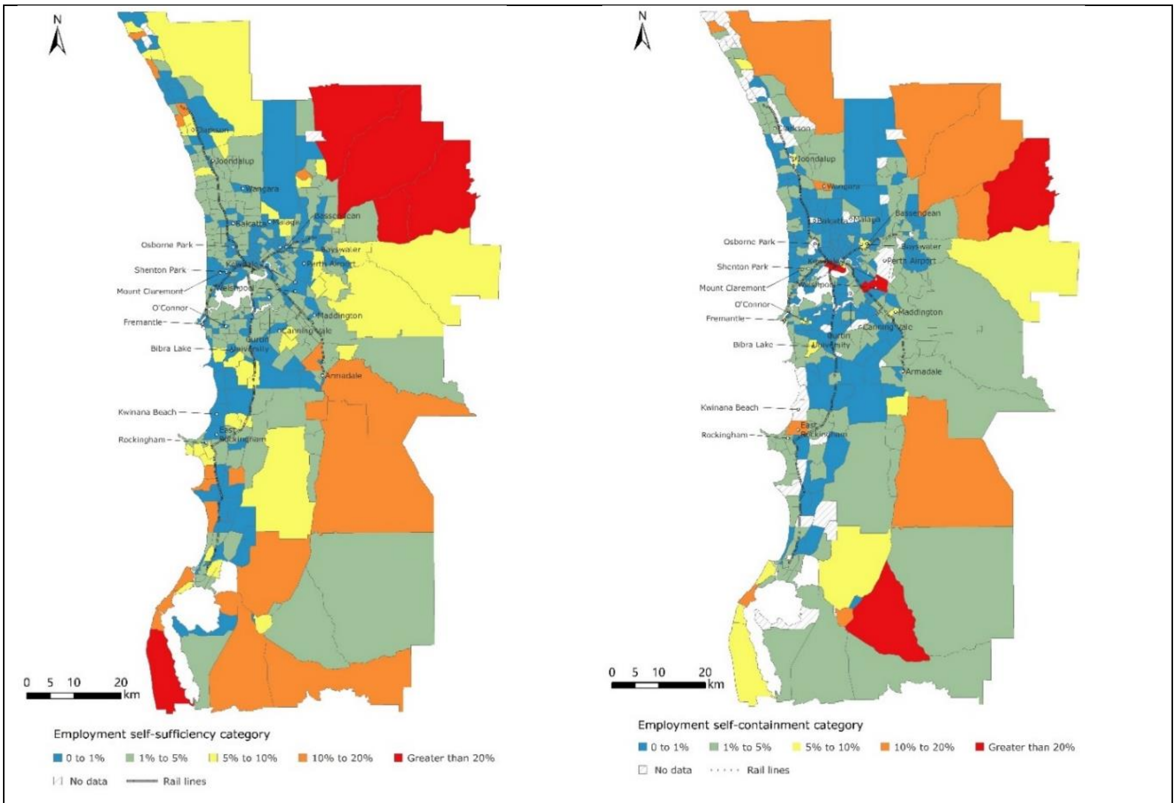
Zones around industrial concentrations (e.g. Welshpool, Kewdale and Kwinana), are evidently job-dominated with higher JWB values. Similar clustering of job-dominated zones occurs around the North-East and North-Western fringes (e.g. Joondalup, Wanneroo, and Swan areas), mainly “driven by the transport, manufacturing and construction industries, generating a rapid growth in the number of people commuting into this sub-region from other parts of Perth” (BIRTE, 2010, p. 229) (p. 229). Sharon Biermann and Martinus (2016, p. 392) further explain that “agriculture, forestry and fishing, education and training, accommodation and food services and retail trade are the industries most linked to internal travel within the North West sub-region” (p. 392). City fringes along North-West (Swan and Wanneroo) and South-East (Peel) show an unlikely job dominance, which is due to the existence of large tracts of agricultural lands with very low population densities, i.e. zones with relatively low employment levels but much lower population levels. It is worth noting that a much poorer balance is particularly seen around the two comparatively newer north-south train lines (Joondalup line and Mandurah line). However, a few places along the older transport corridors have grown over time in response to the natural integration of land and transport or have strategically done so through Transit Oriented Development (Todd Litman & Burwell) projects.

- **Spatial distribution of ESS and ESC**

Generally, most areas in the PMR have very low ESS, meaning that there are not many jobs occupied by people living in the same zones (as their jobs) (see Figure 5.2A). Over 72.4% of zones, containing 71.1% of total workers, have ESS values less than 5%. Only five zones have a self-sufficiency level of more than 20% (containing only 1.3% workers), and they are all at the fringes.

The general spatial pattern of ESS shows a gradual increase from inner Perth to outer Perth. This means that a higher proportion of local jobs are filled by local resident workers in outer Perth as compared to the inner Perth where a lot of commuting is done into the area (Figure

5.2A). Agricultural areas close to the city edge are comparatively self-sufficient (ESS is >10%). In contrast, CBD, inner suburbs and more developed areas have appeared as less self-sufficient. It is evident that the CBD accommodates the highest number of jobs, which are filled by workers coming from outside, leading to a high volume of inflow. It is noted that even some of the job-worker balanced zones have the poorest self-sufficiency, (e.g. Balcatta). This indicates a potential mismatch between the type of local jobs and the occupation of the local resident workers.



(a) ESS **(b) ESC**

Figure 5.2: Spatial distribution of ESS and ESC within STEM zones.

For the ESC index (Figure 5.2B), 384 zones were examined. About 81% of zones (containing 95% of workers) have ESC less than 5%. Only four zones have an ESC greater than 20%, and these are the CBD, Welshpool-Kewdale area and two other fringe zones. It is worth noting that the high values in fringe zones are due to low populations in these zones whereby a few agricultural workers make up a significant portion of the total resident workers.

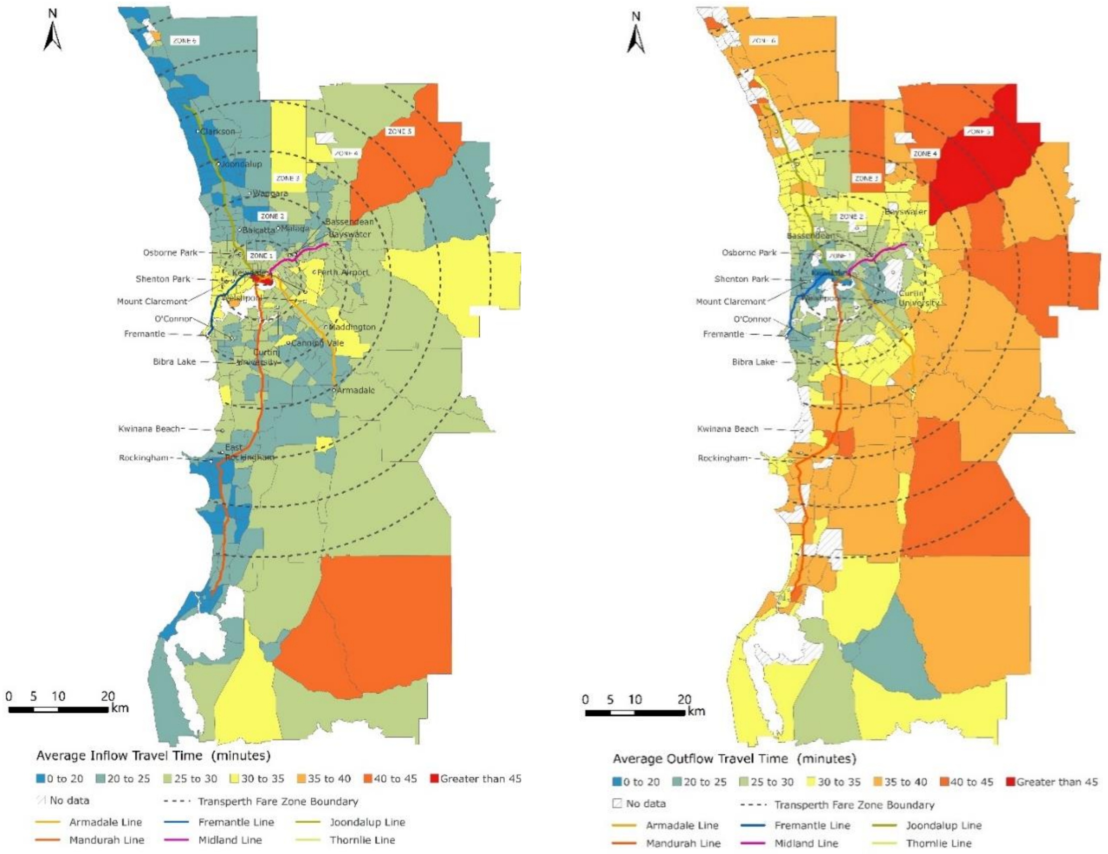
As seen in Figure 5.2, the general pattern of spatial distribution of ESC is similar to that of ESS. This suggests that outer regions have fairly higher proportions of resident workers working locally, as compared to the inner parts of the city. However, there are slightly more zones with an ESC of less than 1% (46% of zones) compared to those with an ESS of less than 1% (42%). The very low ESC (<1%) zones are more concentrated in the inner regions, while the very low ESS (<1%) zones are mainly distributed around inner areas i.e. along train lines, especially Fremantle and Midland lines, and North-West and South-West coastal areas. None of the zones has achieved a score even close to the target self-containment rate of 60 per cent in the metropolitan area.

5.4.2 Spatial Pattern of Inflow and Outflow Travel Times

As already indicated, the effectiveness of the JWB, ESS and ESC indices is limited by the arbitrary nature of the geographic scale used. Also, these indices treat all external trips (long or short) the same, which can make the commuting situation look worse than it really is. Incorporating average commute times into, (inflow), and out of, (outflow), the zones can help to give a truer picture of the extent of commuting across the zone boundaries.

Inflow travel time is the average duration of trips from other zones coming into a target zone. Figure 5.3(a) shows the spatial pattern of average inflow travel time in the PMR. The result uncovers a graduated decrease in average inflow travel time from CBD to the Western edge along coastal lines, Swan River and train lines. Furthermore, an increasing trend in average inflow travel time was found towards outer Perth areas. Around 87% of the zones have average inflow travel time less than 30 minutes, which is equivalent to Perth's average commuting time (BIRTE, 2015).

The CBD has the highest average inflow travel time (> 45 minutes) which can be attributed to the higher JWB ratio - the strategic nature of many of these jobs drawing from the region-wide labour pool - and Perth's linear city structure. A few inner suburbs near the CBD (<20 km) with high job-dominance, have relatively higher average inflow travel times (30-35 minutes). These include Welshpool-Kewdale (industrial concentration), Curtin University (the second largest job destination region) and Cannington (one of the largest and most popular shopping centres in Perth). On the other hand, the commute times into most of the zones along the two newest train lines (Joondalup (opened in 1992) and Mandurah (opened in 2007)) and coastal areas (Western edge) are less than 25 minutes. While this may seem to suggest the contribution of train services in reducing inflow travel time, a more plausible explanation is that these areas have fairly non-skilled jobs which are filled more locally. The inflow travel time into zones along the older train lines, particularly the Fremantle line, is relatively higher (ranging from 25 to 40 minutes). On the contrary, these areas have more strategic/specialist jobs, e.g. hospitals, private schools and professional practices – which draw their workforce from a wider area.



(a) Average inflow travel time (b) Average outflow travel time

Figure 5.3: Spatial distribution of average travel time based on STEM trip data.

Figure 5.3(b) shows the spatial pattern of average outflow travel time within the metro region. Outflow travel time is the average duration of all trips leaving a zone for work purposes. Apart from the CBD area in particular, most zones have higher outflow travel times than inflow times. Around 50% of the zones have average outflow travel time less than 30 minutes. The outflow travel times show a pronounced concentric pattern: the lowest outflow time was in the areas around the CBD, which increased radially outwards. No obvious spatial patterns of the average outflow travel time around train lines are revealed. However, a noticeable distance impact of the average outflow travel time can be observed, which broadly coincides with the fare zones used by *Transperth* who runs the various public transport modes within the PMR.

5.4.3 Relationships between the Employment Performance Indices and Travel Time

The average inflow and outflow travel times for each category of JWB, ESS and ESC (see Tables 5.1 and 5.2) were summarised to find their effects on commuting time. For JWB, 177 zones (about 36%) scored between 0 and 0.4. This reflects few job opportunities available in these zones, relative to the high number of residents. Only 39 zones (8.9%) have a balanced job-worker ratio (Table 5.1). In terms of the relationship, it was found that on average, as JWB increases, average inflow travel time also increases. This means that resident-dominated zones (zones with JWB less than 0.8) have shorter average inflow travel times than zones with JWB larger than 1.2, or job-dominated zones. The *balanced* zones are roughly in the middle in terms of inflow travel time, and not the shortest as would have been expected. Meanwhile, average outflow travel time displays a contra pattern, i.e. as JWB increases, average outflow travel time decreases. Thus, resident-dominated zones have longer outflow travel times than job-dominated zones. The average outflow travel times of balanced zones is in the middle. Nonetheless, JWB had weak correlations with both inflow (0.09) and outflow (0.12) travel times (Tables 5.1 and 5.2, respectively).

Table 5.1: Relationship between job-worker balance, employment self-sufficiency and inflow travel time

JWB (No. of zones)	Mean (**minutes**)	Std. D	**ESS** (No. of zones)	Mean (minutes)	Std. deviation
0-0.4 (177[1])	23.62	3.74	>20% (5)	28.27	8.26
0.4-0.8 (85)	25.58	4.53	10–20% (21)	22.13	4.33
0.8–1.2(39)	26.28	4.31	5–10% (40)	22.96	3.99
1.2–2(27)		5.71	1–5% (186)	24.94	4.71
>2(57)	26.27	5.73	0–1% (132)	25.93	4.67
Correlation: 0.09			Correlation: - 0.13		

Notes: There are 177 zones with the JWB value between 0 and 0.4. Fifty-five zones had insufficient data and were not included in the study.

Table 5.2: Relationship between job-worker balance, employment self-containment and outflow travel time

JWB	Mean (minutes)	Std. D	**ESC** (No. of zones)	Mean (minutes)	Std. deviation
0-0.4	30.97	4.93	>20% (4)	25.83	9.12
0.4-0.8	31.06	6.02	10–20% (10)	37.09	8.27
0.8–1.2	29.18	6.12	5–10% (14)	30.78	5.76
1.2–2	28.82	7.6	1–5% (155)	31.59	5.68
>2	26.77	5.54	0–1% (255)	28.52	5.09
Correlation: 0.12			Correlation: 0.08		

Table 5.1 indicates that 318 zones (about 73%) have a low ESS level of less than 5%. Only five zones had ESS above 20%, and interestingly, their average inflow travel times were found to be the highest (28.27 minutes). Nonetheless, the standard deviations of travel times for these zones were also highest. For the rest of the zones, there is a clear trend that as ESS increases, average inflow travel time decreases (as expected). The correlation was negative, albeit weak (-0.13). Note that ESS only relates to inflow travel while ESC relates to outflow travel.

For ESC, about 81% of the zones were at less than 5% (Table 5.2). For those zones with the highest ESC of above 20%, average outflow travel time was found to be the lowest at 25.83 minutes. However, there are only four zones in this category and the standard deviations are also highest. When considering all the zones, there was no obvious relationship between ESC and average travel time.

The relationships were further assessed by taking the percentage of trips into consideration. A cross graphical plotting of trips, average travel time and employment performance indices shows the contra distribution of travel time (inflow and outflow) and JWB ratio. The graphs for lower JWB values, i.e. 0-0.4 and 0.4-0.8, are skewed towards shorter *inflow* travel times (see Figure 5.4A), while for *outflow* travel time, lower JWB values correspond with longer *outflow* travel time (see Figure 5.4B). Conversely, the graphs for higher JWB, i.e. 1.2 – 2 and > 2, skewed slightly to the right, that is to longer *inflow* travel times (Figure 5.4A) while in the outflow travel time graph (Figure 5.4B), they are skewed to the left, or to shorter *outflow* travel time. For *balanced* zones (JWB: 0.8-1.2), the majority of trips fell in the 25-30-minute bracket - over 50% for inflow trips and over 60% for outflow trips - with a more symmetric distribution compared to other zones.

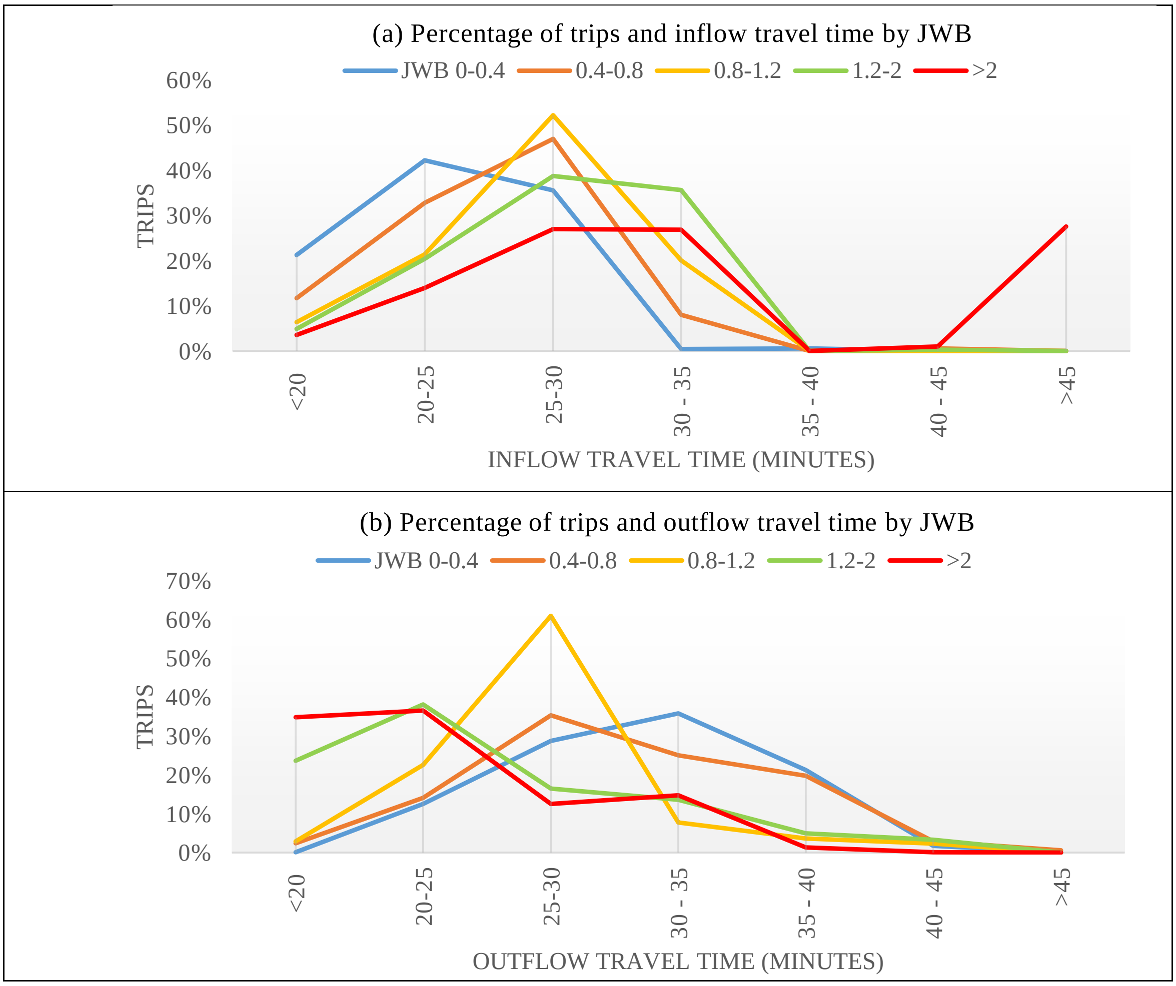


Figure 5.4: Comparison of percentage of trips and travel time by JWB

A similar three-dimensional comparison of ESS, trips and travel time (Figure 5.5) illustrates that in zones with ESS lower than 1%, 40% of trips have inflow travel time in the range of 25-30 minutes. For zones with ESS between 1%-5%, over 40% of trips have inflow travel times longer than 45 minutes. In the case of higher ESS, the inflow travel time becomes shorter, with over 80% of trips taking 30 minutes or less (55% in the 25-30 min bracket and 32% in 20-25 minutes).

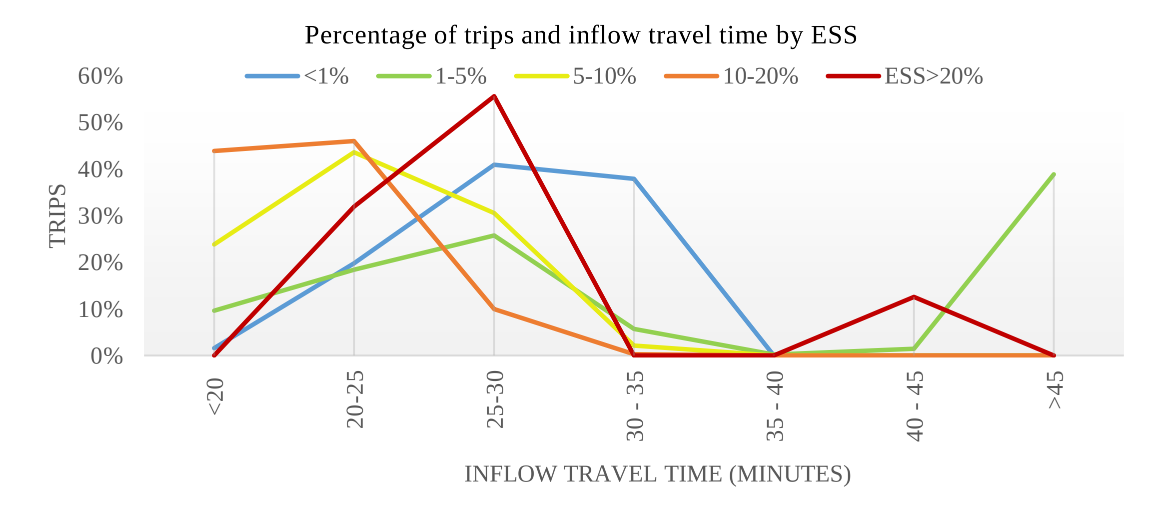


Figure 5.5: Comparison of percentage of trips and inflow travel time by ESS

Based on the mean values of travel time at Table 5.1, it was difficult to identify a pattern between travel time and ESC. In the three-dimensional graph of trips and travel time by ESC (see Figure 5.6), the general trend in the relationship between ESC and outflow travel time is still difficult to discern. In zones with ESC <1%, the percentage of outflow trips peaked at 25-30 minutes of travel time. While the highest proportion of trips from zones with high ESC (>20%) had the shortest average travel time, the other ESC categories' graphs skewed to the longer travel times.

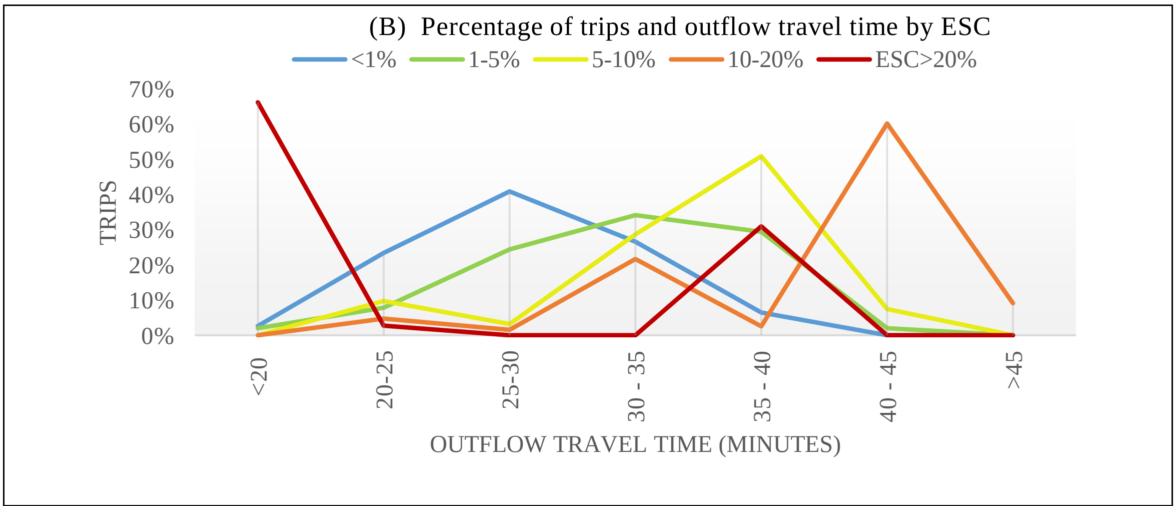


Figure 5.6: Cross-table comparison of percentage of trips and inflow travel time (left) and outflow travel time by ESC.

5.4.4 Spatial Interpretation of Relationships between Travel Time and Employment Performance Indices

To determine the spatial dimension of travel time in relation to the employment indices,

Figure 5.7 (A and B) compares JWB and ESS in relation to inflow travel time. The interaction between spatial distributions of inflow travel time and JWB reveals that most zones located in the far Northern and Southern coastal areas have quite high JWB (some zones are at >2 – job-dominated) and relatively low inflow travel time (under 20 minutes) (see Figure 5.7A). Most of these zones also have very low ESS (< 1%) (see Figure 5.7B). It is also observed across the two figures (A and B) that where JWB is very high (>2), ESS is very low (0-1%). These areas have inflow travel time of less than 35 minutes. The relatively low inflow travel time in these areas indicate that while the proportions of jobs filled locally may be generally low, many of these jobs are filled by workers residing in the surrounding zones close by.

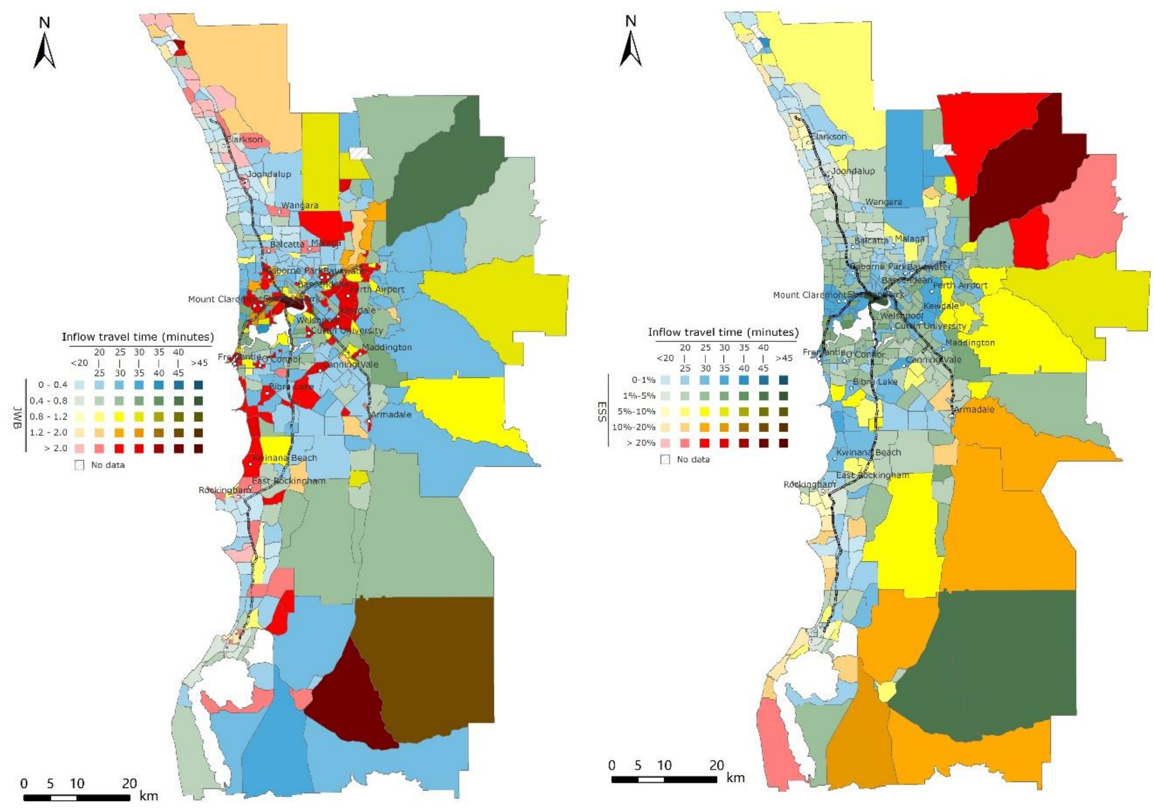
For zones located closer to the central areas, such as the CBD and areas around the Swan River, the inflow travel time is relatively high (>30 minutes). There is a mixture of zones with high JWB (some have >2; highly job-dominated) and low JWB in this area, while the ESS is very low (0%-5%) for almost all of them. As identified in section 5.4.2, the CBD has the highest average inflow travel time (47.5 minutes). It also has a very high value of JWB (23) and a very low value of ESS (1.4%). This means a ratio of 23 jobs available to 1 resident worker and approximately 98% of local jobs in the CBD are filled by non-resident workers. It is a heavily job-dominated zone with a wider worker catchment area, reflecting the monocentric spatial structure of job distribution in Perth.

The average inflow travel time to areas around the Fremantle line is also relatively high, mostly between 30 and 35 minutes. ESS is consistently low in this area (less than 1%). However, mixed values of high and low JWB appear in the area. This means some areas are job-dominated, while others are resident-dominated. These zones represent some of the oldest and most opulent suburbs in Perth with many grand residential structures. There is also a concentration of major health and academic facilities such as Sir Charles Gairdner hospital and Queen Elizabeth II Medical Centre, University of Western Australia (UWA) and a number of renowned private schools.

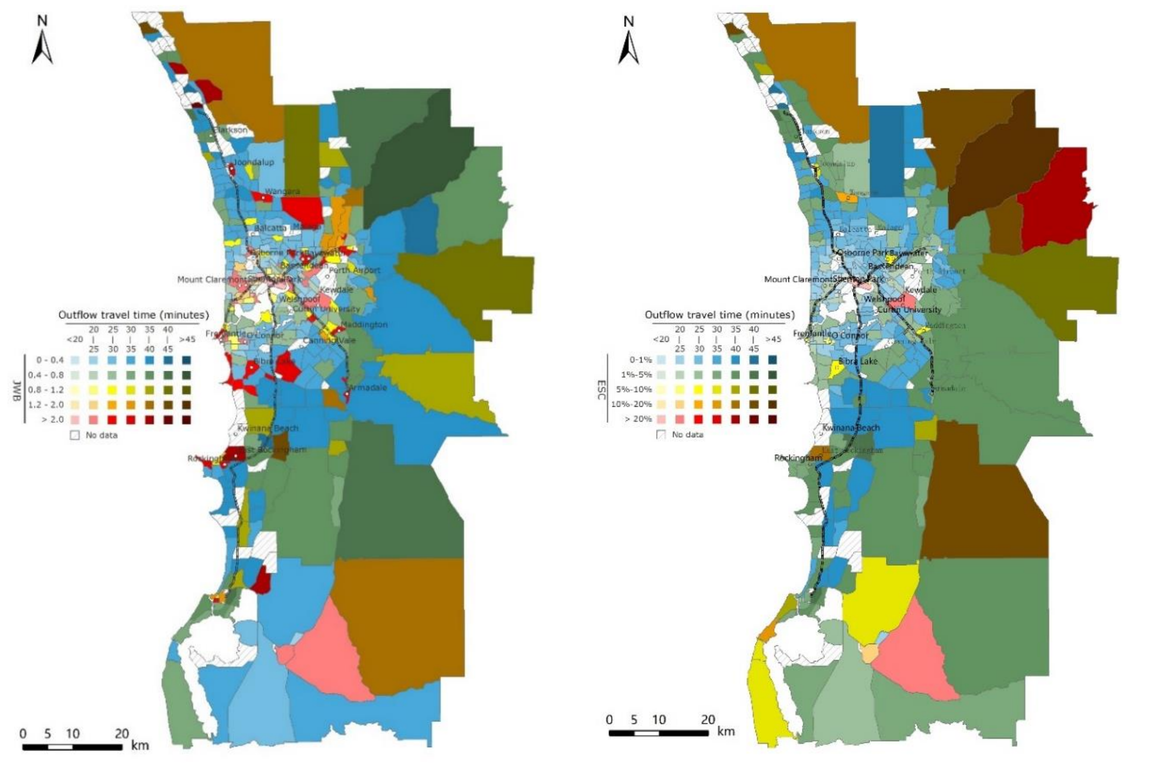
The riparian zones between the Swan River (north) and ocean, and Welshpool/Kewdale regions notably have inflow travel times ranging between 30 and 35 minutes. These areas also have very poor self-sufficiency (ESS = 0% - 5%). Interestingly, none of the five most self-sufficient zones have inflow travel times in the lowest bracket of less than 20 minutes.

Nevertheless, they - apart from one - do fall within the 30 minutes bracket. The size of these zones (outer zones are generally larger) could be the reason why they, despite having relatively higher ESS, do not have the lowest travel times in the region.

The job-worker balanced zones are distributed sparsely over the areas between job-dominated zones and resident-dominated zones. Their inflow travel times range between 25 and 30 minutes. The majority of these zones have relatively low ESS (0% - 5%), except for one, which is located at the edge of the PMR with an extensive boundary.



(A) Inflow travel time by JWB *(B) Inflow travel time by ESS*



(C) Outflow travel time by JWB *(D) Outflow travel time by ESC*

Figure 5.7: Spatial relationship between employment performance indices and travel time

Figure 5.7 (C and D) compares JWB and ESC against average outflow travel time. The majority of balanced areas (63%) are located along train lines and within 30 minutes outflow travel time. Unbalanced areas have a range of outflow travel times. Figure 5.7D demonstrates that higher ESC (>20%) have an average outflow travel times of less than 25 minutes. These zones include the CBD, major industrial areas and two outer Perth suburbs (Pinjarra and Chidlow). The lowest ESC is found in zones around the inner core (excluding the CBD zone), and these zones are evidently characterized by low outflow travel times. Self-containment data shows that the majority of resident workers in the PMR have to travel out of their local zones to work but their travel time becomes less if they live closer to the CBD. Nevertheless, all other zones in the outer suburbs have both low ESC and relatively longer outflow travel times (30 minutes or more), which is consistent with expectation.

5.5 DISCUSSION

This study has examined the degree and spatial patterns of JWB, ESS, ESC and inflow/outflow travel times using household travel data in the PMR, and has empirically examined the relationship between these three indices and inflow and outflow travel times across the region. The analysis reveals that the PMR has a poor JWB, with under 10% of zones being balanced. It also becomes apparent that these balanced areas do not necessarily have shorter commuting times. Resident-dominated zones had relatively shorter inflow travel times, but longer outflow travel times; while job-dominated zones had relatively longer inflow travel times and shorter outflow travel times. The travel times – both inflow and outflow – for the balanced zones were moderate (averaging 27 and 29 min, respectively). The results also demonstrate, and support the assertion, that higher ESS is associated with shorter inflow travel time. This is evident, for example, in the zones located in the far northern and southern coastal areas of the city, where the average inflow travel times were relatively shorter (<25 minutes) and the ESS was relatively high (ranging from 5% going to >20%). This suggests that local jobs may be filled by workers living within the zones or at least in the surrounding zones, thus keeping the travel times relatively low. On the other hand, the outflow travel times of these zones were relatively long, at over 30-40 minutes. This can be expected given the low ESC in these areas. These areas accommodate some Strategic Metropolitan Centres which are planned to generate significant employment opportunities and hence attract further attention to rethink on accessibility and inter-zonal networks. It is however, noted that the distribution of outflow travel time across the study area was not consistent with that of ESC, leading to the conclusion that there is no clear relationship between the two.

The spatial pattern of outflow travel time was a radial increase from the central core, showing a resemblance to the city's centralized public transport zoning system (see Figure 5.3B). This reflects the monocentric urban structure of Perth where commuting is characterized by "strong radial travel to CBD and high public transport use to central locations," (CfP, 2016, p. 47) (p. 47). However, the spatial pattern of inflow travel time indicates cold spots (areas with shorter travel time) around local and regional activity centres (e.g. Joondalup and Rockingham). This may show the effectiveness of decentralisation of jobs in reducing travel time.

The results have also shown that most of the zones are in the JWB category of 0-0.4 (40% of zones representing about 15% of trips) and >2 (25% of the zones representing 61% of trips). These zones are either highly residence-dominated or highly job-dominated with a very small portion of mixed land uses within the zones. Over 72% of zones containing 71%

of workers, have an ESS value of less than 5%. On the other hand, around 81% of zones containing about 96% workers, have ESC less than 5%. This indicates that a large number of people are living and working in different zones in the PMR. This could be ascribed to the increasing trend of suburbanisation and decentralized job locations leading to higher commuting flows across the regions (BIRTE, 2015). It suggests a spatial mismatch between jobs and residential locations as well as inter-regional disparity in terms of employment opportunities and housing provision (Ihlanfeldt, 1994; O'Connor & Healy, 2002). Although job decentralisation is a priority in Perth's urban planning and development system (Western Australian Planning Commission, 2018), it is proving difficult to relocate jobs from the central areas or move people into the job-dominated areas.

The findings of this study contribute to the growing debate on the effectiveness of JWB in tackling urban transportation problems and distribution of economic resources. A number of studies have suggested that a decentralisation of jobs that is accompanied by balancing the number of local jobs and worker residences may lead to shorter commuting (Gordon et al., 1989; Mark W Horner & Mefford, 2007; Ta et al., 2017). In effect, it may reduce general vehicle-miles travelled (Cervero & Duncan, 2006) and increase job opportunities close to the residents. Such strategies are inclined to take that opportunity to minimize disutility in a city's resource distribution policies (Geyer & Molayi, 2017). While others argue that living close to work may not be a priority for many people as a complex range of other factors may influence residential location choices, such as housing affordability, quality of neighbourhood and quality of schools (BIRTE, 2015; Cervero, 1995a; Genevieve Giuliano, 1991). Therefore, policies solely relied on balancing the number of jobs and workers in certain areas may not be effective in reducing commuting time.

The study has evaluated the three standard indices: JWB, ESS and ESC - for the PMR, as well as additional indices based on average travel times to work into each zone as well as from each zone. The production and assessment of these indices have raised a number of methodological issues. The first was discussed earlier in the chapter pertaining to the geographical scale chosen and associated MAUP. Dividing the study area into a few large zones would be likely to give better JWB, and potentially higher ESS and ESC levels than the results for the same area divided into many smaller zones, even though the underlying spatial distribution of jobs and workers remains the same. In addition, in the case of Perth (and likely in many other cities), zones tend to be selected based on the land use type and can be quite homogeneous. For example, a residential area would be one zone and an adjacent employment area a separate zone. This can result in poor JWB, ESS and ESC values for both zones. A different zone system that had, say, half the residential area and half the employment area in the same zone would give a different, and indeed better result.

ESS and ESC are essentially ratios of the work trips made within a zone to those entering or leaving that zone. In addition to being susceptible to the MAUP, they also provide no information on, and take no account of, the length of trips made outside the zone. They only count trips crossing the zone boundary, not where these trips are going to or coming from, e.g. whether 100 meters or 100 kilometres away. Figures 5.4 – 5.6 somewhat illustrate this problem, showing that zones within a given ESS or ESC band can have a wide range of average travel times. Hence, ESS and ESC provide no information on the external component of the trip. The JWB, ESS and ESC values derived for an area are very much a function of the zone system selected and therefore do not necessarily provide a reliable measurement of the efficiency of the work commute or the spatial balance between workers and jobs. The ability to reliably compare across a city, and indeed between cities, is therefore compromised. Additionally, containing trips is a difficult and complex task that both depends on and may lead to changes in the socio-economic make-up (e.g. wage levels) of the sub-regions due to the variety in commuting patterns of workers in different industries and occupations (Martinus & Biermann, 2018).

This chapter presents two additional indices, the average travel times to work into and out of the zones (inflow and outflow travel times). As these simply use travel times between zones they are far less sensitive to the selected zone system and hence MAUP. Changing the zone system has little impact other than changing the zonal travel times, (measured as zone centroid to zone centroid). In this case, reducing the zone size improves the accuracy of the results as travel times better represent all workers in a zone. Clearly, the indicators include time travelled outside the zone, removing the limitations of ESS and ESC. They also provide for more reliable and consistent measurement across a city and allow comparison between cities, largely independent and irrespective of the zone systems chosen.

Studies have previously identified some shortcomings of JWB and self-containment measures, where it was found that self-contained cities in Britain did not rely on sustainable modes of transport, but rather they were relatively auto-dependent. On the other hand, those towns that were less self-contained in France and Sweden had most of their external trips done by non-auto modes including rail (Cervero, 1995b). The findings further showed that the relationship between ESC and commuting time was an unexpected positive correlation, suggesting that self-containment does not lead to shorter travel times. While ESS and ESC measures might require more appropriately selected zones to allow for a good land use mix, there will always be some trips crossing the boundaries that are not fully accounted for. The above evidence suggests that policies aimed at directly cutting down commuting times for a majority of the commuters such as investment in fast rail transit and coordinated transit services may be more effective in reducing commuting times than self-containment initiatives. For cities with low density developments and low transit patronage such as Perth, densifying developments around transit stations has great potential to yield significant improvements by enabling more people to enjoy faster commutes by public transport.

The results of this study can provide insight to planners and policy makers in both large and growing cities pursuing commute reduction through JWB and trip containment objectives. City councils and governments relying on these measures should complement them with travel time (and/or other socio-economic factors) to increase their reliability and reflect a truer picture of the commuting situation.

5.6 SUMMARY AND CONCLUSION

This chapter sought to evaluate the levels of JWB, ESS and ESC in the PMR, assess their spatial patterns and examine their impact on commuting time. Using STEM zones as the geographic scale, it was found that the levels of all the three indices were rather poor/low across the region. The JWB analysis revealed that balanced zones were few and far between; only 9% were balanced. Most zones fell to the extremes; either highly residence-dominated (40% of zones) or highly job-dominated (25% of all zones). An overwhelming majority of zones are under 5% of both ESS and ESC, and only very few zones are above 20%.

For balanced zones, the majority of trips fell in the 25-30-minute bracket - over 50% for inflow trips and over 60% for outflow trips. However, the shortest inflow travel times were in residence-dominated zones (and not balanced zones), while job-dominated zones had longer inflow times. The outflow travel times, on the other hand, were longer in resident-dominated zones and shorter in job-dominated zones. The general relationship between ESS and travel time showed that inflow travel time gets shorter with an increase in ESS. The relationship between ESC and travel time was inconclusive. Outflow travel times were lowest in the CBD, a stark opposite to inflow times. Also, most zones (apart from the CBD) had longer outflow than inflow travel times. Overall, the inflow travel times were not too high (most were under 35 minutes), considering the rather poor levels of JWB and ESS across the entire metropolitan region.

Findings of this study show that while trip data can accurately reveal the patterns of JWB, ESS and ESC, these measures themselves do not give a complete picture of the level of commuting. Due to their failure to account for the external part of the trip, planning policies relying on these measures 1) could lead to a misdiagnosis of the commuting situation, and/or 2) may not lead to the desired commute reduction. The proposed additional travel time indices address the above issues and are considered to be more reliable indicators of the efficiency of the work commute. Thus, this study recommends that planning policy that relies on these measures also incorporates a component that accounts for the part of trip that is outside the zone, such as travel time, to better represent the commuting situation. Future studies should explore these indices in more cities and a wider variability of land uses to refine these results and enable generalisation to a wider variety of contexts.

The next chapter will evaluate Perth's employment decentralisation agenda as a means of improving the city's spatial efficiency. The employment projections and targets for subregions and activity centres will be critically reviewed, and a suitable/potential location for a primary centre will be identified.

CHAPTER 6 OPTIMISATION OF EMPLOYMENT DECETRALISATION THROUGH DENSITY AND ACCESSIBILITY

This chapter consists of research that has been published in Kelobonye, Xia, et al. (2019a).

6.1 INTRODUCTION

The previous chapter investigated the effectiveness of employment self-sufficiency measures in reducing commuting time. This chapter presents the second component of the thesis that analyses spatial efficiency from a functional perspective. Evidence from the literature has shown that intensification and densification of population and land use have a direct influence on travel demand (Chatman, 2008). This chapter employs density and accessibility indicators to analyse Perth's employment decentralisation policy. The sufficiency of the employment targets set for activity centres are investigated through estimating the potential improvement in job accessibility that they could generate. An ideal location for a primary centre is identified from the currently designated strategic centres using their catchment area density and accessibility rankings.

6.2 RESEARCH CONTEXT

While urban populations are continually increasing and pushing suburban expansions, employment opportunities often remain concentrated in central business districts (Australian Bureau of Statistics, 2016; Weller, 2009). This has led many cities around the world to experience rising challenges of excessive commuting and inner-city congestion. Owing to their threat to the environmental, social and economic sustainability of urban areas, these challenges are increasingly taking the centre stage of planning and development policy. Employment decentralisation is often promoted as a solution to these challenges, through creating a scenario of cross-commuting to multiple work destinations, well connected by public transport (PT). Decentralisation aims to decongest the central core, correct fundamental land use imbalances and bring jobs closer to the people (Frémont, 1993; McCarney & Biermann, 2016).

In Perth, the central subregion hosts 64% of the total metropolitan employment while only about 40% of workers live here. The CBD and its surrounds account for 15% of total jobs in the metropolitan area but is residence to only 2% of workers (Western Australian Planning Commission, 2018). While these numbers may not portray a highly centralised structure, they undeniably engender a high level of commuting into the central subregion and the CBD in particular. As with other major Australian cities, such as Sydney and Brisbane (Burke, Li, & Dodson, 2010), Perth has developed a major program of encouraging job growth outside of the CBD areas and in the suburban-based sub-centres. The Western Australian government has identified areas in the suburbs where employment concentration, high-density development and PT coverage will be promoted to minimise commuting – termed as activity centres (ACs) (Western Australian Planning Commission, 2010b). ACs can be defined as hubs that host a variety of activities such as working, living, shopping and studying (Western Australian Planning Commission, 2010a), and have a higher employment concentration than the areas surrounding them (Casello & Smith, 2006). The ACs, which include both existing and proposed, are in the categories/levels of; capital city, strategic metropolitan centres, secondary centres, district centres, neighbourhood centres and specialised centres. The planning document (Perth and Peel @ 3.5 million) has made projections for the number of jobs to be located in each sub-region and set specific employment targets to be achieved in strategic, secondary and specialised ACs when Perth's population reaches 3.5 million (by 2050). In the AC hierarchy, there are 10 strategic metropolitan centres (including one proposed). Interestingly, none of the centres, either existing or proposed, has been designated a primary centre (yet). Some of the strategic centres are expected to emerge into primary centres. However, the AC policy neither identifies the centres nor indicates how they will be identified for potential development into primary centres.

A primary centre would be just below the capital city in the hierarchy. It would be a dominant employment area and would serve a sub-regional catchment much larger than the strategic centres, but self-contained to reduce the number and length of trips. The analysis of this chapter focuses on the strategic metropolitan centres, from which the policy indicates that a primary centre will be identified and developed. Given the morphology of Perth and its obvious north-south divide, perhaps a minimum of two primary centres would be ideal to enable a greater level of self-containment, (and reduce the need to cross the Swan River with its limited number of crossings). This, however, can start with identifying and prioritising development of one in the short to medium term.

McCarney and Biermann (2016) note that decentralised employment has been a common feature in a series of strategic spatial plans but ACs have not developed at anticipated levels. Decentralisation requires understanding business location decisions, and developing implementable and effective strategies. Two indicators are employed, which can be considered as both a requirement and objective or yardstick for a successful decentralisation process; density and accessibility. It can be argued that density is a factor of accessibility because it can be a reflection of the increasing value of locations with better accessibility. “As residential areas become denser, more residents experience the local accessibility; as employment areas become denser, more jobs can be accessed through the same road and highway network” (Owen et al., 2017, p. 13). Therefore, achieving high densities in less accessible areas could disadvantage large numbers of people. Meanwhile, low density can be a hindrance to the attraction of businesses in the sub-centres because it affords businesses a smaller customer base and potential labour pool, and has been linked to lower productivity (Alonso, 1971; Marelli, 1981; Segal, 1976). In Figure 3.4, for instance, scenario 2 presents an opportunity case; to raise density to capitalise on the high accessibility, but scenario 3 presents a problem case needing immediate attention as a high number of people suffer the poor accessibility.

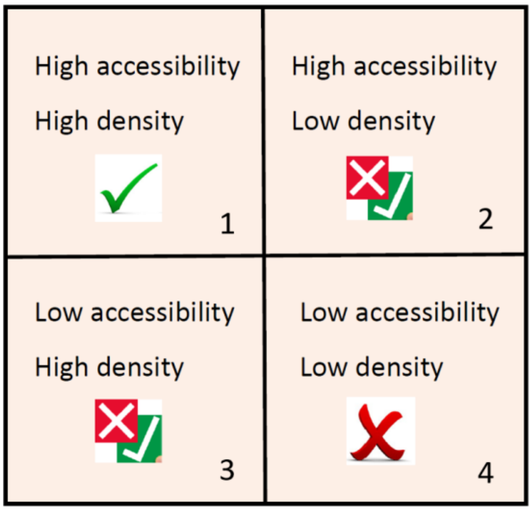


Figure 6.1: The different accessibility and density scenarios

This chapter examines worker density around a selection of four ACs, and their respective job accessibility levels. While a few researchers have examined policy targets against implementation progress (in the Perth Metropolitan Region - PMR), the focus of this chapter is on the targets themselves; are they sufficient? All else being equal, if employment targets for ACs were achieved, what would be the impact on accessibility and its spatial equity? Therefore, transport networks and systems, traffic conditions and travel times are assumed to remain the same. This chapter further contributes to the empirical literature on the decentralisation agenda by evaluating the sufficiency of the *Perth and Peel@ 3.5 million* employment targets for ACs. An investigation of the potential improvements in job accessibility and spatial equity is performed to demonstrate potential impact of the resultant job distribution pattern. The study performs worker density and catchment area analyses to identify, from the existing strategic centres, a potential primary centre for development prioritisation in the short to medium term.

6.3 LABOUR DENSITY AND CATCHMENT AREAS OF ACTIVITY CENTRES

In this section the spatial distributions of job and worker densities across the PMR (Figure 6.1) are examined, as well as the worker density (measured by place of residence) within the catchment areas of selected ACs (Figures. 6.2 and 6.3).

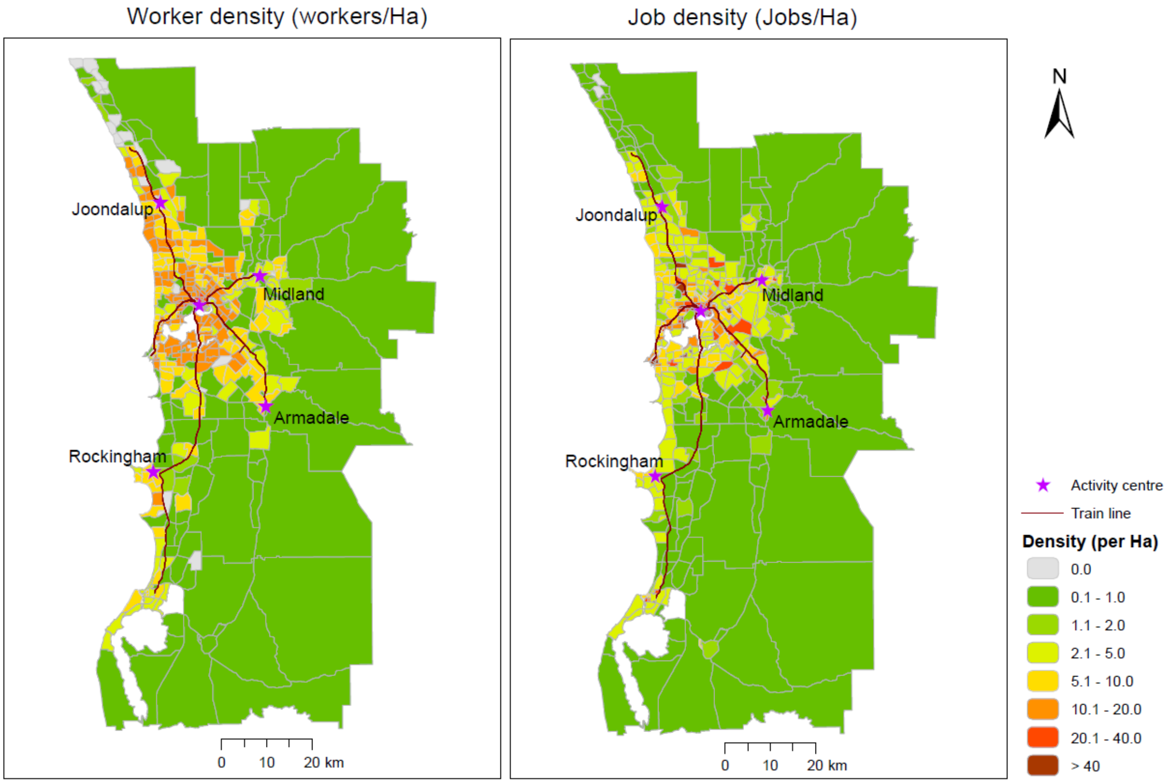


Figure 6.2: Worker and Job density spatial distribution

Higher worker density is found in the inner zones but it spreads further out than the job density distribution, which is more concentrated in fewer zones. Farther from the city centre, higher worker density seems to be closer to the passenger train lines. More jobs added in these zones could benefit the firms with a wider labour pool close by, and promote PT-based job accessibility. Save for the few zones in and around the CBD area (all north of the Swan River), all zones have a worker density of less than 20 workers per hectare. Job density is obviously very high in the CBD. There are also noticeable spots of high job density, albeit to a lesser extent, in a few other zones which include some notable employment attractions such as the Welshpool, Kewdale and Canning Vale industrial areas, QEII, Curtin University, and the big shopping/activity centres in Cannington, Midland, Morley, Stirling and Joondalup. All these zones have over 20 jobs per hectare. These results reflect the high concentration of jobs in the inner zones and the outspreading low-density population.

6.3.1 Selection of activity centres

The focus is directed on four strategic metropolitan centres for catchment area analysis and further appraisal to identify a potential primary centre, which is currently missing in the existing centres and undesignated in the future plan. The four centres are Joondalup, Midland, Rockingham and Armadale; selected for a number of reasons which mainly centre on their location. Starting with what they have in common: 1) they are outside the central subregion which hosts the majority of jobs and is a major importer of labour – thus their growth could alleviate pressure on the central subregion; 2) they are reasonably distant from the city centre which gives them greater potential to change the overall travel patterns within the metropolitan area, particularly reducing traffic on the city-bound network routes; and 3) they are connected to the existing rail network which is a significant factor in promoting PT access. These locational characteristics make the selected centres good candidates for development into a primary centre. The four centres were also selected for their variety in locational characteristics: 1) two of them are along the main corridor of the city's north-south expansion (Joondalup and Rockingham) while the other two are on the eastern edge beyond which not much of the city's expansion will occur; and 2) two are on the northern side of the CBD (and the Swan river) (Joondalup and Midland) whereas the other two are on the south. The even spatial distribution of these centres provides a good opportunity to improve the spatial equity of access to amenities across the metropolitan region.

6.3.2 Worker density of catchment areas

Catchment areas of the four selected strategic ACs were identified based on car and PT travel times. A catchment area is defined by all zones from which the AC zone can be reached within the threshold time i.e. AC is the destination. The catchment areas differ in size and geographic coverage depending on whether the travel mode is car or PT. The spatial patterns of worker density within the catchment areas of each AC have also been indicated. The car-based threshold time used was 30mins while the PT-based one was 45mins. The main reason for this is that the PT catchment areas covered a very small area/number of zones in 30mins. A longer travel time for PT could also be justified by the utility value of a PT trip i.e. passengers may be able to use the time spent on the bus/train for other things such as on the phone or laptop.

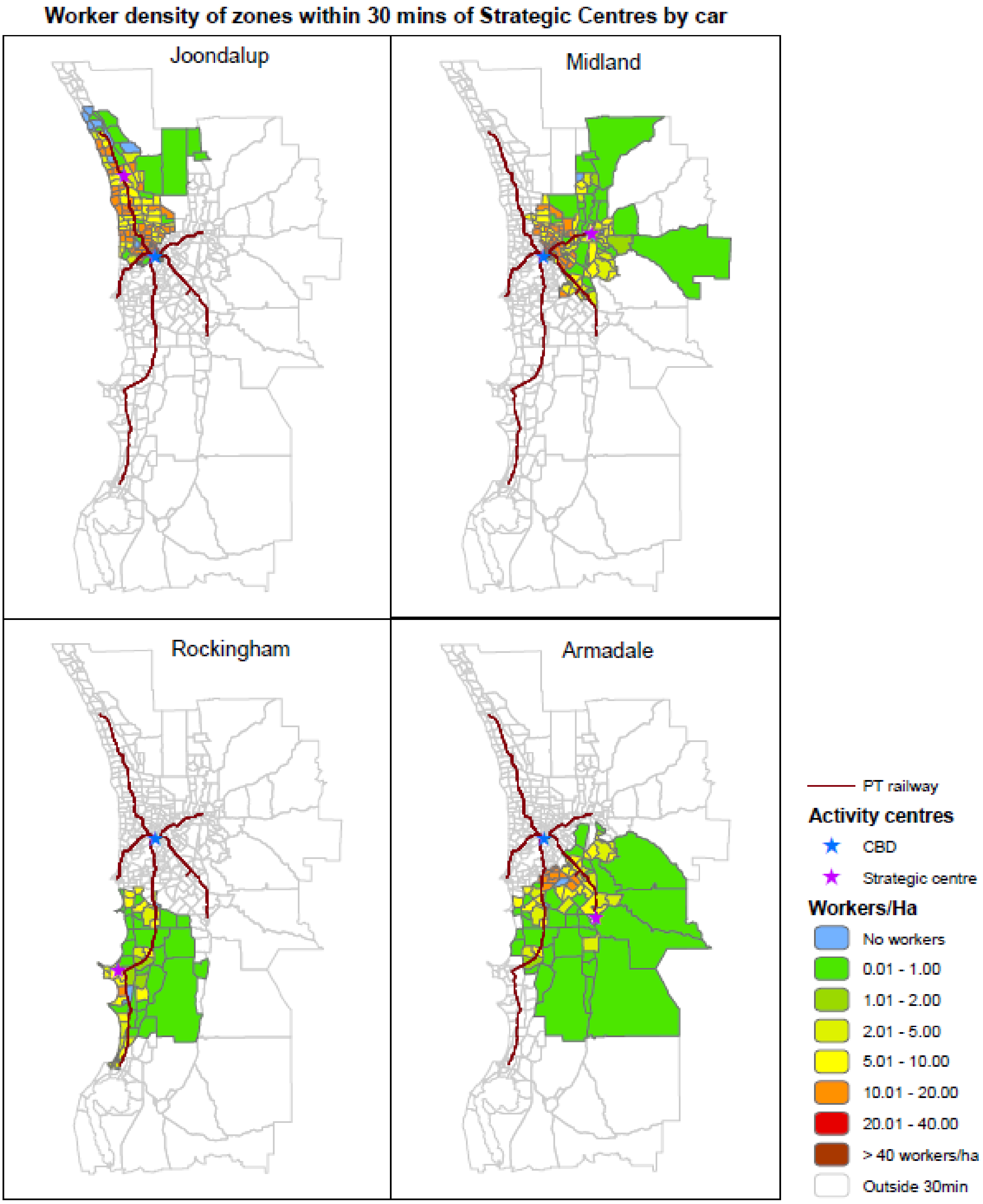


Figure 6.3: Catchment areas of ACs' labour pool (access to workers) within a 30 min drive

The car enables a fairly balanced catchment area from all directions (Figure 6.2). The ACs are largely surrounded by zones of low density, while higher-density zones are farther from the ACs. Midland and Armadale have most of the labour force located mainly on one side of the AC, with far fewer people living on the side closer to the fringes of the city's built-up area. Thus, even though the car enables access from these areas, the ACs effectively only have 'half catchments' of labour pool. Moreover, the city's eastward expansion is curtailed, so it is not expected that worker density will improve evenly across the catchment areas. In contrast, Joondalup and Rockingham lie on the main corridor along which population growth is projected stretching north and south.

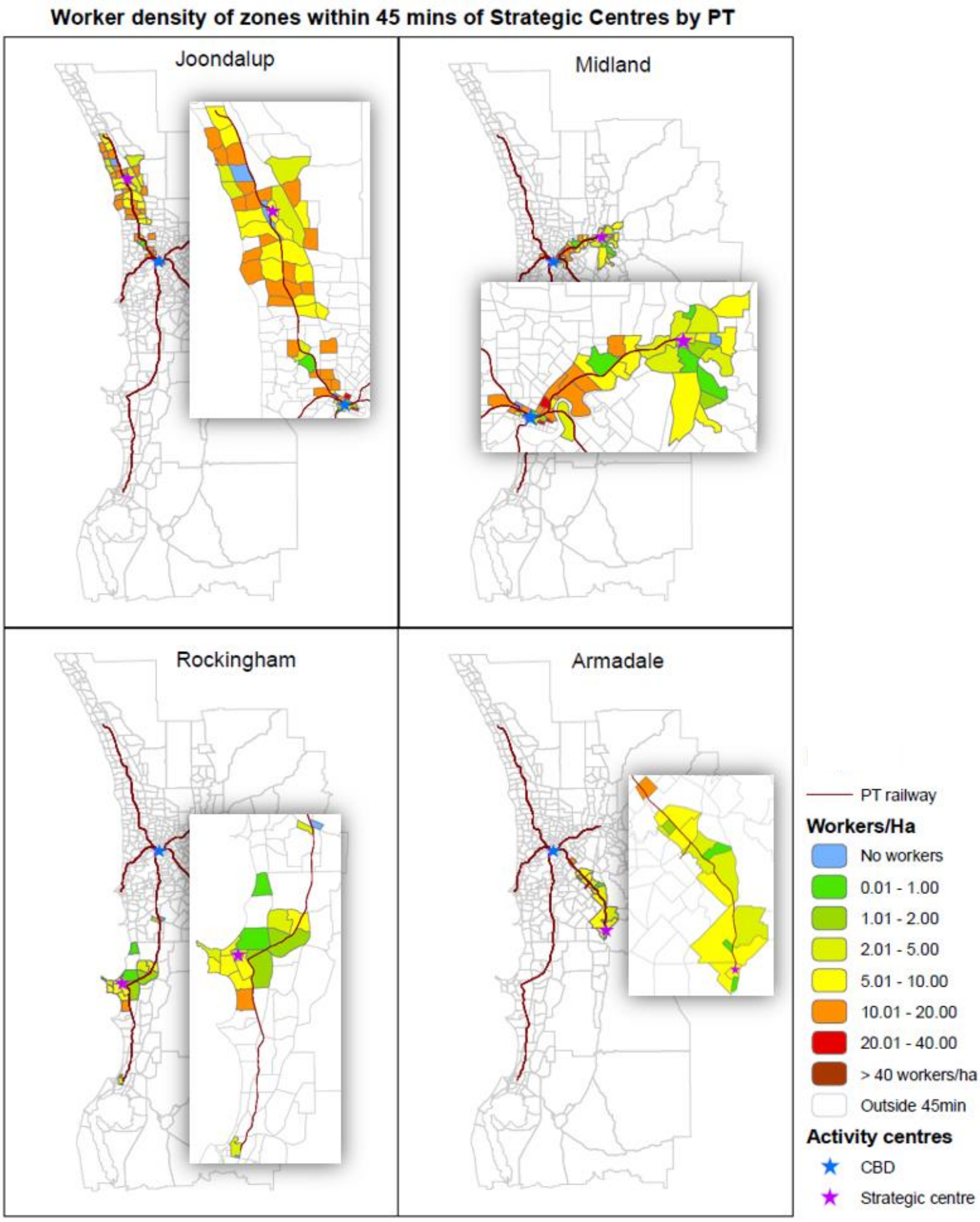


Figure 6.4: Catchment areas of ACs' labour pool within 45 min by public transport

Despite the PT threshold being set at a longer 45 min travel time, the PT catchment areas (Figure 6.3) are much smaller than those based on car travel time. While this is general testament to the inferiority of PT versus private car in Perth's accessibility maps, it also evidences, in particular, the low accessibility provided by PT in the outer areas relative to the CBD. A strikingly obvious pattern about these catchment areas is their alignment with the train lines, which highlights the value of the train in providing PT-based accessibility to the ACs. The Armadale AC catchment area even ends only a short distance beyond the railway terminal. The upcoming 8km extension of the Armadale Line to Byford under the METRONET Project (Australian Government, 2018) could therefore play a critical role of widening the catchment area of the Armadale AC and improving its accessibility. The low density around this area, however, is a challenge that should be taken note of. In fact, for all four ACs, the PT catchment area leaves out many higher-density zones that are covered by the car catchment area. This might indicate a possible discrepancy between the location of ACs and the desired residential locations, which in turn could reinforce car reliance at the expense of sustainable modes like walking, cycling and PT. Meanwhile, the low density in PT catchment areas could hinder the attainment of sufficient patronage levels, thus posing a challenge to the sustenance of PT services in the medium to long term.

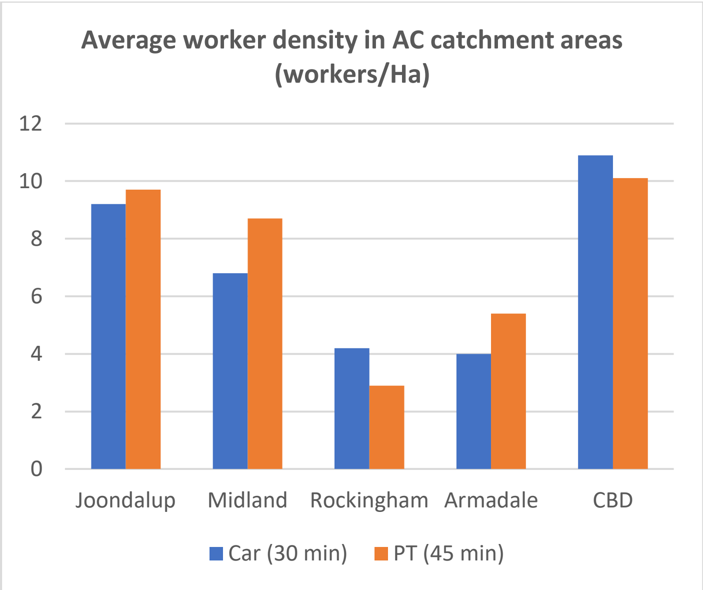


Figure 6.5: Average worker density in AC catchment areas

Table 6.1: Total number of workers living in activity centre catchment areas

Activity Centre	Number of workers within catchment area	
	Car (30min)	PT (45min)
Joondalup	333,897	155,658
Midland	266,901	60,000
Armadale	225,723	49,287
Rockingham	113,963	41,950
CBD	248,547	332,264

Average worker densities within the four ACs' catchment areas were also computed and compared (Figure 6.4). The CBD is also provided as a benchmark (using example of one of the 34 zones making up the CBD (zone 171 – selected due to its central location in the CBD). An interesting result here is that the average densities around the four centres are higher in PT catchments than in car catchment areas (except only at Rockingham). This is because even though the car catchments cover more higher-density zones, they are larger and so also include zones with very low worker density. The highest average density among the four centres is in the Joondalup catchment area, followed by Midland, both by PT and car. For Midland and Armadale, the car provides access over a much larger catchment, but the eastern parts of these catchments are under-populated areas (Figure 6.2). Thus, the average densities in car catchment areas for these two centres are much lower than those in PT catchment areas i.e. there is greatest discrepancy in their average densities (Figure 6.4). Note that these two centres are served by terminal train stations, hence it could be argued that they have half catchments by PT (since the train clearly has great influence in shaping the PT maps). In terms of total populations, all car-based catchments had at least twice as many workers as the PT catchment areas, with Joondalup topping the list under both travel modes (see Table 6.1). Interestingly, this is an opposite trend to that exhibited by the CBD, where the PT catchment area has more people than the car catchment area. This shows that although the car is a popular mode of travel for work commute in Perth, it is not as effective as PT in accessing CBD-based jobs. In fact, the CBD falls behind Joondalup and Midland in terms of the number of workers within its car catchment area. The low density in the AC catchment areas indicates that there is potential for adding more houses/workers.

6.4 POTENTIAL JOB ACCESSIBILITY IMPROVEMENT FROM THE EMPLOYMENT TARGETS

6.4.1 Measurement of accessibility

While accessibility can have many definitions and methods of measurement, it is defined here as "the number of job opportunities that can be reached from a zone within a given travel time threshold". Thus, the more job opportunities that can be reached from a zone the better accessibility that zone is deemed to have (Owen et al., 2017; Sun et al., 2017). Thus, accessibility here is calculated as:

$$A_i = \begin{cases} \sum_j a\,,\ if\ t_{ij} \leq k, \\ 0,\ if\ t_{ij} > k, \end{cases} \tag{6.1}$$

where a is the number of job opportunities in zone j, t_{ij} is the travel time from home zone i to zone j, and k is the travel time threshold within which jobs are deemed to be accessible.

6.4.2 Changes in job accessibility

The spatial distribution of job accessibility across the metropolitan area shows clear spatial inequity between the city centre and outer suburbs (Figure 6.5). Decentralising employment from the city centre and concentrating more jobs in ACs is expected to improve job accessibility for residents of the outer suburbs, creating a more even spatial distribution, and hence, better spatial equity of job accessibility. This in turn should reduce excess commuting particularly to the CBD, contributing to better travel efficiency overall. Figure 6.5(a) presents the spatial pattern of job accessibility throughout the metropolitan region as it was in 2011. In Figure 6.5(b), the target numbers of jobs for all ACs in 2050 (after the implementation of *Perth and Peel @ 3.5 Million*) were added to determine the level of improvements in job accessibility for the outer sub-regions. Due to data restrictions, the model's 2011 travel time estimates were used for modelling future accessibility. While this does not account for the planned road network improvements, it can reveal the expected employment distribution and provides a good basis to assessing potential accessibility changes. We should expect to see visible hotspots develop around ACs in 2050, reflecting the concentration of jobs in those areas, and consequent improvement in job accessibility. Given that there is no growth target for the CBD, we also expect to see a reduction in the CBD dominance, and accessibility levels evening out to ACs. Note that job accessibility here is based on car travel times, which is the most efficient travel mode in Perth and is used for the majority (almost 80%) of trips to work (Australian Bureau of Statistics, 2017).

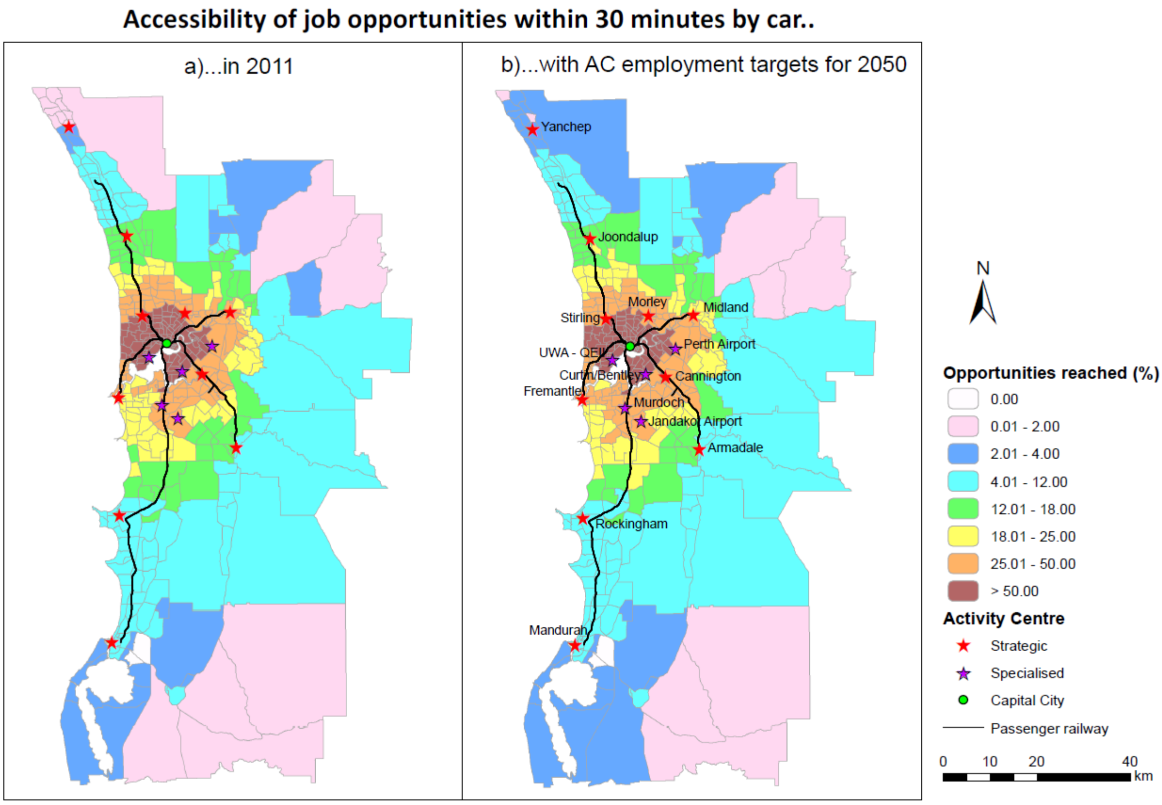


Figure 6.6: Impact of the Perth and Peel@3.5 million employment targets on accessibility

The 2011 results showed that some zones located in the central subregion could provide access to almost 80% of total metropolitan jobs within 30 minutes drive time. Only two of the 10 strategic centres had an accessibility of more than 50% (Morley, 53.4% and Stirling 52.6%), and both are in the central subregion and on the northern side of the river. Job accessibility from ACs is important for the anticipated growing number of people living there, as they are to host high-density residences (Western Australian Planning Commission, 2010b).

After adding employment targets for all existing strategic, specialised and secondary centres, car-based job accessibility in 30 minutes was recalculated. Assuming other factors remain the same, this shows the spatial pattern of accessibility and its equity, or lack thereof, that will be attained in 2050. It should be noted that this is a simplified approach that could be improved by future travel time estimates which will differ from current ones due to population growth, transport investments and changing traffic conditions. Although preliminary, the results of this task can provide a good indicator of future accessibility for these centres and guide planning and spatial distribution of jobs and workers.

Interestingly, the improvement from 2011 is almost unnoticeable (Figures. 6.5(a) and (b)).

The most obvious improvement is on the immediate south of the Swan River, west of the Mandurah line. Slight decline in the central-area dominance and improvement along the Armadale line are also visible. Of the four selected ACs, Joondalup and Rockingham experience a slight improvement, while Midland and Armadale see a decline in their levels of job accessibility (as a proportion of total jobs in the metropolitan region) (see Table 6.2). Therefore, the current employment targets, while they may seem radical to some, are actually not that different from business-as-usual, and will have little impact overall. Given that the employment base in the metropolitan region is projected to almost double by 2050, and numbers in other areas will also inevitably increase, including in the CBD itself, ACs can, and need to, add significantly more than double their current employment sizes to become competitive sub-centres that can improve accessibility in the outer subregions and impact on Perth's monocentric and dispersed spatial structure.

Table 6.2: Job accessibility comparison for strategic activity centres between 2011 and 2050

Activity centre	Accessibility in 2011 (%)	Accessibility in 2050 (%)*
Stirling	52.6	48.94
Morley	53.36	48.38
Cannington	42.21	42.42
Fremantle	23.08	26.71
Midland	26.87	25.46
Joondalup	13.78	14.92
Armadale	13.26	12.1
Rockingham	8.22	8.37
Mandurah	5.46	5.89
Yanchep	2.43	3.15

*table sorted by this column

6.5 A CRITICAL REVIEW OF POLICY EMPLOYMENT TARGETS: THE SPACE BEHIND THE NUMBERS

The metropolitan region is projected to double its employment base to 1.7 million jobs by 2050, from an estimated 0.85 million in 2011 (Western Australian Planning Commission, 2018). The Perth and Peel @3.5 million makes projections for employment growth according to four major subregions;- South Metropolitan Peel (consisting of South West, South East and Peel), North West, North East and Central sub-regions (see Figure 3.1). It further makes specific employment targets for ACs, where jobs are aimed to be concentrated. Comparing these targets to the wider subregional projections, however, suggests that jobs will actually not be concentrated in ACs. For instance, the North-West subregion is projected to have an additional 143,560 jobs by 2050 (Table 6.3), but only about 17% of these will be in strategic centres (Joondalup and Yanchep) while 18% will be shared between the six secondary centres. This leaves 65% of additional jobs in the sub-region to be located anywhere but in the areas planned for intensive densification and high accessibility.

In the North-East sub-region, only about 9% of additional jobs will be in the only strategic centre in the sub-region (Midland). The secondary centres will share about 4%, meaning that about 87% will not be in a major AC. The South Metropolitan Peel sub-region will grow the most with 293,750 new jobs, a 204% change from 2011. However, the three strategic centres in this sub-region (Armadale, Rockingham and Mandurah) will share about 5% (14,460) of the new jobs. The six secondary centres will share 9%. Thus, 253,370 (86%) of additional jobs in South Metropolitan Peel will be in neither a strategic nor secondary centre.

The Central sub-region, while it is projected to add more jobs than North-East and North-West (285,840), will have the least growth with a total change of only 52%. This is a welcome projection as the central dominance is sought to be reduced. However, as with the other sub-regions, major centres will host only a small share of the additional jobs. The four strategic centres will take a combined 6% of additional jobs. The eight secondary centres will share 7% of the subregion's job growth between them. This sub-region also has five Specialised centres, targeted to host a combined 19% of the additional jobs. Thus, about 32% of additional jobs in the Central sub-region will be in strategic, secondary or specialised centres. There are also 10 industrial centres which together are projected to contribute 33% of the new jobs in this sub-region. It is a notable observation that the strategic planning document makes no specific projections for the CBD, which will undoubtedly take a sizeable portion of job growth in this sub-region. It is therefore unclear how the remaining 36% (103,041) will be distributed across the sub-region. However, the more these jobs are spread to other centres (than the CBD) the better for the spatial equity of opportunities, as well as their accessibility (because the CBD is already congested and the ACs will get increasingly better access). It is noted that the CBD has the best level of PT access at a regional level and putting these additional jobs in other locations may well reduce PT access – but may improve car access. A decentralisation agenda that strengthens concentration in ACs could minimise this effect and give PT the best chance of competing with the car.

The 2050 vision entailed in the Perth and Peel@ 3.5 million presents a good opportunity to decongest the inner city and drive towards a polycentric urban structure and spatially equitable accessibility, but this opportunity will be lost if more effort is not directed towards growing the job share of ACs. While the ACs are not (currently) in the most accessible zones, they are anticipated to be anchors of future growth and their accessibility is expected to improve significantly as the transport infrastructure and services will be added or improved specifically to service them. Thus, by not adding a larger share of jobs to these areas, the opportunity to harness the benefits of these investments, and to improve accessibility in the sub-regions, will also be lost.

Table 6.3: Jobs by sub-region 2011-2050 and respective share of strategic centres (adapted from PnP @3.5 mil)

Sub-region	Jobs		Total change	Total % change	Jobs added in ACs	Growth share in ACs*
	2011	2050				
Central	546,120	831,960	**285,840**	52%	103,041	**63.95%**
North-East	82,380	192,950	**110,570**	134%	14,440	**13.06%**
North-West	80,570	224,130	**143,560**	178.2%	50,200	**34.97%**
South Metropolitan Peel	143,970	437,730	**293,750**	204%	25,810	**8.79%**

*This column shows the proportion of new jobs in activity centres (strategic, specialised and secondary centres).

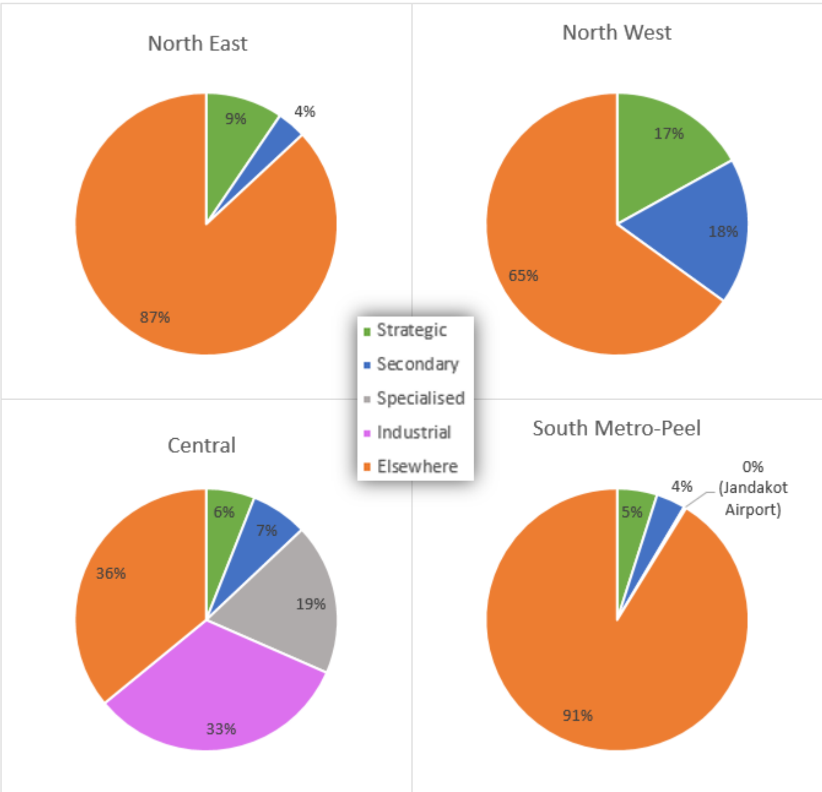


Figure 6.7: Share of projected subregional jobs located at ACs

Figure 6.7 illustrates that the projected job shares of ACs will be quite low among all the four subregional frameworks. Given the large proportions of jobs expected to be in the subregions but not in ACs, it can be predicted that the plan would deliver a dispersed structure rather than a polycentric one. This will bring a serious challenge to the accessibility of those jobs, particularly by PT whose coverage is quite limited in the suburbs. Therefore, this growth pattern is likely to reinforce reliance on the undesired private car as the only viable travel option outside of ACs. Indeed, labour productivity, agglomeration benefits and the efficient performance of the urban structure will be imperilled.

6.6 CHAPTER SUMMARY

This chapter evaluated the urban spatial structure of the Perth Metropolitan Region with respect to its transformation into a polycentric structure. This was done through an investigation of the city's employment decentralisation agenda, using density and accessibility indicators. Using these indicators, strategic centres were scored and ranked to aid the process of identifying the best suited for development into a primary centre. The ability of the suburban areas to support the ACs was investigated by identifying the catchment areas of selected strategic centres and determining their labour densities. The sufficiency of the policy employment targets for ACs was also critically evaluated through predictive accessibility assessment.

The results show that the catchment areas based on PT travel times were significantly smaller than those of private car, despite having a threshold of 45 min as opposed to the 30 min for car. However, the average labour density was higher within the PT catchment areas in three of the four selected ACs (except Rockingham). Labour density is higher closer to the train lines, and the PT catchment areas are also closely aligned to the railway, which explains their higher average when compared to car-based catchment area densities. Joondalup strategic centre had the highest labour density in both PT and car catchment areas, and most expected improvement in job accessibility compared to the other three selected strategic centres. Midland had the highest accessibility (both current and projected) among the four ACs, and this is mainly due to its proximity to the job-rich central subregion. Midland and Armadale have limited growth potential on their eastern side, and are therefore not best suited for primary centre development. Thus, Joondalup is recommended as having the best potential and being most suited for prioritisation and development into a primary centre in the short to medium term.

The results of this work further suggest that the employment targets for ACs from the projections of Perth and Peel@ 3.5 million will have little impact on job accessibility in the outer subregions. The central subregion will retain its dominance of the job share and overwhelming accessibility advantage. For many of the ACs, the projections indicate a lower growth rate than the overall growth in their respective subregions, and indeed in the entire metropolitan region. This trend more likely reflects 'scatteration' rather than employment concentration in ACs. This will exacerbate rather than alleviate challenges of poor accessibility in the outer subregions (accessibility inequity), particularly by PT. Employment targets for ACs need to be higher and more radical in order to create competitive employment hubs, maximise PT accessibility and transform the city to a multi-destination, polycentric urban spatial structure.

It is worth noting that while decentralising jobs can improve opportunities near suburban residents, it could also reduce accessibility by PT due to limited coverage in the suburbs compared to the CBD. This is because PT accessibility in Perth is highest in the CBD. In the suburbs, ACs are relatively well connected to the PT network and should host majority of suburban jobs to maintain good PT accessibility. Failure to adopt appropriate employment targets and residential densities for ACs will create, at best, low-density, dispersed commercial districts that can only be accessed by car. A notable limitation of this study is in the use of current travel time estimates in the projected job accessibility maps, which do not account for future improvements to road and PT infrastructure and services. The results are also dependent on the STEM zones used for this analysis (the MAUP).

The next chapter continues the theme of optimising employment decentralisation by proposing a new measure for identifying and evaluating ACs. An effective density-based measure is proposed to replace the commonly used accessibility measure, as it incorporates both the scale/size and transport/proximity dimensions without any additional data requirements. It can therefore reflect potential for agglomeration externalities, which is important to firms/businesses. In the next chapter, both measures are applied in the PMR, and variations in their results are examined.

CHAPTER 7 OPTIMISATION OF EMPLOYMENT DECENTRALISATION THROUGH EFFECTIVE DENSITY

7.1 INTRODUCTION

The previous chapter evaluated the sufficiency of the employment targets provided in Perth's job decentralisation targets, and identified a potential primary centre using density and accessibility indicators. The decisions of locating and prioritising the additional centres are often based on an accessibility score, leaving out other essential factors such as the spatial variations of labour density and agglomeration externalities. In this chapter, the validity of using an accessibility score to prioritise activity centres is examined and tested against an effective density-based measure. The chapter proposes an effective density measure for evaluating and deciding the prioritisation of activity centres, which can be used to guide their order of development in phases.

7.2 RESEARCH CONTEXT

The spatial structure of cities has been steadily changing over recent decades. The traditional monocentric structure which was the standard image of a city has gradually become obsolete (Evert J Meijers & Burger, 2010). Many cities in Australia, Europe and America are pursuing a decentralisation agenda to reduce the absolute dominance of a single urban core, by particularly nurturing job growth in suburban centres. A stronger growth in suburban centres (compared to city centre) has already been noted in European and American settings, leading to a rise in suburban urbanisation economies and a dominance of inter-suburb commuting (Garcia-López & Muñiz, 2010; S. Lee, Seo, & Webster, 2006). Advances and investments in transport infrastructure, technology and telecommunication are increasingly negating the benefits of agglomeration (Anas, 1998), while offsetting the diseconomies (e.g. high land rent and congestion). Meanwhile, the rising challenges associated with large monocentric cities, such as excessive commutes, inner city congestion and accessibility inequity, impede their productivity, efficiency and sustainability (C. Kim & Choi, 2019; Todd Litman & Burwell, 2006). Therefore, the validity of agglomeration economies, which led to the formation and growth of monocentric spatial structures, has been a subject of theoretical discussion (Garcia-López & Muñiz, 2010; Gordon & Richardson, 1996).

Even though the polycentric city structure is certainly becoming more evident in the 21st century, a polarising debate remains about whether it is the appropriate answer to the efficiency and sustainability challenges of the modern and future city. There is a body of literature in urban economics that suggests that decentralisation threatens the productivity and efficient performance of cities through the loss of agglomeration economies. In separate studies of American cities, Alonso (1971) and Segal (1976) found that productivity was significantly higher in larger centres. Marelli (1981) found that productivity was positively correlated with size, but only up to a certain threshold before it starts to decrease. On the other hand, Evert J Meijers and Burger (2010) noted a positive relationship between polycentricity and higher labour productivity. T. Zhang et al. (2017) reported similar findings on Chinese cities, where the polycentric urban spatial structure was found to be associated with better economic performance. Another recent study of metropolitan labour productivity in the USA found polycentric metropolitan areas to have higher agglomeration economies than monocentric ones (E.J. Meijers, 2013). This is because cities in a polycentric structure can ‘borrow size’ from each other which ‘regionalises’ agglomeration advantages, while diseconomies of agglomeration remain more localised (E.J. Meijers, 2013).

Polycentric urban developments are increasingly deemed desirable with claims that they could generate greater agglomeration externalities, while also delivering on the goals of economic, social and environmental sustainability (Parr, 2004). Nevertheless, some critics have posited that policentricity is just a transitional stage from monocentricity to a rather amorphous and unstructured urban form – 'scatteration' (Gordon & Richardson, 1996). The premise of this argument is that with distance becoming less and less important (due to transport and communication improvements), employment clustering becomes ever less necessary (Gordon & Richardson, 1996; Lang, 2003). Many empirical studies, such as those by Kloosterman and Lambregts (2001) Leslie and HUallacháin (2006), Genevieve Giuliano, Redfearn, Agarwal, Li, and Zhuang (2007) and T. Zhang et al. (2017) have provided strong evidence to the contrary, highlighting both the existence, as well as the economic benefits, of sub-centres from a decentralisation process. Thus, an increasing number of cities are nurturing development of suburban-based sub-centres to balance out or reduce the dominance of CBDs.

The central subregion and CBD in Perth, Australia host about 64% and 15% of all metropolitan jobs, respectively, while only about 40% and 2% of workers live here (Western Australian Planning Commission, 2010a). The government of Western Australia has identified several locations for Activity Centres (ACs) (sub-centres) across the PMR, where it seeks to densify and diversify developments. The ACs in PMR are expected to be anchors of socio-economic growth within their respective sub-regions, hosting larger proportions of jobs to decrease the CBD dominance, thus reducing the need to travel into the city centre, cutting down commuting times and congestion (Western Australian Planning Commission, 2010a). They would also be well-connected by public transport to reduce car dependence and promote sustainable travel modes.

An isochrone-based accessibility measure is often used to determine suitable/potential AC locations, evaluate AC performance and decide on their prioritisation in different phases of their development (Moniruzzaman et al., 2017; Sun et al., 2017)). However, this approach has a major limitation of ignoring the density effect, which is a critical factor for the success of firms in ACs (Graham, 2007; Venables, 2007). In this study, an effective density measure is proposed for determining the development potential and prioritisation of ACs, which integrates a proximity dimension with a scale/size dimension in the form of job/labour density. While the two measures are similar, it is argued that effective density (which has the same data inputs as the accessibility measure), is better suited for the purpose as it can further reveal the potential for agglomeration externalities which is important for firms/businesses. It is sought to highlight and demonstrate the limitation in relying solely on the accessibility approach for evaluating and assessing the development priority of ACs. Thus, both measures (accessibility and effective density) are applied to evaluate the suitability of, and rank, the ACs, and demonstrate the discrepancy in the two approaches in a case study of strategic ACs in the PMR.

In the next section a brief discussion of accessibility and effective density measures from existing literature is provided. A background to the study area and description of the methods follow in section 7.3. The results and discussions are then presented in section 7.4, before ending the chapter with concluding remarks and recommendations from the study.

7.3 METHODOLOGY

7.3.1 Determining accessibility

To measure accessibility, the cumulative opportunities method was used for two main reasons: 1) it has been used for the purpose of evaluating and prioritising ACs in Perth (Moniruzzaman et al., 2017); and 2) due to its ease of interpretation and application for planners and policy makers (Bertolini et al., 2005). This is a widely used method and it is believed to be "the most comprehensible and transparent as well as the most directly comparable across cities" (Owen et al., 2017, p. 1). It is also the mostly used accessibility measure in the study area (Moniruzzaman et al., 2017; Sun et al., 2017). The procedure entails finding the zones that can be reached from each zone within a specified cost threshold by a given travel mode (car or PT), and then summing up the number of opportunities (jobs/workers) in those zones. The resulting number of opportunities was then converted from an absolute value to a relative, percentage value, for easier interpretation (i.e. percentage of the total opportunities in the metropolitan area). Using percentage allows us to see which areas have had an increase in accessibility relative to other zones and which have had a less than average increase. This is particularly useful in determining whether spatial equity has improved over time. Percentages also allow direct comparisons of spatial equity between different cities or towns that may have different levels of employment, (and the same bands (ranges) and colours can be used). We could, for example, see that smaller cities tend to have better spatial equity than larger cities, although residents in larger cities may have access to more employment opportunities. Job accessibility is calculated based on the origin (home) zone and labour accessibility is based on the destination (business) zone, expressed as follows in Equations 7.1 and 7.2, respectively:

$$E_i = \begin{cases} \sum_j x\,,\ if\ t_{ij} \le C, \\ 0,\ if\ t_{ij} > C, \end{cases} \tag{7.1}$$

$$L_j = \begin{cases} \sum_i y\,,\ if\ t_{ij} \le C, \\ 0,\ if\ t_{ij} > C, \end{cases} \tag{7.2}$$

where E_i is employment or job accessibility of home zone i, x is the number of jobs in zone j, t_{ij} is the travel time from zone i to j, and C is the travel time cutoff or threshold beyond which opportunities are deemed inaccessible, L_j is the labour accessibility of business zone j and y is the number of workers living in zone i.

A travel time threshold of 30 minutes was adopted for car-based job accessibility. The 30-minute threshold is extensively supported in the literature whence it is demonstrated that commuting times in cities across the world have remained constant throughout history (Marchetti, 1994). It has also become a policy objective in many cities around the world to avert, or at least minimise, the challenges caused by commuting times longer than 30 minutes (e.g. the Smart Cities Plan by the Australian Government (2016)). For PT-based travel, a cost threshold of 45 minutes was used because (1) only a small number of zones was covered by PT in 30 minutes, and (2) 45 minutes is consistent with the average one-way trip by PT in Perth (Moniruzzaman et al., 2017). PT accessibility in Perth has already been found to be significantly behind the car in Perth, and the extra 15 min used here for PT could give more insight into this disparity. Nonetheless, comparing car and PT accessibility is not the main purpose of this study.

7.3.2 Calculating effective density

This study measures the level of agglomeration using an effective density model modified from Graham (2007) and Nurlaela (2016) (discussed in Chapter 2.7). Improvements are introduced to the effective density measure, that more accurately capture the transport dimension, while preserving the density effect i.e. calculating the actual job/worker densities and discounting them by network travel time to/from a given zone. A differentiation is made between Effective Employment Density (or effective job density – EJD) of a business zone – which represents the magnitude of business agglomeration, and Effective Labour Density – which reflects the labour pool available to firms/businesses.

Thus, the Effective Employment Density of a business zone *a* is a function of the number of jobs in and around that zone and the respective areas of the zones, discounted by the travel time to that zone (Equation 7.3). It takes the form;

$$EED_a = \frac{J_a/A_a}{T_{aa}^{\alpha}} + \sum_{b}^{a \neq b} \frac{J_b/A_b}{T_{ab}^{\alpha}} \tag{7.3}$$

Where:

EED_a is the effective employment density of business zone *a,*

J_a is the number of jobs in zone *a*,

A_a is the area of zone *a*,

T_{aa} is the estimated average travel time within zone *a*,

J_b is the number of jobs in zone *b,*

A_b is the area of zone *b*,

T_{ab} is the time it takes to travel from zone *a* to *b,* and
$\propto$ is a parameter reflecting the rate of decay in the value of other businesses as travel time increases.

The first term $\left(\frac{J_a/A_a}{T_{aa}^{\beta}}\right)$ accounts for the density effect that arises within the zone. STEM estimates travel times between zones assuming trips start and end at the zone centroids. Thus, the travel time between two zones is estimated as the travel time between the centroids. For internal trips, this would result in a bogus travel time of zero. STEM circumvents this problem by separately estimating travel times for intra-zonal trips, based on the average distance between any two points within the zone.

Equation 7.4 can be slightly modified to determine the labour pool available to any given zone. The effective labour density (ELD) of a zone *i* is determined using the number of workers and the time it takes them to reach it (Equation 7.4);

$$ELD_i = \frac{L_i/A_i}{T_{ii}^{\propto}} + \sum_{j}^{i \neq j} \frac{L_j/A_j}{T_{ji}^{\propto}} \quad (7.4)$$

Where:

ELD_i = the effective labour density of zone i,

L_i is the number of workers (labour force) of zone i,

A_i is the area of zone i,

T_{ii} is the estimated average travel time within zone i,

L_j is the number of workers located at zone j,

A_j is the area of zone j,

T_{ji} is the time it takes to travel from zone j to zone i, and

$\propto$ is a parameter reflecting the rate of decay in the value of residents as travel time increases.

7.4 RESULTS AND DISCUSSIONS

The accessibility of each zone in the PMR was determined based on car and PT travel times. As indicated in the previous section, two types of accessibility were determined; job accessibility and labour accessibility (access to workers). Similarly, the effective density of each zone was determined based on car and PT travel, for both jobs and labour force i.e. effective job density (EJD) and effective labour density (ELD). This was done for the entire metropolitan region, and the results presented in thematic maps in this section. Results for the ACs were extracted from the overall metropolitan results and presented in ordered tables to demonstrate their variations in performance scores and rankings between the accessibility and effective density approaches.

7.4.1 Accessibility

In this section the results of job accessibility and labour accessibility for each zone in the metropolitan region are presented in thematic maps, and the ACs are extracted into ranking tables. Job accessibility is determined by the number of jobs that can be reached from a given zone, while labour accessibility (or access to workers) is determined by the number of workers that can reach a given zone, within the travel time threshold. The resulting totals are also expressed as percentages of the overall metropolitan area, for easier interpretation.

- Job accessibility

The spatial distribution of job accessibility across the metropolitan area is an important indicator of spatial equity. Adding more jobs in the ACs could increase job accessibility for residents of the outer suburbs, creating a more even spatial distribution, and hence, spatial equity of job accessibility. This in turn could reduce excess commuting particularly to the CBD, contributing to better travel efficiency. Figure 7.1(a) shows the spatial pattern of job accessibility across the metropolitan region with car as the mode of travel (within the travel time threshold of 30 min). Figure 7.1(b) shows the job accessibility spatial pattern based on PT travel mode (within a travel time threshold of 45 min). AC zones are extracted and ranked in Tables 7.1 and 7.2 for car and PT travel, respectively.

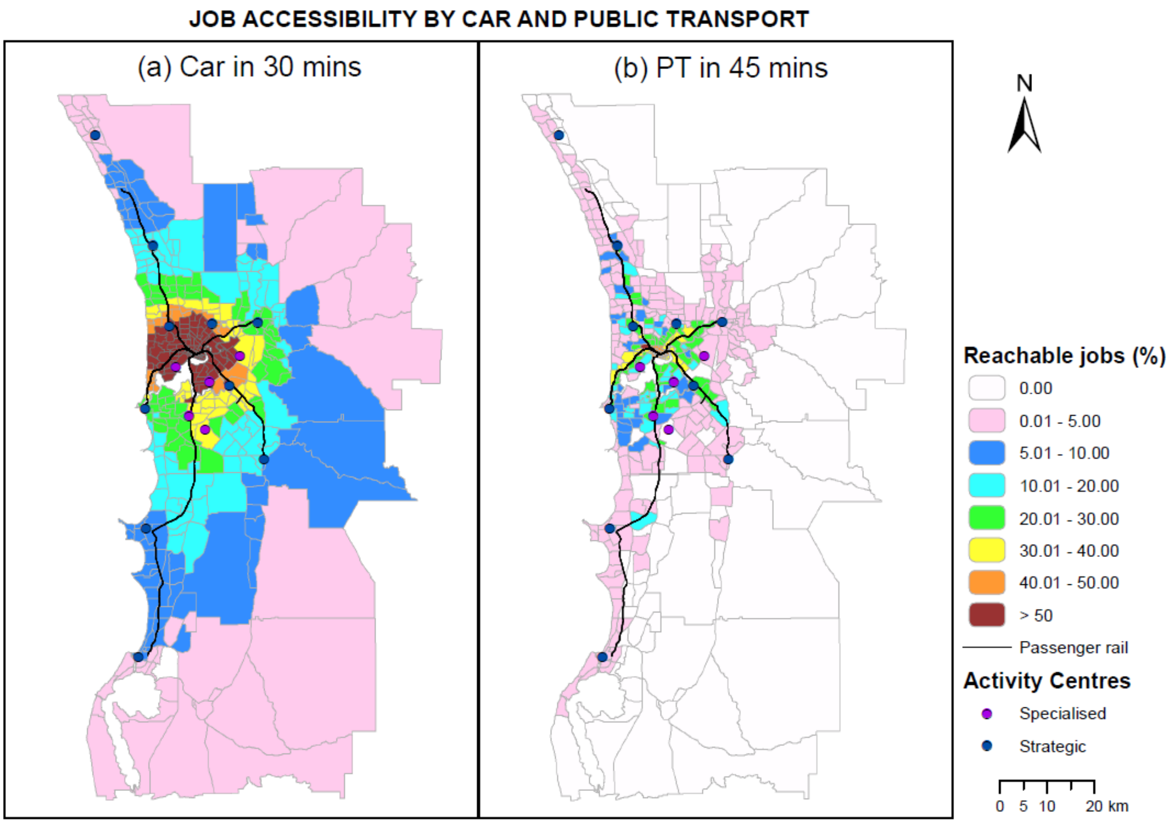


Figure 7.1: Spatial pattern of job accessibility by car in 30 min and public transport in 45 min

The spatial pattern of job accessibility reflects a clear monocentric urban structure, with a strong dominance of the city centre. The car provides a clearly superior level of accessibility over PT, despite a 50 percent longer travel time threshold for PT. The general pattern of car-based accessibility shows a radial decrease from the city centre, while PT-based accessibility is higher in the CBD and along the railway lines. From the 472 zones in the metropolitan region, 86 zones had a PT-based job accessibility of zero (mainly in the outer subregions – Figure 7.1(b)), while all zones were served (had some level of accessibility) by car (Figure 7.1 (a)). This reflects the overwhelming advantage of the central subregion in terms of job accessibility, and the limited capacity of the ACs particularly in the outer subregion. The results also reflect the value of the passenger train in job accessibility, and its great potential towards improving the overall low PT ridership. It is noted that part of the relatively higher job accessibility for the inner ACs comes from their proximity to the job-rich CBD rather than from their own employment capacity. Nonetheless, the results highlight the limited efficiency of PT compared to the car in Perth – in general, and in the suburbs in particular. Thus, decentralisation of jobs from the city centre where PT access is highest, to outer subregions, could further reduce PT ridership and reinforce car dependence. It is, therefore, highly imperative that ACs have good PT connection and high frequency services, particularly by train, which the results (Figure 7.1(b)) indicate are associated with better job accessibility.

In Tables 7.1 and 7.2, strategic AC zones are ranked according to their job accessibility by car and PT, respectively. The order of the table compares the ACs amongst themselves, starting with the one with the highest accessibility. The ranking in the last column indicates the level of accessibility of that zone compared to all the other 471 zones within the metropolitan area.

The accessibility rankings of zones hosting ACs were found to be quite low (Tables 7.1 and 7.2), suggesting that there are many other zones with better accessibility, and thus, where ACs could potentially be better located. No Strategic AC ranked in the top 100 in terms of job accessibility by car (Table 7.1). The ACs of Morley, Stirling and Cannington have the best accessibility among Strategic ACs, and they are all in the central subregion. In PT-based job accessibility, four Strategic ACs are in the top 100 zones, with Fremantle, which is also located in the central subregion, replacing Morley in the best three ACs (Table 7.2).

Table 7.1: Ranking of Strategic AC zones based on their accessibility to jobs by car in 30 min

Strategic Centre (zone no.)	**Car (30 min)**		
	Jobs	**Percentage**	**Ranking**
1. Morley (206)	450,000	53	113th
2. Stirling (98)	445,000	53	122nd
3. Cannington - Carousel (363)	360,000	42	147th
4. Midland (227)	230,000	27	210th
5. Fremantle (323)	195,000	23	247th
6. Joondalup (59)	115,000	14	325th
7. Armadale (387)	110,000	13	330th
8. Rockingham (416)	70,000	8	372nd
9. Mandurah – Foreshore (467)	45,000	5	412th
10. Yanchep (12)	20,000	2	453rd

Table 7.2: Ranking of Strategic AC zones based on their accessibility to jobs by PT in 45 min

Strategic Centre (zone no.)	**Public transport (45 min)**		
	Jobs	**Percentage**	**Ranking**
1. Cannington - Carousel (363)	300,000	35	48th
2. Stirling (98)	260,000	31	57th
3. Fremantle (323)	255,000	30	62nd
4. Morley (206)	225,000	27	90th
5. Joondalup (59)	185,000	22	115th
6. Midland (227)	155,000	18	134th
7. Armadale (387)	40,000	5	201st
8. Rockingham (416)	36,000	4	214th
9. Mandurah – Foreshore (467)	15,000	1	301st
10. Yanchep (12)	0	0	394th

- Labour accessibility

Accessibility to labour force is a critical factor for business location. It is vital for businesses that they are located in areas that have good accessibility for potential workers (and clients/customers). One advantage of a monocentric urban structure is that it favours public transport through a radial network that converges in the centre. Thus, deconcentrating the inner core poses a challenge of reduced accessibility by PT. Even by car, Schwanen, Dieleman, and Dijst (2004) found that polycentric cities in the Netherlands had longer commuting distances and times than those with centralised (monocentric) employment structures. Thus, an important step in employment decentralisation is understanding the accessibility of ACs from a labour force perspective.

The labour accessibility results for the PMR are presented in Figure 7.2, where (a) shows accessibility by car and (b) shows accessibility by PT. This answers the question; if a business is located in zone *x*, how many (or what proportion of) workers living within the metropolitan area can reach it within the given time threshold? Ideally, ACs should be located in zones with the best accessibility to workers (and customers), particularly by PT to reduce automobile dependence as well as to cater for those without access to a car.

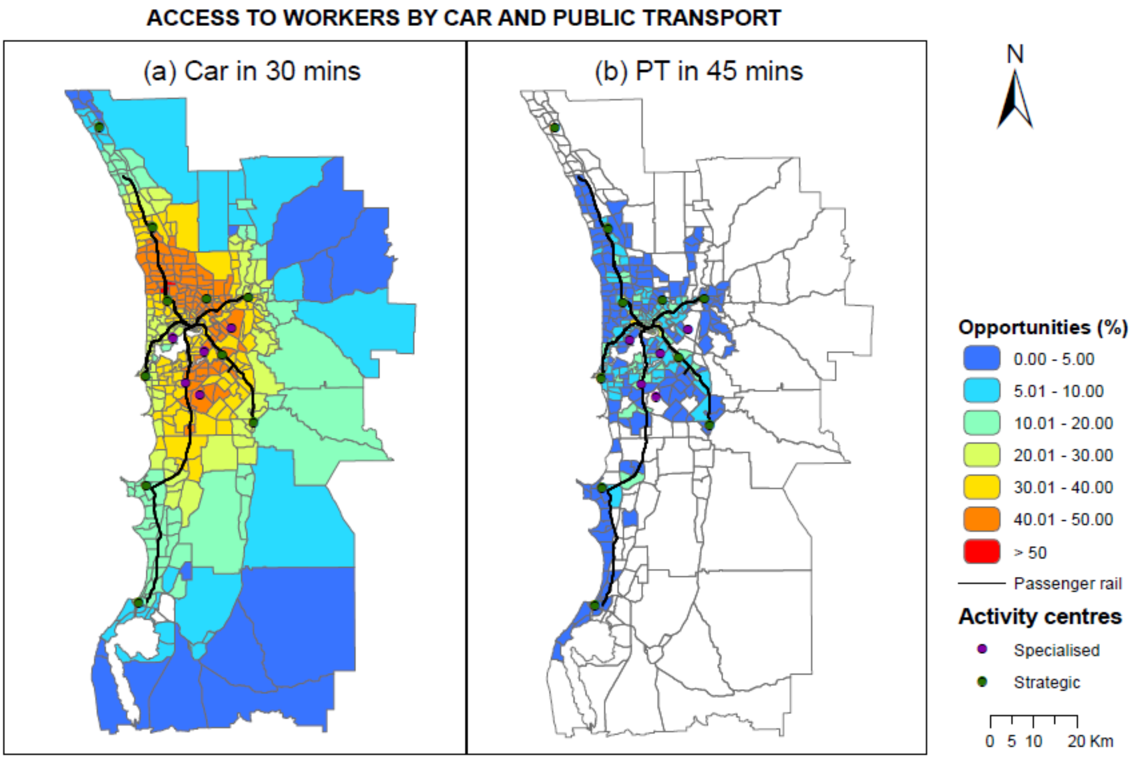


Figure 7.2: Spatial pattern of access to workers by car and PT

The spatial distribution of worker accessibility shows that in a 30-minute car journey, the most accessible zones are outside of the CBD. There are a few zones with access to 50% or more of workers but none of them is a designated strategic AC. Access to workers by PT is noticeably better in zones close to the railway line, suggesting the value of the passenger train in improving accessibility. However, PT provides accessibility to a much smaller spatial coverage, and for a much smaller number of workers compared to the car. This is so despite the PT threshold used here being 15 min, (i.e. 50%), longer than that of car. The highest PT-based accessibility is found in the CBD, and it quickly diminishes as one moves outward. This is an important result for a car-dominated city like Perth, because it highlights the disparity between car and PT in terms of accessibility provided, which explains why PT is failing to compete with the car as a preferred travel mode for commuters. It also suggests, as previously indicated, that moving jobs out of the CBD to other centres could reduce the PT share – which is highest in the CBD – and increase the car share. Significant improvement of these centres' accessibility by PT would be needed for them to be able to compete with the CBD, as well as to make PT competitive against the car. These could include rail connection, improved bus route network and higher service frequency.

Table 7.3: Ranking of Strategic AC zones based on their accessibility to workers by car in 30 min

Strategic Centre (zone no.)	**Car (30 min)**		
	Workers	**Percentage**	**Ranking**
1. Morley (206)	370,000	40	61st
2. Cannington - Carousel (363)	360,000	39	87th
3. Joondalup (59)	330,000	36	116th
4. Stirling (98)	300,000	32	179th
5. Midland (227)	265,000	29	218th
6. Armadale (387)	225,000	24	297th
7. Fremantle (323)	220,000	24	299th
8. Rockingham (416)	115,000	12	387th
9. Mandurah – Foreshore (467)	85,000	9	423rd
10. Yanchep (12)	78,654	8.5	430th

Table 7.4: Ranking of Strategic AC zones based on their accessibility to workers by PT in 45 min

Strategic Centre (zone no.)	**PT (45 min)**		
	Workers	**Percentage**	**Ranking**
1. Stirling (98)	160,000	18	34th
2. Joondalup (59)	155,000	1	46th
3. Cannington - Carousel (363)	155,000	17	51st
4. Fremantle (323)	95,000	10	83rd
5. Morley (206)	90,000	10	94th
6. Midland (227)	60,000	7	150th
7. Armadale (387)	50,000	5	171st
8. Rockingham (416)	40,000	5	193rd
9. Mandurah – Foreshore (467)	10,000	1	315th
10. Yanchep (12)	0	0	394th

Note: Total jobs = 847,039; Total workers = 925,016.

Rankings of labour accessibility of the ACs are presented in Tables 7.3 and 7.4. Based on car travel (Table 7.3), many of the strategic AC zones ranked poorly – Morley was the best ranked at 61st (40% of workers in the metropolitan region can reach it by car in 30 minutes), followed by Cannington at 87th (38.7%). The worst ranked were Mandurah and Rockingham at 423rd (9.3%) and 387th (12.3%), respectively (Yanchep is not yet an existing strategic centre). This shows that there are a lot of zones that have better accessibility to workers by car in 30 min than those currently designated as ACs. With PT travel (Table 7.4), most of the zones' rankings improve significantly (only Morley's ranking worsens). The best ranked here is Stirling at 34th followed by Joondalup at 46th. This is an encouraging result considering the goal to promote PT access for ACs. However, all the centres do have much higher levels of access by car (at least double) than by PT. Thus, decentralising services to the outer subregions poses a potential challenge of increasing car dependency at the expense of PT usage. Furthermore, there are still many zones that have better worker accessibility by PT than many of the designated AC zones. The worst AC accessibility is at Mandurah and Rockingham - ranked 315th and 193rd, respectively.

7.4.2 Effective density

The effective density results for jobs and workers are presented in this section, separated into car and PT travel modes. Effective job density, or effective employment density, gives an indication of the amount of job opportunities available to, and the ease of reaching them from, a given zone – which is important to residents or potential job seekers. It is also a measure of economic agglomeration, as it is a reflection of both the density and proximity of jobs, and hence it is also important to businesses for agglomeration benefits (Graham, 2007). Effective labour density indicates the size of labour pool, density and proximity from any given zone, and is therefore important to firms/businesses. It may also signify higher potential competition for job opportunities from a job seeker's perspective. To the extent that the size of labour force is proportional to the population, ELD is also important to firms/businesses for its reflection of the customer base available in different locations.

- Effective job density

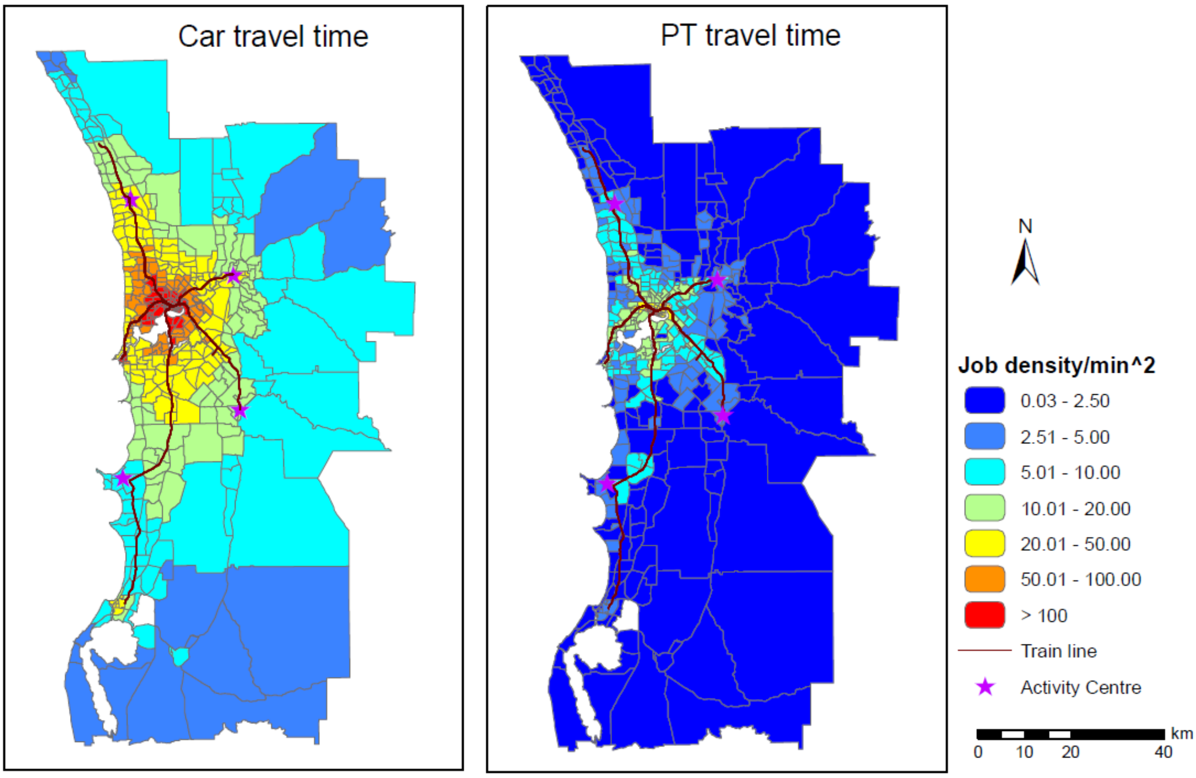


Figure 7.3: Spatial pattern of EJD by car and PT travels

EJD results show that the inner-city area has the highest effective density (for both travel modes), which is expected due to the concentration of jobs in the central subregion (Figure 7.3). Better effective job density is achieved through car travel than with PT. The spatial pattern of EJD with car travel decreases radially from the city centre. PT-based EJD reflects the pattern of passenger train lines i.e. zones with higher values are concentrated nearer to and along the five train lines. There is no obvious influence of the strategic ACs on the spatial pattern of EJD. This is an important result because it shows that if the city's footprint continues to expand more people might be disadvantaged in terms of job opportunities and accessibility. These results also suggest that employment decentralisation to ACs faces a challenge of poor agglomeration externalities due to lower effective job density.

In comparison with other zones in the metropolitan region, the ACs ranked rather poorly in terms of EJD (Tables 7.5 and 7.6). It is noted that a significant majority of designated strategic centres rank higher among other zones with PT travel. This is not to say that PT provides better opportunity than car. Rather, it shows that there are fewer zones which are more accessible by PT than the current AC zones, while by car there are many more zones that are more accessible.

Table 7.5: Ranking of Strategic AC zones based on their EJD and car travel times

Strategic Centre	EJD ranking
1. Fremantle	72nd
2. Stirling	95th
3. Joondalup	97th
4. Cannington (Carousel)	104th
5. Midland	124th
6. Morley	139th
7. Rockingham	351st
8. Mandurah - Foreshore	368th
9. Armadale	387th
10. Yanchep	445th

Table 7.6: Ranking of Strategic AC zones based on their EJD and PT travel times

Strategic Centre	EJD ranking
1. Fremantle	60th
2. Stirling	64th
3. Morley	87th
4. Cannington (Carousel)	90th
5. Joondalup	112th
6. Midland	133rd
7. Armadale	184th
8. Rockingham	216th
9. Mandurah - Foreshore	334th
10. Yanchep	415th

- Effective labour density

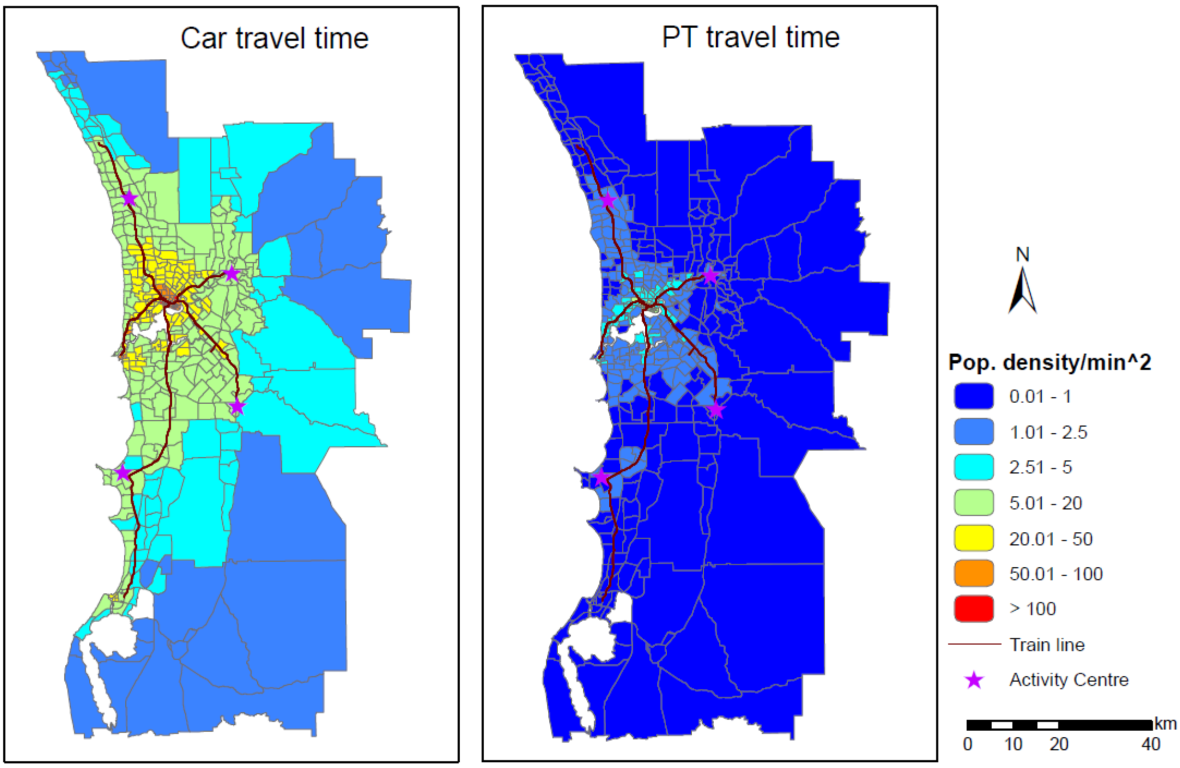


Figure 7.4: Spatial pattern of ELD by car and PT travels

The spatial pattern of ELD (Figure 7.4) is generally similar to that of EJD in that better opportunities are available in and around the city centre. However, ELD has a much smaller range between the most and least advantaged zones by both modes. This comes from the fact that the population is distributed more evenly than jobs, making job access excessively better for inner zones and very poor for outer. The influence of the passenger train is also evident from the ELD spatial distribution map, indicating both ease of travel by train and relatively higher labour densities closer to train lines.

Table 7.7: Ranking of Strategic AC zones based on their ELD and car travel times

Strategic Centre	ELD ranking
1. Morley	54th
2. Cannington (Carousel)	97th
3. Joondalup	108th
4. Stirling	189th
5. Midland	224th
6. Fremantle	260th
7. Armadale	279th
8. Rockingham	380th
9. Mandurah - Foreshore	404th
10. Yanchep	438th

Table 7.8: Ranking of Strategic AC zones based on their ELD and PT travel times

Strategic Centre	ELD ranking
1. Stirling	45th
2. Joondalup	72nd
3. Fremantle	86th
4. Morley	104th
5. Cannington (Carousel)	113rd
6. Midland	171st
7. Rockingham	190th
8. Armadale	204th
9. Mandurah - Foreshore	310th
10. Yanchep	411th

The rankings of ACs in Tables 7.7 and 7.8 show that many of them have a relatively poor ELD compared to the rest of the zones in the metropolitan region. This was more so by car travel than PT travel. With PT travel, there were generally fewer zones better than the AC zones compared to when the travel mode is car. The best ranked AC by car travel was Morley followed by Cannington and Joondalup (with overall metro rankings of 54th, 97th and 108th, respectively). In terms of PT travel, Stirling had the best ELD at an overall ranking of 45th. Joondalup and Fremantle followed at 72nd and 86th, respectively.

7.4.3 Comparison of accessibility and effective density results

Two measures were used, namely accessibility and effective density, to evaluate the development potential of strategic ACs and aid prioritisation for phased development. The two measures used the same data inputs – number of jobs and/or workers and travel time, and are therefore equally applicable in any given study area. The major difference between these measures is the ease of computation and interpretation. The cumulative accessibility measure is fairly simple as it just sums up jobs/workers within the travel time threshold, and more is interpreted as better. Effective density, on the other hand, is relatively more computationally intensive. The accessibility measure also produces outputs that are easier to interpret; the total number of jobs/workers, while effective density produces index values that might be harder to interpret. However, when deciding on the ranking and prioritisation of ACs, a more comprehensive representation of the character of a location is crucial, and choosing a ranking method based on its simplicity could lead to inaccurate results and potentially costly policy decisions. Therefore, the level of computation involved in determining effective density should not be a hindrance for the method's application. In fact, effective density is a more desirable measure for the purposes of comparative evaluation and prioritisation since it not only is more comprehensive but also incorporates the proximity effect of the former method – in addition to the density effect.

The results of this study have shown that evaluation of ACs using these two methods leads to two different prioritisation outcomes. For instance, if job accessibility by PT was used to make priority decision for strategic centres, Cannington would be deemed to have the best potential and prioritised for development ahead of the other strategic centres (Table 7.2). However, EJD by PT shows that there are three strategic centres that have better potential than Cannington, which are Fremantle, Stirling and Morley (Table 7.6). Secondly, Cannington ranked 48th in terms of accessibility among all the metro zones, but it ranked much lower at 90th in terms of EJD. So, while accessibility results indicate that only 47 other zones are better that Cannington, there are 89 other zones which are better in terms of EJD and therefore, better potential for agglomeration benefits. Therefore, in terms of PT access for jobs, Fremantle is a much more suitable AC than Cannington, as are Stirling and Morley.

With regards to the labour force and PT travel, ranking results for both accessibility and ELD gave Stirling and Joondalup as the two best ranked strategic ACs, although the order changed on the third ranked from Cannington to Fremantle (Tables 7.4 and 7.8). Moreover, accessibility put Stirling and Joondalup at respectable rankings of 34th and 46th, respectively, while they both showed to be worse than that in terms of overall ELD – ranking 45th and 72nd, respectively. The best five ACs ranked in the top 100 based on accessibility, but only three were in the top 100 bracket based on the ELD measure. Generally, ACs ranked better among the metro zones based on accessibility than on ELD by PT (Tables 7.4 and 7.8). This indicates that there are a lot more zones with better potential than the designated ACs, than can be revealed by the accessibility measure alone.

For car travel, labour accessibility results were closely similar to effective labour density results in terms of the order of AC ranking – the only difference being Armadale and Fremantle which ranked sixth and seventh, respectively, based on accessibility, but swapped positions in ELD. Nonetheless, the overall metropolitan area rankings from the two measures were all different. There was no clear indication of ACs ranking higher or lower under any particular measure i.e. some zones ranked higher on accessibility while others ranked higher on ELD. For example, Morley ranked 61st on accessibility but had a higher ranking of 54th on ELD, whereas Cannington had a higher accessibility ranking of 87th compared to its ELD ranking of 97th. Employment or job rankings by car travel had the biggest variation in terms of both the AC order (rankings amongst ACs themselves only) and the overall metropolitan area ranking. Additionally, all ACs had better EJD than accessibility ranking. Morley had the best job accessibility by car (with an overall metropolitan area ranking of 113th), but was 6th best among the ACs with respect to EJD, with an overall metropolitan ranking of 139th. While car accessibility is not a major objective for the ACs, it is still an important factor in a car-dependent city like Perth, as it is often the most convenient/accessible travel option for many people and trip purposes (Australian Bureau of Statistics, 2016).

Overall, it could be argued that among the currently designated strategic ACs, Stirling was the most suitable AC and should be considered for prioritisation to capitalise on this potential. This is because it had the best ELD by PT travel and the second best EJD (and by extension, economic agglomeration) by PT after Fremantle. Fremantle cannot be recommended before Stirling because it had a lower ranking sitting at sixth in terms of ELD by PT. My recommendation does not base on car travel because PT is a key element of AC development, and a desired mode of travel over car particularly for accessing the ACs.

7.5 SUMMARY AND CONCLUSION

This chapter contributed to ongoing research on employment decentralisation by investigating the suitability of a cumulative-opportunities accessibility measure in evaluating and determining development priority of ACs. It has developed a modified effective density measure based on Graham's model that captures the scale and proximity of economic activity. The analysis presented two independently determined prioritisation/ranking results of ACs in the PMR to demonstrate the disparity between accessibility and effective density measures in AC evaluation. The motivation for the study emanated from the need to determine suitable centre(s) that could be prioritised for development in the short to medium term as the city's employment decentralisation agenda gets well underway. The prioritisation could also be necessary in identifying potential primary centres (currently missing in the policy), which the policy indicates will emerge from some of the strategic level ACs, but does not specify those ACs expected to do so.

Generally, the ranking exercises by the two methods suggest that the ACs may not be optimally located. There were many other zones that ranked higher than those designated as ACs, and many of the designated ACs had quite low rankings based on both accessibility and effective density measures. Nonetheless, the major finding of the study is that the two methods led to different outcomes, which suggests that the widely applied cumulative accessibility measure may not be appropriate for comparative evaluation of ACs or determining their order of suitability for priority development. With the same data inputs as the accessibility measure, the proposed effective density measure provides a richer representation of AC development potential, while also taking their accessibility into account through its transport dimension. It is, therefore, a more comprehensive and appropriate measure for making prioritisation decisions of ACs. Effective job density also provides a measure of business agglomeration, which can reveal business potential at various locations and more meaningfully inform employment decentralisation. The results of this study can help planning authorities in Perth to optimise the employment decentralisation process, and deliver a more efficient and sustainable polycentric urban structure. The proposed effective density measure can be applied in other cities pursuing employment decentralisation.

CHAPTER 8 RELATIVE ACCESSIBILITY OF KEY URBAN SERVICES

This chapter is made up of research material that has been published in Kelobonye, McCarney, et al. (2019).

8.1 INTRODUCTION

The previous four chapters thoroughly explored the spatial efficiency of urban structure, with chapter 4 employing a morphological perspective while chapters 5, 6 and 7 employed a dynamic/functional perspective. This chapter will present the study's first component of spatial equity analysis. The cumulative opportunities accessibility measure is comprehensively employed to explore the spatial equity of five urban services: jobs, primary/secondary education, tertiary education, shopping and health care. Comparisons are drawn between the accessibility and spatial equity of the five services, as well as between access by private car and public transport, the two major travel modes in the Perth metropolitan region.

8.2 RESEARCH CONTEXT

The accessibility of major destinations/activities within an urban system provides a framework for evaluating the urban spatial structure and understanding the land use and transport systems. Travel emanates from the spatial separation of people's desired destinations (workplaces, schools, shops, hospitals recreational sites etc.) from where they live. Thus, improving the travel efficiency within, and liveability and sustainability of, cities requires understanding and optimising the accessibility of such destinations. Accessibility can be provided by proximity, e.g. co-locating residences, jobs and shops, and/or by transport infrastructure and services, e.g. building roads and providing public transport (PT) services to link residences with jobs, shops, schools and other major destinations (Austroads, 2011). Good accessibility provides residents with opportunities to reach vital services and participate in important activities such as school, work, recreation and social interaction (Golub & Martens, 2014; S. L. Handy & D. A. Niemeier, 1997). On the other hand, poor accessibility to services and opportunities can lead to or exacerbate poor socio-economic and health effects (J. Lee & Miller, 2018) and social exclusion (Social Exclusion Unit, 2003) for the affected neighbourhoods.

The concept of accessibility has been receiving growing attention from researchers in recent decades. Research efforts have been directed towards defining the concept of accessibility, developing accessibility measures and advocating accessibility into plan and policy developments (Bertolini et al., 2005; K.T. Geurs & Ritsema van Eck, 2001; Hansen, 1959). While the concept of accessibility is simple to understand, measuring it is often complex and diverse. Four major approaches can be identified, through which accessibility measurement can be undertaken; gravity-type, utility-based, space-time and opportunity based (K.T. Geurs & Ritsema van Eck, 2001; K. T. Geurs & van Wee, 2004; J. Lee & Miller, 2018). The variety of the measures and their complexity create different interpretations of accessibility and hamper their application by planners and policy makers (Bertolini et al., 2005). This is a particularly important challenge to researchers because as more data and knowledge become available, (including behavioural, temporal, spatial and socio-economic components), more factors can be taken into account to make the measurements more accurate (Bertolini et al., 2005; Cheng & Bertolini, 2013). This, on the other hand, makes them more complicated and consequently less appealing to policy makers. Therefore, there is a critical trade-off to be struck between making accessibility measures/indicators more accurate versus keeping them simple and easy to interpret. For accessibility measures to be useful they need to be both consistent with the perceptions and uses of the people and understandable to planners and policy makers (Bertolini et al., 2005).

Moreover, most accessibility studies have focused on job accessibility and little attention has been given to other important destinations such as schools, shops and hospitals (e.g. (Cheng & Bertolini, 2013; Kawabata & Shen, 2007; Shen, 1998). This study employs a simple cumulative opportunities measure to evaluate the relative accessibility of five key land uses within metropolitan Perth. The significance of non-work travel in understanding urban spatial structure is asserted by extending the attention from job accessibility to other key destination types such as schools, shopping areas and health care institutions. By mapping each in a GIS, the accessibility of these key land uses is evaluated to understand the spatial equity of essential opportunities across the study area. An assessment of the disparity between accessibility by private car and PT, as the major travel modes in Perth – and indeed in most, if not all, modern cities – is also undertaken. As a sustainable mode of travel, PT has to be able to compete with the private car in order to offer a viable alternative to travellers. Insights gained from this study will shed more light on the accessibility, (or lack thereof), of opportunities as facilitated by the car and transit travel modes, and aid planning for improved accessibility equity for not only work but other essential destinations in the Perth Metropolitan Region. In the next section the existing literature on the definition and measurement approaches of accessibility is briefly discussed, followed by a description of the methodology employed in this study. The results and discussions are then presented, and the chapter ends with a conclusion of the major findings.

8.3 METHODOLOGY

8.3.1 Determining opportunity accessibility

The same approach used in the previous two chapters is adopted to determine the number of opportunities reachable from each zone. The average travel time between zones is used to determine services that can be reached within a given time threshold. Two important assumptions are made in this approach: (i) people prefer to have a choice from the widest and most diverse range possible (Doi & Kii, 2012), and travel time restricts the extent to which this can be possible (Bertolini et al., 2005). The travel times differ according to mode and time of travel i.e. whether the trip is made by car or PT and whether it is made at peak or off-peak time. It is assumed that all work trips are made during peak time, and use average morning peak (AM) travel times in measuring the accessibility of job opportunities. The peak times (AM and PM) are critical times for infrastructure supply because they reflect the most congested car travel and most frequent transit situations. Shopping and medical trips are assumed to be made during off-peak times. Education trips are a little more complex in that they include primary & secondary schools and tertiary institutions. Primary and secondary school trips tend to be during peak time in the morning but ahead of afternoon peak hours for the return home. Tertiary institutions often have staggered classes and part-time enrolments which allow students to make their trips at various times of the day. For simplicity, peak time was used for accessibility of both primary/secondary and tertiary education opportunities.

Travel time thresholds

The selected threshold of allowable travel time to reach a service is an important factor in determining its accessibility, or lack thereof. Changing the threshold can significantly change the results. Accessibility measures and acceptable travel times for different services are a whole area of debate in the fields of transport and urban geography. In this study 30 minutes was used as the threshold for allowable travel time to work, informed by the Marchetti constant and '30-minute cities' idea proposed in 2016 by the then Australian prime minister (Australian Government, 2016). The Marchetti constant posits, in support of Yacov Zahavi's concept, that people allocate a 'travel time budget' of one hour - 30 minutes each way - for their daily commute, (Marchetti, 1994; Zahavi, 1979). Studies are scant and varied with regard to ideal travel times for shopping, health and education trips. However, one consistent notion throughout the literature is that these are more local destinations than work. As such, 15 minutes was deemed to be a reasonable time to reach those services in a liveable city. For tertiary education institutions[1], since they are fewer in number and have sub-regional catchments, a travel time of 30 minutes is deemed reasonable. Thirty minutes is consistent with the journey to work time and is also justified by the fact that tertiary education is usually only attended for a period of two to five years. Indeed, another approach like using multiple thresholds could be used, but here the study adopts 'design thresholds' as per the state and national planning policy travel/accessibility objectives. Figure 8.1

[1] Tertiary education includes universities and technical and further education (TAFE) institutions.

represents a graphical illustration of how the accessibility measure was determined for the different destinations.

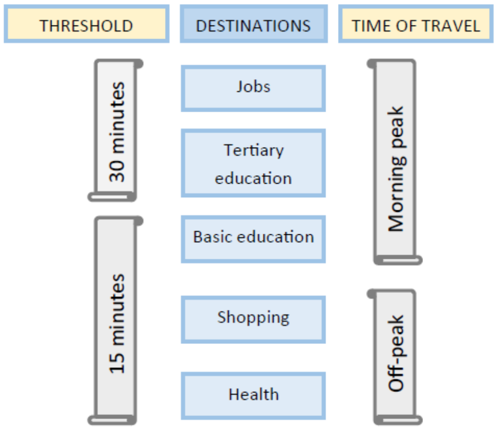


Figure 8.1: Conceptual framework for measuring the accessibility of different destination types

The process of determining accessible services entails two steps; finding the zones that are reachable within the given time threshold; and summing up the opportunities in those zones. The total accessible opportunities from a zone can be expressed as A_i in Equations 8.1 and 8.2;

$$A_{i(car)} = \sum_{j=1}^{j} O \tag{8.1}$$

where $O = O_j$ if $T_{ij(car)} <= Th$

$O = 0$ if $T_{ij(car)} > Th$

$$A_{i(pt)} = \sum_{j=1}^{j} O \tag{8.2}$$

where $O = O_j$ if $T_{ij(pt)} <= Th$

$O = 0$ if $T_{ij(pt)} > Th$

where T_{ij} is the travel time from zone i to j, Th is the travel time threshold. $A_{i(car)}$ and $A_{i(pt)}$ are numbers of opportunities accessible from origin (residential) zone i within the time threshold Th by car and PT, respectively, j is destination zone and O_j is the number of opportunities in zone j.

8.4 RESULTS AND DISCUSSION

The main results of this work are presented in Figure 8.2, comprising the accessibility maps of the five different services, both by car and PT travel. These show the percentages of opportunities (out of the total in the metro region) that can be reached from each zone by car and PT. The accessibility can thus be compared between the various services as well as between car and PT for each service. Also calculated was the average level of accessibility for each service by each of the two travel modes. These results are presented in Figure 8.3, showing zones that are above average (i.e. potentially over-served) and those that below average (i.e. potentially under-served). The later sections of this chapter present the modelled travelled times for the five trip purposes in the PMR. Lastly, to validate the equity results, the five services were mapped relative to the local demand. The opportunities accessible from each zones were divided by the number of users e.g. school age children for primary & secondary education and total population for jobs, health care, shopping and tertiary education.

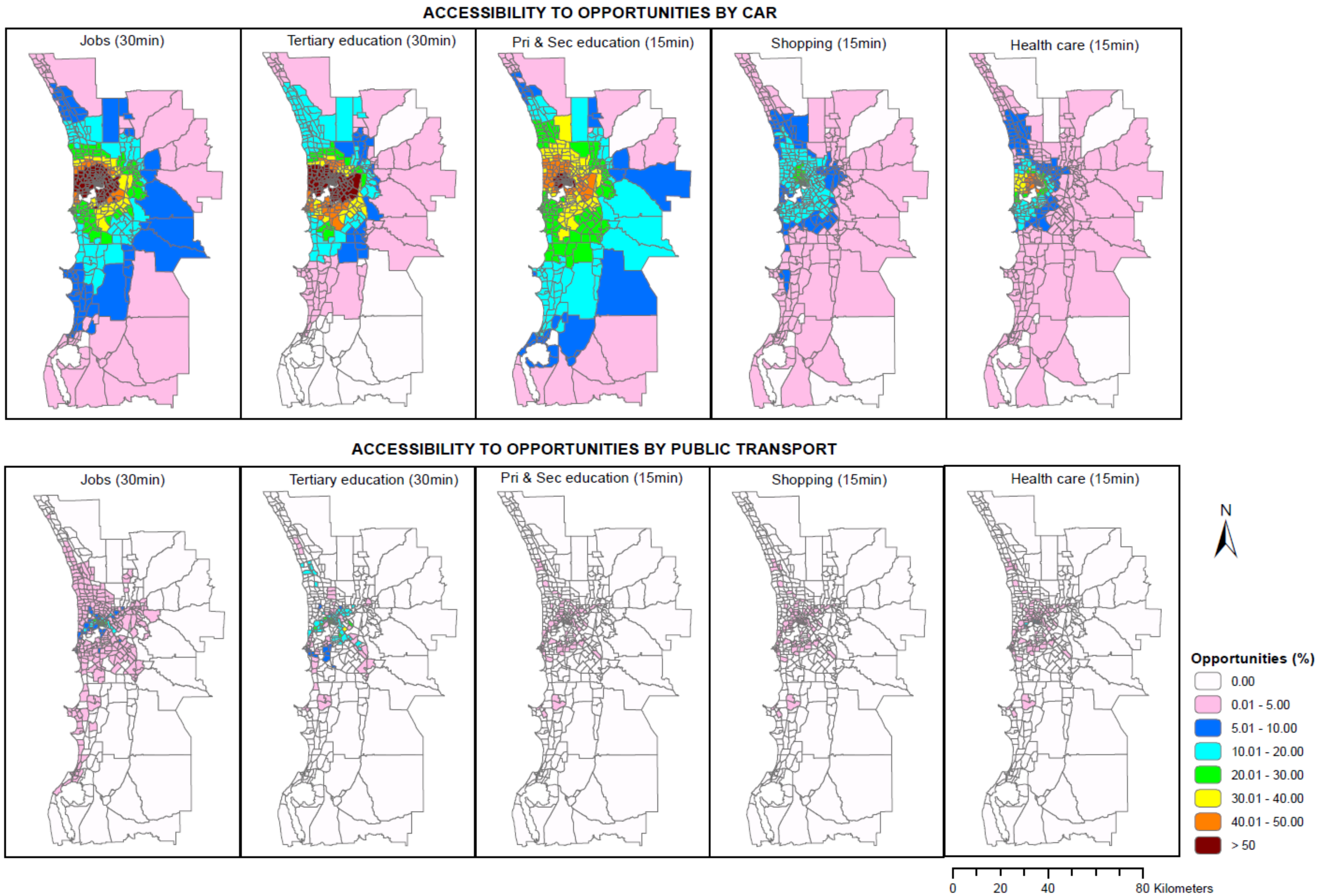


Figure 8.2: Accessibility of various services by car and PT. Opportunities are expressed as a percentage of the total in Perth metro region.

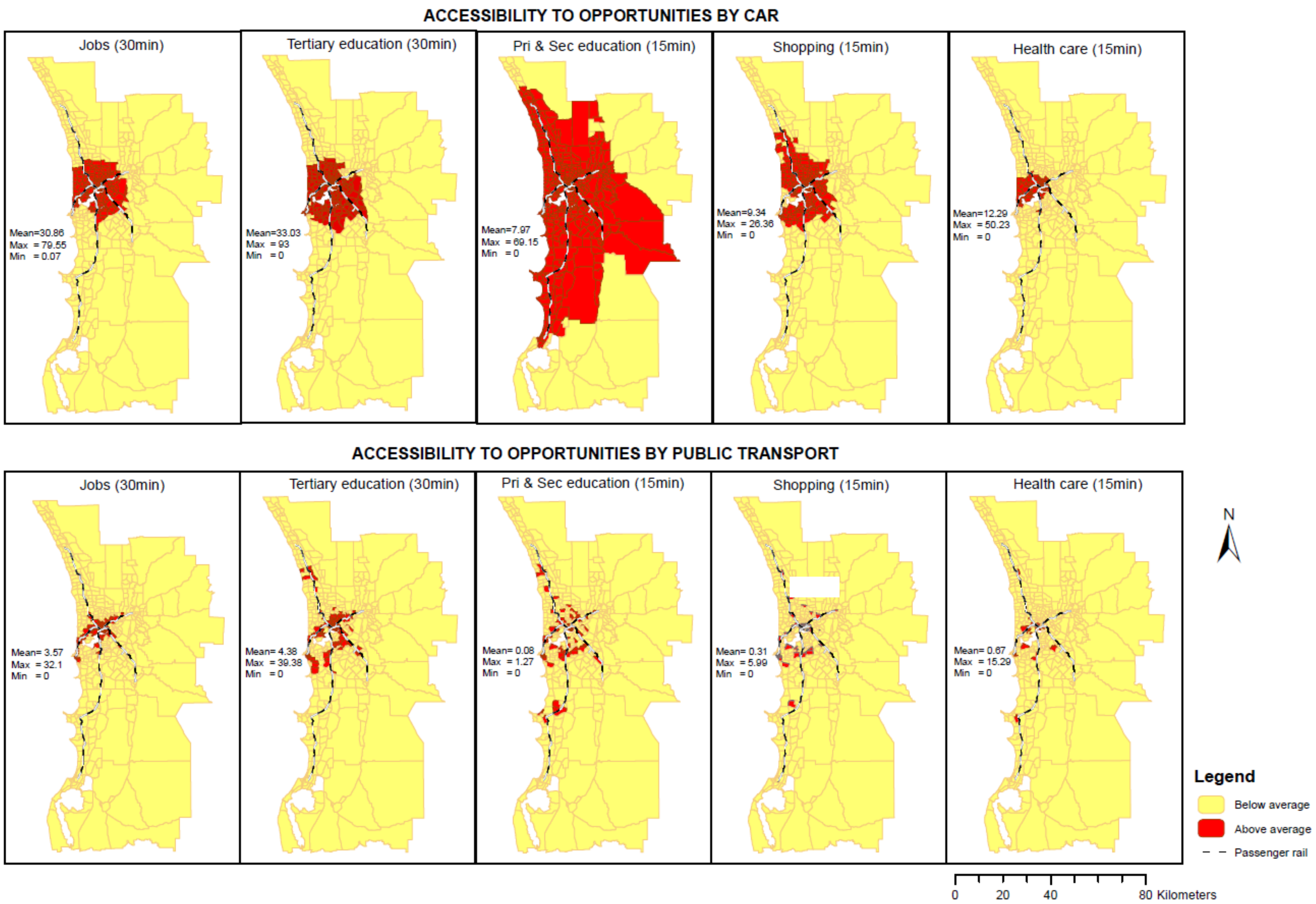


Figure 8.3: Spatial distribution of zones with above and below average accessibility by car and by PT.

8.4.1 Comparing accessibility by private car and public transport

The private car and PT are the most dominant modes of travel in Perth. Even though the car is far more ubiquitous, urban and transport researchers often lament its popularity for breeding congestion and pollution problems. In this view, PT is often postulated as a viable and sustainable solution (Friman, Gärling, & Ettema, 2018; Holmgren, 2007; Kawabata & Shen, 2007; Rabl & de Nazelle, 2012).

The results in Figures 8.2 and 8.3, however, show that PT provides very poor accessibility for all services compared to the car. The radial pattern of Perth's PT system is also evident. With PT, the highest job accessibility is at 32%, and limited to origin zones in the CBD, while car-based job accessibility is as high as 79% for a much larger area of origin zones[2]. Even though some zones have low job accessibility, all zones are served with the car while, with PT, a lot of the outlying zones have no job accessibility within 30 minutes. Job opportunities are the most accessible by PT, compared to education, shopping and health care. This is due to the fact that the majority of jobs are found in the inner zones in and around the CBD, an area which is the most accessible by Perth's radial PT network. However, few of these jobs are located close to the train stations, making the leg from train station to destination, (the "last mile"), a constraint to PT use. Hence, access to job opportunities by PT is still at a very low level compared to access by car. The PT job accessibility map reflects the train network pattern, with zones along/closer to the lines having relatively higher job accessibility than those further away.

There is virtually no accessibility, (within the adopted 30-minute and 15-minute travel time thresholds), for any of the five services by PT in the outer zones of the PMR. Considering that the land values are higher in inner suburbs, lower income groups are pushed to the outer suburbs where land is cheaper. In turn they lose PT access whose supply is limited to inner areas. This creates great inequality and disadvantage for the low income groups who may not have other travel options. The poor level of accessibility provided by PT in Perth is an indication that, for geographically large, sprawling cities such as Perth, it may be difficult, if not impossible, for PT to adequately serve, and therefore create, the desired '30-minute

[2] This means that the most advantaged zones in terms of job accessibility by PT provide access to 32% of total jobs in the study area, while with the car people living in the most advantaged zones can reach up to 79% of the jobs.

city' (Australian Government, 2016).

While Perth has invested heavily in PT, (suburban rail), in recent years and has the newest and fastest rail service in Australia, the results here show limited success in providing a viable alternative to the car for the majority of commuters. (This is borne out by the main north-south freeways having probably the highest level of congestion in Perth, in spite of the railway running down the central median). The issue is primarily the "first mile – last mile" problem, i.e. getting from home to the nearest train station and from the destination train station to the final destination (work). These two short legs can easily take at least 10 - 15 minutes, each, leaving very little, if any, of the 30 minutes travel time for the fast train leg. Hence, one would question whether a policy of investing heavily in suburban rail is consistent with producing a "30 minute city" outcome – certainly in the context of Perth, and probably the other big Australian cities.

Low density cities with a radial transit network like Perth not only favour the use of private car but need it to improve the accessibility of destinations outside the central core. While it has been argued that poor access to PT exacerbates social exclusion for the disadvantaged populations (Noel, Elizabeth, & John, 2005; Social Exclusion Unit, 2003), helping carless people gain access to cars has been propounded as a possible effective way to increase opportunities for disadvantaged residents (Grengs, 2010).

While it is highly undesirable for an average resident to have to spend an hour each way on travel to local facilities, my analyses reveal that even at such a long time threshold, a significant portion of the study area remains unserved, (no accessibility), if the mode of travel is PT. Thus, this leads to a conclusion that the urban spatial structure of Perth is neither designed for nor supportive of PT and it cannot be an efficient mode of travel connecting the outer, newer suburbs where most of the growth is taking place. This position is further supported by the fact that even those (outer) zones close to train stations have very low accessibility, if any. Although job decentralisation from the CBD could reduce 'peak-hour' congestion in the central sub-region, it could also reduce job accessibility for the carless, unless most of those jobs were relocated to train stations, particularly on the north – south lines. To realise the worth of PT investment, it will have to be accompanied with bringing major services (not just jobs) into easily accessible zones around transport nodes. To date this is proving a difficult challenge with PT continually needing government subsidy while its patronage experiences a yearly decline (Public Transport Authority, 2016, 2017).

8.4.2 Accessibility equity for key services

- **Comparing car-based accessibility between different services**

Perth has a monocentric urban structure that entails the majority of jobs being in the central area and majority of workers living in the suburbs. This creates spatially inequitable accessibility of job opportunities, disadvantaging the outer suburb residents. While decentralising jobs would increase job access equity, other essential services (education, health, shopping) also have to be equitably distributed for meaningful travel efficiency to be achieved. In Figure 8.2, relative accessibility levels for different services by car and PT were presented. As indicated earlier, accessibility for job opportunities and tertiary education is measured at a 30-minute travel time threshold using morning peak travel times. A shorter travel time threshold of 15 minutes is used for the other services (primary & secondary education, shopping and health care). The reason for this is that schools, shops and health care services should be more local and easily accessible at the neighbourhood level. Morning peak travel times are used for schools and off-peak times for shopping and health trips. This subsection compares accessibility for these five services by car - which is the most efficient mode (provides best accessibility) for users in the PMR. Since PT accessibility is either very low or non-existent in most zones, it is not considered for the comparative discussion.

The results (in Figure 8.2) confirm the great spatial inequity in job accessibility, with central zones having access to more than 50% of all jobs in the region (within 30 minutes of peak time travel), while most outer zones can only reach less than 5% within the same time. The other services still reflect a monocentric urban structure, albeit to a lesser extent – centrally located zones have access to more opportunities. The least variation is in shopping accessibility, suggesting that shopping opportunities are the most equitably distributed. The most served zone is under 30%, a large majority of the zones have under 20% of opportunities and almost all of them have some accessibility (except only seven very peripheral zones in the Peel and North West subregions). Nonetheless, primary & secondary education have the least standard deviation (4.18) among the five services (Table 8.1) while shopping follows with 6.62. Opportunities for primary & secondary education are the most widespread; only a few peripheral zones have access to under 5% – a lot of the outlying zones have access to 10% or above. Health care services are also evidently concentrated in the inner region, and particularly north of the Swan River. Apart from just one, all zones that have 30% or more health care accessibility are on the north side. Tertiary education is the least spatially equitable of the five services and largely inaccessible for outer zones – almost the entire Peel subregion has nothings (save for a few zones around the TAFE campus), while some inner zones have almost everything (up to 93% - see Figure 8.2). This is consistent with tertiary institution locations which are mostly in the central subregions, especially universities, which have the higher numbers of enrolments.

- **Accessibility relative to local demand or accessibility gap**

The accessibility maps in Figure 8.2 suggest that the service supply is spatially inequitable across all the five services as evidenced by the variation particularly between the central and outer subregions. This implies that, in terms of the level of supply of services, living in the inner suburbs has an advantage of more opportunities, and outer suburbs are highly disadvantaged. However, if the service supply level is consistent with spatial distribution of users, that will tell a different story. i.e. if a zone has high accessibility (more opportunities) and high population, that means many people competing for those opportunities. Hence, such a zone is not necessarily more advantaged. Figure 8.4 maps accessibility of the five services as a function of the number of users/people living in each zone. Opportunities for jobs, tertiary education, shopping and health care are standardised by total population and primary & secondary education by number of school age children in each zone. This essentially compares the level of service supply with the level of demand in a given area, which enables collating the spatial variations of each and make an assessment of spatial equity across the region.

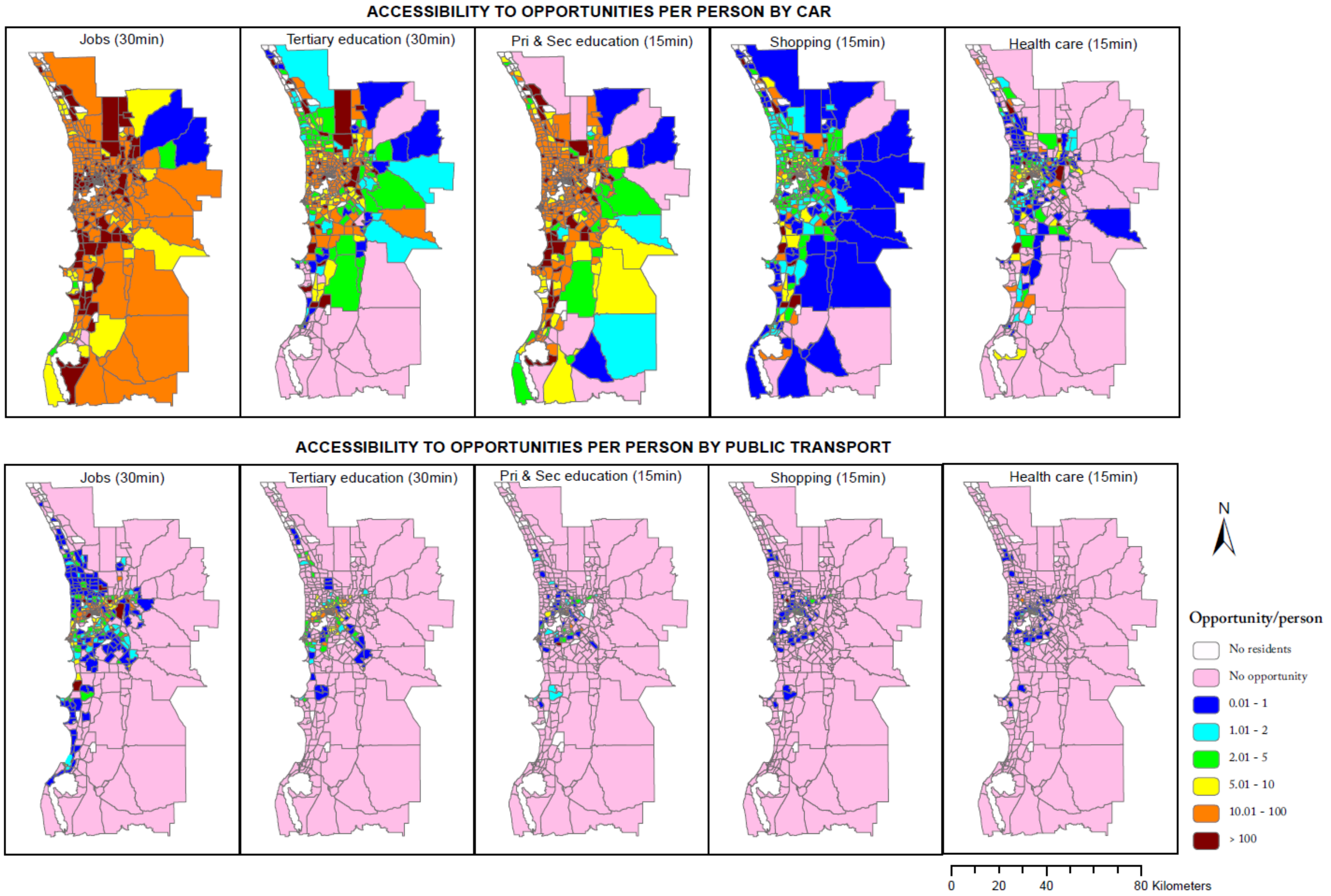


Figure 8.4: Accessible opportunities relative to number of local users (supply vs demand)

With a consideration of both supply and demand, the spatial variations change somewhat. The most notable difference is in the job opportunities, which have a strong concentration in the city centre but a fairly flat distribution in terms of opportunities per person reachable by car. Additionally, most zones have at least 10 job opportunities per person. With travel by PT the CBD dominance is still apparent but the opportunities quickly come down to less than one per person within the central subregions. The spatial pattern of PT accessibility mimics the main transport corridors, with the 'one opportunity/person' zones going north-south from the city centre, as well as eastwards along the Midland and Fremantle lines.

Other services are also concentrated in the central subregions but diminish much faster from the CBD. PT provides opportunities to a very limited area, and at very low levels – mostly one opportunity per person. Education opportunities are much higher per person (for tertiary) or per school age children (for primary and secondary) over a much larger area (compared to shopping and health care) by car travel, and to a lesser extent, by PT. Overall, despite a clear concentration in the inner subregions, job accessibility is more equitable by car travel than the other services when standardised by local demand. However, it remains highly inequitable by PT. The spatial inequity between inner and outer suburbs is more pronounced in education, shopping and health care services, with health care being unavailable in more outer areas than any other service (by car), and primary & secondary education higher in the central and western zones. Shopping opportunities, while generally lower, are available in the most zones with car travel.

8.4.3 Relative comparison of accessibility among the zones

How many services/opportunities accessible within a given time constitute adequate supply? At what point is more supply unnecessary? The solution to these questions is complex and subject to a myriad of factors relating to people's residential location choices, mobility needs and other personal preferences. If we take the level of service accessible from an average zone as a proxy for the opportunity threshold, zones below the average accessibility level can be deemed to be 'under-served' and those above the average to be 'over-served'. Both of these scenarios need attention from land use planners, but perhaps over-served zones are a lesser problem if they are in future residential growth areas. As expected, the results show inner zones to be better than outer zones (Figure 8.3). If the recent trend of more new developments in fringe than inner areas continues then the imbalance will be exacerbated.

However, the policy-advocated brownfield and intensive developments in inner areas has the potential to restore service equity. Average accessibilities by PT for all five services are significantly lower than by car (see Figures 8.3 and 8.5 and Table 8.1). The distribution graphs in Figure 8.5 visualise the significant differences between car-based accessibility and PT-based accessibility for all services. Zones above average by PT are more spatially dispersed and the few that are outside of the central subregions are generally close to train stations - particularly along the Fremantle and Midland lines for job accessibility and Joondalup-Mandurah lines for education accessibility. However, most of the zones along the railway are below the average, the worst services being shopping and health care.

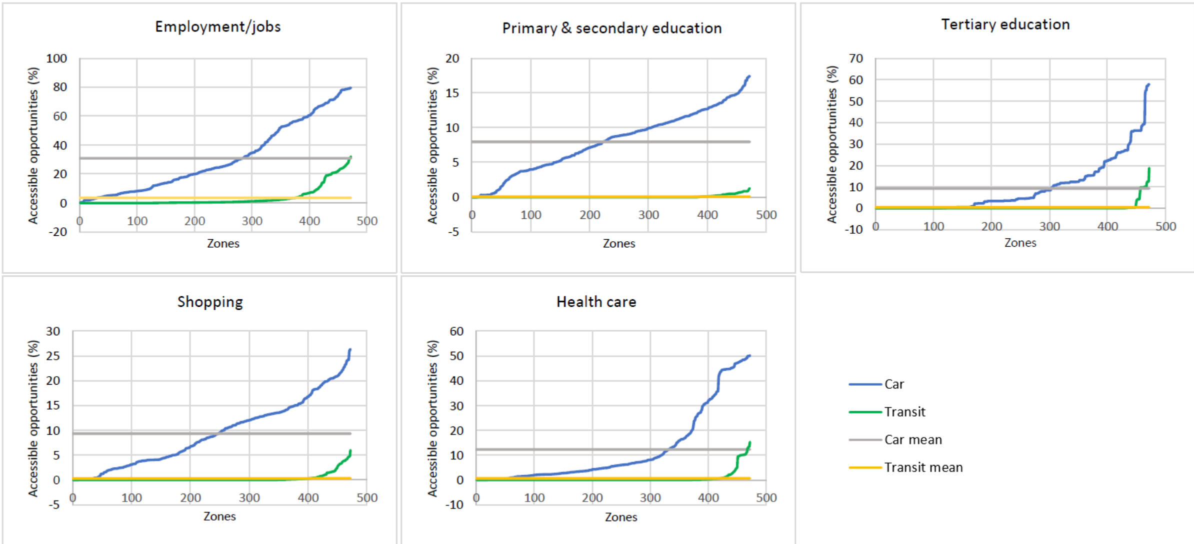


Figure 8.5: Distribution graph of accessibility values for various services by car and PT

Table 8.1: Relative accessibilities for the major services by car and transit

Service	Mode	Mean (%)	Std. deviation
Jobs	Car	30.86	23.60
	Transit	3.57	6.97
Pri & sec education	Car	7.97	4.18
	Transit	0.08	0.20
Tertiary education	Car	33.03	29.74
	Transit	4.38	7.95
shopping	Car	9.34	6.62
	Transit	0.31	0.90
Health care	Car	12.29	15.01
	Transit	0.67	2.37

8.4.4 Travel times

The average travel times from the STEM data were also calculated for the five trip purposes by car and PT. This shows the modelled travel times (averaged by total trips) spent on accessing the services by each mode of travel. The maps in Figure 8.6 show average times for each zone. For all five services, the shortest times are in the central subregions. Car times in these areas are within the desired thresholds of 30 minutes for work and tertiary education, and 15 minutes for primary schools, shopping and health trips. However, PT times are significantly higher, and outside of the desired thresholds for all purposes. In fact, in Table 8.2 we see that average travel times by PT are more than an hour for each of the five services. Average times by private car are much lower, and within the desired thresholds; under 10 minutes for each of shopping, health and primary & secondary education, and under 30 minutes for both work and tertiary education trips. The highest number of zones average between 20 and 30 minutes on travel for work and tertiary education by car and under 10 minutes for primary & secondary education, shopping and health care. By PT, most zones average more than an hour in all services (Figure 8.7). This means people living in most zones spend over an hour using PT to reach all services. While there are fewer people living in the outer zones which make the large majority of the more-than-an-hour bracket, this result shows that there is a big accessibility gap between the carless who rely on PT and those who use a car for these trips. Note that the car versus PT average travel times may be distorted somewhat by PT tending to be used for longer trips and the majority of shorter length trips being by car. This is a function of short length trips by PT taking significantly longer than the same trip by car due to the access times at each end, i.e. walking to the bus stop and waiting for the bus then walking from the destination bus stop to the final destination. The results therefore reinforce the efficiency of the car over PT for the user for shorter length trips, the railway only coming into its own for longer distance trips where the congestion effect for cars can counter the PT access time effects.

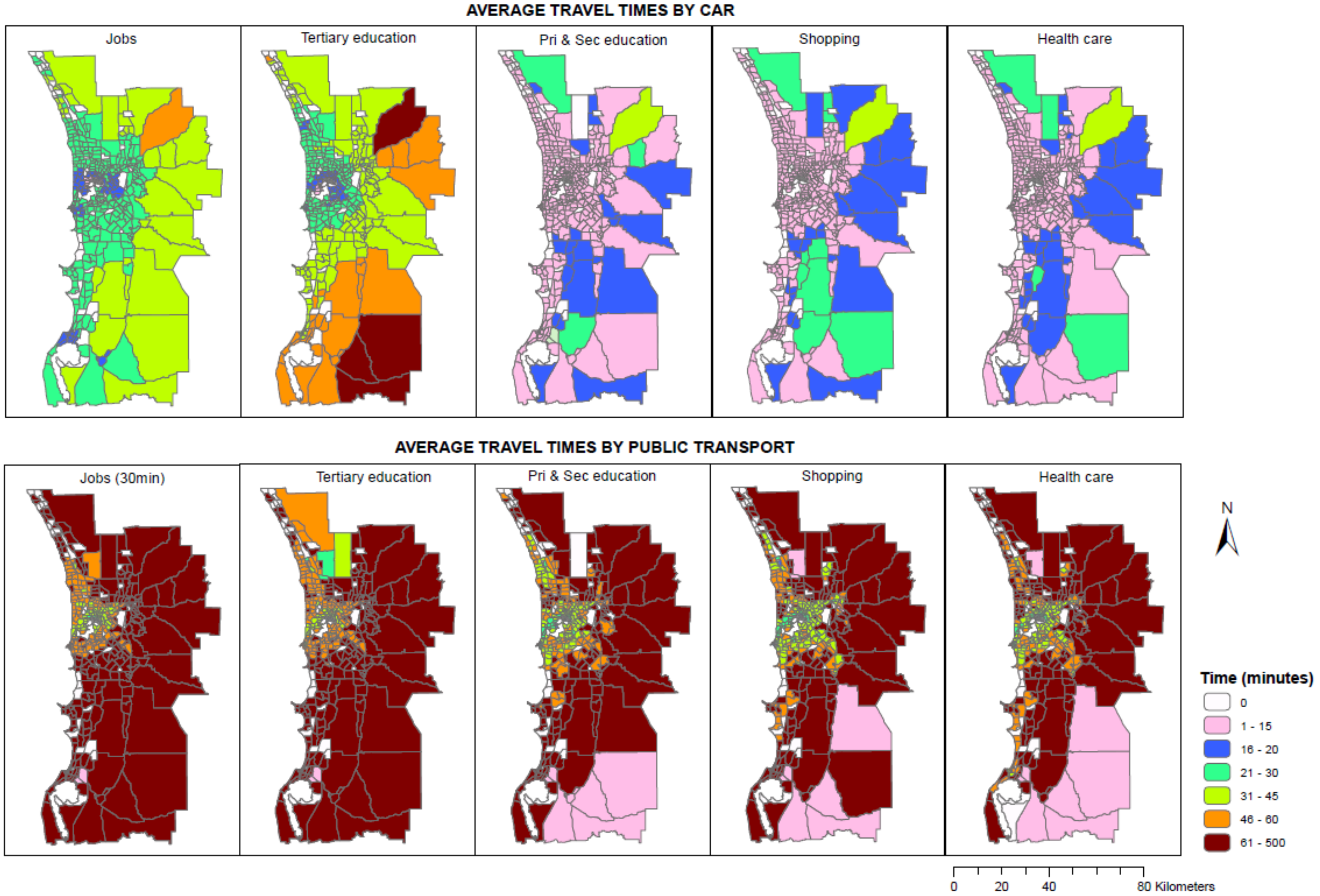


Figure 8.6: Average travel times for various purposes by car and PT.

Figure 8.7: Travel time frequency graph from car and PT trips

Table 8.2: Travel time statistics for car and PT trips

Service	**Mode**	**Mean** (minutes)	**Std. deviation**
Jobs	Car	20.56	9.03
	Transit	62.78	38.44
Pri & sec education	Car	7.50	4.61
	Transit	67.87	93.79
Tertiary education	Car	26.21	13.90
	Transit	61.67	34.82
shopping	Car	7.94	4.88
	Transit	73.22	95.14
Health care	Car	9.16	4.52
	Transit	71.76	88.25

8.4.5 PT/car accessibility ratios

To examine and compare the performances of PT and private car more directly, a PT/car accessibility ratio map was designed for all the five services (Figure 8.8). The ratio maps more clearly visualise and further emphasise the limitations of PT accessibility over the car. Additionally, and quite importantly, they also show specific zones where PT is relatively competitive.

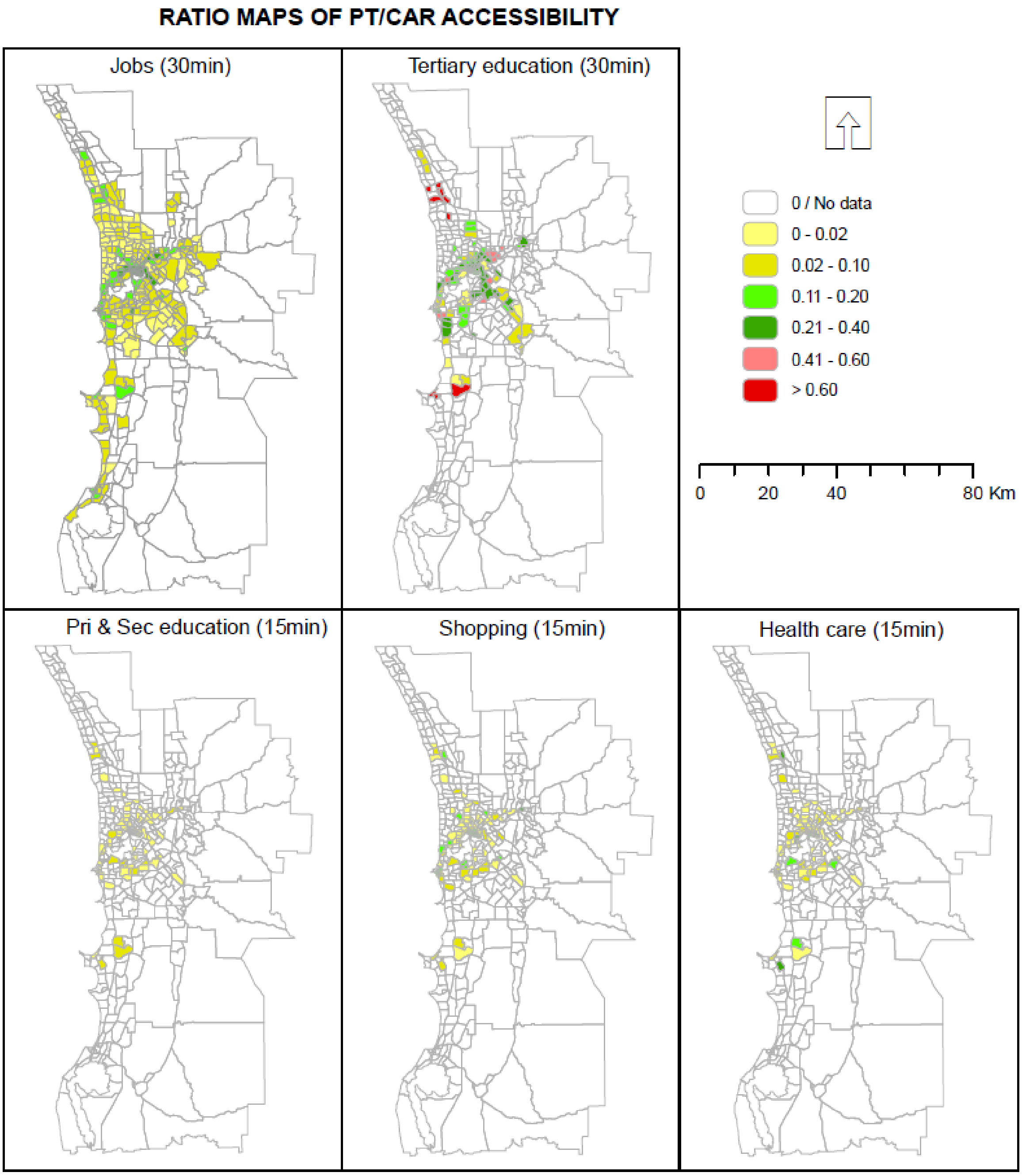


Figure 8.8: PT/car accessibility ratio maps

As revealed in the previous sections, the accessibility ratio maps in Figure 8.8 show that PT accessibility is relatively limited compared to that of the car, across all the five services. There were no zones, among all the services, in which PT provided better accessibility than the car (i.e. no zones above 1). Tertiary education was the service in which PT was most competitive with some zones reaching a ratio of up to 0.95. Some zones in the mid-north (Joondalup area) and mid-south (Kwinana area) had a PT/car accessibility ratio of greater than 0.6. For job accessibility, only one zone – in the CBD – was greater than 0.4 (zone 170, exact ratio = 0.427259). There was a sizeable amount of zones in the range of 0.2-0.4, and their spatial pattern depicted the passenger train network. It is also worth noting that, while PT often appears to favour the work commute, particularly for the CBD-based jobs, its performance is, relatively, much lower than the car. In comparison with tertiary education, a lower relative PT performance was found in job accessibility. However, PT accessibility was limited to fewer zones in tertiary education than for jobs services. This is linked to the low number and more sparse distribution of tertiary institutions compared to jobs across the metropolitan region. Thus, job accessibility by PT had a wider spatial coverage (i.e. more zones had a PT-based job access), albeit at a very low level – less than 0.1 ratio, compared to tertiary education opportunities. The other three services (primary/secondary education, shopping and health care) had mostly less than a 0.1 ratio, with a few zones notably in health care recording above 0.1. Many of these zones were concentrated in the Central subregion, while those in the outer subregions were closer to the train lines. Overall, primary/secondary education was the service in which PT was least competitive, followed by shopping. The impact of short time thresholds on the ratios must, however, be acknowledged. For short thresholds, a significant amount of the time goes to accessing PT (walking to bus stop / train station and waiting) while the in-vehicle time is proportionally much short. Comparatively, for the car, almost all of the time threshold is in-vehicle time.

8.4.6 Areas of concern

The areas where further land use planning attention may be warranted are either those that have too little (or no) access to services or more access than is necessary/beneficial (excess supply). Theoretically, a spatially equitable supply would produce similar, consistent accessibility across the region. However, the higher population density in the inner zones obviously creates higher demand, for which the corresponding high supply can create at least the appearance, if not the reality, of spatial inequity. Residents of zones with no or limited accessibility, however, are disadvantaged. Due to the largely centralised job locations, PT provides the best accessibility for jobs than for any other type of destination. The rest of the services have very poor accessibility by PT across the region, which makes private car the more viable travel mode regardless of the purpose of travel.

8.4.7 Limitations

This study has some limitations related to its scope and methodology. The use of STEM zones requires noting that they are quite large and jobs and houses are not necessarily evenly distributed in the zones. STEM assumes that everything in the zone is located at the centre and has equal accessibility. In large zones, this can be misleading because in reality some of the services can be reached from the origin zone within the access time while others in the same zone cannot. While the large zones are at the peripheries and house fewer people, their results must be used carefully. Also, the results of this study are as at the year 2011, due to data restrictions. It therefore does not reflect the demographic changes that have occurred since, or the transport improvements such as the WA Gateway project and new PT services.

It is also noted that primary schools have catchment areas as demarcated by the State government. However, this study does not make use of such. In future work, the approach employed in this study could be built on to test whether these catchment areas provide the best accessibility for primary schools.

It is also worth reiterating that the cumulative accessibility measures have a major shortcoming of sensitivity to travel time threshold. Changing the threshold slightly can often produce significantly different results. Even though the thresholds used in this study were justified by and aligned with policy objectives, their sensitivity was tested by picking job accessibility and adding and subtracting 2 minutes from the chosen 30 minutes. The results showed the thresholds of 28 minutes and 32 minutes were very similar to the chosen 30 minutes (see Figures 8.9 and 8.10). There were no unexpected jumps or drops in the trends and the areal difference under the graphs was quite small, suggesting that these results are not too sensitive to the travel time thresholds.

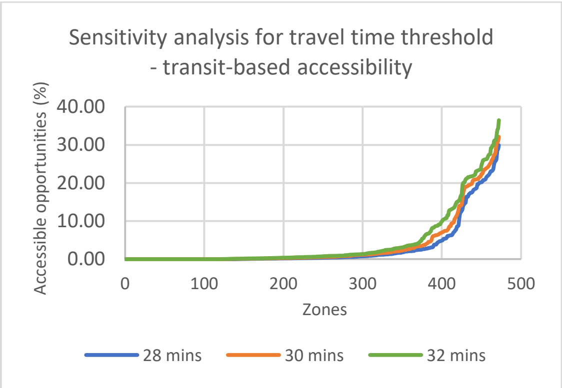


Figure 8.9: Threshold sensitivity test: job accessibility by transit

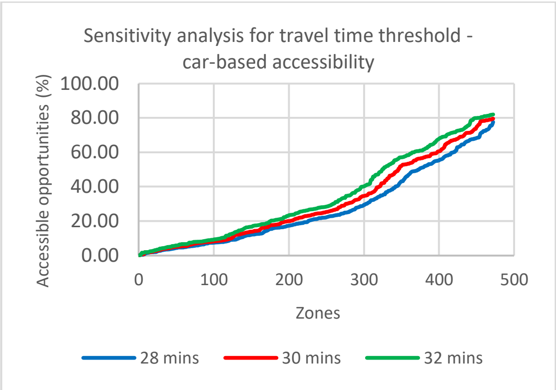


Figure 8.10: Threshold sensitivity test: job accessibility by car

A common disadvantage of simple methods is often that they compromise the accuracy. While the applied method is practical, easy to understand and implement for a wider range of users, it does not consider other important travel factors beyond travel time. This can overestimate the level of accessibility, which can be curbed by combining it with other cost measures (El-Geneidy et al., 2016). Futures studies should consider incorporating other factors such as mode cost, comfort level etc. in addition to travel time. The challenge is in finding the balance between improving the level of accuracy while keeping the measure simple and practical.

8.5 SUMMARY AND CONCLUSION

This study employed a simple ‘cumulative opportunities’ approach to comparatively evaluate the accessibility of various services/land uses by car and by PT. The measure of accessible opportunities presents a comprehensible and policy-friendly approach that enables comparison not only across services/land uses and travel modes, but can also be applied across cities. With this approach, this study highlights disparities across the PMR in terms of the accessibility of jobs, colleges, schools, shopping and health care. While all five land uses considered exhibit a monocentric urban spatial structure, the centre is most dominant in the employment sector. Shopping has a much less dominant centre, and tertiary education is accessible in the smallest area that mostly excludes the Peel subregion. With consideration of local demand, job accessibility flattens out across the region by car travel, but the centre remains dominant for other services. PT provides the best accessibility for jobs (compared to other services) in terms of both the proportion of reachable opportunities and number of zones served. This shows that the measurements of accessibility that is focused only on job travel can overstate the accessibility levels. Generally, the PMR has great spatial inequity with people living in the central sub-region having the best accessibility (most opportunities) while those living in the outer suburbs have the least opportunities across all sectors/land uses. Thus, the further out one lives from the city centre, the more disadvantaged they are with regard to job, education, shopping and health care opportunities.

A large disparity also exists between the accessibility provided by car and PT. Given the radial network of Perth’s transit system around the city centre, we possibly should not expect people to rely on PT for trips not involving the city centre. Hence, PT is not able to compete with the car, which remains the best travel option especially for people living outside of the inner core. PT also seems to cater for people with cars through its Park & Ride facilities - without a car, the ‘park’ stations are inaccessible to many people. This work has revealed the least/under-served areas both in absolute (total opportunities) and relative (proportions per users) terms. The results of this work can be a useful planning tool for transport and land use investments. The approach employed in this study could be used to test the accessibility/equity of the *Perth & Peel @3.5 million* scenarios (population projections). The projections for workers/jobs/services could be moved around to get better spatial equity.

It must be noted that the PT in Perth has a predominantly radial pattern which services the inner areas and in particular the CBD. Apart from those living closer to train stations, people living in the outer areas have little to no supply of PT services, especially to cross city destinations. As a result, the very poor scores found in this paper are inevitable. However, the competitiveness of PT against private car is unlikely to improve based on the scale alone, particularly considering the magnitude of the disparity between the two modes. Furthermore, the peak travel times used for jobs and education trips represent the period when PT is at its highest efficiency due to high service frequency and spatial coverage and car at lowest efficiency due to congestion (train is unaffected by congestion and bus-only lanes reduce the impact on buses). Thus, PT accessibility results for education and jobs represent the best-case scenario, yet the car still proved to be far too superior in terms of accessibility provided.

CHAPTER 9 IMPACT OF COMPETITION IN CUMULATIVE OPPORTUNITIES ACCESSIBILITY

9.1 INTRODUCTION

The previous chapter analysed the spatial equity of various urban services using the cumulative opportunities accessibility measure. As accessibility becomes an increasingly relevant concept in the analysis of sustainable transport and urban development, the accuracy of accessibility measures becomes increasingly vital. While the cumulative opportunities measure is the most widely applied accessibility measure in planning practice, it is also among the least accurate due to its lack of consideration of the impact of competition for those opportunities. In the thesis' second component of spatial equity analysis, this chapter explores the impact of competition on cumulative opportunity-based accessibility. A competition component is incorporated in the cumulative opportunities measure, which is then applied to a case study of three different urban services; jobs, primary/secondary education and shopping. The chapter is one of the significant and novel contributions of the thesis that will benefit urban service accessibility research and support meaningful decisions on land use planning.

9.2 RESEARCH CONTEXT

Accessibility is a key indicator of the functional efficiency and spatial equity of an urban spatial structure. It is a widely used concept in the fields of urban development and transport planning (Gonzalez-Feliu, Salanova Grau, & Beziat, 2014). The notion of accessibility was the outcome of a paradigm shift from mobility, bringing the focus from enabling easy travel to all locations, mostly by car, to promoting access through proximity as well as efficient transport systems (Cervero, 1997; Curtis & Scheurer, 2010). The questions of what can be reached from a given point and how, provide a useful framework for the integration of land use and transport planning (Bertolini et al., 2005). It is anchored on the core objectives of achieving more sustainable land use and transport outcomes. Consequently, improving accessibility and/or its equity is often noted as a planning policy objective and as one of the channels toward improving the sustainability of cities.

Several methods have been developed to measure accessibility within an urban structure. While there are many debates about what type of measures are needed when, their added value to planning is widely accepted (Brömmelstroet, Pelzer, Klerkx, & Schaminée, 2013; Pelzer, Geertman, Heijden, & Rouwette, 2014). The most widely used accessibility measure in planning applications is the cumulative opportunities measure. It is a powerful accessibility measure that has been extensively adopted by researchers and applied by planners and policy makers (Åslund, Östh, & Zenou, 2009; Bertolini et al., 2005; Levinson, 1998; Merlin & Hu, 2017), owing to its ease of understanding and interpretation, repeatability and direct comparison across cities (Merlin & Hu, 2017; Owen et al., 2017). However, as with many empirical models, the ease of applicability and interpretation is often a trade-off against accuracy and realism. As more data become available and computational resources improve, methods become more accurate, but they also get more complex and difficult to interpret. Thus, there is a fine balance to be struck between improving the accuracy of methods and keeping the measures simple and practical. Keeping accessibility measures simple and practical is a critical factor in land use and transport systems evaluation, because complex methods are less likely to be applied by planners and policy makers (Bertolini et al., 2005; Lotfi & Koohsari, 2009).

A critical limitation of the cumulative opportunities measure, as widely adopted in policy, is its failure to incorporate the effect of competition for the available opportunities. The cumulative opportunities measure assumes that people will take up the opportunities nearest to them, and more opportunities nearby translates to more choices for residents. Furthermore, it is assumed that there is no limit on the capacity of these opportunities (Shen, 1998). In reality, however, there are often other people competing for the same opportunities and, in cases such as employment, one job can only be taken by a single person. Thus, the assumption that more opportunities translates to more choices, without considering the competition or potential demand for those opportunities, can be misleading.

Accessibility measures are quite useful in understanding the urban structure because "they reveal basic information about the spatial organization of urban systems" (Mark W. Horner, 2004, p. 264). Their ability to capture the distribution of human activities enables them to reveal key aspects of urban structure (Geertman & Ritsema Van Eck, 1995; Mark W. Horner, 2004). However, many studies have limited their scope to the accessibility of one type of urban service, with little attention given to how it might differ with other key urban services. Arguably, the most studied is job accessibility (Boisjoly & El-Geneidy, 2016; Cheng & Bertolini, 2013; Fransen, Boussauw, Deruyter, & De Maeyer, 2019; Kawabata & Shen, 2007; Moniruzzaman et al., 2017; Owen & Levinson, 2015; Shen, 1998). Job accessibility is indeed vital in revealing critical information about the urban spatial structure including the urban form, excessive commuting, modal mismatch and job-housing balance (Cheng & Bertolini, 2013; Mark W. Horner, 2004). However, it does not tell the complete story of the urban structure since the spatial distribution and dynamics of other urban services, such as access times (morning/afternoon/evening) and capacity limits, may be completely different. Health care accessibility is also widely studied (Luo & Qi, 2009; Luo & Wang, 2003; Matthew R. McGrail & Humphreys, 2009; Oppong & Hodgson, 1994; Vadrevu & Kanjilal, 2016), and to a lesser extent, other services such as recreational parks (J. W. Kim, 2015; S. I. Kim & Fesenmaier, 1990; Omer, 2006; Talen & Anselin, 1998), but there remains limited research interest into how the accessibility of various urban services compare within an urban spatial structure. While focusing on one urban service enables examination in more detail, a comprehensive understanding of the underlying urban spatial structure requires the relative accessibility of other key urban services (e.g. education, health, shopping, recreation etc.) to be understood, capturing the distribution of both opportunities and their respective users/seekers.

This study contributes to ongoing research in this area by incorporating competition for various service opportunity types into a cumulative opportunities measure, and performing comparative spatial equity assessments of those services. It seeks to modify and enrich the cumulative opportunities measure to address competition effects while preserving the objectivity of the measure, and with minimal increase in complexity. This study builds on the method and results of the previous chapter to demonstrate the usefulness of the cumulative opportunities measure with and without competition for the accessible opportunities. The method is applied to a case study of the PMR by modelling the 'effective accessibility' of three key urban services – work, primary/secondary education and shopping – with competition on the demand side, and comparing their levels, spatial patterns and spatial equity of, accessibility. Thus, this study is of relevance to planners and policy makers as it demonstrates application of the cumulative opportunities measure in a more realistic (and more accurate) manner that is responsive to competition effects. The study also provides empirical insight that can be relevant to other contexts and/or regions.

In the next section a brief contextual background is provided from existing literature on accessibility measures, competition and cross-service comparison. The section that follows describes the study area and methodology of the chapter. The results and discussions are then presented in the next two sections, before ending with concluding remarks and future research directions.

9.3 MATERIALS AND METHODS

9.3.1 Data

This chapter used the same source of data as the previous ones (STEM) but there were additional elements of data from the model that were included here. Data elements relevant to the analysis in this chapter include, for each zone, the population, labour force, number of jobs by different industries, number of school-age children and number of school enrolments, among other variables. In this study, three urban services of employment, primary/secondary education and shopping were selected for investigation. The number of jobs in each zone was used to represent job opportunities, and school enrolments as a proxy for education opportunities. The number of retail jobs in each zone was used as a proxy for shopping opportunities. The population P in Equation 9.1 was represented by the number of people constituting the demand demographic for each service i.e. the demand/competition for jobs was represented by the labour force – consisting employed and unemployed people, demand for primary/secondary education was represented by number of school-age children (5 – 18 years), while the total population was used as demand for shopping opportunities.

9.3.2 Calculation of accessibility with competition

The cumulative opportunities approach is a widely favoured measure of accessibility because of its practicality. However, the simplicity of this measure is also directly related to its greatest limitation, as it is a direct trade-off against accuracy. In reality, the value of a reachable opportunity goes down when the competition for it increases, so the cumulative opportunities measure can be made more realistic by accounting for the level of demand or competition for the opportunities. A competition component is incorporated into the traditional cumulative opportunities method to reflect the degree of competition for the same, limited opportunities. This keeps the method fairly simple but the accuracy is improved as available/accessible opportunities are related to the size of existing demand.

The method uses a probabilistic approach to estimate the share of accessible opportunities between zones proportional to their sizes of active demand, and then averages it out for each individual constituting the total demand. In the illustration on Fig. 9.1, assuming that the arrows represent trips that can be made within the given threshold time, then an individual living in zone i can reach jobs in zones j_1 and j_2. Additionally, people living in zones $k_{j=1}$ and $k_{j=2}$ are also within the travel time threshold to zones j_1 and j_2 respectively, and hence are competing for opportunities with the individual in i. Thus, to find the effective accessibility[3] for the individual in zone i, the jobs in each zone j that can be reached from i are divided by the number of people living in all the zones that can also reach zones j, including those in zone i. The results are then summed for each zone i (Equation 9.1).

[3] The term 'effective accessibility' is used to differentiate from accessibility by the traditional cumulative opportunities measure without consideration of competition. Without considering competition, people in big cities will always appear to have better accessibility to opportunities than those in smaller towns, simply because there are more opportunities. However, a better supply-demand ratio in a smaller town would mean that they have a greater chance of a reachable opportunity being available i.e. they 'effectively' have relatively better accessibility, although you could argue they have a potential smaller range of opportunities/choice. This raises the issue of matching users with opportunity type (e.g. type of worker with type of job), which is important but beyond the scope of this thesis.

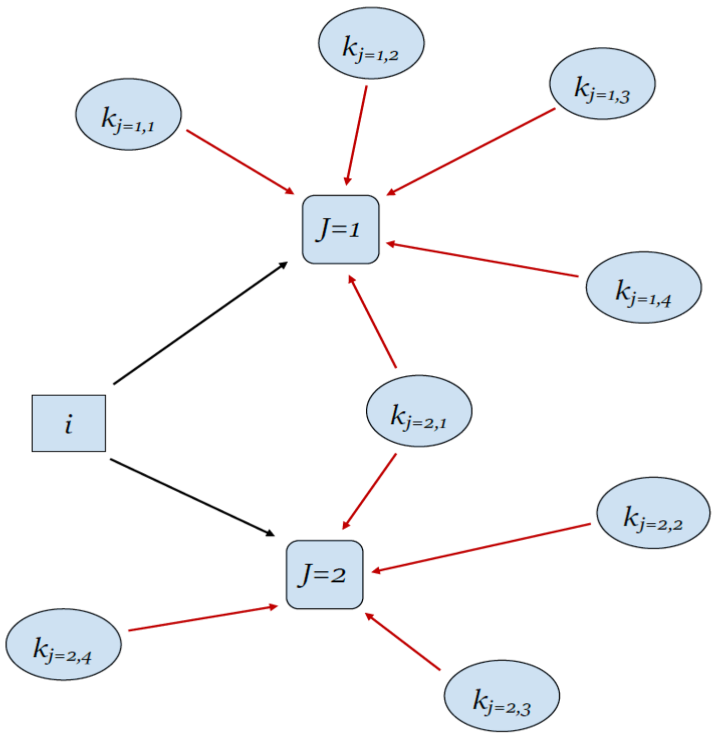


Figure 9.1: Illustration of the probabilistic accessibility in a competitive setting

$$A_i = \sum_{j=1}^{n} \frac{cE_j}{\sum_{k=1}^{n} yP_k} \quad (9.1)$$

where:

A_i is the effective accessibility at zone i (opportunities available to an individual person living in zone i), n is the total number of zones in the study area, and c has a value of 1 for zones j reachable from i within a given cost (time, distance) threshold, and 0 otherwise. E_j is the total number of opportunities in zone j, P_k is the population/demand size of zone k that is competing for the opportunities at (within the access time threshold to) j, y is a constant with a value of 1 for competition zones k that can reach j within the given cost threshold, and 0 otherwise. Note that i can equal j because of other people living in i who also form part of the demand/competition, and similarly, j can equal k. The final results are expressed in opportunities per person (opps/person), which implies the total number of opportunities available to each individual person in a specific demand demographic e.g. labour force or school children.

The results are divided into three categories of car, PT and a combination of both. Investigating car-based and PT-based accessibility separately enables for a determination of each mode's performance and contribution to the overall accessibility maps. Thus, in the car results it is assumed that a resident has access to only the car as a mode of travel, and they are competing for opportunities with other people who can also only travel by car. Similarly, PT results are based on the assumption that residents and their competitors can only reach the services by PT. These scenarios could also be useful in measuring accessibility in areas where one mode is significantly limited or non-existent e.g. in inner-city areas where parking is severely limited, or in outlying suburbs not reached by PT. Nevertheless, the main results are in the third category which combines the two modes, and assumes that residents have access to both car and PT alike. This means a person living in a given zone can access opportunities either by car or PT, and they are competing for those opportunities with other people who also have a choice between these two modes. In each category, the effective accessibility of jobs, education and shopping has been determined, and a visualisation created through thematic mapping.

Python programming language was used to implement the procedure through the big data, (222,784 records for each of the three services, and for each travel mode – 1,336,704 records altogether). Finally, *ArcGIS* was used to create thematic maps for presenting the final results.

9.4 RESULTS

The unit in which the results are expressed – opportunities per person (opps/person) – is a comparative measure where a greater value represents better accessibility. An accessibility value of two, for instance, means that the total number of opportunities that an individual can reach from that zones is twice the number of potential competitors or all other people that can reach them. Residents in zones with accessibility values less than one have significant potential competition for the opportunities that they can reach, meaning that some residents in these zones would need to travel for longer than the time threshold to reach their desired opportunities.

Note that jobs and education have demand and supply that balance out since one person/student takes one job/school place. For shopping retail jobs were used as a proxy for opportunities, but 1 retail job will generate more than 1 trip, which means demand and supply do not balance out (see Table 1). To enable parallel comparison with jobs and education, shopping opportunities (retail jobs) were rescaled by the overall supply/demand ratio (total population divided by number of retail jobs). This way there would be enough shopping opportunities for everyone to shop while also reflecting the fact that each retail job can cater for multiple shoppers. So overall supply would match overall demand, as it does for jobs and education.

Table 9.1: Supply-demand ratios of the entire Peth metropolitan region

Service	Supply	Demand	Total ratio
Jobs	847039	925016	**0.92**
Education	253275	267519	**0.95**
Shopping	122570 (x 14.87)	1822093	0.067 **(1.00)**

Note: Retail jobs were rescaled by the overall demand/supply ratio (1,822,093/122,570) to match the population.

9.4.1 Effective accessibility by car as a mode of travel

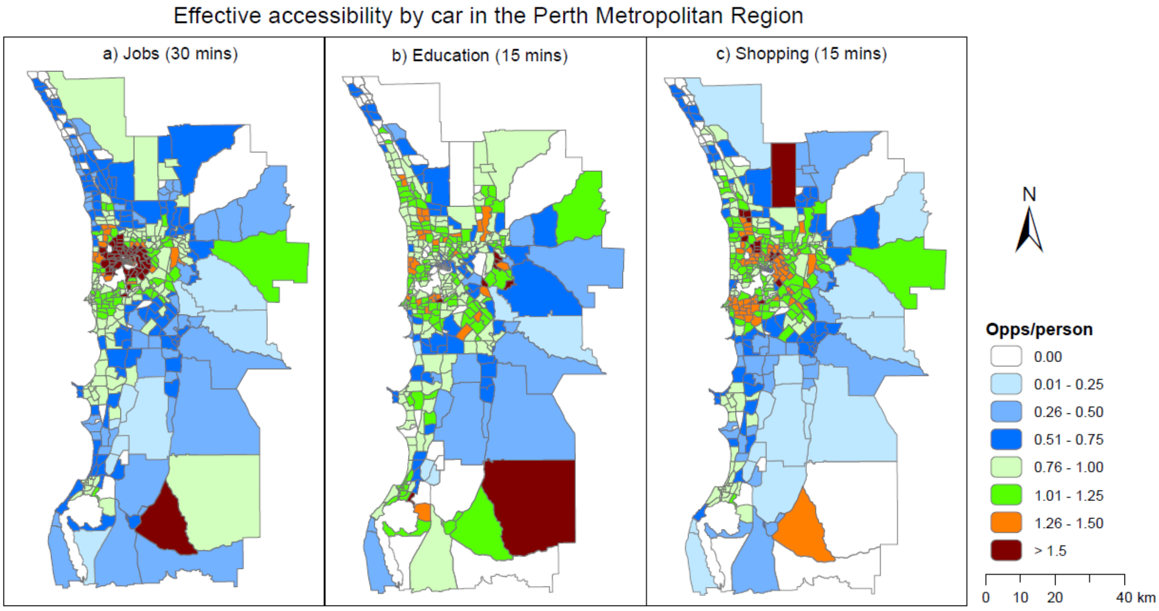


Figure 9.2: Effective accessibility by car for (a) jobs, (b) education, and (c) shopping in the Perth Metropolitan Region.

The spatial patterns of car-based accessibility for the three services of work, primary/secondary education and shopping are presented in Fig. 3. The pattern of job accessibility reflects a higher job concentration in and around the CBD (Fig. 3a). However, the highest job accessibility is not found in the CBD itself (1.26 – 1.5 opps/person) but rather in its surrounds where the effective accessibility values are greater than 1.5 jobs per person. Save for that, the general job accessibility pattern shows a radial decrease with distance from the city centre.

For primary/secondary education, the accessibility pattern becomes more even (Fig. 3b). Zones with a high education accessibility (>1.25) are scattered across the metropolitan region. Many zones in the central subregion and along the north-south corridor or coastline have an effective accessibility in the 'balance' range between 0.76 and 1.25 opps/person. The CBD has a low education accessibility of mostly less than 0.5 opps/person. Apart from the CBD itself and its immediate northern periphery, many of the zones in the low accessibility range (<0.5) are distant from the city centre, with all those in the lowest range (below 0.25) falling outside the central subregion.

Shopping accessibility (Fig. 3c) also had the general pattern of a radial decrease of accessibility with distance from the city centre but, likewise, a large part of the CBD was in the lower range (0.51 – 0.75 opps/person). There were clusters of zones with high accessibility (>1.25) in the Central Subregion, but majority of zones in this subregion were in the green, 'optimum' range of 0.76 – 1.25 opps/person. More zones fell in the lower class of 0.01 – 0.25 opps/person (15 zones) compared to the other two services (9 for jobs and 10 for education) and all of them were outside the Central Subregion, scattered in the other five subregions.

9.4.2 Effective accessibility by public transport as a mode of travel

The accessibility provided by public transport (PT) travel is limited by the geographic coverage of its network, and since it is mainly concentrated in and around the central subregion and the north-south corridor, many zones in the North East, South East and Peel subregions have no effective accessibility for any service by PT (Fig. 4). There are also many zones within the central subregion and other areas covered by the PT network, whose effective accessibility is zero. This means that no opportunities can be reached from these zones by PT within the given travel time threshold.

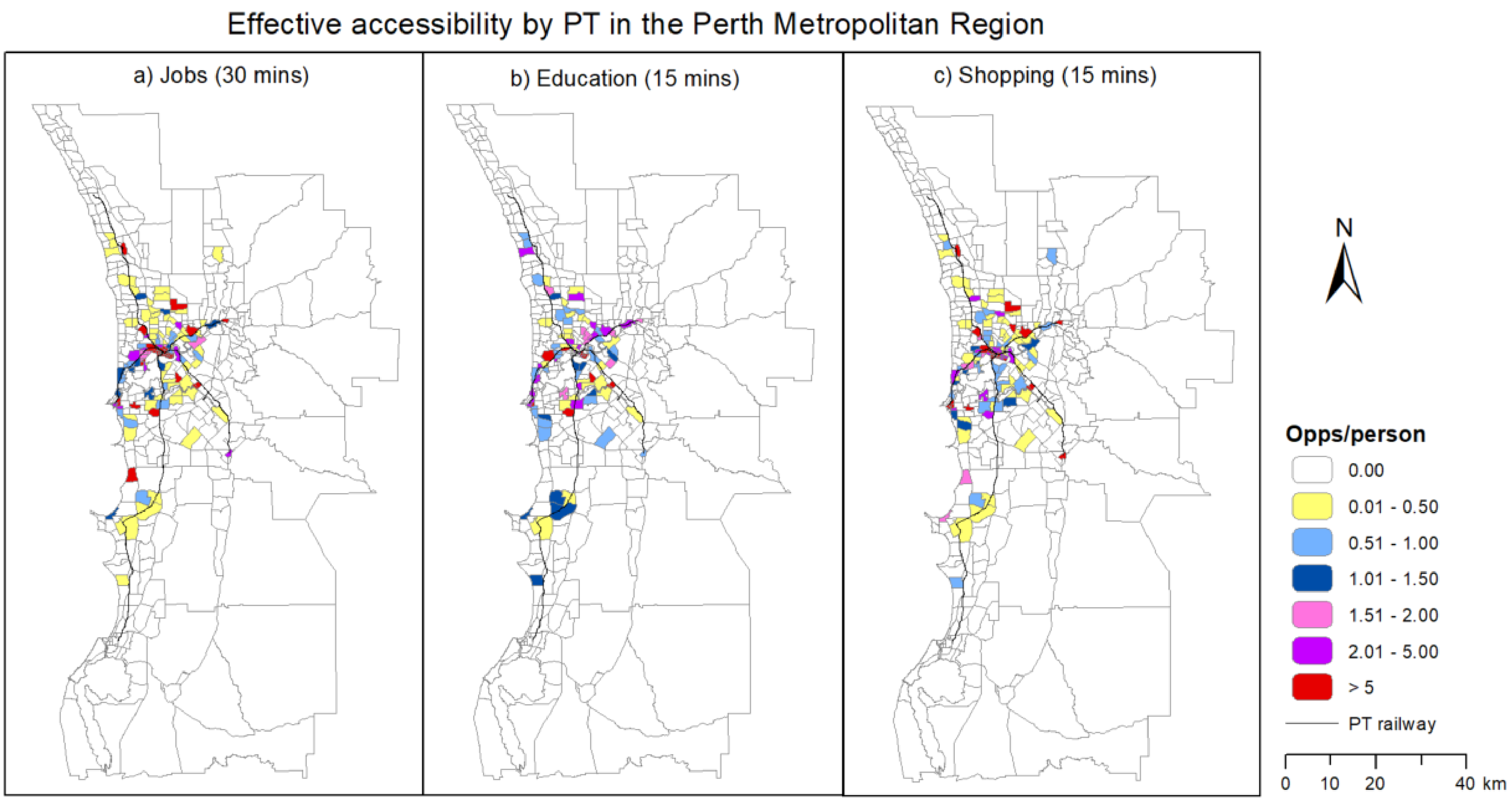


Figure 9.3: Effective accessibility by PT for (a) jobs, (b) education, and (c) shopping in the Perth Metropolitan Region

The spatial pattern of job accessibility by PT (Fig. 4a) shows a wide variation across the zones, with both high and low values dispersed across the metropolitan region. The entire CBD is in the highest class of greater than 5 opps/person. Nonetheless, the top four zones with the highest job accessibility by PT are not in the CBD, and one of them is outside the central subregion i.e. in the North East subregion. Zones along the Fremantle line mostly have a higher job accessibility of above one job per person, but the general pattern is low job accessibility by PT (<0.5 opps/person) as distance from the centre increases.

Education accessibility by PT also has high and low zones spatially dispersed in a random pattern, but a pattern of higher accessibility closer to train lines is visible particularly along the Fremantle and Midland lines (Fig 4b). The majority of the CBD zones (19 out of 34) have either no education accessibility by PT (10 zones) or no education demand i.e. no school-age children (9 zones). All these zones lie on the western end of the CBD. The eastern side of the CBD falls in the highest range of greater than five opps/person. Similar to job accessibility, the four (4) zones with the best education accessibility are not in the CBD. Rather, they are all south of the Swan River, and in the Central subregion. For shopping accessibility (Fig. 4c), the top eight zones with the best accessibility by PT were not in the CBD – two were in the North East subregion, and three each in the north and south of the Central Subregion. A pattern of the train network is also visible, with majority of lower accessibility zones falling farther from the railway line. In fact, four of the best eight zones mentioned above were directly accessible by train (one each on the Joondalup and Armadale Lines, and two on the Midland Line).

9.4.3 Effective accessibility by both car and public transport

Assuming that everyone has access to both car and PT, we can determine the accessibility from each zone by whatever mode. That means the opportunities are deemed accessible from a given zone if their host zone can be reached within the threshold time either by car, PT or both. This varies from the car accessibility in that travel between some zones is within the time threshold by PT but outside it by car, increasing both the zones that can be reached from a zone and the competition for opportunities in those destination zones. This particularly relates to the CBD and other zones served by the high-speed railway where car travel times suffer from congestion.

The job accessibility results show that many zones in and around the central area are in the 'balanced' range of 0.76 – 1.25 opps/person (Fig. 5.a). Apart from some three small zones in the middle of the Peel region, all zones have a job accessibility of less than 1.5 opps/person. All zones with above 1.26 opps/person are south of the Canning River and mostly along the freeway. Interestingly, the spatial patterns and levels of accessibility for education and shopping services with combined travel modes (Figs. 5b and 5c) were exactly the same as when the travel mode is car only (Figs. 3b and 3c). This indicates that PT cannot reach any education or shopping opportunities within the 15-min threshold where the car cannot, whilst the car also reaches additional opportunities that are not accessible by PT.

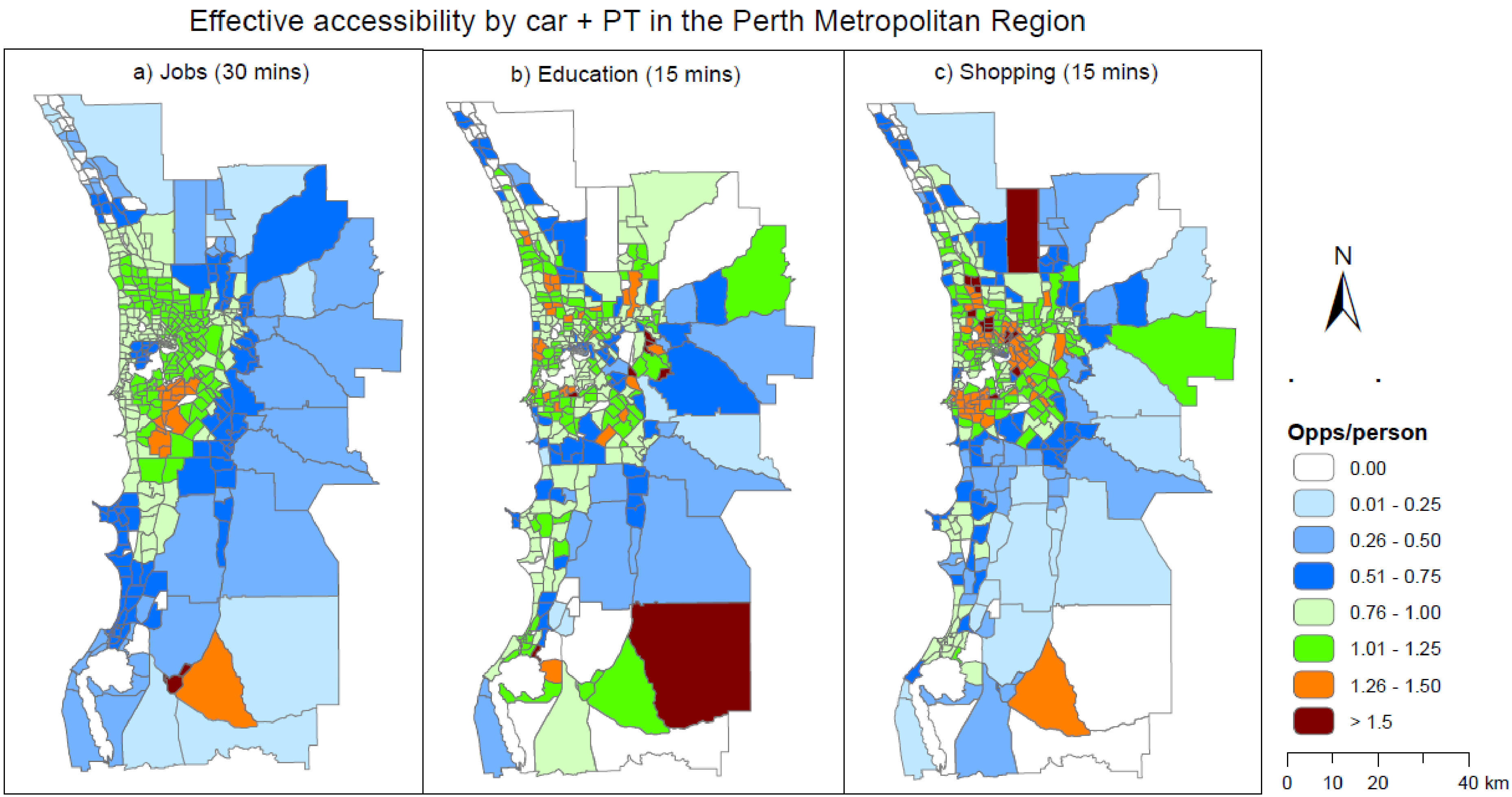


Figure 9.4: Effective accessibility based on both car and PT travel for jobs, education and shopping in Perth

The accessibility statistics also showed, through the high standard deviations and coefficient of variations, that there were great variations in PT accessibility values across all three services, which implies poor spatial equity of PT-enabled accessibility (Table 9.2). In contrast, there were much lower variations within the car-enabled accessibility values for all three services.

Table 9.2: Effective accessibility descriptive statistics for jobs, education and shopping

Service	Travel mode	Mean accessibility (opps/person)	Std. deviation	Coefficient of Variation
Jobs (*n*=438)	Car	0.97	0.80	0.82
	PT	24.09	393.29	16.33
	Car & PT	**0.85**	**0.55**	**0.65**
Education (*n*=423)	Car	0.89	0.30	0.34
	PT	1.38	12.75	9.24
	Car & PT	**0.89**	**0.30**	**0.34**
Shopping (*n*=438)	Car	0.91	0.35	0.38
	PT	42.24	787.09	18.63
	Car & PT	**0.91**	**0.35**	**0.38**

Note: *n* is the total number of zones with valid effective accessibility. Some zones were excluded due to no resident demand (division by zero).

Table 9.3 shows the percentages of zones within an optimum range of accessibility by each travel mode. An effective accessibility of one would be ideal, suggesting that under a competitive environment, the number of opportunities matches the number of people who can reach them within an acceptable travel time. Since it is difficult to have such a perfect match, optimum accessibility is deemed to be within the range of 0.76 – 1.25 opps/person. Table 9.3 shows that job accessibility results improved quite noticeably, with the number of zones in the optimum range rising from 37% of car-only travel to 62%. The majority of these zones were in the inner and westerly areas (as seen in Fig. 5a,). Education and shopping accessibility did not improve from car-only travel, remaining at 64% and 50% of zones in the optimum range, respectively. The combined-mode results show that in all the three services, at least 50% of zones had optimum or equitable accessibility, but PT contributed very little to this equity.

Table 9.3: Percentage of zones with optimum accessibility by service type and travel mode

	CAR	PT	Car & PT
JOBS	37.00%	2.97%	**62.33%**
EDUCATION	63.59%	2.84%	**63.59%**
SHOPPING	50.23%	3.20%	**50.23%**

9.5 DISCUSSIONS

9.5.1 Effective accessibility – opportunities discounted by competition

The cumulative opportunities measure is a powerful tool for measuring location-based accessibility. Its ease of application and interpretation is of great value to both researchers and policy makers, as demonstrated by its wide usage in scientific studies and application in policy instruments (Curtis & Scheurer, 2010; K.T. Geurs & Ritsema van Eck, 2001). However, without a consideration of the amount of competition for opportunities, the traditional cumulative measure provides an optimistic and perhaps misleading view of accessibility, as any rise in the number of reachable opportunities is deemed as an increase in accessibility. In reality, however, the likelihood of an opportunity that one can reach being available will reduce with a rise in demand or competition.

This study attempted to reveal the value (and not the mere magnitude) of opportunities available to an individual person living in a given zone i.e. the effective accessibility. Effective accessibility is significantly more meaningful to planners and transport policy makers because it can help identify areas that may be under-served or over-served (demand-supply imbalances) and reveal the level of service need for people living in specific locations. This is achieved while keeping the method fairly simple, giving results that are easy to interpret for a wide range of users.

A critical flaw in using the traditional cumulative opportunities measure to draw spatial equity conclusions is that it only considers one side of the supply-demand equation. This always implies that people in city centres have better accessibility than those further out, or those in large cities better accessibility than those in smaller towns. This may or may not be true but without adding the missing component (supply or demand) we do not know. The introduction of competition for opportunities is an attempt to address this deficiency. While it is still simply a numbers game (i.e. ignoring skills and job matches, parental school preferences and other accessibility complexities), it adds the value of showing not just how many opportunities can be reached but also the likelihood that an opportunity would be available when you reached it (i.e. the competition component). For example, consider a large city with 500,000 jobs and 550,000 labour force with the average worker being able to reach 300,000 jobs in 30 minutes, and a small town with 50,000 jobs and 51,000 workers with all workers able to reach all 50,000 jobs. With the traditional measure the big city worker appears to have access to six times more opportunities than one in the small town. But the probability of having a job is 500/550 or 91% for the big city but 98% for the small town (ignoring job/worker mismatches). Thus, the big city / CBD may be said to provide high accessibility in the sense of a large labour force and customer base being able to reach it. So, it is sensible for businesses to pay more to be in the CBD if they want/need access to a large regional labour force or customer base, but it makes less sense for jobseekers to pay the higher costs to live in the CBD if none of the opportunities are actually available to them (because of the higher competition/demand). Ultimately for an opportunity seeker / worker, it is not just about being able to reach an opportunity, but also the likelihood that the opportunity is available when reached – hence the competition component. Without the competition component, we would draw the conclusion that the city workers had much better accessibility than those in the small town i.e. the wrong spatial equity conclusion.

Our results revealed a significant difference in the levels and patterns of accessibility and spatial equity compared to when competition was not factored into the cumulative opportunities measure (see Figs. 6 and 7). Previous studies found the Perth CBD to have the best/highest accessibility by both car and PT, based on a cumulative opportunities measure with no consideration of competition effects (Moniruzzaman et al., 2017). In Chapter 8 it was concluded that the functional spatial structure of Perth was highly monocentric, and CBD and inner core of the Central subregion had a disproportionately high level of accessibility for each of job, education and shopping opportunities. However, in the current chapter it is found that competition effects are also high in the CBD and its surrounding zones, and thus living in the CBD does not provide the high accessibility reported. Education and shopping were both fairly equitable across the metropolitan region (Fig. 5b & c), and did not show the monocentric structure that was otherwise apparent in the absence of a competition component (see Fig. 6b & c). The results here show that while there may be higher numbers of opportunities in the inner zones, these do not necessarily translate to better accessibility because a higher competition also exists in this area (i.e. more people can access them within a reasonable time). It is therefore clear that ignoring competition for opportunities in measuring accessibility can lead to inaccurate conclusions. Addressing competition in the cumulative opportunities measure provides better insight into the spatial equity of services and can more accurately identify areas requiring planning intervention.

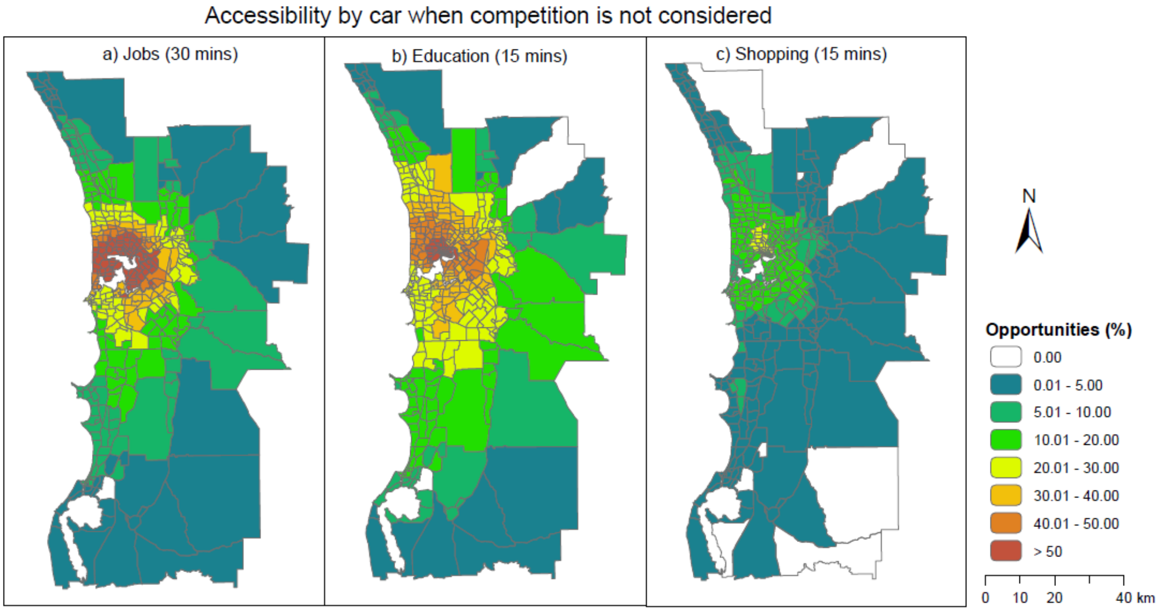


Figure 9.5: Car-based accessibility using the cumulative opportunities measure without the competition component

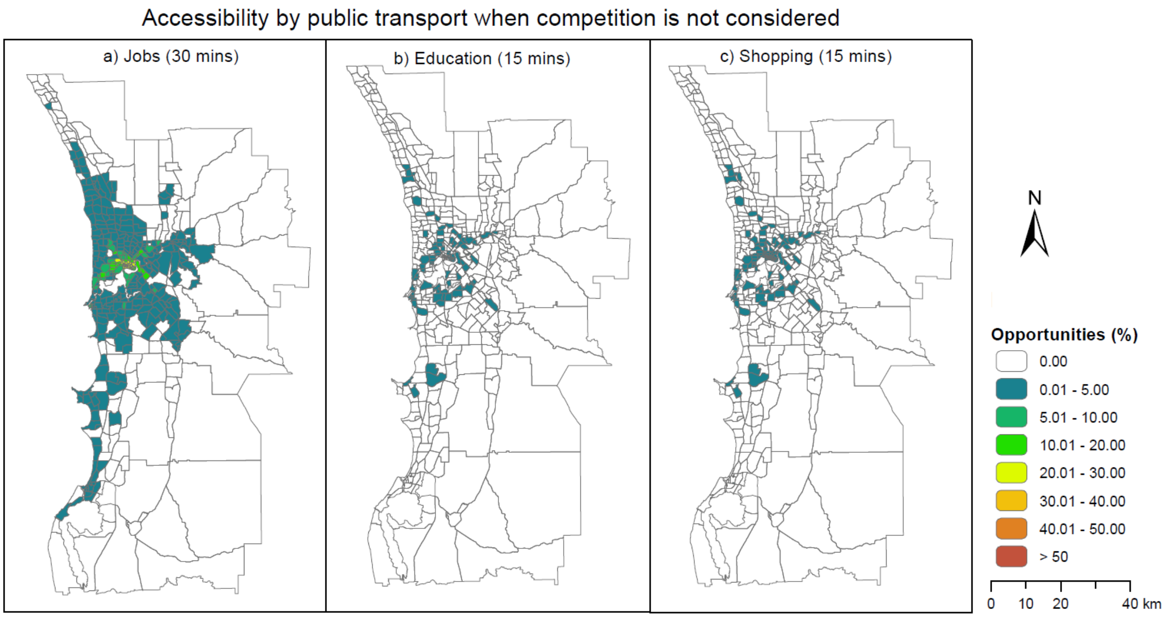


Figure 9.6: PT-based accessibility using the cumulative opportunities measure without the competition component

9.5.2 Private car versus public transport performances

The dispersed, low population density that constitute Perth's urban spatial structure makes it difficult for other travel modes to be effective. As a result, the private car has become the most popular mode of transport in Perth, mainly because of its flexibility and ubiquity. The 2016 census revealed that the car was used for as much as 85% of trips to work (Australian

Bureau of Statistics, 2016). While the car is the most viable travel option for most inter-suburb trips, its rising usage feeds back into, and facilitates, further urban sprawl as it enables people unrestricted travel flexibility (Steg, 2005). The discrete assessment of car and PT in sections 9.4.1 and 9.4.2 enables to draw some further comparison between the two travel modes. Additionally, it also gives insight into the contribution made by each mode to the overall accessibility maps.

In comparing car and PT in Perth, the previous chapter established that PT fell significantly far behind car in providing access to key urban services. By and large, this chapter's results are consistent with this finding – a large number of zones that are sufficiently served by car had no effective accessibility by PT, across all three services (see Figs. 3 and 4). However, the analyses have also revealed some interesting results which suggest that there are some zones in which PT provides better accessibility than the car. This is due to the separate treatment of the two modes which assumes that PT users do not face competition from car travellers and vice versa. Therefore, the higher effective accessibility by PT in some zones is, paradoxically, a result of its limited flexibility – which implies that the opportunities that can be reached from these zones, a lot of other people cannot get to by PT, thus limiting competition in these zones.

Some may question the exclusive treatment of competition from car and PT travellers, but it could be critical for a number of areas and scenarios where other travel modes are non-existent or restricted e.g. in limited car-access areas due to shortage or high-cost of parking, or in inner-city areas where only sustainable modes like transit are allowed. Hence, these results could also be used to guide the formulation of such policies in areas where authorities seek to limit unsustainable car usage. Zones with good accessibility by PT reflect good potential for prioritisation of higher-density developments and implementation of initiatives such as TODs (transit-oriented developments). Furthermore, the results also point to the higher spatial inequity of PT services. This is particularly evident in the accessibility of jobs where the majority of zones fell in the two extreme classes of either significantly low (less than 0.5 opps/person) or significantly high (over 2 opps/person) effective accessibility (Fig. 4a). It was also evident that the car provided not only a more efficient and flexible accessibility, but also a far more spatially equitable one, when compared with PT, across the PMR (Table 2).

The accessibility results for PT travel also reflected the pattern of the railway network. Zones with higher accessibility values were along or closer to the railway line and those with lower accessibility were generally farther from the train network. This supports previous findings where it was found that the train significantly shapes accessibility maps in Perth (Moniruzzaman et al., 2017). My results reaffirm this assertion with each of the three services analysed, indicating the value of the train in improving accessibility for jobs, education and shopping, and plausibly many other key urban services.

9.5.3 Combined car and PT travel

While there may be some people who have access to only one of the two travel modes of car or PT, there are limited cases in which users of one mode will not face competition from those of the other. In a large majority of cases, PT travellers compete for the same opportunities with car drivers and/or passengers. In section 9.4.3 the accessibility of each zone was determined assuming that all residents have access to both car and PT. That means they have a choice to travel with whatever mode is quicker, but they also compete for opportunities with residents of other zones travelling with either mode. The combined-travel mode approach to account for competition is the more realistic as, in practice, both car and PT travellers compete for the same opportunities. In theory, combining the two travel modes would lead to a higher number of opportunities that can be reached from an origin zone, but at the same time it also enables more people from other zones to reach those same opportunities (more competition). It is therefore, an interesting and practical way of evaluating the impact of competition in accessibility for the majority of zones particularly in the inner suburbs where PT services are concentrated, and most people also have access to a car.

The first and obvious thing to note from the results (in Fig. 5) is that they revealed a rather similar pattern to those of travel by car (in Fig. 3). In fact, the education and shopping accessibility maps were exactly the same as those of car-only travel. Nonetheless, there was a noticeable variation in both the levels and spatial pattern of accessibility with respect to job opportunities (Figs. 5a and 3a). The difference between the combined car & PT accessibility and the individual modes accessibility clearly shows the impact of accounting for competition. The results imply that there were no zones from which PT could reach any education or shopping opportunities that could not be reached by car within the 15-min threshold time. However, with regard to jobs, there were several zones from which opportunities could be reached by PT in 30 min but not by car (i.e. PT provided better job accessibility for some zones than car). As a result, the relatively better job accessibility advantage that was seen around the city centre area in the car-only and PT-only scenarios – which aligned with the monocentric structure reported in the previous publications – diminishes significantly.

The approach of measuring accessibility accounting for competition by both travel modes is the more realistic for cities like Perth where car ownership and travel are high, and most travellers have a choice of the fastest or most convenient mode. Moreover, this approach produced the best effective accessibility results compared to each of the two modes considered separately, as seen in Table 3 with the majority of zones falling inside the optimum accessibility range. Therefore, the spatial equity discussion in the next section focuses chiefly on the combined car and PT travel.

9.5.4 Spatial equity of job, education and shopping accessibility

While many accessibility studies have sampled one urban service, it can be misleading to draw spatial structure and equity implications from a single service (Tsou et al., 2005). This is because the pattern of spatial distribution of labour force/job seekers, for instance, is not necessarily the same as that of shoppers, or school-age children. Therefore, achieving a high job accessibility does not imply that shopping or education accessibility will also improve. My analysis relates the spatial distribution of service supply to that of its corresponding users, and thus can more accurately reflect any mismatches within each individual service type. The demographic that can reach a specific opportunity within a given travel time constitutes its demand or competition. Moreover, the accessibility of each service is directly determined, and not conjectured or inferred from another, potentially unrelated, service.

An important aspect of this study is the consideration of competition for opportunities in establishing accessibility levels and drawing spatial equity implications. There was a significant difference in the results compared to those in the existing literature where the standard cumulative opportunities measure was used to investigate accessibility levels in the same study area, including in the previous chapter (Moniruzzaman et al., 2017). These studies found the CBD to have the best job accessibility by both car and PT. In the previous chapter it was found that, in addition to jobs, other services (such as education, shopping and health care) also had a highly monocentric and spatially inequitable pattern of accessibility in the PMR:

"Generally, the Perth metro region has great spatial inequity with people living in the central sub-region having the best accessibility (most opportunities) while those living in the outer suburbs have the least opportunities across all sectors/land uses. Thus, the further out one lives from the city centre, the more disadvantaged they are with regard to job, education, shopping and health care opportunities" (chapter 8 conclusion).

In the present study it is found that the spatial pattern of accessibility completely changes when competition for opportunities is factored into the cumulative opportunities measure. Furthermore, the three services investigated were quite dissimilar in their accessibility variations. Job accessibility distribution was much flatter with a large number of zones in and around the centre falling in the 'balanced' range of 0.76 – 1.25 opps/person, based on the travel by both modes (Fig. 5a). This implies that there is about a match between the number of people living in this area and the job opportunities they – and their potential competition – can access within the 30-minute threshold. The CBD itself had slightly less job accessibility (0.76 – 1 opps/person) than its surrounding zones particularly to the north, east and south. This indicates that although the CBD hosts a large concentration of jobs, it is also easily accessible to many people from a wide range of zones, which leads to higher competition and thus lower opportunities available for its resident labour force. The zones surrounding the CBD, on the other hand, cannot be reached as easily by as many people, and thus experience less competition. Meanwhile, their proximity to the job-rich CBD brings up their own accessibility levels.

Education accessibility showed a fairly even spatial distribution of zones with low, optimum and high accessibility (Fig. 5b). Education had the highest proportion of zones in the optimum accessibility range (64%) compared to jobs (62%) and shopping (50%) (Table 3), suggesting that education opportunities, and by extension, schools, relatively match the number of school children within the reasonable access time of 15 min. Furthermore, those zones falling in this range were concentrated in the inner area and along the north-south corridor/coastline, where majority of the population resides. The descriptive statistics in Table 2 also showed that out of the three services, education had the lowest variability within its accessibility values. These results suggest that primary/secondary education had the most spatially equitable and optimal accessibility among these services.

The map results suggest that shopping had more zones in the higher accessibility range (>1.25) clustered in a few blocks in the Central Subregion. Moreover, it also had the most zones in the lower accessibility range (<0.25) compared to the other two services, located mostly in the outer zones. It is, therefore, no surprise that shopping had the fewest zones in the optimum range (50%) and almost half of the zones were outside the optimum range (Table 3). However, the descriptive statistics indicate that there was less variation in shopping accessibility across the entire metropolitan region compared to jobs, as evidenced by both lower standard deviation and coefficient of variation (Table 2).

Overall, the three services showed different levels of accessibility and patterns of spatial equity. Education was the most equitably accessed both in terms of the variation across the entire metro region and the number of zones in the optimum accessibility range. Jobs were the least equitable in terms of the overall descriptive statistics i.e. it had the highest standard deviation and coefficient of variation, but with regard to the number of zones in the optimum range, shopping came last with 50% of zones in the optimum range. These results highlight the variation among urban services and the complexity of urban spatial structure. Furthermore, they indicate the need to include a comprehensive list of urban services in accessibility, spatial equity and performance analyses, particularly when drawing urban spatial structural implications. It is important to note that spatial equity is not just about even spatial distribution of amenities, but rather it is about a service supply distribution that is consistent with the spatial distribution of demand. The integration of competition relates service supply to corresponding demand, thus ensuring that the ‘real’ value from reachable opportunities is not overstated, and spatial inequalities are more accurately reflected. Therefore, without incorporating a competition component, the cumulative opportunities measures may not be adequate to provide spatial equity implications.

9.5.5 Study limitations

This study considered only two travel modes. While the modal split in Perth is primarily distributed between the private car and PT, the model (STEM) also only provides accurate travel time estimations for these two. This is because active modes, for instance, require very small zones and detailed road, cyclepath and footpath networks to reasonably reflect accessibility by these modes. The STEM zones and road networks do not meet these requirements. Hence, other modes such as walking and cycling, cannot be considered in this analysis.

In the combined modes approach it is assumed that everyone has access to both car and PT. While this may not be entirely true, it is close to reality in the case of Perth where car ownership/commute is quite high. Some studies have used household car ownership ratio to estimate the proportion of people accessing the services by either mode (e.g. Kawabata and Shen (2007)). However, ownership does not necessarily correlate directly to availability e.g. only one person in the household may be able to use the car. Kawabata and Shen (2007) further note that a large majority of PT users are actually from households with one or more cars. Thus, it is believed that the current approach is more appropriate for accounting for competition from users of both car and PT, although this limitation is worth noting.

Competition is extremely complex, both on the demand and supply side, and different for different services. The cumulative opportunities measure makes certain assumptions that ignore these complexities. For example, assuming that people will take the nearest opportunities disregards job seekers' skill sets and job specificities and parental school preferences for certain schools (e.g. private/public, catholic or not, performance record etc.). These complexities cannot be tackled in the cumulative opportunities approach (Fransen et al., 2019).

Demand constraints in retail are likely to play out differently to those in employment and education. Firstly, shopping supply has a more flexible capacity, since each retail job (which was used as a proxy for shopping opportunities) can cater for multiple shoppers, unlike jobs and education which have a more restricted capacity (one person per vacancy). Secondly, the retail industry is relatively more amenable to ramping up supply to respond to demand, as it is in their interest to maximise the number of customers and profits. Thus, spatial equity implications for shopping may be different than for jobs and education.

9.6 SUMMARY AND CONCLUSION

This study incorporated a competition component to the cumulative opportunities measure and applied it in the assessment of accessibility and spatial equity of job, education and shopping opportunities in the PMR. The goal was to provide a nuanced understanding of accessibility in an urban spatial structure, acknowledging the variety in spatial distribution and functionality dynamics of the different key urban services. The results showed a significant difference in the spatial pattern of accessibility when competition effects are addressed in the cumulative opportunities measure. The existence of competition for opportunities (higher demand) reduces the value of those opportunities accessible to potential users. Therefore, the addition of a competition component to the cumulative opportunities measure is an essential step that not only increases the richness of the measure but also makes it much more realistic. The measure also remains easy to interpret since accessibility is measured by opps/person, which is easy to communicate to the public and policy makers. This also makes accessibility results to be directly comparable between different services and locations/cities.

Integrating car and PT travel in the accessibility measure led to different results (from each of the travel modes considered alone) only in the case of jobs, revealing a higher level of spatial equity with optimum values in the inner areas including the CBD. However, for education and shopping, the combined car and PT approach had the same results as when the car was considered alone. This shows that PT contributes more to job accessibility than it does to education and shopping accessibility. There were no instances where PT could provide access to shopping or education opportunities within the threshold time of 15 min where the car could not. The three services analysed in this study exhibited notable variations in terms of both the level and spatial equity of effective accessibility. This results shows that indeed jobs alone, or any single urban service for that matter, may not tell a comprehensive story of the urban spatial structure, its efficiency or spatial equity.

More attention is needed to reduce the considerable gap between the car and PT-based accessibility in the PMR. My results imply that urban and transport development that improves PT accessibility should be strongly encouraged to enhance the competitive advantage of the carless community in accessing education and shopping opportunities. This could be done by improving PT systems in areas experiencing low education/shopping accessibility and growth in local populations. Similarly, areas of growing employment could also be targeted for transit system improvements to reduce the inequality with cars and encourage more people to use the more sustainable PT travel modes.

The next chapter will present an overview and evaluation of the study's major findings. The major contributions made by this research to the existing body of knowledge are discussed, and some recommendations for future research and policy directions are proposed.

CHAPTER 10 EVALUATION AND CONCLUSIONS

10.1 INTRODUCTION

This chapter revisits the main findings of this research and explores their contribution to the existing body of knowledge. It highlights the empirical and theoretical contributions made by this thesis and summarises the implications of the results to planning policy and future research. A word is also provided on the spatial efficiency-spatial equity dilemma, highlighting how the two are more complementary than contradictory. The methodological and data limitations incurred in the research are also summarised, and some recommendations for future research are made. The chapter ends with an overall conclusion of the thesis.

10.2 OVERVIEW OF MAJOR FINDINGS AND THEORETICAL CONTRIBUTIONS

This research sought to make empirical and theoretical contributions to understanding urban spatial structure using multi-methods and transport-land use data. It evaluated the spatial efficiency and spatial equity of the PMR, using accessibility and other spatial efficiency indicators. Urban structure was defined both from a morphological perspective and a functional perspective.

10.2.1 The spatial efficiency of urban expansion – morphological perspective

As Catalán et al. (2008) indicated, the study of urban form "must be approached and understood taking into account specific geographical and historical contexts in which particular urban forms shape cities" (p. 174). Therefore, the thesis objectives started with providing a comprehensive review of the urban form evolution since the establishment of Perth as a British colony in 1829. This component of the thesis (covered in Chapter 4) mainly focused on the efficiency of urban land expansion with regard to the rate of the expansion, alignment with transport infrastructure and/or services, and adherence to the planning policy framework. The results of this task showed that generally there has been a positive trend of improvement under all three. During the 20th century, the rate of urban expansion and greenfield developments was much higher and there was much less adherence to the metropolitan spatial plans. Since the beginning of the 21st century, expansion has been contained as plans increasingly prescribe compact development. The urban form evolved along major transport routes, but later expanded further beyond them. Thus, while it is a widely established trend that urban form is closely shaped by major transport routes (J. S. Adams, 1970), it is evident that Perth has deviated from this trend since the late 19th century.

While several spatial plans have been formulated for the PMR since the Stephenson-Hepburn Plan in 1955, it is also important to note that a significant amount of development still happened outside of the growth areas identified by such plans. For example, during the era of the Corridor Plan, urban zoned land spread "into many other areas which had not been identified for urban growth potential" (T. Adams, 2010, p. 39). This research has shown that the city spread more widely as mobility became easier and more flexible.

Efficiency of the urban structure was not a key feature of the earlier metropolitan plans – particularly in the form of commuting distances/times. Development was mainly driven by the need to accommodate growth demand at the rate permitted by economic growth. The 'Great Australian Dream' (standalone houses in large lots with backyards) was largely supported and facilitated by the statutory spatial plans. Even then - as already indicated, the plans were not strictly followed so land was often availed for development against the initial recommendation of the zoning system. These trends resulted in an unsustainable urban growth pattern that was characterised by a high rate of greenfield developments and rising distances from the city centre for the majority of the population.

The rate of urban expansion has slowed down significantly since the turn of the century. During this period, advocacy for compact development grew in the planning agenda as the state government sought to restrain sprawl and move towards greater density through infill and mixed-use developments. Three strategic planning documents were developed (*Directions 2031 and Beyond*, *State Planning Strategy 2050* and *Perth and Peel @ 3.5 million*), at the core of which was advocacy for compact, high-density development to accommodate current and future land demands. The slower urban expansion rate in recent years is ascribable to these efforts. Between 2002 and 2016 the total urban land increased by only 1.26% compared to the 2.75% over a shorter period of 1992 to 2002 (Table 4.1). At the same time, the loss of rural and state forest land to urban development also decreased. This might suggest that recent plans have been applied relatively more stringently than those of the mid- to late 19th century. Therefore, it could be argued that the efficiency of urban growth and spatial plan implementation in the PMR improved over the recent decades.

Despite urban growth having slowed since the beginning of the 21st century, services are still slow to catch up. For instance, the three oldest railway lines (Fremantle, Midland and Armadale) from the late nineteenth century have never been extended despite that the city long sprawled away from and/or beyond them. The Joondalup line was constructed after a century-long hiatus, and still did no go the full extent of the urban expansion. While it was later extended to Butler in 2014, works are still ongoing to further extend it to Yanchep under the *Metronet* plan. The 2016 MRS showed that urban land had gone beyond each of the terminal train stations and some lines may require extension. From this information, it is evident that the MRS has been availing land for urban development well ahead of transit development, which led to the deviation from the earlier trend of urban expansion following the direction of major transport links. This has led to a prominent level of dependence on the automobile in Perth (Alexander & McManus, 1992; P. Newman & Kenworthy, 1999), as it is the most accessible transport mode particularly for the outlying residents where transit options are limited. Meanwhile, most services (e.g. jobs, health care, education) remained concentrated in the inner suburbs, which resulted in longer travel distances (and times) and consequently, inefficient travel patterns. The efficiency of travel in the study area was analysed under various approaches in this research, and its main findings are evaluated in the next section. The mismatch between residential land expansion and urban service supply also brings up another issue of spatial equity. With many services remaining in the older, inner suburbs, the spatial equity inevitably got poorer – disadvantaging particularly those in the lower economic class who cannot afford land in the inner, better-serviced suburbs. The spatial equity of services was addressed in the latter chapters of the thesis.

10.2.2 The spatial efficiency of land use distribution and travel patterns – functional perspective

As its second objective, the research in this thesis also explored urban spatial efficiency from a functional perspective, using land use and travel data and various measures or indicators. There is a body of knowledge in the literature which argues that employment decentralisation and job-worker balance can lead to shorter commuting distances and times (Cervero & Duncan, 2006; Gordon et al., 1989; Mark W Horner & Mefford, 2007; Ta et al., 2017). These strategies have been propounded to increase job opportunities closer to the residents to reduce general vehicle-miles travelled, while also minimising disutility in the city's resource distribution (Geyer & Molayi, 2017). This is, of course, assuming that people are inclined to take job opportunities closest to them (or take residential location options that are closer to their workplaces), which may not always hold true. In reality, a complex range of factors influence residential location choices (e.g. housing affordability, quality of neighbourhood and quality of schools) so living close to work may not be a priority for many people (BIRTE, 2015; Cervero, 1995a; Genevieve Giuliano, 1991). On the other hand, there needs to be an adequate match between the type of job opportunities and the skills of people living in a given area. Hence, this research applied three spatial efficiency indicators that investigate the numerical job-worker balances within the various zones, as well as the jobs-skills match reflected through the proportion of jobs filled locally and the level of local labour capture (JWB, ESS and ESC). The impact of each on commuting times was explored (Chapter 5).

Results of this task revealed that the levels of JWB, ESS and ESC in Perth were generally poor. This kind of result suggests a spatial mismatch between jobs and residential locations as well as inter-subregional disparity in terms of employment opportunities and housing provision (Ihlanfeldt, 1994; O'Connor & Healy, 2002). According to the statistical correlation results, only ESS (proportion of jobs filled by residents) could be associated with lower commuting time. This means higher ESS, which implies fewer number of work trips coming into a zone, led to shorter average commuting time. However, better JWB and higher ESC did not necessarily lead to shorter travel times. While higher ESC (proportion of labour force working locally) does imply fewer trips leaving the zone, the statistical correlation suggested that it does not necessarily lead to shorter average commuting time. This brings up another interesting finding of this research, which is the limitation of ESS and ESC as supposedly better measures than the mere numerical balance of JWB. While these measures indeed indicate the amount of trips coming into and leaving a zone, they provide no indication of the extent of travel involved in such trips. There is no difference between a trip that originates/ends in an adjacent zone nearby and one that links to a zone several tens or hundreds of kilometres away. Thus, ESS and ESC cannot provide a full reflection of the commuting situation and may lead to the level of commuting in the area being overestimated or underestimated. A way to circumvent this limitation is to incorporate average travel times into the analysis to supplement ESS and ESC results and enable a more accurate interpretation and understanding of the commuting situation.

The poor levels of JWB, ESS and ESC suggest that there is a mismatch between jobs and residential locations across the metropolitan area. The majority of jobs in the PMR are located in the central subregion and the CBD while smaller proportions of workers live in these areas (Western Australian Planning Commission, 2018). The Government of Western Australia has developed specific objectives to address this disparity through the development of activity centres and employment decentralisation. The detailed objectives and how they will be achieved are fully described in two planning documents; *Perth and Peel @ 3.5 Million* (Western Australian Planning Commission, 2018) and the *Activity Centre Policy* (Western Australian Planning Commission, 2010b). In spite of the foregoing, McCarney and Biermann (2016) note that activity centres have not developed at anticipated levels. Further to this, findings of this research have revealed that the employment targets set for activity centres by 2050 will have very little impact in transforming the urban structure and, particularly, improving job accessibility (Chapter 6).

Thus, this thesis applied a modified effective density method to help evaluate and optimise the employment decentralisation process. An effective density-based measure is used to assess the development potential and prioritisation of activity centres. It is proposed to replace the accessibility measure that is often used for this purpose in the PMR. Given that decentralisation seeks to improve accessibility while limiting the loss on density, the effective density-based measure is a more appropriate indicator to assess it, as it incorporates both the scale/size and proximity/transport dimension. With the same data requirements as the cumulative opportunities measure, effective density enables to estimate the potential for agglomeration externalities, and thus provides more information for identifying new, as well as evaluating existing, activity centres. A cross comparison of the two measures (accessibility and effective density) showed that they produced varying outcomes, which suggests that the omission of a thorough transport dimension in the cumulative opportunity measure could lead to inaccurate and costly policy decisions.

10.2.3 The spatial equity of services in the Perth Metropolitan Region

In addressing its third objective, this thesis used a cumulative opportunities accessibility measure to examine the spatial equity of Perth's urban structure. The main reasons for choosing this measure were because it is the most widely applied in planning practice due to its low complexity and ease of interpretation. Firstly the measure was used in its traditional form to investigate and compare the accessibility patterns of five services (jobs, primary/secondary education, tertiary education, shopping and health care – Chapter 8). Then the measure was modified to address competition effects, and tested on three services (jobs, primary/secondary education and shopping – Chapter 9). The modification sought to improve the accuracy of the measure while safeguarding its low complexity. The measure also remains easy to interpret and communicate to the public and policy makers. This also makes accessibility results to be directly comparable between different services and locations/cities.

The common findings between the two approaches was a clear variation in the spatial patterns of accessibility across all the services, and the superior performance of the private car over PT. However, there was an important difference brought by the introduction of a competition dimension in the measure. While accessibility studies have unanimously reported a monocentric pattern in Perth, and a rising opportunity advantage with proximity to the city centre, addressing competition effects disputes this claim quite decisively. This thesis found that the CBD and inner-city areas have relatively larger numbers of residents, and are also relatively easier to access for non-residents (both by car and, particularly, by PT). This increases competition for opportunities in the inner-city areas, thus reducing their residents' effective accessibility. The addition of a competition component to the cumulative opportunities measure is therefore an essential step that not only increases the richness of the measure but also makes it much more realistic. Additionally, the consideration of both the supply and demand side of the equation means that spatial inequalities are more accurately represented – hence the measure becomes more appropriate for drawing spatial equity implications.

10.2.4 A consolidated 'spatial efficiency-spatial equity' framework

The thesis employed a multi-method approach to investigate the spatial efficiency and spatial equity of Perth's urban structure. It is obvious that as the urban footprint increased, travel distances (and times) got longer. On the other hand, service distribution did not keep up with the footprint expansion, which created more excess commuting and thus, a decline in the overall travel efficiency. Moreover, the mismatch in the urban growth and service locations led to deteriorating levels of spatial equity. These trends give a clear indication of how the static/morphological urban structure can either aggravate or enhance the dynamic, functional structure.

The functional spatial efficiency of the urban structure was first investigated using JWB, ESS and ESC, whose levels in Perth were found to be generally poor. This suggests a spatial mismatch between jobs and residential locations as well as inter-subregional disparity in terms of employment opportunities and housing provision. Despite all JWB, ESS and ESC being very poor, the travel times were reasonably short. Inflow travel time was less than 30 mins for a large majority of zones across the metropolitan area. Outflow travel times were generally longer – less than 30 min in the inner zones but increasing radially outwards. Only ESS had an expected negative correlation with travel time, while JWB and ESC interestingly had positive correlations. It should be noted, however, that all these correlations with were very weak. This highlighted the limitation of ESS and ESC relating to their failure to account for the exogenous component of the trip, which can lead to inaccurate interpretations of the commuting situation. Therefore, integrating travel times enables us to understand that the spatial efficiency across the metropolitan area was not as bad as the three indicators would suggest.

The aims of Perth's ongoing decentralisation agenda include to bring jobs closer to the people and correct these job-worker imbalances (McCarney & Biermann, 2016; Western Australian Planning Commission, 2018). While challenges to meet the decentralisation targets have already been noted (McCarney & Biermann, 2016), this thesis has further established the inadequacy of the targets themselves. Thus, even if the employment targets for activity centres were to be met, their impact on travel efficiency and job access equity would be minimal. The targets are not that different from business-as-usual and may in fact resemble 'scatteration' given that the growth rate for some activity centres will actually be lower than that projected for their respective subregions. With this trend, job accessibility in the outer suburbs particularly by PT will worsen, given that its coverage is mostly limited to activity centres and virtually non-existent elsewhere.

The thesis proposed an effective density-based measure to more accurately evaluate and achieve spatial efficiency in employment decentralisation through estimating both the accessibility of activity centres and their potential for agglomeration externalities. The better effective density was found in those activity centres located in the central subregion, which also suggests a lack of spatial equity (of both accessibility and agglomeration benefits). Even though the two approaches employed for spatial equity measurement (with and without competition) revealed markedly different outcomes, it was evident that the distribution of services was not spatially equitable. It was, however, clear that the disregard for competition effects could exaggerate the spatial inequity.

- Achieving efficiency and equity in urban structure – the trade off fallacy

Discussions about efficiency and equity often assume an inevitable trade off between the two. This is particularly the case on market efficiency in the field of economics, where it is essentially argued that achieving greater equity will diminish the level of efficiency (Andersen & Maibom, 2019; Krongkaew & Kakwani, 2003; Ward & Pulido-Velázquez, 2008). In other words, inequity (and/or inequality) is a consequence of growing efficiency. While this is generally agreed in market economics, the validity of an efficiency-equity trade off in spatial economics is questionable. Moreover, the assumption of a trade off discourages thoughtful consideration of integrating spatial equity and efficiency objectives in development policy. As a result, urban planning literature often focus on one and completely ignore the other, often making the assumption of a trade off implicitly. Notwithstanding the foregoing, existing studies and policy documents reflect little on determining an appropriate trade-off between efficiency and equity. Some have even argued that it is unlikely that the two concepts could be combined to find a definitive trade-off (Truelove, 1993).

This thesis contends that the pursuit of a vibrant and sustainable urban structure should promote both spatial efficiency and equity as complementary, rather than competing objectives. In spatial economics, particularly of socially driven (rather than market driven) services such as education and health, it is quite possible, and even essential, to argue of efficiency and equity being two goals of the same policy. Some authors have already disputed the validity of a trade off outside the area of market economics. For instance, Reidpath et al. (2012) strongly condemned the application of the trade off argument to health, arguing that it is quite possible to have equity as a desirable output of a health system, as well as the efficient production of that output. In education, the evidence suggests that improving access equity leads to a higher efficiency of the education system. “Among individuals of similar abilities, if some have more access to education than others, those with greater access will enjoy a higher income” (Birdsall, Graham, & Sabot, 1998, p. 308). Evidence also suggests that productivity is higher among more educated workers, and they are more adaptive to new technologies. Therefore, promoting equal access to education can enhance both equity and efficiency (Birdsall et al., 1998). Incorporating equity into policy has also been found to enhance efficiency in infrastructure and resource planning (Howe, 1996).

The argument of a spatial efficiency-equity trade off presupposes that a choice has to be made between the two as desired but contrasting outcomes. It requires an answer to the misdirected question: what is more important, an efficient urban structure or a spatially equitable one? This question is misdirected because whereas spatial equity is a potential outcome of urban structure, spatial efficiency on the other hand is not an outcome by itself. “Efficiency describes a functional relationship between inputs (e.g. money) and outputs (e.g. health gains) – but it is not in and of itself an outcome” (Reidpath et al., 2012, p. 1). To recall the Sarzynski and Levy (2010) definition, spatial efficiency refers to the geographic organisation of residences, businesses and infrastructure that minimises the cost (effort, time etc.) required for performing economic activities for the whole metropolitan district. Central to this definition is the relation between land uses (and not merely the organisation of the land uses itself), considered in three classes: business-to-consumer; business-to-worker; and business-to-business interactions. In this case, the term business can be extended to public services/facilities such as education and health care.

An efficient urban structure ensures adequate access to urban facilities, and this adequate access is enhanced by equity in the geographical arrangement of such facilities (Ashik, Mim, & Neema, 2019). Thus, it can be argued that 'efficiency is not efficient without equity'. Given that efficiency is a relationship between investment inputs and the desired output(s), the level of spatial efficiency achieved is reflected by the level of desired output. What remains to judgement, then, is the decision of which outputs are desired (Reidpath et al., 2012). In the scope of this thesis, such output would be defined in terms of average travel times by service users, which are managed by limiting the spatial separation between land uses and/or improving transport links between them (morphological and dynamic/functional approaches). A number of methods that could deliver this outcome were investigated in this research (e.g. JWB, ESS, ESC, decentralisation and accessibility). These methods/indicators do not preclude the pursuit or achievement of spatial equity, but rather would require it to maximise gains.

This thesis revealed a great potential for improvement in Perth's spatial efficiency. While management of urban expansion/sprawl has improved, spatial efficiency in a functional sense is still very low, as indicated by the levels of JWB, ESS, ESC, and indeed, spatial equity of services. The more sustainable PT mode is highly inadequate in providing service accessibility particularly in the outer suburbs. Additionally, employment decentralisation targets are too low to cause impactful change, both in the competitiveness of activity centres and spatial equity of access to opportunities. Many accessibility studies have argued that activity centres are easier to reach by PT than by private transport (Antwi, Quaye-Ballard, Arko-Adjei, Osei-wusu, & Quaye-Ballard, 2020). At the same time, the Western Australian government is investing heavily on suburban rail and other modes of PT. However, with the activity centres lagging in development (and low growth targets), the policy of such investment leaves much to be desired.

10.3 LIMITATIONS OF THE RESEARCH

This section looks at the limitations of the data and methods used in the study for evaluating the spatial efficiency and spatial equity of urban structure. Limitations regarding the study design/approach are also discussed.

10.3.1 Limitations relating to the scope of the research

The study of the urban form evolution and the timelines developed covered a long period of about two centuries. While an earnest attempt was made to highlight the major milestones of development, it would be impossible to include all of them and as noted by Dear (1986), such historical interpretations are often shaped by idiosyncrasies of the observer and observed.

Another possible limitation of this research is that it analysed efficiency at a macro level, and mainly focusing on management of urban sprawl and geographical distribution of employment opportunities. Employment details like industry types and skill sets of the labour force were not considered. While this was meant to maintain a manageable scope that enables a broader understanding of the urban structure, it ignores these complexities which are inherent in an urban structure. For a more vertical/deeper understanding of these complexities, a more nuanced approach that addresses the variety of not only job types but also land uses would be needed. For example, employment self-containment might be different for different industries. However, this will make the study more bulky and computationally intensive. Such level of detail might benefit from a narrower study scope, like focusing on one service and delving into its unique characteristics.

10.3.2 Limitations of the data

- The Modifiable Areal Unit Problem (MAUP)

The analyses of this research relied mainly on the STEM data. STEM uses predefined geographic units (zones) built based on Australian Bureau of Statistics (ABS) census collector districts. The districts are developed such that they have a similar number of households, hence they tend to be smaller in denser areas and larger in more rural areas. At the larger metropolitan scale, the number of jobs and workers are approximately balanced. If the zones were to be drawn differently, or a different classification system was used, the results would turn out differently even though the spatial distribution of services and users is identical.

- Data currency

The STEM data used for this research are as at the year 2011. It therefore does not reflect the demographic changes that have occurred since, or the transport improvements such as the WA Gateway project and new PT services. Also, in estimating the accessibility patterns for the year 2050, the employment targets for 2050 were used but the travel times were still from 2011. While the use of 2011 travel times helps to have the essential variable of employment as the only one that changes, it certainly has an influence on the results since traffic conditions are bound to change e.g. transport infrastructure and service improvements, and new infrastructure and transport services added to the system. Additionally, the transport model is held by a third party (Department of Transport) who would not release the latest data (including the predicted travel times) as they were still being worked on. Modelling the expected network and service changes and estimating the resulting travel times could provide a more accurate estimation of the expected accessibility patterns.

10.3.3 Limitations of the modelling methods

- Cumulative opportunity-based accessibility modelling

One of the major limitations of the cumulative opportunities measure of accessibility is its reliance on and sensitivity to a binary travel time threshold. Selecting the appropriate threshold is a fairly subjective task, and it becomes more contentious when different travel purposes are considered. A slight change in the threshold can often produce significantly different results. In this thesis, the sensitivity of the thresholds was tested using job accessibility, by reducing and then increasing the chosen 30 minutes by 2 minutes. The results showed the thresholds of 28 minutes and 32 minutes were very similar to the chosen 30 minutes, suggesting that these results are not too sensitive to the travel time thresholds.

- Effective density-based efficiency modelling

The effective density model was not calibrated in a traditional manner to determine the distance decay parameter. Rather, the widely accepted value of 2 was used, and it was applied to both effective job density and effective labour density. In reality, the ease of interaction between businesses may be different to that between firms and the labour force, and thus a different decay function might be appropriate. In future, the model could be calibrated systematically to determine the respective rates of distance decay in business-to-business interactions and business-to-worker interactions.

10.4 FUTURE RESEARCH DIRECTIONS

Given that this research faced some limitations relating to the data and measurement methods used, there is potential for future research to build on the current analyses to further test and validate the results under different settings and to improve their accuracy. As a start, more recent data that have become available such as the 2016 census results could be used to update the STEM parameters, and re-evaluate changes in the accessibility patterns and assess progress in activity centre development. Also, more disaggregated employment data could be adopted in the calculations of JWB, ESS and ESC. This will help reveal if any specific industries have shorter or longer commutes, which ones are more self-sufficient or self-contained, and where more effort should be focused to improve overall travel efficiency.

Another possible research direction is to focus more on PT-based accessibility. PT is mostly used for longer trips and therefore will inevitably perform badly in shorter travel time thresholds. In future, the performance of PT in Perth could be tested at multiple thresholds, particularly for those services where shorter thresholds were used such as primary/secondary education, shopping and health care. Moreover, the analysis of accessibility, particularly for spatial equity implications, could incorporate various demographic groups to reveal if any particular groups are disadvantaged for certain services. This will, however, significantly increase the time and effort for computations, especially when multiple distinct services are considered.

Future studies / transport models may need to consider travel time as a "lost opportunity cost", especially when driverless vehicles become available. That is, need to consider what the traveller can do while travelling. Obviously driving a car has the highest lost opportunity cost. Driverless vehicles with office like facilities may reduce the time cost of travel to virtually zero. A major disruption effect!

Lastly it is noted that primary schools have catchment areas as demarcated by the State government, which this research did not make use of. In future work, the approach employed in this study could be built on to test whether these catchment areas provide the best accessibility for primary schools.

10.5 DID THE STUDY MEET ITS OBJECTIVES?

This research has dealt with the evaluation and application of measures or models that are/can be used to evaluate and enhance urban spatial structure within the frameworks of spatial efficiency and spatial equity. Four specific objectives were set at the beginning of the research in Chapter 1, which were achieved successively in the subsequent chapters. Firstly, a rigorous review of existing literature was conducted to provide clear explanation and definitions of the key terms, and measures applied in evaluating urban spatial structure (Chapter 2). A general description of the research methodology and theoretical framework were provided in Chapter 3. The first objective was addressed in Chapter 4, whereby a historical investigation of chronological milestones in land development, transport, planning policy and economic development was conducted, and a two-century timeline was deconstructed to determine influence on the urban form evolution. Transport developments and planning policy frameworks were found to have facilitated urban expansion for a long period, but the trend was reversed in the 21st century i.e. the urban footprint expanded beyond the transport networks, and recently the results of compact development objectives are visible through the declining rate of footprint expansion and Greenfield conversion.

From a functional perspective, the investigation of spatial efficiency started with a novel application of trip data to evaluate the levels of JWB, ESS and ESC and their relation to commuting time (Chapter 5). The three indicators were found to be weakly correlated with commuting times, suggesting that they cannot be exclusively relied upon for eliminating excess commuting. In chapter 6, the spatial efficiency of urban structure was measured through a critical evaluation of the employment decentralisation policy agenda in the PMR case study. Chapter 7 proposed an effective density-based measure for determining the agglomeration potential and development priority of activity centres, which can further enhance the decentralisation agenda.

On the question of spatial equity, a total of five key urban services were included in an accessibility study to address the empirical gap in the literature where little effort has been made to consider multiple urban services to draw spatial structural implications (chapter 8). The findings showed that relying on one urban service to draw spatial equity implications for the general urban structure can be misleading. Chapter 9 integrated a competition dimension into the cumulative opportunities measure to determine the accessibility levels of three urban services (jobs, education and shopping). The competition component was found to improve the utility of the cumulative opportunities measure, enabling it to more accurately reflect spatial equity based on demand-supply mismatches.

Lastly, this thesis disputes the presupposition of a trade off between effeciency and equity in urban spatial structure. While there is evidence of existance of a trade off in market economics, extension of this argument to spatial economics is erroneous, as it is quite possible to argue of both spatial efficiency and spatial equity being realistic objectives of the same policy. From a functional perspective, achieving spatial efficiency of travel requires adequate access to services, and adequate access requires spatial equity in the distribution of facilities. Thus, optimum spatial efficiency cannot be achieved without edequate spatial equity. It is, therefore, imperative that spatial plans adopt both spatial efficiency and spatial equity as complementary, rather than competing objectives.

10.6 CONCLUSIONS

A city's spatial structure is a slow and complex process driven by a myriad of socio-economic, political and environmental factors. Nonetheless, the pattern of urban spatial structure is an essential factor of the day-to-day performance and long-term sustainability of any city. Research on urban spatial structure, however, remains limited and largely ad hoc. This thesis has developed a comprehensive framework for understanding urban spatial structure from both morphological and functional perspectives. It employed a suite of existing and new indicators and strategies to evaluate, quantify and optimise the spatial efficiency and spatial equity of an urban structure. A case study of Perth, Western Australia, was used to implement the framework and validate the innovative approaches.

Perth – a city with a long history of rapid suburbanisation, low population density and high private vehicle usage – has developed clear policy objectives that seek to reverse this trend and limit urban expansion, increase population density and land use diversity, and promote active and public transport modes. It is hoped that this will change the morphological and functional structures of the city for better land and resource efficiency, spatial equity, and ultimately productivity and sustainability. Thus, Perth presented an opportune place to study urban spatial structure, particularly from the perspectives of spatial efficiency and spatial equity.

From a morphological perspective, this thesis investigated the evolution of Perth's urban form in relation to key drivers and established that the role played by transport developments on the shape and direction of urban expansion has changed dramatically in the 21st century. From a functional perspective, the thesis critically evaluated the employment decentralisation agenda and proposed strategies and measures/models for assessing and/or enhancing the spatial efficiency and spatial equity of Perth's urban structure. The proposed measures (or modifications) are practical (easy to understand and implement), more comprehensive and/or accurate, hence favourable to the urban and transport planning community. The results of this work can be a useful planning tool for transport and land use investments. The methodology employed in this thesis can also be directly transferred and applied to different cities or urban spatial structures.

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Appendix A Permission from Co-authors

K Keone Kelobonye
To Cecilia Xia (C.Xia@curtin.edu.au); Swapan; Gary; 毛*; 'Heng Zhou'
Wed 12:53 PM

Dear Co-authors,

I am going to include 3 manuscripts of our published papers in my PhD thesis which will be submitted soon. May I please have your permission to include them. The 3 papers are:

Kelobonye, K., Xia, J. C., Swapan, M. S. H., McCarney, G., & Zhou, H. (2019) . Drivers of Change in Urban Growth Patterns: A Transport Perspective from Perth, Western Australia. *Urban Science*, 3(2), 40. doi: https://doi.org/10.3390/urbansci3020040

Kelobonye, K., Mao, F., Xia, J., Swapan, M. S. H., & McCarney, G. (2019). The Impact of Employment Self-Sufficiency Measures on Commuting Time: Case Study of Perth, Australia. *Sustainability*, 11(5), 1488. doi: https://doi.org/10.3390/su11051488

Kelobonye, K., McCarney, G., Xia, J., Swapan, M. S. H., Mao, F., & Zhou, H. (2019). Relative accessibility analysis for key land uses: A spatial equity perspective. *Journal of Transport Geography*, 75, 82-93. doi:https://doi.org/10.1016/j.jtrangeo.2019.01.015

Kind regards,

Keone Kelobonye
PhD Candidate | Spatial Sciences
School of Earth and Planetary Sciences

Curtin University

PC 毛* <efeng522@126.com>
To Keone Kelobonye
Wed 1:35 PM

Hi Keone,

Yes please. Go ahead:)

Regards,

Charles

Cecilia Xia <C.Xia@curtin.edu.au>
To Keone Kelobonye; Mohammad Swapan; Gary; 毛*; Heng Zhou
Wed 3:10 PM

Hi Keone,

I approve it.

Cheers,
Cecilia

Jianhong (Cecilia) Xia
Associate professor | School of Earth and Planetary Sciences

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---

Heng Zhou
To Keone Kelobonye
Cc Cecilia Xia (C.Xia@curtin.edu.au); Swapan; Gary; 毛*
Wed 3:35 PM

Hi Keone,

Sure, I approve, all the best!

Kind Regard,
Heng

Mohammad Swapan <M.Swapan@curtin.edu.au>
To Heng Zhou; Keone Kelobonye
Cc Cecilia Xia; Gary; 毛*
Wed 11:05 PM

Hi Keone
Off course, I approve that.
regards
Swapan

Dr. Mohammad Swapan
Senior Lecturer | Urban and Regional Planning
School of Design and the Built Environment (201.607)

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ginn8a . <garyviaje@gmail.com>
To Keone Kelobonye
6:34 AM

Hi Keone,

Yes, you have my permission as well.

Cheers,

Gary

Appendix B Co-author Attribution Statements

Some of the work presented in this thesis has been published or submitted for publications by the thesis author and the paper co-authors.

Journal papers (peer-reviewed and fully refereed)

1. **Kelobonye, K.**, Xia, J. C., Swapan, M. S. H., McCarney, G., & Zhou, H. (2019) . Drivers of Change in Urban Growth Patterns: A Transport Perspective from Perth, Western Australia. *Urban Science*, 3(2), 40. doi: https://doi.org/10.3390/urbansci3020040

2. **Kelobonye, K.**, Mao, F., Xia, J., Swapan, M. S. H., & McCarney, G. (2019). The Impact of Employment Self-Sufficiency Measures on Commuting Time: Case Study of Perth, Australia. *Sustainability*, 11(5), 1488. doi: https://doi.org/10.3390/su11051488

3. **Kelobonye, K.**, McCarney, G., Xia, J., Swapan, M. S. H., Mao, F., & Zhou, H. (2019). Relative accessibility analysis for key land uses: A spatial equity perspective. *Journal of Transport Geography*, 75, 82-93. doi:https://doi.org/10.1016/j.jtrangeo.2019.01.015

4. **Kelobonye, K.**, Zhou, H., McCarney, G., & Xia, J. (2020). Measuring the accessibility and spatial equity of urban services under competition using the cumulative opportunities measure. *Journal of Transport Geography.* 85, 102706. https://doi.org/10.1016/j.jtrangeo.2020.102706

5. **Kelobonye, K.**, Xia, J., Zhou, H., & McCarney, G. (2020). Assessing the Potential of an Effective Density-Based Measure for Evaluation and Prioritisation of Activity Centres: A Case Study of the Perth Metropolitan Region. *Manuscript under review in Applied Geography*.

Refereed conference papers:

6. **Kelobonye, K.**, Xia, J. C., Swapan, M. S. H., McCarney, G., & Zhou, H. (2019). Analysis and Optimisation Strategy of Employment Decentralisation in Perth through Density and Accessibility Indicators. Paper presented at the *State of Australian Cities National Conference*, Perth, Western Australia, Australia. 3 – 5 December 2019.

Thesis attribution of papers published or under peer-review

Author: Keone Kelobonye

	Paper					
Role	**1**	**2**	**3**	**4**	**5**	**6**
Supervision						
Conceptualization	✓	✓	✓	✓	✓	✓
Data curation	✓	✓	✓	✓	✓	✓
Methodology	✓	✓	✓	✓	✓	✓
Software	✓		✓	✓	✓	✓
Formal analysis	✓	✓	✓	✓	✓	✓
Visualisation	✓	✓	✓	✓	✓	✓
Interpretation and discussion	✓	✓	✓	✓	✓	✓
Writing – Original Manuscript	✓	✓	✓	✓	✓	✓
Writing – Review and Editing	✓	✓	✓	✓	✓	✓

Co-author: Jianhong Cecilia Xia

	Paper					
Role	**1**	**2**	**3**	**4**	**5**	**6**
Supervision	✓	✓	✓	✓	✓	✓
Conceptualization	✓	✓	✓			✓
Data curation						
Methodology	✓	✓		✓	✓	
Software						
Visualisation						
Formal analysis						
Interpretation and discussion	✓	✓	✓	✓	✓	✓
Writing – Original Manuscript						
Writing – Review and Editing	✓	✓	✓	✓	✓	✓

Co-author: Mohammad Swapan

Papers	**1**	**2**	**3**	**4**	**5**	**6**
Supervision	✓	✓	✓			✓
Conceptualization	✓	✓				✓
Data curation						
Methodology	✓	✓				
Software						
Visualisation						
Formal analysis						
Interpretation and discussion	✓	✓	✓			✓
Writing – Original Manuscript						
Writing – Review and Editing	✓	✓	✓			✓

Co-author: Gary McCarney

Papers	1	2	3	4	5	6
Supervision	✓	✓	✓	✓	✓	✓
Conceptualization	✓	✓	✓	✓		
Data curation			✓			
Methodology	✓	✓	✓	✓		
Software			✓			
Visualisation						
Formal analysis						
Interpretation and discussion	✓	✓	✓	✓	✓	✓
Writing – Original Manuscript						
Writing – Review and Editing	✓	✓	✓	✓	✓	✓

Co-author: Heng Zhou

Papers	1	2	3	4	5	6
Supervision						
Conceptualization			✓	✓		
Data curation	✓			✓		✓
Methodology			✓	✓		✓
Software	✓			✓	✓	
Visualisation						
Formal analysis						
Interpretation and discussion			✓	✓	✓	
Writing – Original Manuscript						
Writing – Review and Editing				✓		

Co-author: Feng Mao

Papers	1	2	3	4	5	6
Supervision						
Conceptualization		✓				
Data curation		✓	✓			
Methodology		✓				
Software		✓	✓			
Visualisation		✓				
Formal analysis		✓				
Interpretation and discussion						
Writing – Original Manuscript						
Writing – Review and Editing						
Funding acquisition		✓				