WALKING ACCESSIBILITY AND CONNECTIVITY OF TRANSIT: MODELLING AND IMPACT ANALYSIS ON TRANSIT CHOICE AND NETWORK COVERAGE

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Abstract

Getting people out of their private vehicles and onto transit (also known as public transport) is the long-standing goal of transit agencies and planners. Despite all the benefits that transit can offer, the reluctance to use transit has made mode shift difficult. Due to the inherent complexity of mode choice and the associated human behaviour, it is a challenging task to accurately predict mode choice. In general, travellers will consider the transit mode, if (1) a transit service is available within reasonable walking distance, and (2) a transit service connects the origins and destinations. This thesis, in its first phase, explores walking accessibility to transit. The walking access to transit is analysed in relation to travellers' socio-economic standings, to examine their correlation. Having a transit stop near the trip origin and destination will not necessarily guarantee a good connectivity between the origin and destination. The second phase of this thesis studies transit service connectivity and the impact of cognitive transfer location. The concept of cognitive transfer location is incorporated into the transit network connectivity in the last phase. A new approach to quantify the transit network connectivity (i.e.: how well a transit network is connecting a zone to other zones) is proposed in this phase of the thesis.

Using Brisbane as a case study, this research first examines the existing "one size fits all" 400m walking distance to define the bus catchment area. Bus users in Brisbane are divided into true transit captive users and choice users to compare the walking time to bus stop between the two groups; this comparison shows no significant difference. In the subsequent analysis, choice users are further categorised into eight homogeneous groups by their socio-economic characteristics, using a two-step clustering technique. A comparative analysis reveals that walking time is most sensitive amongst part-time workers, high income earners, and elderly travellers. Walking time is least sensitive amongst post-secondary students who are studying and working at the same time. Findings from this study contribute to the understanding of people's walking access to transit, the reasons for variations across individuals and potential impacts of individuals' socio-economic characteristics, which assist transit service planning to tailor different market segments more effectively.

In terms of transit service connectivity, the decentralisation of cities creates a challenge for transit agencies to meet increasingly diversifying travel needs. Transit transfers are deemed to be necessary to expand transit service coverage, whilst the inconvenience of transfer has been identified as a main impeding factor to transit use. Existing literature captures transfer impact as a generalised cost, such as the extra time taken and monetary cost incurred while conducting transfers. This study presents a cognitive transfer map of travellers by projecting 125,215 journey OTD (Origin-Transfer-Destination) triangles into a standardised two-dimensional Euclidean space, using a one-week Brisbane smart card dataset, to discover transit users' preference for the direction of travel towards transfer locations. This study employs grid-based hierarchical clustering to identify preferred transfer locations, which is later used as a new categorical variable for mode choice analysis. This newly developed variable is tested and found to be statistically significant at 95% confidence level, and to improve the model predictabilities. This reveals that transit users perceive the cognitive transfer location as important, which would influence their decisions regarding travel mode.

The last phase of this study incorporates the cognitive transfer location variable into quantification of transit network connectivity. It demonstrates a better measure to accurately quantify how well a transit network connects one zone to others based on the transit travel time and the cognitive transfer location. Brisbane's transit network orientation takes a radial form, therefore it is expected that those areas in or near to the city-centre would have a relatively higher connectivity level over outer zones if only the travel time factor is considered. With the cognitive transfer location factor incorporated in the network connectivity mapping, it shows that those zones located along the major bus corridors have a higher connectivity level. The mapping also shows that some zones in the city-centre do not necessarily have a well-connected transit network to the remaining zones.

This research contributes to a number of academic discussions. In general, despite the few disparities among different socio-economically homogeneous groups, the aggregate approach of using 5 minutes or 400m walking access to bus stops is likely to work for most groups in the society. This research develops a new measure to quantify transit users' perception on travel direction towards transfer locations. The impact of cognitive transfer location will be more significant in a radial transit system, where travelling from an outer zone to another zone may require a transfer in the city-centre. Integrating this variable to quantify transit network connectivity could present a more accurate illustration of how well the transit network serves each zone. Findings of this research support transit agencies and transport planners to better assess the spatial coverage of existing transit systems to further improve the effectiveness of the existing service, to better plan and design new transit services and routes.

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List of Abbreviations

ABS	Australian Bureau of Statistics
AFC	Automated Fare Collection
ASGC	Australian Standard Geographical Classification
ASGS	Australian Statistical Geography Standard
CBD	Central Business District
CCD	Census Collectors Districts
GIS	Geographical Information Systems
GTFS	General Transit Feed Specification
HTS	Household Travel Survey
OD	Origin - Destination
SA1	Statistical Areas Level 1
SA2	Statistical Areas Level 2
SA3	Statistical Areas Level 3
SA4	Statistical Areas Level 4
SEQ	South East Queensland
SEQHTS	South East Queensland Household Travel Survey
SLA	Statistical Local Area
TCQSM	Transit Capacity and Quality of Service Manual

Statement of Original Authorship

The work contained in this thesis has not been previously submitted to meet requirements for an award at this or any other higher education institution. To the best of my knowledge and belief, the thesis contains no material previously published or written by another person except where due reference is made.

Signature : QUT Verified Signature

Date : July 2017

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Chapter 1: Introduction

1.1 RESEARCH BACKGROUND

The primary concern of transit agencies is to adequately evaluate service performance, to improve the quality of transit service, and to encourage mode shift from private vehicle to transit. Transit provides personal mobility, freedom and opportunities for people from every walk of life. From the environmental point of view, transit is known for its ability to save fuel, reduce congestion and carbon footprint. Despite all these benefits, it has been a constant challenge to encourage people to move out of their cars. In Australia, the latest census (2011) shows that only 10.4% of workers used transit to travel to work, while 65.8% of workers drove to their workplace. The reluctance of using transit has made the mode shift difficult. Inconveniences, such as lack of direct service and longer travel times, are known to be the main impediments to using transit service (Bush, 1999; Kim et al., 2009). In essence, transit must be a viable alternative, getting people from where they are, to where they need to go, in a reasonable amount of time (Murray, 2001). The increase of travel time due to congestion has failed to attract motorists to make the shift to transit. In Australia, the composition of the labour force has changed across the years, especially the increase of work opportunities in suburbs with low-density transit corridors. This has created a huge challenge for transit to provide sufficient services to these low-density suburbs.

Quantifying the quality of transit service is challenging as there are many factors that could affect transit choice, such as walking distance to transit, in-vehicle travel time, waiting time and number of transfers needed to reach destinations (Mishra et al., 2012). Quality of transit service is most commonly defined by Transit Capacity and Quality of Service Manual (TCQSM) as "*the overall measured or perceived performance of transit service from the passenger's point of view*" (Kittelson & Associates Inc. et al., 2003). TCQSM breaks down the decision-making process into two parts, namely (1) availability and (2) comfort and convenience. Unless a transit service is available to potential transit users, they will not weigh the comfort and convenience of transit against other competing modes such as private vehicles. Similarly, Walker (2012) documented seven broad expectations that transit users have of a transit service, in the order in which transit users will evaluate them. The first demand is: "*It takes me where I want to go*". The first demand involves two key measurable features of a transit system, firstly the location of stops and stations. Second is a connectivity measure to identify whether transit service links the origins and destinations. Having transit stops near to origins and destinations does not necessarily guarantee good connectivity between origins and destinations (Walker, 2012). Easy access to transit and the transit service connecting the origins and destinations by a reasonably direct path, are the utmost important factors to increase transit ridership.

Firstly, a transit service must be accessible from origins and to destinations, for people to consider using transit. The maximum walking access, either in terms of distance or time, has been extensively studied in the literature (Alshalalfah & Shalaby, 2007; El-Geneidy et al., 2014; Jiang et al., 2012; Loutzenheiser, 1997; O'Sullivan & Morrall, 1996; Weinstein Agrawal et al., 2008). Current practice uses 400m walking access to bus stops and 800m to train stations as the rule of thumb to define the transit catchment areas (Horner & Murray, 2004; Kittelson & Associates Inc. et al., 2003; O'Sullivan & Morrall, 1996; Weinstein Agrawal et al., 2008). At the same time, significant variations are observed between studies and further evidence has recently emerged about the complexity of walking behaviours (El-Geneidy et al., 2014). It is highlighted that the 'one size fits all' solution to define transit catchment areas is unlikely to be effective (Zhao et al., 2003). This study seeks to study the variation in walking access across individuals with different socio-economic standings. While accessibility to transit is an important determinant to mode choice, it does not consider the transit service connectivity from origins to destinations.

The dispersion of population and employment to surrounding suburbs has made it difficult for transit agencies to meet increasingly diversifying travel demands, due to limited transit services in some residential areas and poor transit network connectivity across suburbs (Hensher, 2000). This necessitates significant expansion and improvement of transit networks and services (Pickrell, 1985). It is almost impossible for transit agencies to provide direct connections for all origin-destination (OD) pairs. The extra effort in making transfers has been deemed to be necessary (Ceder et al., 2013) to expand transit service coverage and to provide private vehicle competitive citywide access (Currie & Loader, 2010). At the same time, the extra effort required in making transfers has been recognised by transit users as an impeding factor that disrupts the transit travel experience and deters the usage of transit (Guo & Wilson, 2011; Hadas & Ranjitkar, 2012). Transfer has been extensively discussed in the literature. Existing studies formulate transfer impacts in terms of additional time and cost incurred during transfer, including walking time, waiting time, extra in-vehicle time and transfer cost (Sharaby & Shiftan, 2012; Wardman et al., 2001). Despite an extensive range of research on transfer, the current literature has neglected the potential implication of travel direction towards transfer location in the decision-making process of travel mode choice.

The study on transit service connectivity and transfer is route specific. In other word, it is a disaggregate approach that studies the impact of transfer locations on decision making at an individual level. In any transit system, it consists of many routes; to determine the extent to which the routes are integrated and coordinated is essential. Current literature relies on travel time (based on both transit and private vehicles) and inconvenience of transfer (based on number of transfers) as the proxy to measure transit network connectivity (Curtis & Scheurer, 2016; Derrible & Kennedy, 2009; Lam & Schuler, 1982; Lei & Church, 2010; Mamun et al., 2013). This study is interested in understanding how well a transit network is connecting a zone to other zones based on the transit travel time and the directness of the route between origins and destinations.

1.2 RESEARCH QUESTIONS

Various travel behaviour studies have proposed different measures to capture the inherent complexity of transit choices, in order to provide more effective decision support tools for analysts and policy makers (Diana & Pronello, 2010). Determining the quality of transit service from origin to destination is essential to evaluate the effectiveness of transit networks. Easy access to transit and the transit service connecting the origins and destinations by a reasonably direct path, are the utmost important factors to increase transit ridership. For example, having transit stops near to origins and destinations does not necessarily guarantee good connectivity between origins and destinations. This forms the conceptual framework of this research that, in order to increase transit ridership, (1) the transit system is accessible from origins and destinations, and (2) the transit service connects the origins and destinations. The following research questions steer and guide this research. These research questions evolved from the themes that emerged from the literature review, and the gap identified therein.

Question 1: Is it appropriate to have a standardised walking access regression curve for all population groups, or to consider a more disaggregate approach?

Question 2: Do current measures have the ability to sufficiently quantify the impact of transfer on mode choice? If not, what is missing and how can the existing approach be enhanced to more accurately quantify the inconvenience of transfer?

Question 3: How can the connectivity of a transit network be measured and quantified? Do existing methods accurately define the transit network connectivity?

1.3 RESEARCH AIM AND OBJECTIVES

The aim of this study is to better understand and contribute to the existing knowledge base in the areas of (1) walking accessibility to transit (2) transit service connectivity and cognitive transfer location and (3) transit network connectivity. The definition of transit connectivity in the literature is inconsistent. In this research, transit service connectivity is defined as the smoothness of service transfers, while transit network connectivity is referred to the ability of a transit network connecting a zone to other zones. In order to achieve this aim, three research objectives are defined as follows.

Objective 1: To better understand the variation in the practical walking accessibility to bus stop for different homogeneous population groups.

More evidence is emerging about the complexity of walking behaviours to access transit. The “one size fits all” approach (400m) to define bus catchment area is unlikely to be accurate (Zhao et al., 2003). To address this objective, this research categorises the study population into several homogeneous groups based on their socio-economic standings, to study the variation in their walking times to transit.

Objective 2: To better understand and quantify the transit service connectivity and potential impact of transfer location on mode choice.

Transfers are inevitable in today's transit system. Existing studies formulate transfer impact in terms of additional time and cost incurred during transfer. This research builds on the hypothesis that transit users have a preference for the direction of travel towards transfer location. To address this objective, each journey's origin, transfer and destination points from transit smart card data are projected to a standardised, two-dimensional Euclidean space. Next, this study employs the grid-based hierarchical clustering method to identify the "preference" for transfer direction, based on cell density. Mode choice analysis is used to test the significance of the newly developed variable.

Objective 3: To account for the transfer location factor in quantifying the transit network connectivity.

To address this objective, this research defines transit network connectivity using two factors, including transit travel time and cognitive transfer location. As transit travel time increases, the probability of choosing transit as the mode of travel decreases. Adopting a similar concept, the farther the transfer location deviates from the straight route from origin to destination, the more unlikely travellers are to choose transit as the mode of travel.

1.4 RESEARCH SIGNIFICANCE

This research contributes to extending the existing knowledge base of transit and travel mode choice. This research highlights the variation in individuals' walking access to transit, depending on their socio-economic standing. The findings will support transit planners for a tailored approach in designing a transit service, especially for the areas with distinct socio-economic characteristics, such as retirement villages and university dormitories.

Next, this research provides a comprehensive analysis of travellers' behaviour on transit transfer. This study presents a new method to quantify the inconvenience of transit transfer based on the direction towards transfer location. When a transfer location is severely deviated from the direction towards the destination, it does impose significant impedance to use transit. This scenario is common in a radial transit network orientation, where transit riders travelling to neighbouring suburbs, are often required to make a transfer in the city-centre. The findings support transit planners in improving transit service routing and network coverage.

In view of the findings that transit users have a preference towards transfer locations, this research develops a new measure to better quantify transit network connectivity to support transit planners and analysts. With this new measure, the existing and new transit network can be assessed more accurately in terms of the network connectivity or spatial coverage to improve the effectiveness of the existing service, to better plan and design the future transit network.

1.5 THESIS STRUCTURE

This thesis is organised and set out in seven sequential chapters. Each chapter documents a specific aspect of the research and is structured to demonstrate the consistent chain of logic, connecting the research aim and objectives with research design, in the context of a case study. An overview of the purpose and context of each chapter follows.

Chapter 1: Introduction

This chapter presents the research background on the primary concerns of the transit sector. It discusses the research questions, research aim and objectives of this study. Next, this chapter highlights the significance of this research and provides insight into the flow of this thesis.

Chapter 2: Literature Review

Chapter 2 documents the literature review. It starts off with the review on the relationship between transit and urban form. Next, the review delves more deeply to specifically discuss the (1) walking accessibility to transit, (2) transit service connectivity and cognitive transfer location, and (3) quantification of transit network connectivity. The chapter presents the current state-of-the-art in transit research, and identifies the research gaps, which inform the research design.

Chapter 3: Research Design

This chapter provides an overview to the development of a theoretical framework, as well as the staged process to achieve the identified aim and objectives. This chapter justifies the selection of Brisbane as the case study area. Next, the chapter gives an in-depth description of the dataset used in this study.

Chapter 4: Accessibility to Transit

This chapter studies the variation of walking access amongst individuals with different socio-economic standings. It uses cluster analysis to categorise transit riders into different distinct groups with similar socio-economic standings. Next, it draws the relationship between the socio-economic standings for each group and their walking access to transit stops.

Chapter 5: Transit Service Connectivity and Cognitive Transfer Location

Chapter 5 develops the new measure to quantify the inconvenience of transfer. It describes thoroughly the process to transform all the single-transfer journeys unto a standardised space to discover transit users' cognitive "preference" towards transfer location. To validate the real effect of the cognitive transfer location, two binomial logit models (base and expanded model) are drawn between private vehicle and bus.

Chapter 6: Transit Network Connectivity

This chapter seeks to develop a better measure to quantify the ease of reaching multiple destinations using transit. It explores travellers' behaviour in choosing transit, as a function of transit travel time, and the travellers' preference towards transfer location. The chapter presents a thorough process to quantify transit network connectivity of a 10-zone study area, and extends this to the whole of Brisbane.

Chapter 7: Conclusion

This chapter consolidates the findings of the previous chapters, in the light of the research questions, aim and objectives. It highlights the theoretical and methodological contributions of this research, to inform transit planning and policies. Mention is made of the limitations of this research and directions for future research.

Chapter 2: Literature Review

2.1 INTRODUCTION

A transit service must be accessible and provide reasonable good connection between the intended trip origin and destination for travellers to consider transit as their mode of travel. Recent research by Thompson et al. (2012) found that the most important determinant of transit choice is the ease to access destinations. The chapter first review the relationship between transit and urban form (Section 2.2). Next, the review focuses on the walking accessibility to transit (Section 2.3), transit service connectivity and cognitive transfer location (Section 2.4), and quantification and mapping of transit network connectivity (Section 2.5). Section 2.6 highlights the main findings from the literature, which forms the foundation of the conceptual framework of this research.

2.2 TRANSIT AND URBAN FORM

Urban transit is an essential component in supporting passengers and freight mobility of large urban agglomerations (Rodrigue et al., 2006). It becomes a challenge for transit planners and agencies when cities are developing their spatial structure in a way that increases the reliance on private vehicles (Mishra et al., 2012; Rodrigue et al., 2006). On numerous occasions, the decline in transit ridership is associated with the increasing decentralisation of population and employment (Brown & Thompson, 2008a; Brown & Thompson, 2008b). Today, the widespread use of the city-centre oriented transit does not necessarily convey that it is the most effective approach to increase transit ridership (Mees, 2010; Thompson, 1977).

2.2.1 Transit Network Orientations

In earlier times, cities were much smaller. Getting from one place to another was done either by walking or using horse-drawn carriages. Most people lived near their primary work location, or even above some ground-floor commercial activity in the city-centre. This contributed to the features of high density, mixed land use, joined together by narrow streets in an organic structure (Newman & Kenworthy, 1996; Stover & Koepke, 2002). In the late 19th century, the use of train and tram became more widespread and affordable. As transit agencies extended transit lines from the city-centre to outer suburbans, population moved out along those transit lines, which had enabled urban families to establish residences farther away from the central business district (CBD). This has resulted in a radial transit network orientation. In a radial transit network, it is designed to connect all points in a metropolitan area to the city-centre (Mees, 2010; Thompson, 1977). The routes radiate from the centre like spokes of a wheel, as illustrated in Figure 2-1.

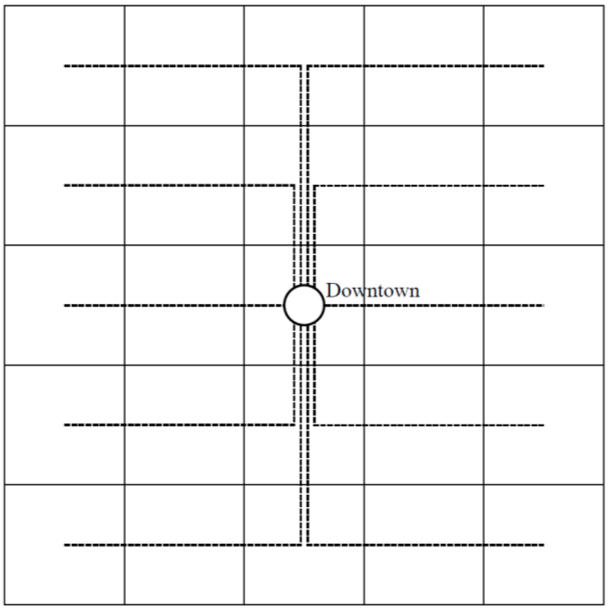


Figure 2-1: Radial transit network orientation

Just before the Second World War, private vehicles progressively became the transport technology that shaped cities. Private vehicles offered greater speed, convenience, and flexibility (Stover & Koepke, 2002), which made it possible to expand cities in any direction, and consequently, led to the rising of new suburbs. As such, cities began to decentralise and disperse and many activities and employment opportunities relocated to the suburbs (Rodrigue et al., 2006). Most of the transit network kept its radial orientation, despite the rapid decentralisation, which made it challenging or nearly impossible for transit agencies to extend their services to meet rapidly diversifying travel demands (Thompson, 1977; Thompson & Matoff, 2003). In reference to Figure 2-1, the straightforward method to improve transit service to all destinations is to provide direct routes connecting each pair of grids with its own route. This may not be a practical approach as it requires a large volume of transit service. A more efficient measure is to utilise transfers, to connect all grid pairs at a greatly reduced number of transit routes. At least two systematic methods have been successfully used by transit agencies to provide multi-destination transit network orientation, namely time transfer points and grid methods (Thompson, 1977).

Figure 2-2 shows the multi-destination transit network orientation by using timed transfer points. The circles represent the timed transfer locations, also known as pulses (Thompson, 1977; Walker, 2012). This system relies on scheduled connections between routes and a number of strategic locations where several routes intersect (Thompson, 1977). Timed transfer locations often consist of an off-street platform to allow for eight to twelve buses to park. Generally, for fifteen to twenty minutes, the platform is deserted, then different buses start to arrive at the platform to pick up and drop off transferring passengers. In a few minutes, the buses will depart from the platform. This cycle is repeated every thirty minutes (Thompson, 1977).

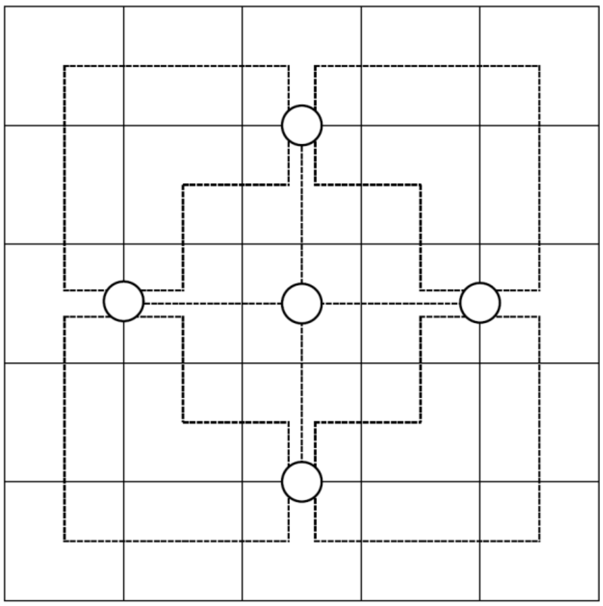


Figure 2-2: Multi-destination transit network orientation – Timed transfer point

This transport system can be quite complicated, as it requires careful planning of how two or more buses can arrive at similar time. This system often works for trains and ferries, but unfortunately, not for transit services that run in mixed traffic, such as buses and trams, which are subject to traffic congestion. In any event of traffic congestion, the risk of buses not getting back to the timed transfer points increases, leaving transit users stranded (Walker, 2012). In order to minimise the waiting time at timed transfer points, the only measure is to increase the frequency of transit services; instead of a thirty-minute headway, it should be reduced to a ten-minute headway. The better the frequency, the less significant it is to have timed transfer locations. This leads to the next multi-destination transit network orientation – the grid system, as illustrated in Figure 2-3.

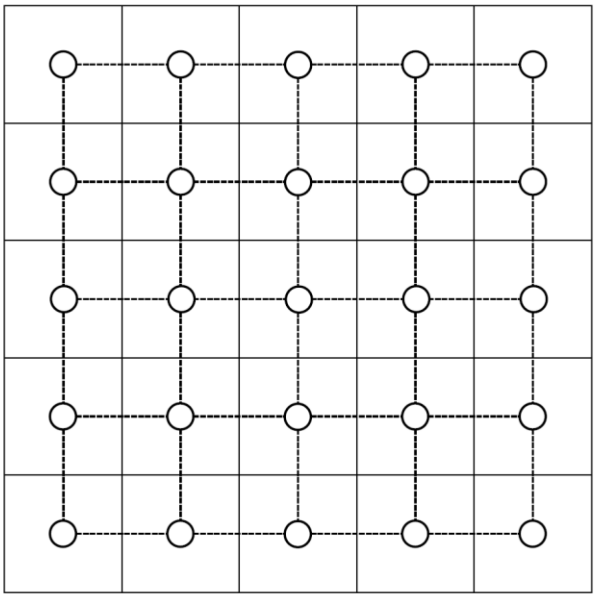


Figure 2-3: Multi-destination transit network orientation – Grid

The circles represent the transfer points, one for each grid. This method consists of two set of routes. The first set consists of parallel routes running in the north-south direction, while the second set consists of parallel routes running in the east-west direction. In an ideal rectangular grid system, everyone is within walking distance either to the north-south line or the east-west line (Walker, 2012). Without any circuitous travel, a traveller could easily travel from one grid to another grid by transferring no more than once following a direct L-shape path (Thompson, 1977; Walker, 2012). For this method to work, it requires frequent transit services to minimise the inconvenience of transfer (i.e.: long transfer waiting time). The spacing between parallel transit lines in a grid system is important. To illustrate, it should not be too far apart, as it will decrease the walking accessibility to transit. In order to achieve the optimum spacing, it should be twice the maximum walking distance (Walker, 2012).

Grid transit network orientation is not limited to cities with a grid street network. In most real-world cities, the transit network takes the combination of both radial and grid orientations, known as the spider web or polar grid, as shown in

Figure 2-4. The circles represent the transfer point. A spider web network consists of two sets of routes, one set of routes radiating from the downtown, and another set of routes circling the city-centre (Walker, 2012). This type of orientation is common among those cities with a dominant centre of demand.

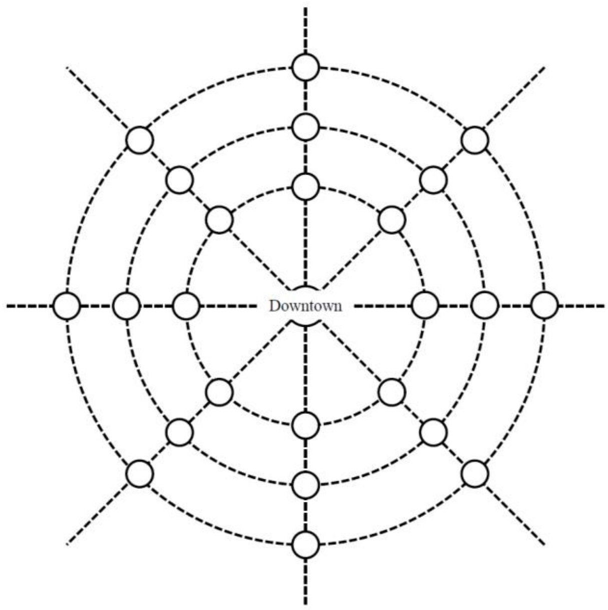


Figure 2-4: Combination of radial and grid transit network orientation – Spider web

Canadian cities were among those cities with the early adoption of multi-destination transit systems. Toronto has utilised a grid transit orientation since the 1920s. On average, over 70 percent of total transit trips do not pass through the downtown area, indicating success in attracting non-downtown travel (Thompson, 1977). Similarly, Edmonton and Vancouver began to convert the radial bus network orientation to a timed transfer network in the late 1900s, and this led to an increase in transit ridership (Thompson, 1977). Today, many large cities' transit systems have employed a combination of grid and spider web transit orientation. To illustrate, a decentralised city such as Los Angeles has strong transit grid network. San Francisco, which has a relatively strong concentration of activities at downtown area, employed a spider web transit network orientation (Walker, 2012).

Following the development of cities in the 20th century, urban planners and transportation engineers failed to understand the relationship between land use and transportation, with most of these plans done separately (Stover & Koepke, 2002). Newman and Kenworthy (1996) addressed this as "functional isolation". These two plans must be fully integrated, as one decision made would have direct impact with respect to the other. Rather than being made independently, decisions concerning land use and transportation must be made conditional on one another. Today’s planners have acknowledged this and they are incorporating transit planning back in its urban context (Newman & Kenworthy, 1996). There must be a balance between land use intensity and transportation system capacity, in order to accommodate the urban growth effectively (Stover & Koepke, 2002).

2.2.2 Relationship between Transit Network Orientation and Transit Ridership

The combination of motorisation and urbanisation leads to the decrease of transit ridership. Private vehicles have changed from being a recreational vehicle to the nation’s most popular mode of transportation. Private vehicles offer much freedom of travel, while transit becomes a secondary mean of travel left for those who do not have access to private vehicles. This phenomena is happening all around the world, both in developing and developed countries (Sinha, 2003). It has been a constant challenge for transit agencies to lure travellers to use transit. The only solution is to increase the relative competitiveness of transit: to provide easy access to transit, and to connect the origins and destinations by a reasonably direct path.

To increase the accessibility of transit users to transit, one school of thought is to bring a greater proportion of the regional population near to transit. This policy tries to reverse the structural change of the urban form, by bringing back more employment to the downtown, and creating high density residential developments around transit stops in the suburbs (Curtis et al., 2009; Pushkarev & Zupan, 1977; Thompson et al., 2012). A study conducted by Cervero (2002) on mode choice analysis in Montgomery County, Maryland, revealed that higher density and land-use mixtures, with good pedestrian design, consistently works in favour of transit mode share.

Other scholars have taken another viewpoint, to question whether transit mode share is dependent on downtown and high density residential clusters. Mees (2010) rejected the theory of “density as destiny”, using the city of Zürich, Switzerland as the framework for multi-destination service orientation. Other studies of multi-destination systems in North America, Europe and Australasia have demonstrated that it is possible to generate high transit ridership even in the absence of high densities. This policy seeks to restructure transit networks around dispersed locations where people live and work, to provide a better link between origins and destinations, in order to induce transit ridership (Thompson et al., 2012).

With the intention to encourage mode shift from private vehicles to transit, the first policy seeks to improve the accessibility to transit, while the second policy seeks to improve the transit service connectivity. Instead of debating which policy works best to improve transit ridership, these two policies could be integrated as one. For example, restructuring of routes into grid or spider web orientation to serve multi-destinations will definitely provide more direct connections between the dispersed population and employment clusters, as compared to the conventional radial transit network routing (Thompson et al., 2012). The only drawback could be longer walking time to transit stations. One of the solutions is to provide better access to and egress from transit, by creating higher density residential developments around transit stops in the suburbs with good pedestrian design (Brown & Thompson, 2008b; Thompson et al., 2012). The remaining sections of the literature review will discuss more thoroughly the current state-of-the-art of accessibility to transit, transit service connectivity and transit network connectivity.

2.3 WALKING ACCESSIBILITY TO TRANSIT

Walking access refers to the ability of individuals to reach transit services, such as bus stops or train stations (Zhao et al., 2003). Transit services must be accessible within reasonable walking access of trip origin and destination in order to facilitate their use. The maximum walking access, either in terms of distance or time, has been extensively studied in the literature (Alshalalfah & Shalaby, 2007; El-Geneidy et al., 2014; Jiang et al., 2012; Loutzenheiser, 1997; O'Sullivan & Morrall, 1996; Weinstein Agrawal et al., 2008). Current practice uses 400m walking access to bus stops and 800m to train stations as the rule of thumb to define the transit catchment areas (Horner & Murray, 2004; Kittelson & Associates Inc. et al., 2003; O'Sullivan & Morrall, 1996; Weinstein Agrawal et al., 2008).

Significant variations are observed between studies and more evidence has recently emerged about the complexity of walking behaviours (El-Geneidy et al., 2014). It is highlighted in the literature that the ‘one size fits all’ solution to define transit catchment areas is unlikely to be effective (Zhao et al., 2003). Recent studies have attempted to identify various factors that influence walking access to transit, including household income (Hsiao et al., 1997; Loutzenheiser, 1997; Weinstein Agrawal et al., 2008), education level (Loutzenheiser, 1997), vehicle ownership (Hsiao et al., 1997; Weinstein Agrawal et al., 2008), street patterns (Hsiao et al., 1997; Jiang et al., 2012), trip purpose (Alshalalfah & Shalaby, 2007; Loutzenheiser, 1997) and quality of transit services such as wait time and number of transfers (Alshalalfah & Shalaby, 2007).

2.3.1 Different Types of Accessibility Measures

Accessibility is an important concept that has always been central to transportation research, in terms of the relationship between transportation and land use (Lei & Church, 2010; Liu & Zhu, 2004). At the same time, accessibility is a concept that is not entirely easy to define, ranging from access to employment within specific travel time to the ease of reaching destinations (Lei & Church, 2010). From past studies, generally transit accessibility can be defined in six different categories.

The first accessibility measure is ***system accessibility***, which deals with the physical access to a system, based on distance, time and effort to reach transit. Murray et al. (1998) defined accessibility to transit as the opportunity to use the service. Current literature uses the walking distance of 400m to evaluate pedestrian accessibility of a local neighbourhood to different destinations such as school and transit stops (Aultman-Hall et al., 1997; Horner & Murray, 2004; O'Sullivan & Morrall, 1996; Weinstein Agrawal et al., 2008). Locating fewer stops along transit routes would potentially increase transit travel speed, however, it should not be reduced to the extent that it decreases access to transit stops (Murray, 2001). While proximity to transit stops is an important determinant to mode choice, it does not consider the travel cost incurred in using the transit service to destinations (Murray et al., 1998).

The second measure is known as ***system-facilitated accessibility***, which takes into account the travel time, cost spent and effort in making the trip. In earlier studies, transit travel times were calculated by dividing distance with average speeds (Liu & Zhu, 2004). This is not the most accurate method, as travel time varies depending on the schedule of the network and transfer time (Lei & Church, 2010). The later studies took into consideration walking time to a stop, waiting time at a stop, in-vehicle travel time, walking time to transfer stop and waiting time at transfer stop. Using system access and system-facilitated access measures, Wu and Murray (2005) developed a model to optimise an existing route structure, improving transit travel times by dropping unnecessary transit stops.

The third measure of accessibility is ***integral accessibility***, or opportunity-based measure. This measure is concerned with the number of opportunities available within a certain distance from the origin (Breheny, 1978). The simplest measure could be counting the number of destinations available within a specific distance from an origin (Wachs & Kumagai, 1973). However, counting available activities within a maximum travel distance does not show the relative closeness (Lei & Church, 2010). The later studies used the aggregate accessibility to plot a location profile based on a series of cut-off distance values (Geertman & Ritsema Van Eck, 1995).

The fourth accessibility measure is the ***utility-based measure***. This measure views all transit users as consumers and alternatives of travel as a choice set. This measure assumes consumers to be rational and choose the opportunity with the maximum utility, dependant on the socio-economic characteristics of users, and attributes of different transport options such as travel time, transit fare and parking costs (Liu & Zhu, 2004). Unlike all the other accessibility measures, this measure is capable of consider a wider range of variables, such as socio-economic variables and environmental impact of each mode, instead of just travel time and travel distance (Lei & Church, 2010). For example, accessibility index could be calculated as the denominator of the logit model (Small & Verhoef, 2007).

The fifth accessibility measure is the ***space-time measure***. This measure emphasises the range and frequency of activities in which an individual takes part. It looks into the possibility of sequencing them so that all activities could be undertaken in one path (Jones, 1981). This measure recognises that good accessibility not only consists of good spatial accessibility but also temporal accessibility (Liu & Zhu, 2004). The fundamental construct of this measure is based on the space-time prism, which recognises that an individual's movement over space and the choice of activities is dependent on their mobility and limited by time budget (Hägerstraand, 1970). Kim and Kwan (2003) improved this measure by considering the facility operating hours and the effect of network topology.

The last accessibility measure is ***relative accessibility***. This measure allows comparison made against other modes or other types of users (Church & Marston, 2003). If an individual has a choice to choose among different transport modes, the decision is made as a function of cost, time, convenience and safety. For example, competitive transit travel times and expensive parking cost will encourage individuals to take transit, and vice versa. This measure calculates the accessibility as a function of the relative value, believing that one's decision is based on the relative value of transit in comparison with another modes (Lei & Church, 2010). Schoon et al. (1999) developed Accessibility Indices (AIs) for a pilot study in northeast Hampshire, England, based on the door-to-door travel times and costs, between specified origins and destinations (O-Ds).

Each of these six accessibility measures can provide useful information in analysing the current transit system, and redesigning future transit system. As aforementioned, accessibility is a concept that is not entirely easy to define. In this research, the working definition of accessibility refers to the system accessibility, which deals with the ease to reach transit. More specifically, this research will study, in-depth, the walking accessibility to transit.

2.3.2 Walking Access

Considering that most transit trips begin and end with walking, understanding the walking access of existing and potential transit users is crucial for transit service planning. Pedestrians seek to minimise the time and distance of walking to transit (O'Sullivan & Morrall, 1996; Weinstein Agrawal et al., 2008). Ideally, a viable transit service must be accessible within reasonable walking access from origin and destination. Locating frequent transit stops provides easy access to users, but on the other hand, it slows down the travel speed of transit, thereby decreasing the spatial coverage of transit reachable within a given travel time limit (Foda & Osman, 2010; Murray & Wu, 2003). Walking access should be given more attention, with the aim to maximise the geographical coverage of transit service, at the same time avoiding redundancy, where the same parcel is being served by multiple stops along the same route (El-Geneidy et al., 2014).

Since the 1970s, numerous studies have attempted to shed light on walking access to transit. Some studies defined the catchment area of bus stops by creating a circular buffer of 400m around bus stops or along transit routes (Hsiao et al., 1997; O'Neill et al., 1992). This simple technique often overestimates the population within the service area as Euclidean distance is used, instead of the actual network distance. The improvement to this method is known as the network ratio method, which considers the actual length of the street network (O'Neill et al., 1992). Similar to the network ratio method, Foda and Osman (2010) identified all the pedestrian network links that lie within the distance of 400m and joined the ends of those links to create a polygonal area. These three methods assume uniform distribution of the population along streets, which is not a strong approach when the analysis zone has a mixed land use of residential, retail, industrial or recreational purposes (Biba et al., 2010; Zhao et al., 2003). To address this weakness, Biba et al. (2010) developed the parcel-network method, which considers the demographic attributes of parcel centroids.

Conventionally, planning practice uses 400m (or 5 minute) walking access to bus stops and 800m (or 10 minute) to train stations to define the catchment area (Horner & Murray, 2004; Kittelson & Associates Inc. et al., 2003; O'Sullivan & Morrall, 1996; Weinstein Agrawal et al., 2008). The 400m and 800m rule of thumb has been challenged by recent studies, where further research is needed to better understand the walking behaviour of transit users and to accurately define the transit service catchment area (El-Geneidy et al., 2014).

2.3.3 Properties of Walking Access

Significant variations are observed between studies and more evidence is emerging demonstrating the complexity of walking behaviours (El-Geneidy et al., 2014). The literature suggests that further research is required to explore beyond the average walking access to better understand how walking access may vary by characteristics of transit users and their trips (Daniels & Mulley, 2013).

Zhao et al. (2003) used a distance decay function to estimate how far people would walk to a transit stop to substitute the typical 400m buffer. The distance decay function showed that farther than 800m away from a transit stop, transit use diminished to 3 percent. They suggested using 800m as the upper limit to determine transit catchment area. More recent studies also provided evidence on walking distance to access transit. In Brisbane, on average, people walk 1,300m to access transit, and 1,090m from transit facilities to destinations (Burke & Brown, 2007). In

Toronto, 80 percent of transit users live within a distance of 500m (Alshalalfah & Shalaby, 2007), while in the San Francisco Bay Area Rapid Transit (BART) case, the probability of an individual to access transit decreases by 50 percent when walking distance from stations increases from the first 500m to the next 500m (Loutzenheiser, 1997).

In addition to the proximity factor, research has identified various factors influencing the walking access to transit facilities. They could be categorised into four groups, namely individual characteristics, household characteristics, built environment characteristics and trip characteristics.

Age and gender are found to evidently be affecting the walking access to transit. Interestingly, Loutzenheiser (1997) reported that age had a negative impact on walking access, while Alshalalfah and Shalaby (2007) argued that there was no difference in walking access between age groups. Similar to age, some studies reported that males had a higher propensity to walk to transit (Loutzenheiser, 1997; Wibowo & Olszewski, 2005), while Alshalalfah and Shalaby (2007) showed that males would walk more only to access bus trips and there was no difference between genders to access train trips. Additionally, higher personal income is known to have a negative impact on walking access (Hsiao et al., 1997; Loutzenheiser, 1997; Weinstein Agrawal et al., 2008).

As for household characteristics, vehicle ownership has a negative impact in general on walking access (Hsiao et al., 1997; Weinstein Agrawal et al., 2008). On the other hand, a positive relationship is found for those who have decided to walk, assuming that car-owning households stay farther from transit stops (Alshalalfah & Shalaby, 2007).

Transit access environment has been discussed in the literature as an important factor to explain walking access to transit. Evans IV et al. (1997) developed a transit friendliness factor to quantify the transit access environment in considering some elements including, the sidewalk conditions, street crossings, availability of transit amenities and proximity to destinations. People walk farther to transit facilities when the walking environments are conducive, such as having shaded corridor and low traffic impacts (Jiang et al., 2012; Park et al., 2015). The same study suggested that people would walk longer to transit stops in residential areas as compared to a CBD, presuming that a city-centre has the highest point of accessibility. Similarly, O'Sullivan and Morrall (1996) compared the walking access to train stations in CBD and residential areas. This study found that the average walking distance to light rail stations in any residential area was 649m, while it was much shorter at 326m to the stations located in CBD stations. A station corridor has a significant effect on walking access to transit. Transit users would walk 160m longer through an integrated, busy and shaded corridor, as compared to the arterial-edge and below expressway corridors (Jiang et al., 2012). Grid-patterned streets provide better pedestrian access to transit than areas with irregular street patterns and lower land use density (Hsiao et al., 1997).

As for trip characteristics, the mode of transit has a significant impact on the walking access. Alshalalfah and Shalaby (2007) suggested that transit users would walk longer to subway stations than to bus or streetcar stations. Similarly, in California and Oregon, Weinstein Agrawal et al. (2008) showed that half of the surveyed transit users walked more than half a mile (805m) to access railway stations rather than bus stops. In Montreal, Canada, the 85th percentile of walking distance to bus transit was around 524m from origins, while it was 1259m for commuter rail (El-Geneidy et al., 2014). Likewise in Sydney, Daniels and Mulley (2013) revealed that once people have made the decision to walk, the main influence on walking distance from home to transit is the mode of transit. This study reported that the mean walking distances to bus and train services were 461m and 805m, respectively. The number of service transfers made during the trip has a negative relationship with the walking access. Trip purpose does have significant impact on walking access, where walking access for work trips are lower than school trips (Alshalalfah & Shalaby, 2007).

2.3.4 Research Motivations on Walking Accessibility to Transit

Transit only becomes a viable travel mode when transit service is accessible within walking access. If so, what is the acceptable walking access? The ability to precisely measure walking access has been elusive, given the extensive range of factors that will affect traveller’s decision making whether to walk to transit facilities. However, little is known about the variation in walking access across individuals with different socio-economic standings. The regression approach has been extensively used in the literature (El-Geneidy et al., 2014; Jiang et al., 2012) to relate walking access to various explanatory factors. Standard linear regression, which uses the ordinary least squares estimator, assumes linear relationship between the dependent walking access variable and independent explanatory variables. This assumption could easily be violated for modelling of walking access. For example, there could be diminishing marginal effects of independent variables on walking access (non-linear function), or some explanatory variables may be strong predictors for certain individuals only. While accessibility to transit stops is an important determinant to mode choice, it does not consider the transit travel journey from origins to destinations. The next section will discuss on the transit service connectivity between origins and destinations.

2.4 TRANSIT SERVICE CONNECTIVITY AND TRANSFER

Providing seamless connection between origins and destinations has always been a long-standing goal of transit agencies, in order to compete with the door-to-door connectivity that private vehicle offers. The dispersion of population and employment to surrounding suburbs impels significant expansion and improvement of transit networks and services (Pickrell, 1985). Rapid suburbanisation has made it difficult for transit agencies to meet increasingly diversifying travel demands, due to limited transit availability in some residential areas and poor transit connectivity across suburbs (Hensher, 2000). Failure of transit agencies to respond to changing travel patterns can significantly contribute to the decline of transit ridership (Pickrell, 1985). Conventional radial transit orientation (as illustrated in Figure 2-1) focuses on providing direct connections to bring commuters from the suburbs to the downtown. Due to diversifying travel needs, transit agencies are unable to provide direct connections for all origin-destination pairs. The extra effort in making transfers has been deemed to be necessary to expand service coverage and provide private vehicle, competitive, citywide access (Ceder et al., 2013; Currie & Loader, 2010). Ironically, the extra effort required in making transfers is recognised by travellers as an impeding factor that disrupts the transit travel experience and deters the usage of transit (Guo & Wilson, 2011; Hadas & Ranjitkar, 2012).

2.4.1 Properties of Transit Transfer

Operational factors such as the service reliability, headways regularity, on-time performance of service and the availability of adequate information affect both actual and perceived waiting time during transfers. (Ceder et al., 2013; Iseki & Taylor, 2009; Mishalani et al., 2006). Providing a guaranteed connection and a through ticket for transfer could significantly reduce transfer penalty (Wardman et al., 2001). An empirical study conducted in Haifa, Israel demonstrated that waiving a transfer fee resulted in a significant increase in the transit ridership (Sharaby & Shiftan, 2012). Another study conducted in metropolitan Los Angeles showed that user satisfaction with a transfer facility has little to do with the physical characteristics of the facility, but service frequency and reliability (Iseki & Taylor, 2010). A study by Currie and Loader (2010) found that the volume of transfers could significantly increase along a major transit route when the service headway is 10 minutes or shorter (Currie & Loader, 2010).

Physical environmental factors such as physical attributes of stops and stations could potentially affect the quality of transfer services. Guo and Wilson (2004) reported that transit users are more likely to transfer if escalators are available at transfer stations to assist with changing of levels. The provision of amenities, such as benches, shades, water fountains and rest rooms would increase the comfort and convenience of transit users while waiting and transferring (Iseki & Taylor, 2009). Security and safety, such as security staff and actual crime rates of transit facilities would influence the perception of waiting and walking for transfer (Loukaitou-Sideris et al., 2001). A case study of the London Underground found that worst transfer locations were stations with the largest and most complex transfer environments, and best transfer locations perceived were those stations with simple transfer environments and heavy use (Guo & Wilson, 2011). In the case of whether to take a transfer or walk a longer distance to a destination, Guo and Wilson (2004) discovered that the demand of transfer decreases if walking environments are improved. If wider sidewalks exist along the non-transfer path, transit riders are less likely to use a transfer service.

2.4.2 Quantification of Inconvenience of Transit Transfer

The inconvenience of transit transfer encapsulates the measurable factors such as additional time and cost spent on transfer, and the additional penalty due to the uncertainty of catching the next transit service during transfers (Guo & Wilson, 2004; Liu et al., 1997). Transfer penalty embraces the subjective and psychological factors based on preferences, attitudes, and the perceptions that further penalised transfer behaviour in addition to the measurable transfer attributes (Guo & Ferreira, 2008). The conventional way of quantifying the inconvenience of transfer has been through generalised cost, an equivalence to travel time or monetary cost (Iseki & Taylor, 2009; Kittelson & Associates Inc. et al., 2003; Wardman, 2001). Wardman (2001) conducted a meta-analysis of 143 studies, which took place between 1980 and 1996 in Great Britain, to infer the values of time and service quality expressed in units of in-vehicle time and monetary cost. On average,

- walking time is equivalent to 1.66 of in-vehicle time,
- waiting time is equivalent to 1.47 of in-vehicle time, and
- other transfer penalties cost USD2.20 per transfer.

Different trip attributes have very different weightings in valuations of time. These weights can be interpreted as the differences between actual time and the perceived travel time by a traveller (Iseki & Taylor, 2009). Currie (2005) listed the key components of a typical trip by transit, which consists of the following: access by walking to bus stop, wait time at a bus stop, in-vehicle travel time, transfer walk time, transfer wait time and other transfer penalties, in-vehicle travel time and egress by walking to destination. The quality of travel could be measured in terms of generalised cost, by converting the time, fare and qualities of travel into comparable costs (Currie, 2005; Iseki & Taylor, 2009), as shown in Equation 2-1.

$$TGC = \{(Walk_t \times Walk_v) + (Wait_t \times Wait_v) + (IVT_t \times IVT_v) + (NT \times TP_b) + MSC_m\} \times VOT + Fare \qquad \text{Equation 2-1}$$

where:

TGC = Total generalised cost

$Walk_t$ = Walking time to and from transit

$Walk_v$ = Passenger valuation of walking time to and from transit

$Wait_t$ = Waiting time for transit vehicles to arrive at the transit stop

$Wait_v$ = Passenger valuation of waiting time at the transit stop

IVT_t = In-vehicle transit travel time

IVT_v = Passenger valuation of in-vehicle transit travel time

NT = Number of transfers

TP_b = Transfer penalty

MSC_m = Mode-specific constant for transit mode m

VOT = Value of travel time

$Fare$ = Average fare per trip

Transfer penalty can be further decomposed, as shown in Equation 2-2.

$$TP_b = (Walk_{tt} \times Walk_v) + (Wait_{tt} \times Wait_v) + TP_n \qquad \text{Equation 2-2}$$

where:

$Walk_{tt}$ = Walking time to transfer

$Wait_{tt}$ = Waiting time for transit vehicles to transfer

TP_n = Transfer penalty, excluding transfer walking and waiting time

Table 2-1 shows a sample of transit journey that involves transfer, and the total generalised cost. This calculation is based on the assumption that the monetary value of in-vehicle travel time is AUD8.50, half of the average hourly wage in Australia (AUD17.00).

Table 2-1: A sample of transit trip and its associated time and monetary costs

Trip attributes	Time (min)	Valuation of time*	Unit Cost (AUD/ min)	Monetary Cost (AUD) Typical transfer	No transfer waiting	No transfer walking	No transfer walking and waiting
Walking access to transit	8	1.66	0.24	1.88	1.88	1.88	1.88
Waiting time at a bus stop	4	1.47	0.21	0.83	0.83	0.83	0.83
In-vehicle travel time (Service 1)	20	1.00	0.14	2.83	2.83	2.83	2.83
Transfer penalties							
Walking time to transfer	6	1.66	0.24	1.41	1.41	-	-
Waiting time to transfer	10	1.47	0.21	2.08	-	2.08	-
Other transfer penalties	-	-	3.00**	3.00	3.00	3.00	3.00
In-vehicle travel time (Service 2)	30	1.00	0.14	4.25	4.25	4.25	4.25
Walking egress to destination	6	1.66	0.24	1.41	1.41	1.41	1.41
Transit fare	-	-	3.93***	3.93	3.93	3.93	3.93
Total				21.63	19.55	20.22	18.14
% of total costs associated with transferring				30.02%	22.56%	25.13%	16.54%

Notes:

* : Valuation of time is taken from Wardman (2001)

** : Other transfer penalties are calculated as AUD 3.00 per transfer (equivalent to USD2.20)

*** : Transit fare is AUD 3.93 per transit journey, based on a 2 zone transit journey

In reference to Table 2-1, this example shows that the transfer penalties (walking time, waiting time and other transfer penalties) account for 30% of the total generalised cost of the trip. When a transfer can be conducted without walking, the percentage of total costs associated with transferring drops to 25%. If no transfer waiting is required, it drops to 23%. When neither walking nor waiting is required to conduct a transfer, the percentage of total costs associated with transferring drops to 17%.

Besides trip attributes, Wardman et al. (2001) calculated value of time to interchange attributes based on a bus users' stated preference survey, and found out that the most important facilities to provide at transfer locations are good shelter, real-time information, printed timetable information and good signage.

The inconvenience of transfer is measured as an equivalence of travel time or money saving, which is done by taking the ratio between the coefficients of transfer variables and time or cost variables. This ratio shows how much further people are willing to travel (time without transfer) or how much they are willing to pay (cost), to save on one transfer, demonstrating the time and money that must be saved in order to justify one transfer (Guo & Ferreira, 2008). Guo and Wilson (2004) used a binary logit model to show the probability of an individual selecting the transfer option. According to the base model (transfer constant and walking time savings), it is discovered that one transfer is equivalent to 9.5 minutes of walking. In other words, if a transfer can save more than 9.5 minutes of walking, a typical transit user will choose to conduct a transfer. The advanced model takes into consideration the different types of transfer stations, transfer attributes and the quality of the pedestrian environment. As more variables are included in the variable, the transfer penalty as reflected in the constant term decreases, while the explanatory power of the model increases (Guo & Wilson, 2004).

2.4.3 Research Motivations on Transit Service Connectivity and Transfer

The literature captures various factors that influence the quality of transfers and its impact on travel mode choice, in the form of additional cost. Much effort has been devoted to study the perceived costs of walking and waiting time during transfers. What is lacking is that instead of quantifying the inconvenience of transfer in scalar form, transit users could also consider the travel direction towards their transfer points. This concept is similar to the concept of "angular cost" in route choice, which measures the directness of chosen route (Raveau et al., 2011). The conventional route choice models includes the service levels of the route alternatives and the socio-economic and demographic characteristics of users (Ortúzar S et al., 2011). Raveau et al. (2011) found that transit users tend to penalise routes that deviate from a direct path to the final destination, and by incorporating this factor into the conventional route choice models has improved the explanatory power of route choice. The "angular cost" is measured as a function of $\sin(\frac{\theta}{2})$, where θ is the angle formed between the origin-destination (OD) straight route with the origin-transfer (OT) straight route, weighted by the Euclidean distance to transfer point (d) , as shown in Equation 2-3.

$$Angular\ cost = d * sin\left(\frac{\theta}{2}\right) \qquad \text{Equation 2-3}$$

The impact of transfer location may be exacerbated if transit users are required to make a transfer in the opposite direction to their destination. This effect will be more significant in a radial transit system, where transit users travelling from an outer suburb to another require a transfer in the downtown or major transit hubs to access connecting transit lines or alternative modes. Despite an extensive range of research on transfer, the current literature has neglected the potential implication of travel direction towards transfer location in the decision-making process of travel mode choice. The study on transit service connectivity and transfer is route specific. In another word, it is a disaggregate approach that study the decision making and choice processes at individual level (Handy, 1996; Wang & Cheng, 2001). In any transit system, it consists of many routes, and to determine the extent to which the routes are integrated and coordinated is another complicated yet essential task (Mishra et al., 2012). To accurately quantify transit network connectivity could help with the evaluation of transit performance as a whole and better develop service delivery strategies, such as prioritising certain nodes and links in a transit system (Mishra et al., 2012). The next section will review the current state-of-the-art to quantify and measure transit network connectivity.

2.5 TRANSIT NETWORK CONNECTIVITY

A critical factor in transit planning is to accurately assess the effectiveness of a transit service, focusing on the spatial efficiency of service coverage in meeting transport needs of the community. This includes both expanding the service coverage and increasing the efficiency of transit routes (Mishra et al., 2012; Murray, 2003).

The performance of any transit system could be measured by its ability to meet mobility and economic needs efficiently and equitably, in an environmentally sound manner (Mamun et al., 2013). A considerable amount of studies were conducted in quantifying transit connectivity; however, the definition of transit connectivity is ambiguous. Transit connectivity, in broader terms, could refer to the ease of getting from one place to another; while in a narrower definition, it could refer to the physical properties of the network system, such as the transfer system (Mamun et al., 2013). In this study, the working definition of transit network connectivity is the ability of a transit network connecting a zone to other zones.

It has been a complex task to quantify transit network connectivity. Firstly, a transit system consists of many different routes and the extent to which the routes are integrated (i.e.: to accommodate transfers with minimum of transfer inconvenience) determines many qualities of the transit system. Secondly, there are many factors related to service quality that could possibly influence an individual's decision to use transit as the mode of travel, such as walking distance to access and egress from transit stops, transfer time and transit service frequency. Thirdly, a transit system serves people, and different riders perceive the quality of the transit service differently, which is often hard to quantify (Lam & Schuler, 1982; Mishra et al., 2012).

2.5.1 Current Measures to Quantify Transit Network Connectivity

Earlier studies on transit network connectivity are based on graph and network theory (Derrible & Kennedy, 2009; Lam & Schuler, 1982; Lee & Lee, 1998; Mishra et al., 2012; Scott et al., 2006). These studies break down a transit network into nodes and links. Nodes refer to transit stops while links refer to the infrastructures supporting the flows from, to and between nodes (Mishra et al., 2012; Rodrigue et al., 2006). Well-coordinated lines enable individuals within the service area to use transit to satisfy the mobility needs of transit users. The node's connecting power is measured using centrality measures. To illustrate, degree centrality counts the number of direct connections a node has to other nodes in the network, but does not account for the quality of connection. Eigenvector centrality takes into consideration that not all connections are equal, by assigning relative scores to all nodes based on the principle of connections. Closeness centrality takes the sum of graph-theoretic distances from all other nodes. For example, nodes with low closeness scores have shorter distances from others, which means they are relatively more accessible. Betweenness centrality counts the number of geodesic paths that pass through a node. In essence, a betweenness centrality of node n is the share of times that a node needs node n to reach another node via the shortest path (Mishra et al., 2012).

Quantification of transit network connectivity based on centrality measures does not necessarily reflect the quality of transit service, such as travel time, waiting time, walking time or distance, number of transfers and transfer time. To improve on these indicators, Lam and Schuler (1982) considered trip time as a measure of the quality of transit service in terms of mobility. They developed the connectivity index (R) to represent the ability of a transit system to connect urban places, by taking the ratio between the actual reciprocal harmonic mean transit time and the reciprocal harmonic mean transit time on a fully developed network, as shown in Equation 2-4.

$$R = \frac{\bar{T}}{\bar{t}} \qquad \text{Equation 2-4}$$

where:

R = Connectivity index

$\bar{T}$ = Harmonic mean of ideal trip time between origin and destination in the fully developed transit system

$\bar{t}$ = Harmonic mean of actual trip time between origin and destination

The harmonic mean of the actual transit trip time, $\bar{t}$, will often be longer than the $\bar{T}$ (harmonic mean of ideal trip time) and has a connectivity index, R between 0 and 1. If R is equal or near to 1, the system is ideal and well connected. The connectivity index (R) is based on the assumption that riders will always take the shortest route between nodes, which is not necessarily the case. A study conducted by Lee and Lee (1998) discovered that riders favour travelling along the same route and tend to avoid transit transfer, even if this does not correspond to the shortest path. This measure includes all the other probable paths (direct and indirect). A path that involves transfer is scaled down to represent the inconvenience of transfer, according to the number of transfers and the psychological stress imposed on transfer.

Similarly, Derrible and Kennedy (2009) analysed subway network systems around the world using an updated graph theory concept, based on transit coverage (the accessibility to transit), directness (maximum number of transfers necessary to go from one station to another) and connectivity (total number of transfer possibilities in a network). Extending the graph theoretic approach to determine the performance of the multimodal transit network, Mishra et al. (2012) developed a new set of indicators to reflect the connectivity at the node, line, transfer centre and regional level. The connectivity index of a line l at node n, ($P_{l,n}$) is a function of transit capacity, speed, distance, activity density and number of transit line, as shown in Equation 2-5.

$$P_{l,n} = \alpha C_l \times \beta V_l \times \gamma D_{l,n} \times \vartheta A_{l,n} \times \varphi T_{l,n} \qquad \text{Equation 2-5}$$

where:

$P_{l,n}$ = Connecting index of line l at node n

C_l = Average vehicle capacity of line l

V_l = Speed of line l

$D_{l,n}$ = Distance of line l from node n to the destination

$A_{l,n}$ = Activity density of line l, at node n

$T_{l,n}$ = Number of transit line l, at node n

α = Scaling factor coefficient, the reciprocal of the average capacity of the system multiplied by the average number daily operations of each line

β = Scaling factor coefficient, the reciprocal of the average speed on each line

γ = Scaling factor coefficient, the reciprocal of the average network route distance

ϑ = Scaling factor coefficient for activity density

φ = Scaling factor coefficient for the number of transit lines

The total connecting power of a line is the total of inbound and outbound connecting powers for all transit nodes on that line, scaled by the number of stops on each line, to enable comparison of transit lines from different modes. Bus lines usually have many stops, while rail lines have fewer stops. The same concept is used to quantify the connectivity index of a region (large area), scaled by the number of stops in the region. The scaling factor enabled the comparison of the quality of connectivity between areas or regions of differing density. Transfer centres are groups of nodes that are defined by the ease of transfer between transit lines and modes. The connectivity index for a transfer centre is defined as the sum of the connecting power of each node in the transfer centre, scaled by the number of nodes in that transfer centre. Mishra et al. (2012) recognised that riders may give up transferring if the distance between stops is perceived to be too long to walk, and incorporated the passenger acceptance rate to the connectivity index for a transfer centre.

Transit network connectivity should have the ability to quantify the ease of reaching a destination from a given location. Mamun et al. (2013) developed the zone-based public opportunity index to analyse the transit network connectivity level (bus network only) of New Haven, based on both transit accessibility (the level of access to the transit system) and transit connectivity (the system's provision of services between origins and destinations). Transit connectivity is a function of directness and transit travel time. The authors used a binary parameter δ_{ijl} to represent the directness of transit route between OD pairs (1 if there is a direct connection and 0 otherwise). As for transit travel time, the authors developed the logistic decay function (f_{ijl}) based on door-to-door travel time, to reflect decreasing connectivity with increasing travel time. The transit opportunity index (TOI_{ij}) from zone i to zone j, is the sum of all transit lines serving zone i to zone j, normalised by the sum across all OD pairs, as demonstrated in Equation 2-6. The denominator normalises the index and provides a relative value of transit service performance as compared to all other OD pairs.

$$TOI_{ij} = \frac{\sum_l A_{ijl}\delta_{ijl}f_{ijl}}{\sum_i \sum_j \sum_l A_{ijl}\delta_{ijl}f_{ijl}} \qquad \text{Equation 2-6}$$

where:

TOI_{ij} = Transit Opportunity Index from origin i to destination j

A_{ijl} = Transit accessibility score from origin i to destination j for transit line l

δ_{ijl} = Binary connectivity parameter

f_{ijl} = Connectivity decay factor from origin i to destination j for transit line l

With very similar concept, Lee et al. (2015) examined zone-to-zone transit network connectivity based on the directness of transit service using two measures: the degree of competitiveness and degree of circuity. The degree of competitiveness is a measure to show how much additional transit travel time there is in comparison to private vehicle travel time. The degree of circuity measures the additional transit travel time required because of the transit network configuration, as compared to the directly connected hypothetical transit network.

2.5.2 Mapping of Transit Network Connectivity

Integrating the assessment of transit services into geographical information systems (GIS) allows clearer presentation of transit performance. Since the late part of the 1990s, GIS is commonly used to map the accessibility of transit from a specific point. Liu and Zhu (2004) developed an Accessibility Analyst tool that is capable of conducting transit catchment profile analysis and to analyse traveller's ability to visit places at different times of day, using the shortest path algorithm from an origin to destination. The distance is later converted to travel time by dividing each distance by the average speed, while neglecting other essential transit travel time elements, such as transfer times and varying headway times depending on time of day. Most of the GIS measures use travel distance as a proxy for travel time, since many of the metrics are originally specified in distance rather than time (Lei & Church, 2010; Salonen & Toivonen, 2013).

Transit travel time is an important factor to measure transit system performance. O'Sullivan et al. (2000) illustrated the transit coverage map to the downtown area of Glasgow by integrating the shortest travel time algorithm with geographic data on bus and train services. Similarly, Lei and Church (2010) analysed the ability of a transit service in providing access to a given destination and returning to the starting location, for specific time periods – for example, to reach University of California, Santa Barbara campus, no later than 8am, and to leave at 5pm. In the same study, Lei and Church (2010) computed a relative transit coverage map of transit versus private vehicle, based on the findings that transit travel time, relative to other modes of travel, will in part dictate whether non-captive riders will choose to use transit (Church & Marston, 2003). Salonen and Toivonen (2013) mapped out the 20-minute catchment area around the main library in Helsinki using transit and private vehicle respectively.

The ability to visualise transit network connectivity between origins and destination zones helps transit agencies and land use planners to examine performance for each zone (Lee et al., 2015). Besides transit agencies and land use planners, this aggregated destination concept could be of interest to travellers who want to satisfy most of their needs at one location, or zone (Mamun et al., 2013). This model could also be helpful to external parties such as developers and home or business buyers. Quantifying zone-to-zone transit network connectivity is only possible if each zone is represented by a point of reference, and work under the assumption that all trips to start and end at that point (Chang et al., 2002). It is possible to precisely locate where a trip originates and ends through a detailed survey. Due to limited survey coverage, computational considerations and privacy issues, it is not feasible to use data at the level of individual trip makers (Chang et al., 2002).

In transit network studies, it is common for transit agencies to aggregate trips that originate from, and head to, the same zone. Generally, zone centroid is used as the point of reference. Zone centroid is the geometric centre of a zone, identified using the centre of a gravity-based algorithm. This method to define a zone centroid has been criticised because in reality, these origins and destinations are spatially distributed within zones. For private vehicle travel, zones are small enough that errors resulting from representing origin or destination points using centroid are insubstantial. However, for transit trips, for which the access mode is usually walking, errors from representing an entire zone using a centroid could substantially distort the analysis (Furth et al., 2007). Chang et al. (2002) discovered that instead of using a geometric centre option to represent a zone, transit agencies could consider the city location to represent a zone. If a zone has more than one city, they could apply the population-weighted centre option to determine the point of reference. If household data for each zone is available, transit agencies could also consider using the household-density-weighted centre option. By replacing the geometric centroids with derived points of reference, this has reduced the total transit travel time by 10 to 13 minutes at the county level. Similarly, using the derived points of reference has minimised unassigned intra-zonal transfers, and increased assigned inter-zonal trips (Chang et al., 2002).

2.5.3 Research Motivations on Quantifying Transit Network Connectivity

Mapping of the zone-based transit network connectivity level allows for the capacity to understand and analyse every potential trip an individual could make from one particular zone. What is required now is a more accurate model to capture the ease to travel from an origin to destination, both the directness of the route between origins and destinations based on transfer location, and the level of connectivity based on travel time. The fundamental truth is, that in order to establish a successful transit operation, the first and foremost element to look into is the establishment of a well-coordinated service coverage.

2.6 CONCLUSION AND RESEARCH GAPS

Different strategies have been taken to combat traffic congestion. As physical limits of major urban environments become more pronounced, widening of roads and increasing the number of transit services cannot be an effective countermeasure. Promoting transit to reduce private vehicle dependency is critical; however, the reluctance of using transit has made the mode shift difficult. In essence, transit must be a viable alternative to transport people from where they are to where they need to go in a reasonable amount of time (Murray, 2001).

More evidence is emerging demonstrating the complexity of walking behaviours, where walking access (time or distance) to transit varies across different characteristics of users and their trips. Given the known extensive range of factors that will affect making the decision to walk to transit, the ability to precisely measure walking access is elusive. Using the conventional linear regression method to study the relationship between dependent walking access variables and independent explanatory variables is ineffective to capture the distinct differences in walking behaviours across different socio-economically homogeneous groups.

Having reasonable walking accessibility to and from a transit system is insufficient to promote transit use. Transit services need to connect the origins and destinations. Decentralisation accelerates the diversification of travel demand, where transit has no capacity to quickly cope as compared to private vehicles. The extra effort in making a transfer is necessary, yet at the same time, inconvenience of transfer is perceived as one that disrupts transit travel experience and discourages the usage of transit. Quantifying the inconvenience of transfer is not just a matter of calculating the number of transfers needed and the transfer times; it involves transit users' perception, such as the travel direction towards transfer location. This newly developed concept could be incorporated to better define transit network connectivity. Integrating the transfer location factor to the traditional travel-time-based approach could give a better and more accurate representation of the transit system connectivity.

Chapter 3: Research Design

3.1 INTRODUCTION

This chapter presents the analytical approach to research problems, establishes the appropriateness of the research design, and documents the research process. Overall, this study draws on quantitative research methods and practices to address the research problems. Section 3.2 reiterates the research focus of this study. Section 3.3 outlines the research process. Section 3.4 identifies the study area and articulates the rationale and justification of the selection. Section 3.5 lists the four different datasets used in this research. The major contribution of this chapter is to establish relevance and reliability of the data collected, and to ensure the robustness of research findings.

3.2 RESEARCH FOCUS

Making a transit service accessible from one's origin and destination is the first step, but if transit does not connect the origins and destinations by a reasonably direct path, the goal to increase transit ridership will not be realised. The second part of this research is to develop a new measure to quantify the impact of travel direction towards transfer location, based on the hypothesis that greater deviation of the transfer location in reference to the straight route from origin to destination will cause a greater aversion to use transit. To build upon the findings from the first and second phase of this research, the newly developed factor will be incorporated to quantify the transit network connectivity. Building on the same hypothesis that individual will choose not to take transit if they are required to make a transfer that is not "on the way" to a desired destination, regardless of whether it is within the acceptable range of transit travel time. The third phase of this research aims to develop a more accurate model to capture the transit system connectivity, considering both the directness of route and transit travel time (inclusive of walking accessibility). A summary of the theoretical framework is illustrated in Figure 3-1.

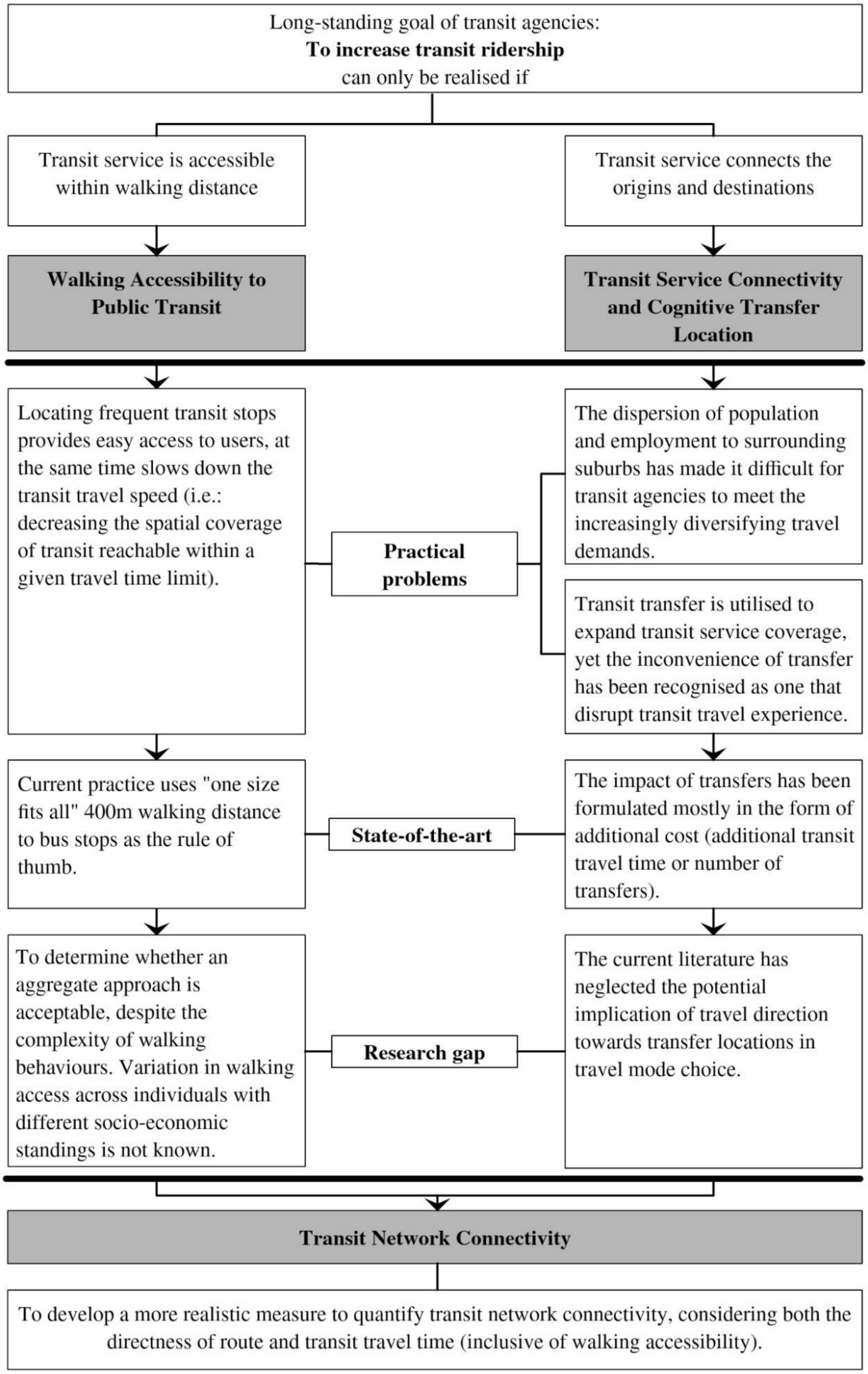


Figure 3-1: Theoretical framework

3.3 RESEARCH PROCESS

The research follows a staged process, starting from background research and literature review, which forms the theoretical framework of this research. Three main research focuses of this study are identified, each with its research gap, based on the theoretical framework. This is followed by data collection and analysis, discussion and findings that contribute theoretically and methodologically to inform transit planning and policies. Figure 3-2 shows a summary of research process.

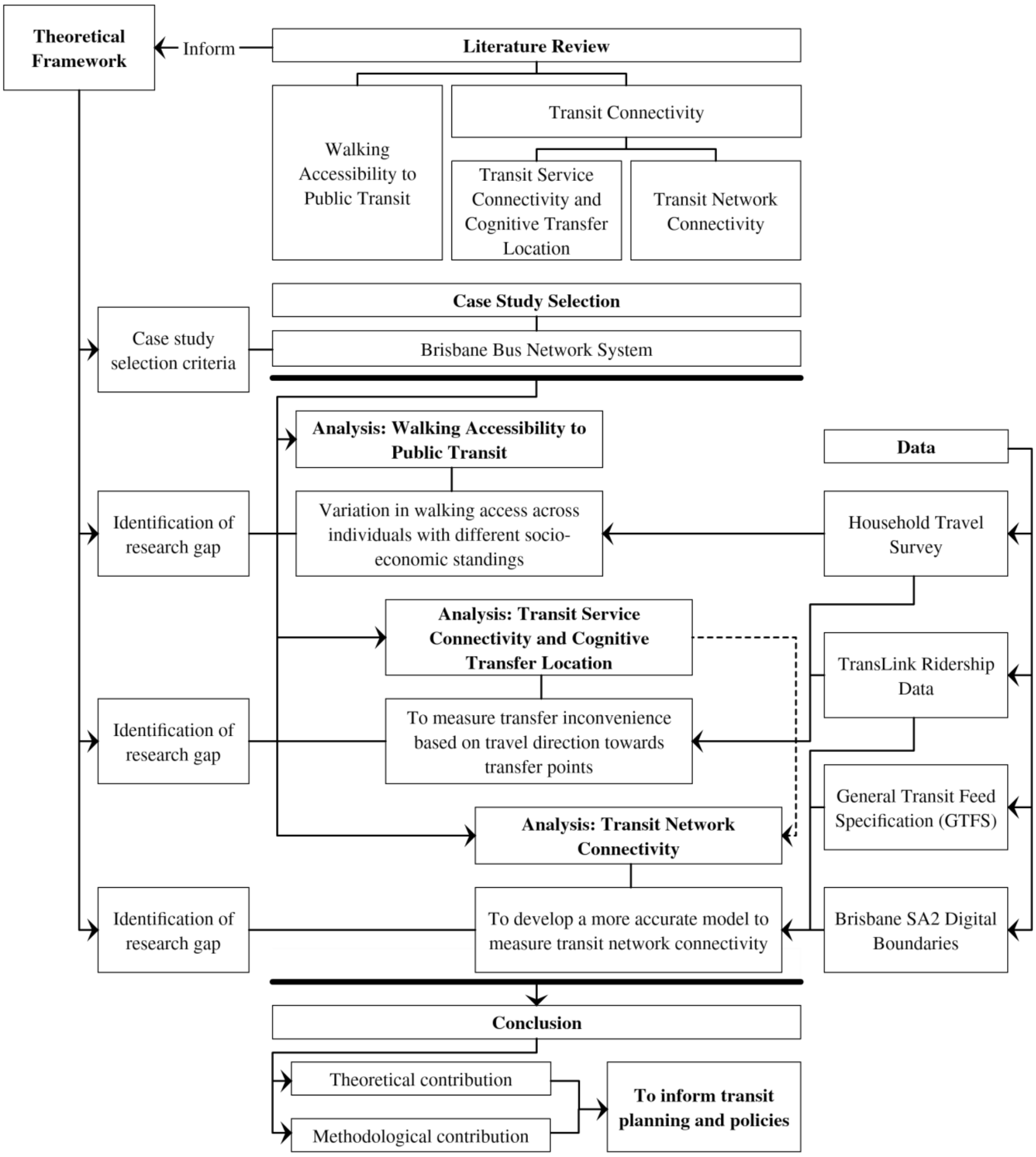


Figure 3-2: Research process

This research process is designed to provide a logical and robust flow of logic which links research gaps, research problems, research methods and research findings. Three main research phases are identified from the literature review, which inform the data collection methods and data analysis methods to ensure that research findings are relevant to address research problems.

3.4 CASE STUDY ANALYSIS

The case study area of this research is Brisbane, the capital city of Queensland, Australia. Queensland is a state in the north-east of Australia, and it borders New South Wales to the south and the Northern Territory to the west. Queensland is Australia’s second largest state by land area, after Western Australia; it is third largest by population, after New South Wales and Victoria, as at 2015. Figure 3-3 shows the study area in Statistical Areas Level 4 (SA4) geographical unit, namely Brisbane-North, Brisbane-West, Brisbane-South, Brisbane-East and Brisbane Inner City, which are located in South East Queensland (SEQ), Queensland, Australia.

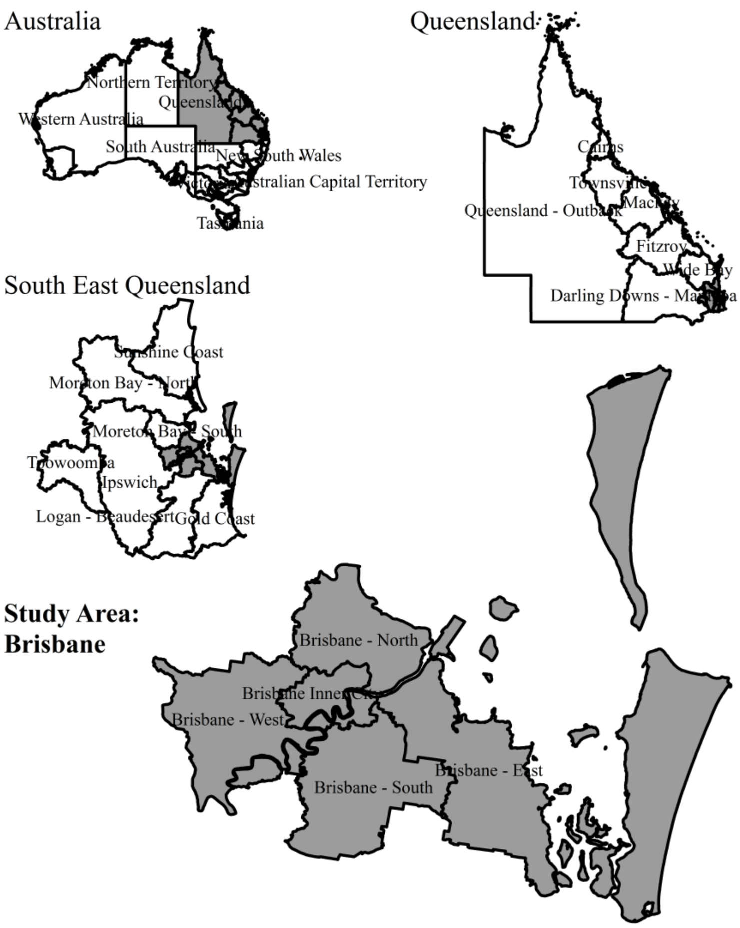


Figure 3-3: Study area

Queensland Department of Transport and Main Roads' TransLink Division is responsible for leading and shaping Queensland's overall passenger transit system. It facilitates passenger transport services and aims to provide a single integrated transit network accessible to everyone, by delivering high-quality transit services, ticketing, information and infrastructure. TransLink provides mass transit including buses, trains, ferries and trams across SEQ. Despite the extensive transit network of bus, rail and ferry systems, the mode share of transit for Queensland is still small at 7.6% as of the 2011 census, whereas the largest component is private car (66.7%).

The city of Brisbane is a good representation of SEQ, where it accounts for approximately 70% of the total daily weekday trips (Queensland Government, 2012). According to the 2011 census, in Queensland, 67,191 employed people (3.3%), aged 15 years and over, used bus as their travel mode to work, as compared to 42,802 Queenslanders (2.1%) that chose train as their mode of travel. In comparison with bus and train, ferry ridership was minimal. The recent report by the Queensland Government (2016) revealed that from January to March 2016, 27.38 million trips were conducted by bus, followed by 12.21 million trips by train, 1.71 million trips by ferry and 1.93 million trips by tram. Bus ridership consisted of more than 63% of total transit ridership. This shows that bus is the dominant transit mode in Brisbane. The benefit of bus, in comparison to train, tram and ferry, is that it has the flexibility to access almost all locations where a road network is present. The nature of buses travelling on existing road networks gives more feasibility of adapting to change, such as addition of new bus routes to serve more destinations. Generally, bus stops are more accessible to the public in comparison to rail and train, as the spacing between bus stops is substantially smaller. From literature, walking accessibility to bus stops and train stations is substantially different. These considerations have steered the scope of this research towards bus ridership in Brisbane.

Since the late 1990s, the Queensland Government and Brisbane City Council have focussed much on developing busways, which are dedicated corridors for bus, to allow for fast, frequent and reliable transit services. The South East Busway is the first of a series of busway networks, opened in September 2000 between Brisbane City and Woolloongabba, and the second section connecting Woolloongabba and Eight Mile Plains opened in April 2001. In August 2009, the Eastern Busway was built to connect the South East Busway at Buranda to Dutton Park, and by August

2011, an additional 1.05km from Buranda was delivered to serve Coorparoo. The Inner Northern Busway was completed in May 2008, linking Brisbane City to Herston. The Northern Busway was built to connect the Inner Northern Busway at Herston to Windsor in August 2009, with an extra 3km of busway between Windsor and Kedron being delivered in June 2012. Different projects to further extend these four major busways are in the pipeline, subject to government funding and priorities. These developments have contributed to the strong radial network orientation in Brisbane. To illustrate, more than 66% of the bus services are operating to the CBD (Devney, 2014). The CBD is the central hub for the bus system to regional centres. Figure 3-4 shows the high frequency bus routes in Brisbane.

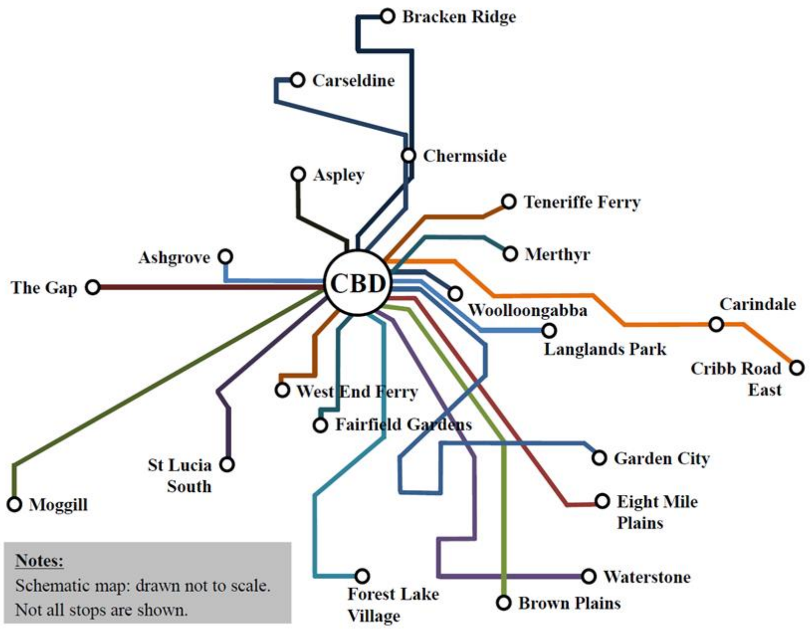


Figure 3-4: High frequency bus network system in Brisbane

3.5 DATA

Different research approaches and data are required in achieving respective research objectives. There are three phases in this research, and each will utilise a different dataset, as illustrated in the research process. Overall, this research will rely heavily on secondary data from the government, both from the Queensland Government and the Australian Government. Table 3-1 shows the summary of dataset used in this research, and where to collect respective data. The remaining of this section describes each dataset more thoroughly.

Table 3-1: Summary of dataset used in this research

Dataset	Source
2009 South East Queensland Household Travel Survey (SEQHTS)	Department of Transport and Main Roads, Queensland Government
TransLink Smart Card Data	TransLink, Department of Transport and Main Roads, Queensland Government
General Transit Feed Specification (GTFS)	Queensland Government
Brisbane Statistical Area Level 2 (SA2) Digital Boundaries	Australian Bureau of Statistics (ABS), Australian Government

3.5.1 2009 South East Queensland Household Travel Survey (SEQHTS)

SEQHTS is an important dataset to inform policy and planning decision. The household travel survey (HTS) captures information on day-to-day travel activities. The survey was conducted as a single cross sectional survey and collected a single day travel data from all members of participating households. The survey was conducted for a 10 consecutive week period from 20 April through 28 June 2009. The travel information was collected in the form of a self-reported travel diary from respondents. Although specific dates were given to the respondents to report, they were allowed to choose any date within the 10 week period to report their travel information. It employed a multi-staged sampling procedure, whereby 202 Census Collectors Districts (CCDs) across 11 sample regions were selected first. Next, households were randomly sampled within the selected CCDs. The survey collected a total of 32,536 door-to-door journeys (i.e.: including every leg of the journeys made by multiple modes), conducted by 8,809 individuals living in 4,240 households. Respondents were instructed to report a range of personal information (e.g.: age, gender, individual income, driver’s licence, etc.), and household related information (e.g.: household size, number of vehicles, etc.). The survey also asked details about their travel for each trip stages within an overall trip. This includes: origin, destination, start-time, end-time, purpose, and transport mode used.

3.5.2 TransLink Smart Card Data

TransLink aims to provide a single integrated transit network accessible to everyone, by introducing the “go card”. The “go card” is the electronic ticket used to travel seamlessly on all TransLink services in SEQ. This modern technology, known as Automated Fare Collection (AFC), provides detailed, continuous and accurate data on behaviour of transit users and enables sophisticated analysis of travel patterns (Finžgar & Trebar, 2011). Before the introduction of AFC, transit agencies relied on travel surveys.

The “go card” records travel data when a traveller touches on at the start of any trip stage, and touches off at the end of the trip stage (only relevant to buses and ferries in Brisbane). Train riders only need to touch on and touch off at the origin and destination station, and not able to capture the train-to-train transfer. This dataset contains information such as “go card” ID, date of service, route ID, service ID, direction (inbound or outbound), boarding time and alighting time, boarding stop ID and alighting stop ID, ticket type, journey ID and trip ID. If it is a transfer journey, it would have consecutive trip ID for each trip stage with the identical journey ID.

For the purpose of this study, five consecutive weekdays of “go card” data, from 17 November (Monday) to 21 November 2014 (Friday), are obtained from TransLink. This piece of data is valuable to the second stage of this research, deriving the transfer patterns of bus riders. A more detailed discussion on the usage of the data is given in Chapter 5.

3.5.3 General Transit Feed Specification (GTFS)

In 2006, Google introduced Google Transit, an additional feature to Google Maps. This service enables transit users to plan their trips from origin to destination. To encourage more agencies to participate and implement this service, Google established a unified specification, known as the General Transit Feed Specification (GTFS). GTFS is a compilation of text files (six required data files and seven optional files); with each file modelling different characteristics of transit information. GTFS aims to provide information about types and locations of stops, routes’ characteristics, trips’ frequency and service timetable. Table 3-2 gives a thorough description of these files. Besides making it convenient for transit users to plan for their trips on any transit applications, the availability of GTFS data provides an opportunity for researchers to analyse transit performance (Hadas, 2013).

Table 3-2: The General Transit Feed Specification (GTFS) data files

Data file	**Description**
Required	
Agency	This file contains information about one or more transit agencies that provide the data in this feed.
Stops	This file contains information about individual locations where vehicles pick up or drop off passengers.
Routes	This file contains information about transit routes. A route is a group of trips that are displayed to riders as a single service.
Trips	This file lists all trips for each route. A trip is a sequence of two or more stops that occurs at specific time.
Stop times	This file lists the times that a vehicle arrives at and departs from individual stops for each trip.
Calendar	This file defines dates for service IDs using a weekly schedule. Specifies when service starts and ends, as well as days of the week where service is available.
Optional	
Calendar dates	This file lists exceptions for the service IDs defined in the calendar.txt file. If calendar_dates.txt includes ALL dates of service, this file may be specified instead of calendar.txt.
Fare attributes	This file defines fare information for a transit organisation's routes.
Fare rules	This file defines rules for applying fare information for a transit organisation's routes.
Shapes	This file defines rules for drawing lines on a map to represent a transit organisation's routes.
Frequencies	This file defines headway (time between trips) for routes with variable frequency of service.
Transfers	This file defines rules for making connections at transfer points between routes.
Feed info	This file lists all the additional information about the feed itself, including publisher, version, and expiration information.

Adapted from "General transit feed specification reference" by Google Developers, 2016.

This dataset is used together with Brisbane Statistical Area Level 2 (SA2) Digital Boundaries in the third stage of the research to quantify transit network connectivity.

3.5.4 Definition of Analysis Zone

In Australia, since July 2011, the Australian Bureau of Statistics (ABS) has introduced a new geographical framework – the Australian Statistical Geography Standard (ASGS) based on the functional area of major cities, towns and gazetted suburbs. This replaces the Australian Standard Geographical Classification (ASGC): Statistical Local Areas (SLAs). The ASGS brings all regions used by ABS together, to output data under one umbrella.

The digital boundaries for the ASGS are the spatial units for the main structure and the Greater Capital City Statistical Areas. Under ABS structures, the smallest geographical region in the ASGS is Mesh Blocks. They form the building blocks for all the larger regions of the ASGS. A few Mesh Blocks will form Statistical Areas Level 1 (SA1), where the average population is about 400 people. Statistical Areas Level 2 (SA2) is a general-purpose, medium-sized area that represents a community that interacts together socially and economically. Statistical Areas Level 3 (SA3) is the functional area of a regional city that portrays similar regional characteristics. Statistical Areas Level 4 (SA4) is the largest sub-state region.

In this study, SA2 will be used as the geographical unit to quantify transit network connectivity of each SA2. The SA2 digital boundaries for Brisbane are illustrated in Figure 3-5. Together with GTFS data, all the bus stops can be displayed on top of the digital boundaries map of Brisbane. A more detailed discussion on the usage of the data is given in Chapter 6.

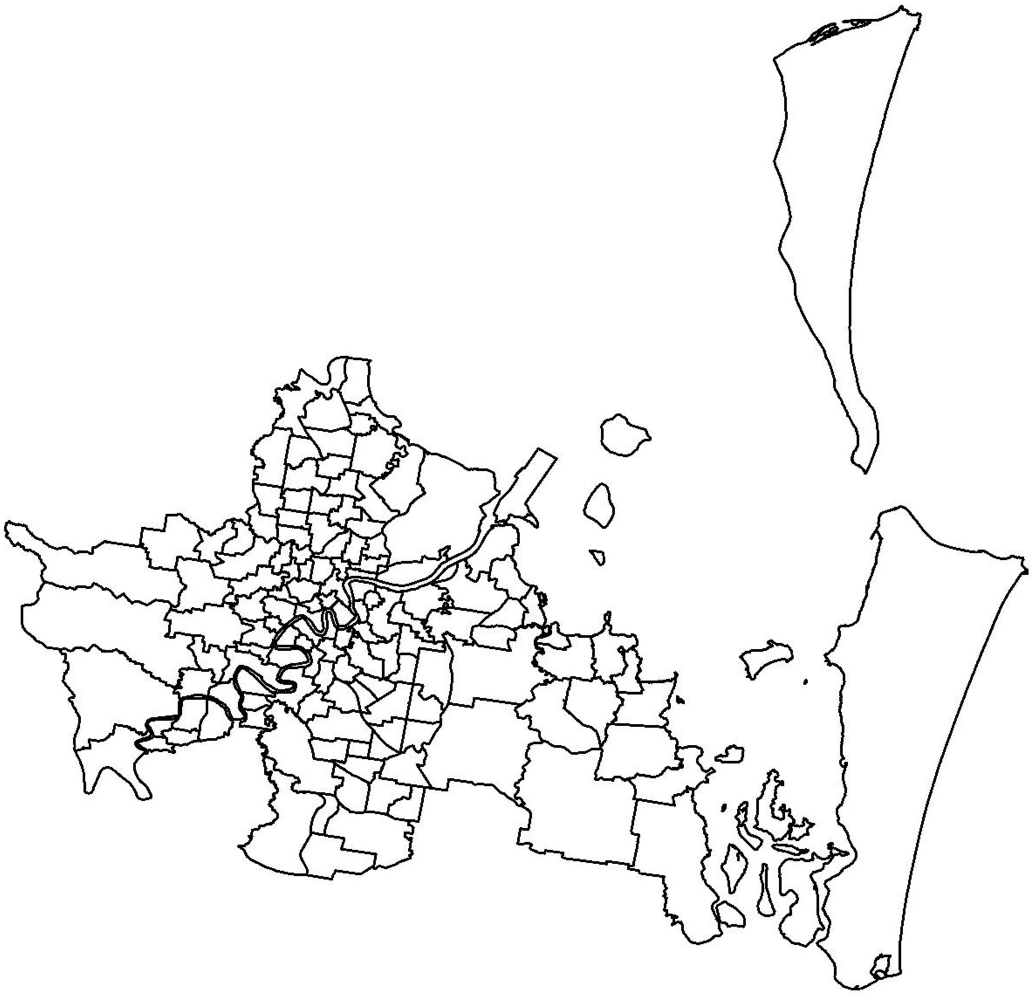


Figure 3-5: SA2 digital boundaries of the case study

Chapter 4: Walking Accessibility to Transit

4.1 INTRODUCTION

Transit only becomes a viable travel mode when transit service is accessible within walking access. Is it appropriate to use the conventional standardised approach of 400m to transit for all population groups, or to consider a more disaggregate approach? The ability to precisely measure walking access has been elusive given the extensive range of factors that will affect transit user's decision making whether to walk to transit facilities. This study focuses on socio-economic conditions to explain the variations in walking access amongst individuals. Section 4.2 expounds on the research method specific to the first phase of this research. Section 4.3 analyses the difference between walking time decay function of the true captive and choice bus riders. Section 4.4 performs the cluster analysis for choice bus riders, and to construe distinct socio-economic standings among different clusters. Section 4.5 shows the comparative analysis among different clusters to infer different variations of walking access to transit. Section 4.6 concludes the findings of the first research phase: Walking accessibility to transit.

4.2 MARKET SEGMENTATION AND WALKING TIME DECAY FUNCTION

To ensure the robustness of research findings, very distinct research methods are employed to address different research questions. For this phase of research, cluster analysis and decay function were used to study the variation of walking access amongst individuals with different socio-economic standings. This section seeks to give a thorough discussion on market segmentation (Section 4.2.1) and walking time decay function (Section 4.2.2).

4.2.1 Market Segmentation

A conventional way of transit market segmentation is introduced by Beimborn et al. (2003). They segmented transit users into choice and captive groups arguing that the traditional mode choice models underestimate the variation in mode choice for captive users, and overestimate the attractiveness of transit for choice users by including transit captive individuals in the model. Adjusting the population to only those who have access to alternative transport modes other than transit could significantly improve the explanation of the mode choice behaviour. Recently, Litman (2014) used the term “transportation disadvantaged” to describe those who have significant unmet transit needs.

Transit captive users have been defined as people who do not have a private vehicle available for their travel and therefore have no choice but to take transit (Beimborn et al., 2003). Transit captive users include those who have no drivers’ licence or who could not use a private vehicle due to their age, disability or past driving behaviour. Polzin et al. (2000) defined transit users with high dependency as individuals who have no personal transport mode available to them and those who have no access to such transport, or are unable to drive.

On the other hand, private vehicle captives have been defined as individuals who must use a private vehicle to complete their trips because no feasible transit alternative is available, from origins to destinations at a preferred time (Beimborn et al., 2003). Unlike transit captives, private vehicle captives are more related to the characteristics of trip, such as flexibility and convenience (Beimborn et al., 2003). Private vehicle captives can also be defined as individuals living in a community with high private vehicle dependency, especially those primary caregivers to non-driving dependants (Litman, 2014).

Choice users are individuals who have alternatives, but choose to use the preferred transport mode. Transit choice users are more sensitive to changes in the fare or service quality because they have alternative transport options available to them (Krizek & El-Geneidy, 2007). Studies have been carried out to expand upon the concept of segmentation. Wilson et al. (1984) expanded the conventional captive and choice users into four market segments for both transit and private vehicle users respectively, namely functional captive mode users, marginal captive mode users, marginal choice mode users and free choice users. Correspondingly, Krizek and El-Geneidy (2007) expanded the conventional paradigm into eight market segments. More recently, Jacques et al. (2013) proposed an alternative segmentation framework that clusters travellers into four distinct groups based on trip practicality and satisfaction.

The traditional segmentation separates transit users into captive and choice users based on drivers' licence and private vehicle ownership. It is arguable that having a drivers' licence or owning a car does not necessarily reflect the availability of a car for all the household members, especially when the vehicle-driver ratio is less than one. Socio-economic factors such as personal income, age, and labour force are also important and should be taken into consideration for segmentation purposes. Research revealed that walking access is primarily influenced by socio-economic factors, while urban design and station characteristics are secondary (Loutzenheiser, 1997).

According to the 2009 SEQHTS, a total of 843 trips were made by bus out of 32,536 trips in Brisbane, which accounted for 2.59% of mode share. Out of 843 bus trips, 798 trips were made with walking as the mode of access. Travel data of all persons 17 and under was eliminated from the pool of data. Their travel behaviour is highly dependent on their parents or those who provide care for them. They accounted for 130 out of 798 entries, which left the pool with 668 entries. In this study, transit market segmentation was conducted in two-ways. The first segmentation removed true transit captive users, individuals who do not have a driver's licence and a private vehicle, to prevent biases in the walking access analysis. They are also known as "functional captive transit users" (Wilson et al., 1984) or "true captivity transit users" (Jacques et al., 2013). The inclusion of true transit captive users may decrease the accuracy of the analysis because captive users do not have any choice of alternative modes of transport other than to take transit. A total of 262 trips were made by true transit captive users out of 668 trips. The remaining 406 entries are defined as choice users and formed the main data for the analysis in this study.

The second segmentation clustered choice users into socio-economically homogeneous groups. Amongst various socio-economic conditions, the clustering employed three factors including: individual income, age, and labour force. Income has always been the core influence of mode choice. As discussed by Polzin et al. (2000), income is the most important factor determining the transit dependent population. Age has been used as a primary factor in segmenting transit users into different groups (Jacques et al., 2013). Studies have shown significant difference in walking access among trips undertaken by working people and students, and thus labour force is taken into consideration in segmenting transit users (Alshalalfah & Shalaby, 2007).

4.2.2 Walking Time Decay Function

In the literature, walking has been commonly measured in terms of time (Canepa, 2007; Daniels & Mulley, 2013; O'Sullivan & Morrall, 1996). Walking distance can be estimated from the given coordinates of the trip origin and the transit stop using GIS software. Unfortunately, this may not always be the best representation of the actual length of walking as travellers may not walk along a road network, but alternatively through parks or pedestrian paths because it is more attractive or safer (Daniels & Mulley, 2013). It is discussed in the literature that in general, people have a good idea on how long it actually takes them to reach their transit facilities, with the argument that they are regular users (O'Sullivan & Morrall, 1996).

The attractiveness of transit will evidently deteriorate with increasing walking time to access transit stops and this effect can be represented by applying a decay function (Zhao et al., 2003). Decay function is widely used in transit planning, especially in the empirical estimation of transit service coverage by pedestrian access (Hsiao et al., 1997; Levinson, 1983; Zhao et al., 2003). The decay function of walking time provides a simple and effective way to display and compare the distribution of walking time amongst different groups and has been recently used in the literature (El-Geneidy et al., 2014; Iacono et al., 2010).

The walking access was measured in terms of walking time in the household travel survey. Respondents were asked to record their time of departure, and the time of reaching a transit stop, as accurately as possible. In this study, walking time to bus was visualised through decay functions, by plotting the percentage of bus riders who walked the given time or more at every minute time interval. For this study, a negative exponential function ($\alpha e^{-\beta x}$) was adopted rather than a power function because it has the advantage of showing a more gradual decline, which better estimates shorter trips such as walking access to transit facilities. β is the parameter of the impedance function, which is to be empirically estimated through the distribution of walking time, x.

4.3 WALKING TIME DECAY FUNCTION FOR TRUE CAPTIVE AND CHOICE BUS RIDERS

Figure 4-1, Figure 4-2 and Figure 4-3 show the decay curves of all bus riders, true captive bus riders, and choice bus riders.

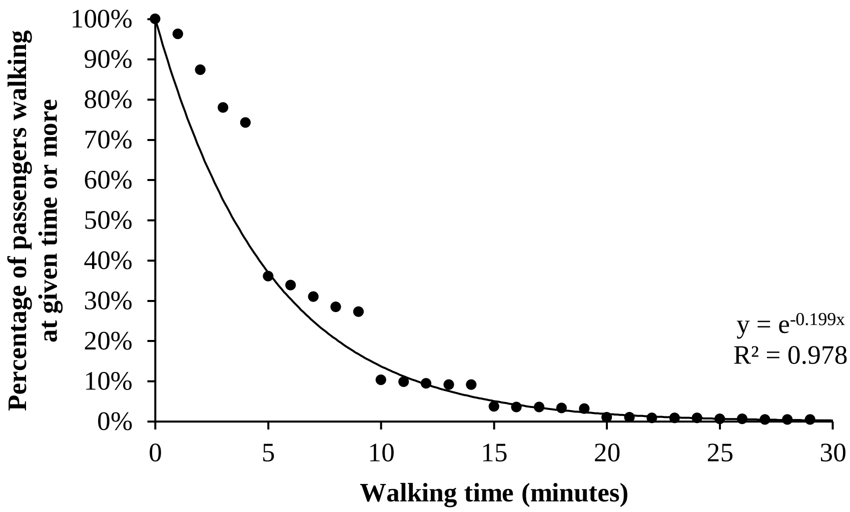


Figure 4-1: Walking time decay curve for all bus riders (668 trips)

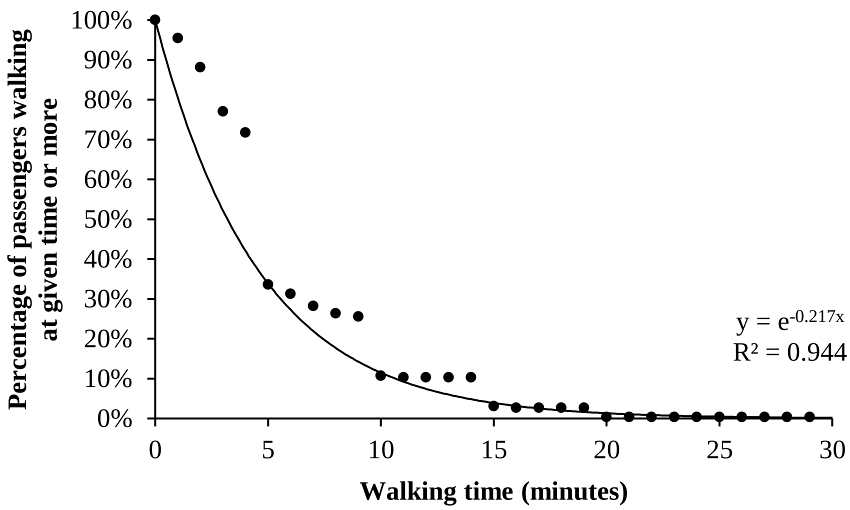


Figure 4-2: Walking time decay curve for true captive bus riders (262 trips)

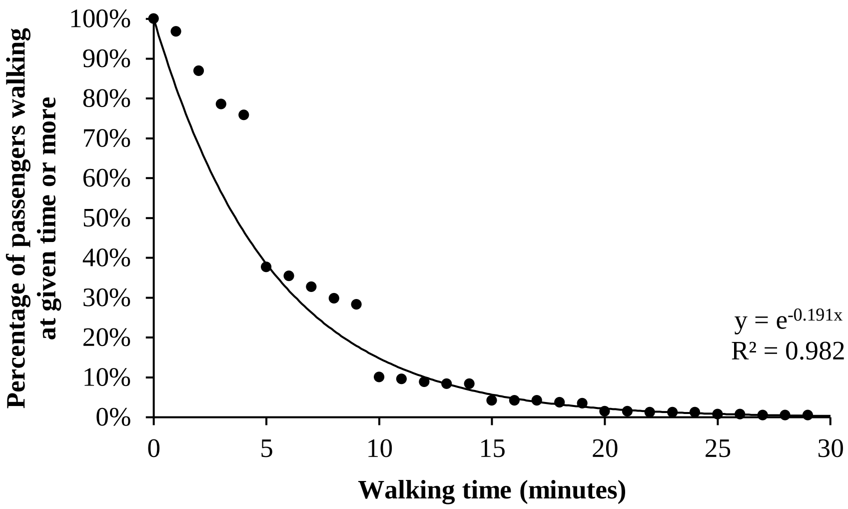


Figure 4-3: Walking time decay curve for choice bus riders (406 trips)

It is interesting to note that two major drops (or discontinuities) are observed at 5 minute and 10 minute. To illustrate, as shown in Figure 4-3 (choice bus riders), the percentage of passengers drops from 76% to 37% when the walking time increases from 4 to 5 minutes. The average walking speed in Brisbane is calculated to be 75m/minute (Burke & Brown, 2007). In this case, instead of the rule-of-thumb of 400m rules, the observed percentage of transit users walking drops drastically to 375m, and another drop at the mark of 10 minute (approximately 750m) by 18%. The remaining 10% of the total bus riders walk 750m or more. The last drastic drop is observed at 15 minute (1,005m). This is very consistent with the current walking threshold used (5 and 10 minute) in many accessibility indices to define walkable catchment (Ker & Ginn, 2003).

It must be noted that the significant drop in the chart may have been exaggerated due to the limitation in the survey method. This is a self-reported data, which respondents were requested to report the start-time and end-time of each trip stage composing the whole trip. Since the question did not explicitly ask the walking time to transit, preferably providing multiple choices, the reported walking time may have been rounded to the nearest 5 minutes.

Table 4-1 shows the statistical difference in the means of these three groups using one-way analysis of variance (ANOVA).

Table 4-1: ANOVA analysis for all riders, true captive bus riders and choice bus riders

Groups	Count	Means	Variance	Standard deviation
All riders	668	6.65	20.72	4.55
True captive bus riders	262	6.47	19.35	4.40
Choice bus riders	406	6.77	21.62	4.65

Source of variation	Sum of square	Degree of freedom	Mean square	F-value	P-value	F-critical
Between Groups	14.24	2.00	7.12	0.34	0.71	3.00
Within Groups	27625.22	1333.00	20.72			
Total	27639.46	1335.00				

From the analysis, the F-value of 0.34 is smaller than the F critical value (3.00). F-value smaller than the F critical indicates that there is no strong evidence to reject the H_0 (all groups are identical) at 0.05 confidence level and there is no significant difference among the groups. The P value (0.71) is larger than 0.05, which indicates that the data does not give any evidence to conclude that the means differ among these three groups.

Table 4-1 demonstrates that the simple segmentation of the bus riders (into true and choice bus riders) failed to differentiate the walking patterns among these groups. The decay rate of true captives (0.217) is faster than the decay rate of choice users (0.191), which indicates that the true captive users are more likely to switch to a different mode, or give up on travelling, if they need to walk longer. This result could be rationalised by noting that people who do not own a car are likely to live closer to transit stations, while private vehicle owners may live farther from transit stations for various reasons (Alshalalfah & Shalaby, 2007). Nevertheless, it is inconsistent with the literature findings, which in general suggested that walking access to transit for true transit captive users is less significant to mode choice, as compared to choice users (Beimborn et al., 2003).

4.4 CLUSTER ANALYSIS FOR CHOICE BUS RIDERS

Choice users were further divided into several homogeneous groups based on their personal socio-economic standing. Cluster analysis is an effective tool to identify groups of individuals which are similar to each other but different from individuals in other groups. There are few clustering techniques. Hierarchical clustering is only useful for small data set when the matrix of distances between all pairs of cases is known, while a *k*-means clustering method is useful for a moderate data set, which requires a predetermined number of clusters to shuffle the cases in and out to find the smallest distance of each case to its cluster mean (Bacher et al., 2004). When the dataset, which consists of categorical and continuous data, gets larger; both hierarchical and *k*-means clustering method will not be suitable. For this study, a two-step clustering method will be adopted.

The two-step clustering method is an exploratory tool designed to reveal natural clusters within a dataset. This clustering method is more effective in handling dataset consists of both categorical and continuous variables, and able to automatically determine the optimal number of clusters, or otherwise can be specified by researchers (Norušis, 2010). This clustering method assigns cases to "pre-clusters"; then "pre-clusters" are clustered using hierarchical clustering algorithm, based on a distance measure that provides best results if all variables are independent (Bacher et al., 2004). The two common distance measures are the Log-likelihood and the Euclidean measure. The Euclidean measure is only applicable if all variables are continuous in nature because it uses "straight line" distance between two clusters. If the dataset is a mixture of both continuous and categorical variables, log-likelihood is a better option because it places a probability distribution on the variables. In this approach, continuous variables are assumed to be normally distributed, while categorical variables are assumed to be multinomial (Norušis, 2010).

Three factors, namely, personal income, labour force and age group, are set to be variables to run the two-step clustering analysis. These variables have been chosen to represent the social-economic status of individuals in the literature. Age, labour force and personal income are significant factors that affect walking time to transit facilities (Alshalalfah & Shalaby, 2007; Daniels & Mulley, 2013; Loutzenheiser, 1997; Wibowo & Olszewski, 2005). Gender, types of car licence and household structure are not used to define the cluster because they were found to add no value to the quality of clustering; however, they are included in the discussion to better explain the variation on walking time to transit facilities.

The choice users were categorised into eight clusters as a result. The quality of clustering was validated using a Silhouette Coefficient of cohesion and separation, as shown in Figure 4-4. This measure quantifies the sum of weight of all links within a cluster (i.e.: cluster cohesion) and the sum of weight between nodes in the cluster and nodes outside the cluster (i.e.: cluster separation). A silhouette coefficient of 1 represents the best quality of clustering that all cases are located directly on their cluster centres and vice versa.

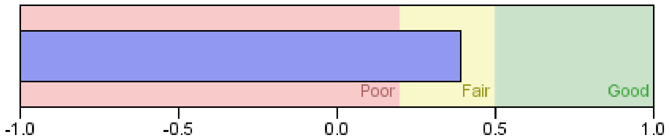


Figure 4-4: Cluster validation using Silhouette measure of cohesion and separation

For these eight clusters, descriptive statistics are presented in Table 4-2 including some categorical variables (i.e.: personal income, labour force and age group) and some other variables not used for the cluster analysis such as gender, types of car licence and household structure.

Table 4-2: Descriptive statistics of walking time to access transit and mean values or percentages (for categorical variables) of independent variables

Cluster	A	B	C	D	E	F	G	H
Total number of sample	91	38	56	38	66	44	26	47
Walk time to access bus stops (minute)								
Mean	6.09	5.61	6.41	6.87	6.42	9.45	8.38	6.45
Minimum	1.00	1.00	1.00	2.00	1.00	2.00	2.00	1.00
Maximum	25.00	12.00	20.00	20.00	27.00	30.00	20.00	20.00
25 percentile	3.00	3.00	5.00	5.00	3.00	5.00	5.00	4.50
50 percentile	5.00	5.00	5.00	5.00	5.00	6.00	6.50	5.00
75 percentile	7.50	8.75	8.50	10.00	10.00	10.50	10.00	9.00

Cluster	A	B	C	D	E	F	G	H
Independent variable individual model								
Gender (%)								
Male	46.15	23.68	60.71	44.74	42.42	22.73	30.77	44.68
Female	53.85	76.32	39.29	55.26	57.58	77.27	69.23	55.32
Age								
Mean	49.15	39.34	36.32	28.61	28.98	23.91	18.27	62.11
Age (%)								
18 – 19	0.00	0.00	0.00	0.00	0.00	0.00	100.00	4.26
20 – 39	0.00	47.37	89.29	84.21	100.00	100.00	0.00	0.00
40 – 59	100.00	52.63	0.00	15.79	0.00	0.00	0.00	21.28
60 – 79	0.00	0.00	10.71	0.00	0.00	0.00	0.00	70.21
80 – 99	0.00	0.00	0.00	0.00	0.00	0.00	100.00	4.26
100+	0.00	47.37	89.29	84.21	100.00	100.00	0.00	0.00
Labour force (%)								
Not working, not studying	0.00	0.00	0.00	18.42	0.00	0.00	0.00	74.47
Not work, studying secondary school	0.00	0.00	0.00	0.00	0.00	0.00	19.23	0.00
No working, studying TAFE[1] / Uni / Post sec study	0.00	0.00	0.00	81.58	0.00	0.00	23.08	4.26
Working full / part time, studying secondary	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Working full / part time, studying TAFE / Uni / Post sec study	2.20	0.00	0.00	0.00	0.00	95.45	46.15	0.00
Working full time, not studying	97.80	0.00	100.00	0.00	100.00	4.55	0.00	0.00
Working part time, not studying	0.00	100.00	0.00	0.00	0.00	0.00	11.54	21.28

[1] In Australia, technical and further education (TAFE) institutions provide a wide range of vocational education and training.

Cluster	A	B	C	D	E	F	G	H
Weekly personal income (AUD) (%)								
$0	0.00	0.00	3.57	21.05	0.00	0.00	26.92	25.53
$1-149	0.00	7.89	0.00	15.79	0.00	22.73	34.62	0.00
$150-249	1.10	5.26	0.00	31.58	0.00	6.82	19.23	14.89
$250-399	0.00	18.42	1.79	10.53	0.00	27.27	19.23	14.89
$400-599	2.20	15.79	0.00	7.89	0.00	15.91	0.00	8.51
$600-799	12.09	18.42	0.00	2.63	30.30	11.36	0.00	12.77
$800-999	6.59	7.89	0.00	5.26	31.82	9.09	0.00	8.51
$1,000-1,299	15.38	2.63	0.00	0.00	37.88	6.82	0.00	8.51
$1,300-1,599	26.37	10.53	46.43	0.00	0.00	0.00	0.00	0.00
$1,600-1,999	14.29	0.00	30.36	0.00	0.00	0.00	0.00	2.13
$2,000+	21.98	13.16	17.86	5.26	0.00	0.00	0.00	4.26
Household structure (%)								
Sole person	8.79	2.63	19.64	0.00	3.03	0.00	0.00	17.02
Couple no kid	26.37	18.42	37.50	18.42	37.88	6.82	0.00	48.94
Couple with kids	49.45	63.16	25.00	26.32	10.61	56.82	80.77	19.15
One-parent	1.10	2.63	0.00	2.63	1.52	0.00	11.54	4.26
Other HH structures	14.29	13.16	17.86	52.63	46.97	36.36	7.69	10.64
Type of car licence (%)								
Full licence	97.80	78.95	94.64	76.32	84.85	50.00	7.69	91.49
Probationary licence	0.00	0.00	0.00	0.00	1.52	31.82	38.46	0.00
Learners permit	2.20	21.05	5.36	23.68	13.64	18.18	53.85	8.51
No car licence	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00

Individuals in Clusters A, C and E are working full time, with different levels of income. Individuals in Cluster C are in their 20s to 40s, earning high income between AUD 1,300 and AUD 2,000 per week. The majority of them are from “couples with no kid” or “sole person” households. They could be the white collar working adults, earning high income with not much family responsibility to bear. Cluster A consists of individuals in the age group of 40 to 59 years old. The majority of the population in this cluster (63%) has an average weekly income of less than AUD 1,600 and is made up of “couples with kids” households (49.45%). These could have mid-aged parents. Individuals in Cluster E are in the age group of 20 to

39 years old, earning the least average weekly income among the three clusters, between AUD 600 and AUD 1,299.

Cluster B comprises individuals working part time, with average income of less than AUD 799. The majority of individuals in this group are in the age group of 20 to 59 years old. It is interesting that 76.32% of individuals in this cluster are female and 63.16% are from “couples with kids” households. It would be fair to deduce that in this cluster, the majority of them could be mothers working part time, who have high caregiving responsibility for their children, or those who inherit similar characteristics.

Individuals in Cluster D, F and G are students. The majority in Cluster D are students in their 20s to 40s who are not working, but studying full time at TAFE, universities, or other post-secondary institutions. Individuals in Cluster F are students, with the majority of them being female, studying and at the same time working on a full-time or part-time basis. They earn a weekly income of less than AUD 799. They are in their early adulthood living independently from their parents. Students in Cluster G are teenagers, in the age group of 18 to 19 years old, working part time while studying. Their income level is very low (less than AUD 399 per week) and the percentage of “one parent” households is the highest of all the clusters at 11.54%.

The majority of individuals in Cluster H are the elderly in their 60s to 80s, not working and earning an average personal income less of than AUD 399 per week. From the household composition, it is observed that more than half of them in this cluster are from “couples with no kid” and “sole person” households. It appears that they are mostly retired or reaching their retirement age, with not much caregiving responsibilities.

4.5 WALKING TIME DECAY FUNCTION FOR CHOICE BUS RIDERS

In order to test whether there is any significant difference between the means of these eight clusters, another one-way analysis of variance (ANOVA) was conducted, as shown in Table 4-3.

Table 4-3: ANOVA analysis eight clusters of choice riders

Groups	Count	Means	Variance	Standard deviation
Cluster A	91	6.09	20.81	4.56
Cluster B	38	5.61	9.98	3.16
Cluster C	56	6.41	13.19	3.63
Cluster D	38	6.87	18.01	4.24
Cluster E	66	6.42	18.89	4.35
Cluster F	44	9.45	48.95	7.00
Cluster G	26	8.38	24.49	4.95
Cluster H	47	6.45	14.73	3.84

Source of variation	Sum of square	Degree of freedom	Mean square	F-value	P-value	F critical
Between Groups	499.16	7.00	71.31	3.44	0.001	2.03
Within Groups	8257.07	398.00	20.75			
Total	8756.24	405.00				

From the analysis, the F-value of 3.44 is greater than the F critical value (2.03) based on two values of degrees of freedom of 7 and 398. Greater F-value than F critical value indicates that there is strong evidence to reject the H_0 (all clusters are drawn from populations with identical means) at 0.05 confidence level. The P value (0.001) is smaller than 0.05, which indicates that it is unlikely that the observed differences are due to random sampling. The idea of populations having identical means should be rejected. It is safe to conclude that a very high significant difference exists among clusters.

From Table 4-2 and Table 4-3, walking time varies across different clusters. This shows that individuals in these eight clusters have significant differences in their respective walking time to transit. Walking time decay curves are plotted for each cluster using a negative exponential function by calculating the percentage of trips at a given time interval. In the first analysis, it is observed that the drastic drop happens at 5 minute and 10 minute. Some could argue that it has to do with rider's perception and tendency to round up to the nearest 5 minutes. Instead of using the every minute interval, an every 5 minute interval was used, as shown in Figure 4-5. The summary of walking time decay function for each cluster is listed in Table 4-4.

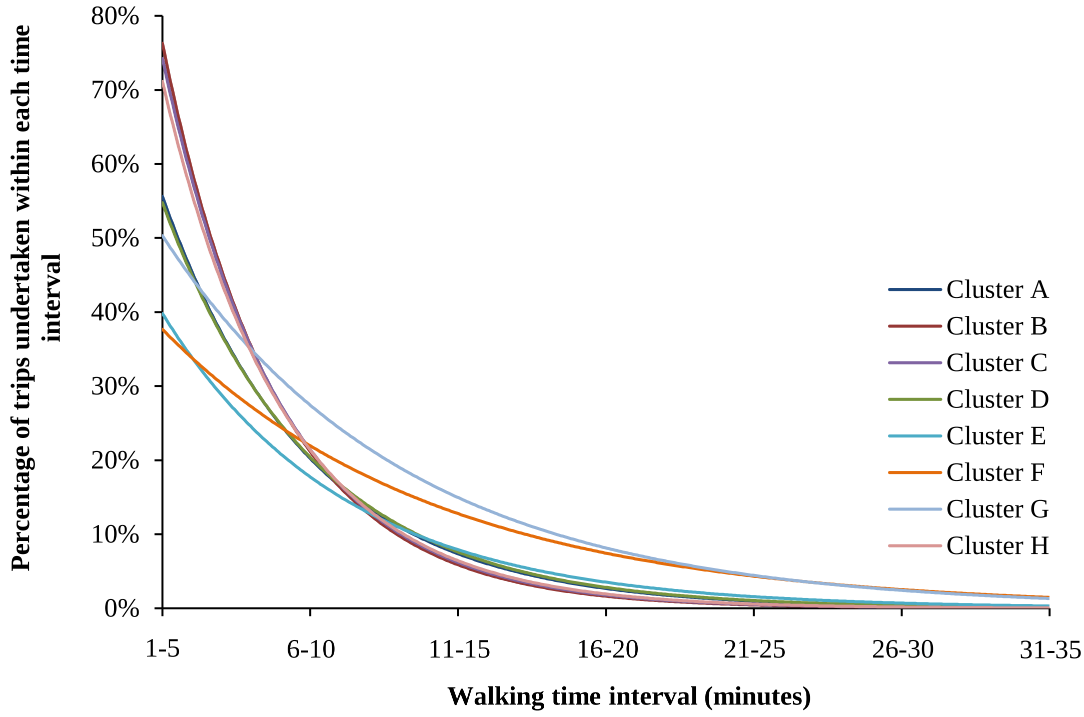


Figure 4-5: Walking time decay function

Table 4-4: Summary of walking time decay function for each cluster

Cluster	Exponential function	R^2 value	Cluster	Exponential function	R^2 value
A	$y = 0.556e^{-0.202x}$	0.962	**E**	$y = 0.398e^{-0.162x}$	0.777
B	$y = 0.763e^{-0.256x}$	0.979	**F**	$y = 0.377e^{-0.108x}$	0.731
C	$y = 0.742e^{-0.248x}$	0.984	**G**	$y = 0.503e^{-0.121x}$	0.987
D	$y = 0.548e^{-0.198x}$	0.752	**H**	$y = 0.711e^{-0.241x}$	0.935

Cluster B has the fastest decay rate, which indicates that when walking time increases, individuals in this cluster are less likely to walk. The majority of individuals are female, part-time workers having one or more children. They must have high caregiving responsibility for their children. Due to the complexity of the trip to drop and pick-up their children, they might choose a private vehicle if access to transit requires a longer walking time. This cluster has an interesting walking time pattern, where no one would walk more than 12 minutes.

Cluster C consists of individuals working full time, high income earners, with not much of family responsibility to bear (partners without child or sole-person households). They are sensitive to walking time to transit and highly likely to switch to a different mode if they need to walk longer. The value of time could be higher for individuals in this cluster as compared to other groups. It is observed that after 4 minutes, the number of bus users drops dramatically from 80% to 36%. The maximum walking time is 20 minutes.

Individuals in Cluster H are the elderly. They may be retired already or those reaching their retirement age. This group walks more than individuals in Cluster B and C, but once it passes 9 minutes, the percentage to use the bus drops from 23% to 6%. It may be reasonable to conclude that physical limitations prevent many individuals in this cluster from walking more than 9 minutes to access transit. Unlike the previous two clusters, the individuals in this cluster could be the "transportation disadvantaged" rather than those having alternative transport modes. Instead of switching to other modes, individuals in this cluster may have given up their travel if they do not own a private vehicle or they are unable to drive a car due to physical limitations.

Moving down the range would be Cluster A. Most individuals in Cluster A are mid-aged parents working full time, but their income level is not as high as individuals in Cluster C. This may contribute to a longer walking time. The lower income families could have been redistributed to the middle and outer suburbs due to lower housing cost, where transit stop density is significantly lower than in the inner-city. This could explain a longer walking access to bus stop. Otherwise, individuals in this cluster could take their health more seriously and thus take walking as a form of exercise. The maximum walking time stretches out to 24 minutes and 9% of individuals in this cluster walk more than 9 minutes.

Similar characteristics are found from individuals in Cluster D and Cluster E. Both groups consist of individuals aged between 20 and 39 years old. Cluster D could be young adults, studying full time at TAFE, university, or post-secondary institutes and not working. On average, this group walks more than Cluster E, where all of them have just completed their high school, university or TAFE, starting to venture into their career, working full time. This result is reasonable, because they are earning relatively low income, which gives them less switching power to a private vehicle. However, the decay rate calculated for the young full-time workers

(Cluster E) is slower than the full-time students (Cluster D) and the longest walking time (27 minutes) is found in Cluster E, as compared to 20 minutes in Cluster D.

Having a very similar decay rate as individuals in Cluster D, transit riders in Cluster G are teenagers (between 18 to 19 years old), working part time while studying. They are the youngest group, but may have to support their family or help out with family business. Private vehicles may not be affordable to them and this makes individuals in this cluster highly dependent on transit.

Cluster F are individuals studying at TAFE, university, or post-secondary institutes and working at the same time. They are in their early adulthood, living independently from their parents. They could be financially insecure yet, which makes them highly dependent on transit. Unlike all the other clusters, Clusters F and G retain at average of 20% of the total bus riders walking 10 minutes or longer to access transit, as shown in Figure 4-5. The decay rate for young adults working and studying (Cluster F) drops relatively slower as compared to teenagers working and studying (Cluster G).

To illustrate the findings, Figure 4-6 shows the normal probability density function of people walking at one minute increment of walking time. The probability density function describes the relative likelihood for a random variable to take on a given value, and as for this study, the likelihood to walk at the given time. The probability of the people walking within a particular range of time can be taken by the integral of the density over that range, which is the area under the density function. This probability function is later being normalised across different clusters so that comparison can be made among the clusters.

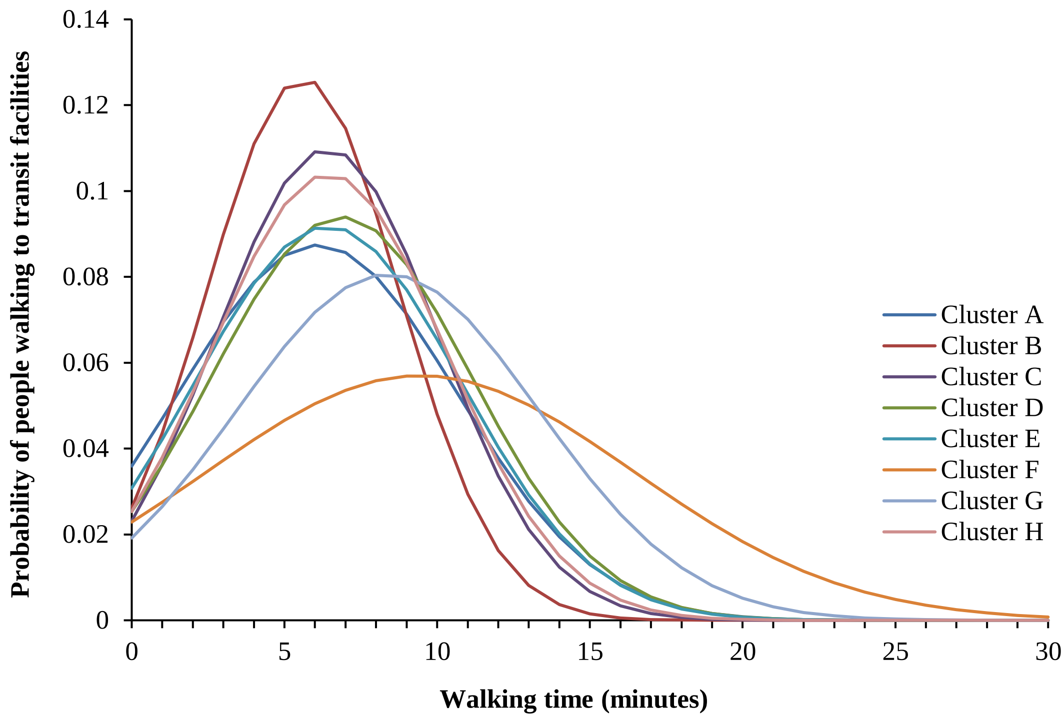


Figure 4-6: Probability of people walking to transit facilities at any point of time

The distribution curves clearly illustrate that individuals in Cluster B (part-time workers), Cluster C (high-income earners), and Cluster H (the elderly) are the most sensitive groups to walking time, whereas individuals in Cluster F (part-time students and workers) are least sensitive to walking time. Clusters located between these two groups show similar patterns and they are Cluster A (full-time mid-aged parents), Cluster D (full-time post-secondary students), Cluster G (teenagers studying and working part time) and Cluster E (full-time young working adults).

4.6 CONCLUSION

More evidence is emerging demonstrating the complexity of walking behaviours, where walking access (time or distance) to transit varies across different characteristics of users and their trips. Given the known extensive range of factors that will affect the decision making to walk to transit, the ability to precisely measure walking access is elusive. To better explain the variations in walking time among individuals, this study adopted two market segmentation methods to identify relatively independent groups who share the similar characteristics across the general continuum of choice. The first (and rather too simple) segmentation method, which divided the bus users into true transit captive users and choice users based on car ownership and driver's licence, induced insignificant difference between the walking time of these two groups. The exclusion of true transit captive users is to increase the accuracy of the analysis because captive users do not have the choice to use alternative modes of transport but must take transit. The second segmentation clustered the choice users into eight socio-economically homogeneous groups based on age, labour force and personal income.

The results demonstrated that the walking time varies across these eight groups, each with distinct characteristics. The walking time decay functions illustrated that part time workers, full-time high income earners and the elderly transit riders are among individuals who have the lowest walking time and thus the most sensitive groups to walking time. The next groups include mid-aged working parents, full-time post-secondary students, teenagers studying and working, and young working adults. Young adults, studying at the same time working on a full-time or part-time basis, have the longest walking time to transit and thus are the least sensitive to walking time in choosing their travel mode. In general, the affordability factor seems to be an important factor affecting the walking access to transit facilities. Trip complexity (due to caregiving responsibility) and physical limitations may deter the use of transit when prospective riders are required to walk longer time.

In general, despite the few disparities among different socio-economically homogeneous groups, the aggregate approach of using 5 minutes or 400m walking access to bus stops is likely to work for most groups in the society. Nonetheless, for policy implications, the findings of this research has contributed to the understanding of people's walking behaviour and reasons for variations, which supports a more tailored approach in design and operation of transit service especially for socio-economically distinct areas such as retirement villages and university dormitories.

Finally, a few limitations of this study should be noted. This study focuses only on the walking access to transit (first mile), and not the walking access from transit (last mile). The general consensus among different transit studies is to adopt similar value for both first and last mile as they share similar walking properties and behaviours. This method purely relies on revealed data - household travel survey. In Brisbane, many parts of the city conform to the stop spacing of 400m, which may explain the tailing-off pattern after 5 minutes for most of the population groups. This research only considers the socio-economic characteristics as dominant factors for individuals to determine their walking time to access transit, without taking into consideration the quality of transit service at the places of origin. Those who walk more do not necessarily mean that they are forced to walk because they have no access to alternative modes of transport; rather it could be their choice to walk more, as a form of exercise.

Chapter 5: Transit Service Connectivity and Cognitive Transfer Location

5.1 INTRODUCTION

Transfer has been extensively discussed in the literature. Existing studies formulate transfer impacts in terms of additional time and cost incurred during transfer including: number of transfers, walking time, waiting time, extra in-vehicle time and transfer cost (Sharaby & Shiftan, 2012; Wardman et al., 2001). Another type of transfer penalty encapsulates subjective and psychological factors based on preferences, attitudes, and perceptions of transit users (Guo & Ferreira, 2008; Liu et al., 1997). The perceived environment of transfer therefore significantly affects the utility of transit and mode choices (Hadas & Ceder, 2010; Iseki & Taylor, 2009).

This study builds on the hypothesis that transit users have a preference for the direction of travel towards transfer location and this will influence the travel mode choice. The attractiveness of transit will decrease when one has to make a transfer that involves a significant deviation from the direction to the destination. The straight route from origin to destination may be considered as the private vehicle path perceived by travellers, although the actual travel path may differ by the network configuration. The deviation may imply intrinsic factors that account for subjective and psychological impedance imposed by the transfer. This effect will be even more significant in a radial transit system, where transit users travelling from an outer suburb to another require a transfer in the downtown area to access connecting transit lines or alternative modes.

This study develops a cognitive transfer map of travellers by projecting the actual transit journey with a single service transfer (i.e.: origin, destination, and transfer point) into two-dimensional Euclidean space (Section 5.2). The transfer data was collected from the smart card data of SEQ, Australia. The “preference” for transfer location is quantified and ranked through grid-based hierarchical clustering (Section 5.3). Using the SEQHTS, the impact of transfer locations preference is validated through mode choice analysis (Section 5.4). Section 5.5 concludes the findings of the second research phase.

5.2 MAPPING COGNITIVE TRANSFER LOCATION

5.2.1 Processing of Single-transfer Bus Journey Data

In order to develop a cognitive transfer map, the first step taken was to reconstruct travel itineraries by combining related trips for each smart card holder to form complete journeys from origins to destinations, including transfers. A one week Brisbane “go-card” data gathering (from 17 till 21 November 2014) was used for the mapping. The data encapsulates the entire Brisbane City Council area, which is equivalent to the total area of Brisbane East, North, South, West and Inner City in the SA2. The go card is an electronic ticket for use on transit services throughout the network and records travel data when a traveller touches on at the start of any trip stage, and touches off at the end of the trip stage. This dataset contains information such as go card ID, date of service, route ID, service ID, direction (inbound or outbound), boarding time and alighting time, boarding stop ID and alighting stop ID, ticket type, journey ID and trip ID. If it is a transfer journey, it would have consecutive trip ID for each trip stage with the identical journey ID. According to TransLink, a journey is defined as the set of trip stages taken under one fare basis, while a trip is a ride on a single transit vehicle. This study adopts the same convention for the terms “journey” and “trip”. The data processing to construct single-transfer journeys is shown in Figure 5-1.

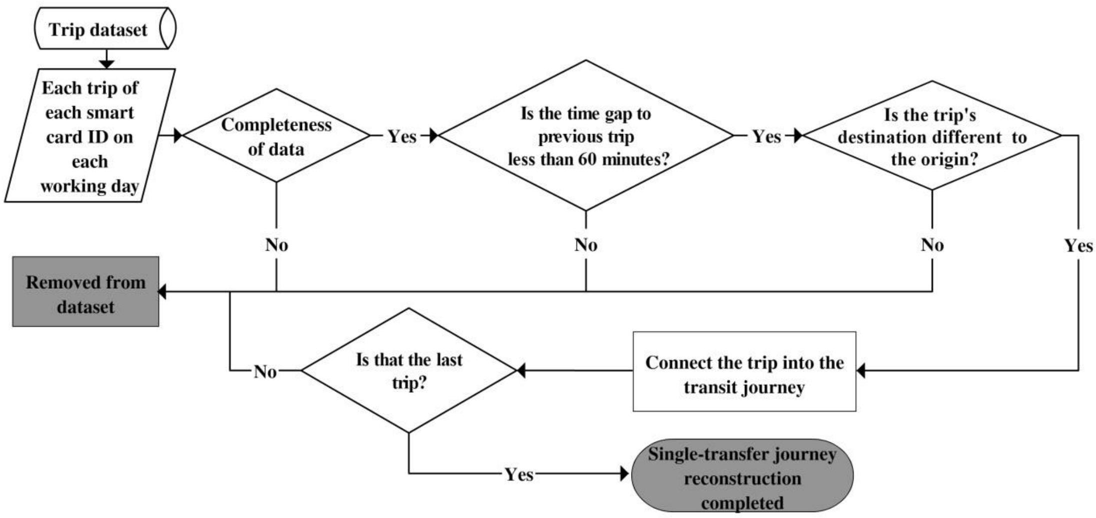


Figure 5-1: Single-transfer travel journeys construction process

The process started with filtering out noise data such as incomplete data of origin or destination information. A threshold of 60-minute time gap is applied to identify whether two transactions are connected as a transfer journey. If transit user stays at a place for more than 60 minutes before making the next trip, it will be counted as a separate trip, rather than a continuous journey through a transfer. The next process was to differentiate return trips from single-transfer journeys. Studies have shown that transit user is willing to walk on average 400 or 500m to bus stops (Chia et al., 2016; Horner & Murray, 2004; O'Sullivan & Morrall, 1996; Weinstein Agrawal et al., 2008). A maximum distance threshold of 1km from origin and destination is used to distinguish single-transfer journeys from return trips. This study is only interested in single-transfer journeys, since the percentage of bus journeys with more than one service transfer is negligibly small. If there is any journey that has more than one transfer, the whole journey will be removed from the dataset. After the reconstruction process, a total of 125,215 journeys were identified.

5.2.2 Mapping Transfer Points in Euclidean Space

Due to the distinct nature of every transit journeys, all the single-transfer journeys are required to be transformed into a standardised space to discover meaningful patterns among them. The first step of the process is to transform the journey triangle OTD (Origin – Transfer – Destination) on a spherical earth's surface to a 2D plan, given the latitudes and longitudes of each point of interest, as shown in Figure 5-2.

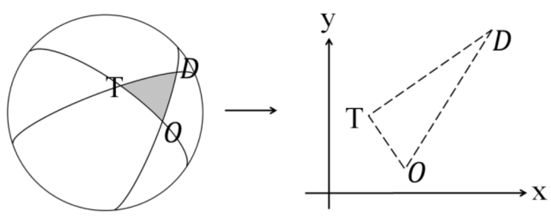


Figure 5-2: Transformation from a spherical earth's surface to a 2D plan

The great-circle distance between two points, which is the shortest distance over the earth's surface, is calculated based on the spherical law of cosines. The spherical law of cosines states that, for a spherical triangle,

$$cos\ OD = cos\ OT\ cos\ TD + sin\ OT\ sin\ TD\ cos\ T \quad \text{Equation 5-1}$$

where:

O, T, D	= Interest points of the journey triangle, OTD
OD	= Distance between origin point and destination point
OT	= Distance between origin point and transfer point
TD	= Distance between transfer point and destination point

The position of any point on the earth can be defined by its latitude and longitude. In reference to Equation 5-1, the OD distance can be calculated as the arccosine of cos OD, as shown in Equation 5-2.

$$cos\ OD = cos\ OT\ cos\ TD + sin\ OT\ sin\ TD\ cos\ T$$
$$OD\ (in\ rad.) = cos^{-1}\ [cos\ OT\ cos\ TD + sin\ OT\ sin\ TD\ cos\ T] \quad \text{Equation 5-2}$$

The unit used for angles is in radians, which gives the distance between origin and destination in radians. Given the convenient mean radius of the earth to be equivalent to 6,371 km, the distance between origin and destination, in km, can be calculated by multiplying OD distance (in radians) with 6,371km, as shown in Equation 5-3.

$$OD\ (in\ km) = cos^{-1}\ [cos\ OT\ cos\ TD + sin\ OT\ sin\ TD\ cos\ T] * 6371\ km \quad \text{Equation 5-3}$$

The same technique is applied to calculate the great-circle distance of OT and TD. With the great-circle distance of OT, TD and OD, the respective angles of any triangle on a 2D plane could be calculated using the law of cosines, as shown in Equation 5-4.

$$cos\ O = (OT^2 + OD^2 - TD^2)\ /\ 2(OT * OD)$$
$$O = cos^{-1}[(OT^2 + OD^2 - TD^2)\ /\ 2(OT * OD)] \quad \text{Equation 5-4}$$

After the journey triangle OTD is obtained, it needs to undergo a series of Euclidean transformations to display all the origin, destination and transfer points in a standardised Euclidean space, as illustrated in Figure 5-3.

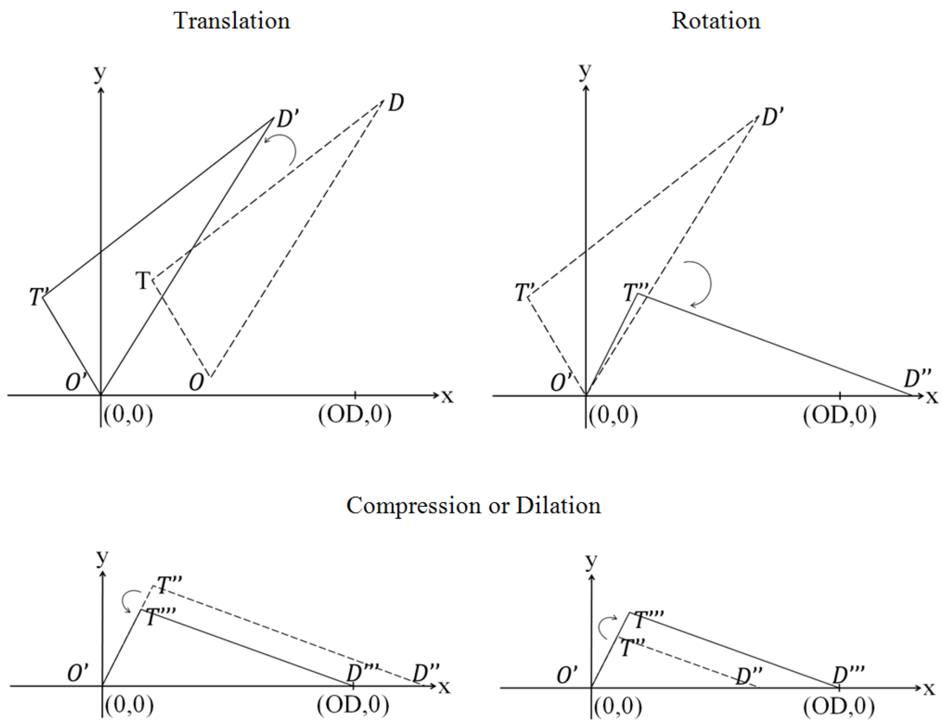


Figure 5-3: Euclidean transformations

The first step of Euclidean transformation is translation. Translation relocates the journey triangle OTD to set the triangle's origin point, O, at (0, 0). This transformation preserves the congruence and distance of the journey triangle OTD. Applying the translation process to the single-transfer journeys results in all the journey triangles originating from the same point at (0, 0). The notation for translation ($T_{h,k}$) is shown in Equation 5-5. The origin and destination points will undergo the same transformation.

$$T_{h,k}\left(T'_x, T'_y\right) = (T_x + h, T_y + k) \qquad \text{Equation 5-5}$$

where:

$T_{h,k}$ = The notation for translation

T_x = The original x coordinates for the transfer point

T_y = The original y coordinates for the transfer point

T'_x = The new x coordinates for the transfer point after translation

T'_y = The new y coordinates for the transfer point after translation

Preserving the congruence and distance, the journey triangle OTD is rotated at O (0, 0) until the triangle plane, OD, rests on the x-axis. This transformation rotates all the journey triangles to lie along the x-axis for the destination point, D, to have the coordinate of (x, 0). The notation for rotation is shown in Equation 5-6.

$$\begin{bmatrix} T''_x \\ T''_y \end{bmatrix} = \begin{bmatrix} \cos\theta & -\sin\theta \\ \sin\theta & \cos\theta \end{bmatrix} \begin{bmatrix} T'_x \\ T'_y \end{bmatrix} \qquad \text{Equation 5-6}$$

where:

θ = The angle of rotation at new origin point (0,0)

T''_x = The new x coordinates for the transfer point after rotation

T''_y = The new y coordinates for the transfer point after rotation

At this stage, all journey triangles OTD lie on the same plane (x-axis). The next step of the transformation is to loosen up the restriction to consider bijection, which preserves the shape and angles of the triangle, but not distance. The aim of this step is to transform all journey triangles OTD to have the same OD unit distance, as shown in Figure 5-3. The notation for compression and dilation (CD_k) is shown in Equation 5-7.

$$CD_k\left(T'''_x, T'''_y\right) = (kT''_x, kT''_y) \qquad \text{Equation 5-7}$$

where:

CD_k = The notation for compression / dilation

T'''_x = The new x coordinates for the transfer point after compression / dilation

T'''_y = The new y coordinates for the transfer point after compression / dilation

Figure 5-4 illustrates the transfer points of the single-transfer bus journeys, transformed to the scale of OD unit distance for both x and y axis. This study assumes this plot represents the cognitive “preference” for transfer location of the travellers in the study area. Consequent analysis quantifies and ranks the “preference” and validates its impact on travel mode choice.

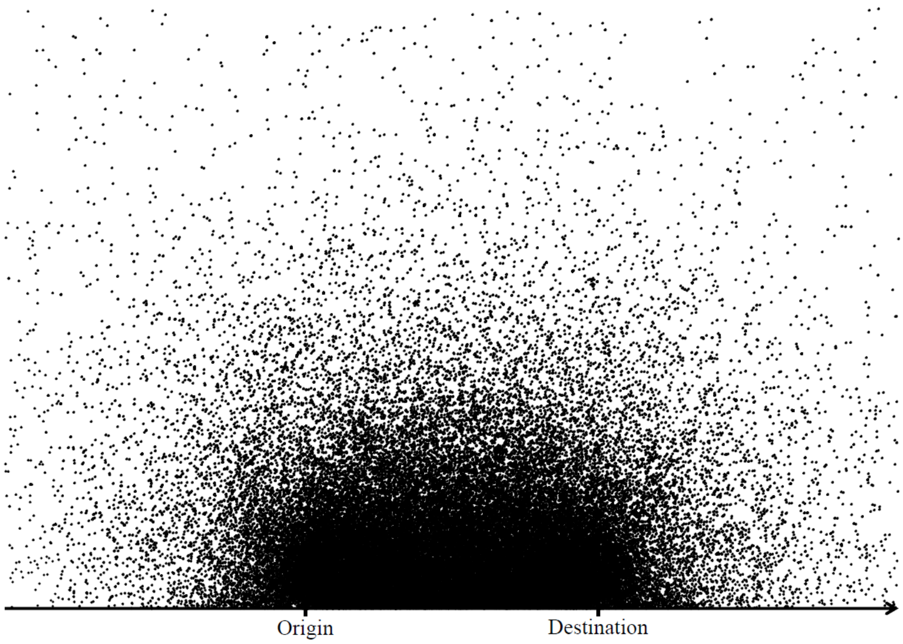


Figure 5-4: Cognitive transfer location in Euclidean space

5.3 GRID-BASED HIERARCHICAL CLUSTERING

The cognitive transfer map displays the actual transfer points transformed in two-dimensional Euclidean space. To identify interesting patterns from the scattered points, this study used the grid-based hierarchical clustering method, which combines the grid-based clustering and hierarchical clustering methods. Cluster analysis is a data reduction tool that partitions a sample dataset into clusters, where objects within a specific cluster share many characteristics, but are very dissimilar to objects not belonging to that cluster (Sarstedt & Mooi, 2011).

The grid-based clustering (also known as density-based clustering) is one of the most efficient approaches for mining large data sets. This method adopts algorithms that partition the data space into a finite number of cells to form a grid structure (Cheng et al., 2013) as shown in Figure 5-5.

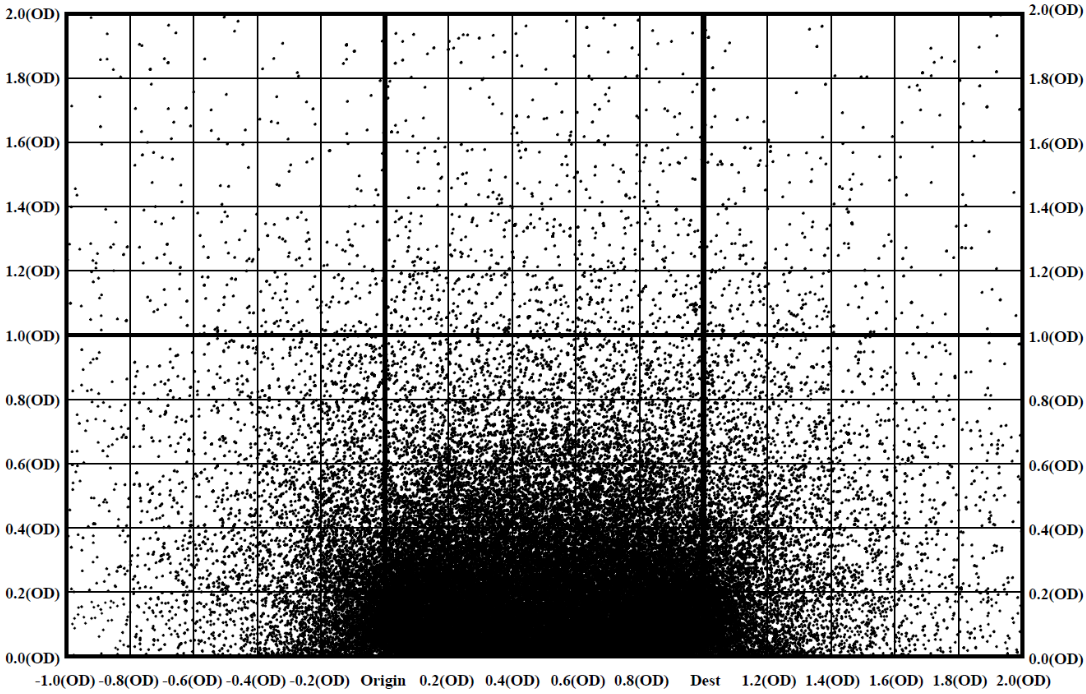


Figure 5-5: Grid structure on cognitive transfer location map

This study used the simplest form of grid-based clustering, by defining each grid with 0.2 OD unit distance increment. These transfer points are plotted in reference to 1.0 OD unit distance. Figure 5-5 shows the clear concentration of transfer points in the cells, along with the "shortcut" distance between the origin and destination. For cell clustering purposes, the cell density is calculated for each cell as follows:

$$Cell\ density = \frac{Total\ number\ of\ transfer\ points\ in\ grid\ x}{Total\ number\ of\ transfer\ points} \qquad \text{Equation 5-8}$$

The hierarchical clustering method was applied to sort the cells into clusters. Hierarchical clustering is useful for finding relatively homogenous clusters of cases based on measured characteristics. It starts off with each case as a separate cluster. Next, these clusters are combined sequentially until only one cluster is left. The algorithm for this clustering method uses the dissimilarities or distances between objects when forming the clusters (Sarstedt & Mooi, 2011). Figure 5-6 shows the cell-density for each cell, and to which cluster each cell is assigned by the hierarchical clustering method.

	A	B	C	D	E	F	G	H	I	J	K	L	M	N	O	
10	0.00%	0.01%	0.00%	0.00%	0.01%	0.01%	0.01%	0.01%	0.01%	0.00%	0.01%	0.00%	0.00%	0.01%	0.00%	10
9	0.00%	0.01%	0.00%	0.01%	0.01%	0.01%	0.01%	0.01%	0.02%	0.01%	0.01%	0.00%	0.00%	0.00%	0.01%	9
8	0.00%	0.01%	0.00%	0.01%	0.01%	0.02%	0.03%	0.03%	0.02%	0.02%	0.02%	0.01%	0.01%	0.00%	0.00%	8
7	0.02%	0.01%	0.01%	0.02%	0.03%	0.04%	0.04%	0.28%	0.05%	0.05%	0.03%	0.02%	0.02%	0.01%	0.01%	7
6	0.01%	0.01%	0.03%	0.04%	0.04%	0.13%	0.10%	0.08%	0.08%	0.11%	0.06%	0.06%	0.02%	0.01%	0.01%	6
5	0.01%	0.03%	0.06%	0.10%	0.25%	0.18%	0.18%	0.23%	0.19%	0.18%	0.18%	0.08%	0.04%	0.03%	0.01%	5
4	0.03%	0.06%	0.06%	0.15%	0.31%	0.37%	0.48%	0.59%	0.59%	0.37%	0.33%	0.12%	0.10%	0.06%	0.02%	4
3	0.03%	0.06%	0.11%	0.27%	0.61%	0.99%	1.37%	1.61%	1.37%	1.05%	0.61%	0.27%	0.13%	0.06%	0.03%	3
2	0.03%	0.08%	0.18%	0.45%	1.61%	4.04%	3.61%	3.93%	3.77%	3.88%	1.55%	0.46%	0.21%	0.09%	0.03%	2
1	0.03%	0.09%	0.18%	0.64%	3.46%	12.52%	8.16%	7.39%	9.05%	12.97%	3.50%	0.72%	0.25%	0.12%	0.05%	1

Origin (between E and F) Destination (between J and K)

Figure 5-6: Cell-density in respective clusters

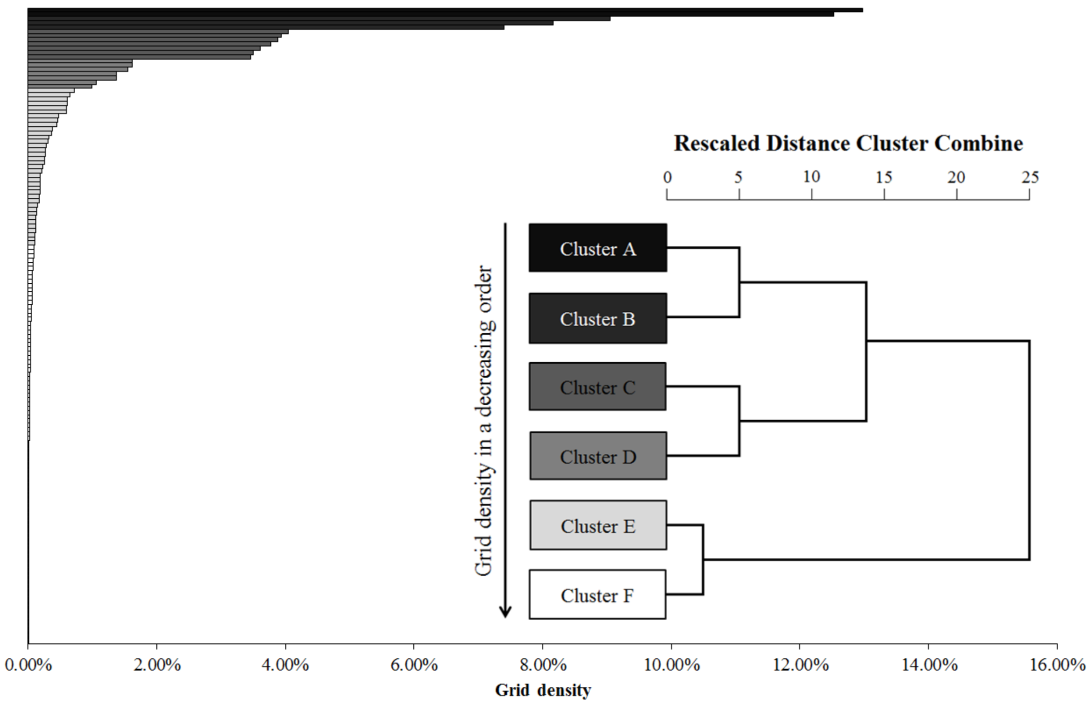


Figure 5-7: Cell density dendrogram

Figure 5-6 presents the cognitive transfer map with the cell density values. Figure 5-7 shows the result of hierarchical clustering. Some interesting results are observed in the travellers' transfer point selection. The majority of bus journeys conducted have made a transfer located in the cells F1 and J1. These two cells are identified to have the highest transfer point density at 12.52% and 12.97%, respectively (Cluster A). These two cells may be regarded as the most preferred cognitive transfer location and by having a transfer service in those cells will increase the likelihood of making a transfer and eventually taking transit, compared to other cells.

All the other cells are categorised into five different clusters by the cell's grid density (Figure 5-7). The hierarchical clustering uses the Ward's method to measure the dissimilarity among clusters. Ward's method uses an analysis of variance approach, instead of distance metrics to evaluate the distances between clusters, where cluster membership is assessed by calculating the total sum of squared deviations from the mean of a cluster (Ward, 1963). The dendrogram allows the tracing backward and forward to any cluster at any level. It gives an idea of how great the distance is between clusters in a particular step, using the 0 to 25 scale along the top of the chart.

Cluster B includes G1, H1 and I1. Transfer points in those five cells of Cluster A and Cluster B account for 50.10% out of the total 150 cells in the map. This implies that most travellers would prefer the transfer point to be located along the direction to their destination. Cluster C consists of seven cells, E1, F2 to J2, and K1. The cell density significantly declines to 3.74% in average. Some bus users travelled to transfer points in the opposite direction from their destination, but the transfer points are not far from their origination. Similarly, some travellers make a transfer farther from their destinations. The cell density further decreases for the cells in Cluster D with the average density value at 1.37%. The transfer points located in the Cluster A to D groups account for 85.85% of the total transfers. The average density value of the cells in Cluster E and Cluster F is negligible at 0.29% and 0.02% respectively although they account for more than 87.33% of the total map area (131 out of 150 cells).

Figure 5-8 reiterates the grid density in the 3-D surface plots, in reference to the predetermined origin-destination distance. Cell density from row 6 and above (as shown in Figure 5-6) are insignificant and this has been omitted for illustration purposes. Given any origin, destination and transfer point coordinate, through

Euclidean transformation technique, the OTD journey triangle can be rescaled to fit the origin-destination unit distance, and to analyse which cell the transfer point falls into. The colour signifies the preference of transfer location in descending order, from darker to lighter colour.

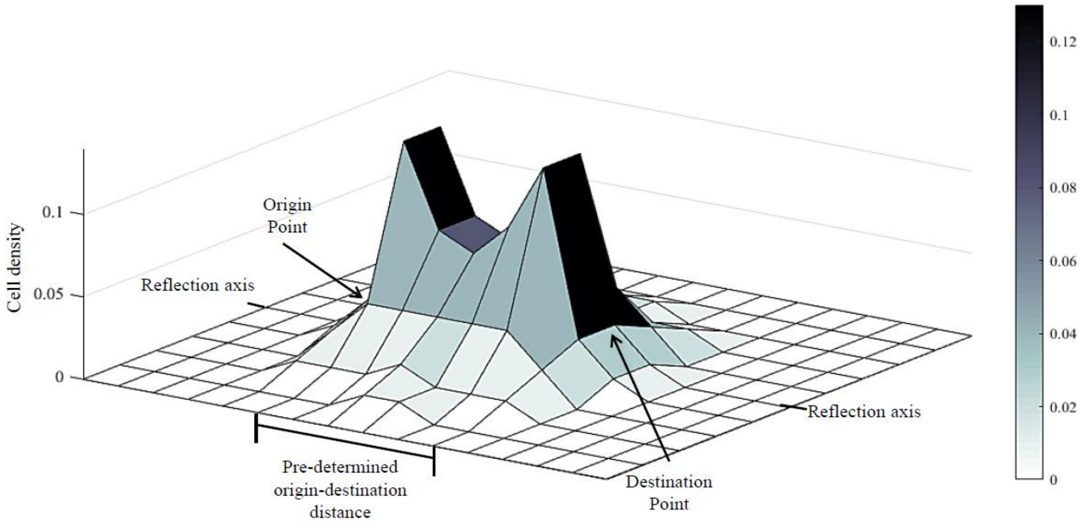


Figure 5-8: 3-D surface plot of cell density

In general, based on the transfer frequency in each standardised cell (cell density), it is observed that majority of transferred are conducted at locations that are near to the OD straight route. Transit users do not mind to travel at the opposite direction to destination, or slightly farther away from destinations to make a transfer. When one is required to make a transfer that has deviated far away from the OD straight route, the realisation of such transfers is small. This demonstrates the travel impedance based on transfer locations. The interpretation of these findings is handled with caution. Transfer locations could possibly be related to the limitations of transit network. For example, a captive transit user would need to conduct a transfer in a less favourable locations, in order to get to the desired destination. Due to the limitations of smart card data, this study is not able to differentiate the trips conducted by captive and choice users. In order to validate the real effect of transfer locations on mode choice, this study utilise a more comprehensive travel survey (i.e.: SEQHTS) to analyse the mode choice of the choice users only.

5.4 MODE CHOICE ANALYSIS

Two binomial logit models (base and expanded model) were drawn on two travel modes: private vehicles and bus. For a mode choice analysis, information for mode specific variables of the alternative (unchosen) mode is necessary. Information of the alternative mode can only be inferred. This study used GTFS data to infer the bus journey information for those who have chosen private vehicle as their travel mode; and Google Maps to infer the private vehicle travel time for those who have chosen bus as their travel mode. To minimise the difference between the actual and inferred travel time (i.e.: taking into account the effect of traffic congestion), this study used the same time of the day as the time recorded in SEQHTS. This analysis considers only the home-based work journeys for choice users. If an individual were to use transit as the mode of transport, it must involve only one transfer. Due to the specific nature of this analysis, only 330 private vehicle journeys and 19 bus journeys fulfilled the selection criteria, and were used in this analysis. In Brisbane, SEQHTS is the most detailed dataset available to demonstrate travellers' mode choice. This study acknowledges that the relatively small sample size is one of the limitations of this study, and could potentially affect the robustness of parameter estimates and inferences, however, this should not affect the marginal effects estimates. Bergtold et al. (2011) conducted a study on sample size and robustness of inferences from logistic regression using Monte Carlo simulation method, discovered that sample size could affect parameter estimates, but the marginal effects estimates are relatively robust to sample size.

The dependent variables of the model are dichotomous, representing the travel mode choice (transit or private vehicle). The independent variables tested in this analysis include individual characteristics (gender, age, individual weekly income, number of cars in the household and household size), journey attributes (travel distance, travel time, walking time, and waiting time) and transfer attributes (in-vehicle bus travel time, transfer walking time, transfer waiting time, the type of transfer and cognitive transfer location). Table 5-1 presents the list of independent variables with brief descriptions.

Table 5-1: List of independent variables

Variable	Description
Socio-economic attributes	
Gender	Dummy variables: 0 – male; 1- female
Age	Age of individuals
Individual weekly income	Individuals' weekly income, given in different income bracket
Number of cars	Total number of cars per household
Household size	Number of persons in the household
Journey attributes	
Distance (kilometres)	The shortest network distance from origins to destinations for private vehicle users
Car travel time (minutes)	Total time taken to travel from origins to destinations using private vehicle
Bus travel time (minutes)	Total time taken to travel from origins to destinations using bus
Total travel time saving (minutes)	Total time saving if individual is to use private vehicle than bus
First mile walking time (minutes)	Total walk time taken to access bus stations
Last mile walking time (minutes)	Total walk time taken from bus stations to destinations
Initial wait time (minutes)	Total wait time for the first bus service
Transfer attributes	
In-vehicle bus travel time (minutes)	Total in-vehicle travel time spent on bus
Transfer walking time (minutes)	Total time spent to walk to the next bus station to make a transfer
Transfer waiting time (minutes)	Total wait time for the next bus service during the second leg of the trip
Type of transfer	Dummy variables: Dummy variables: 0 – non-walking transfer; 1- otherwise
Cognitive transfer location	The cluster developed using smart card data (i.e.: Cluster A – F encoded to 1 – 6), of which individual transfer location falls into

Two different models were developed to demonstrate the effect of the cognitive transfer location. The base model (Model I) took the conventional approach to account for the effect of transfers through integrating the in-vehicle travel time, transfer walking time, and transfer wait time components. The expanded model (Model II) added the "cognitive transfer location" factor. The results of the two models are presented in Table 5-2.

Table 5-2: Binomial logit model results: Basic vs. expanded models

Variables	**Model I Base Model**			**Model II Expanded Model**		
	Coefficient	Std. Err.	Exp. β	Coefficient	Std. Err.	Exp. β
Constant	2.48*	1.41	11.88	4.31**	1.68	74.40
Socio-economic attributes						
Individual weekly income	-0.00*	0.00	1.00	-0.00**	0.00	1.00
Household size	0.65***	0.22	1.91	0.60***	0.22	1.83
Number of cars	-0.95***	0.37	0.39	-1.10***	0.40	0.33
Journey attributes						
Car travel time (minutes)	-	-	-	0.07*	0.04	1.07
Bus travel time (minutes)	-0.16***	0.04	0.85	-0.18***	0.05	0.84
Transfer attributes						
In-vehicle bus travel time (minutes)	0.17***	0.05	1.18	0.18***	0.05	1.20
Type of transfer	-1.37*	0.77	0.25	-1.34*	0.79	0.26
Cognitive transfer location cluster	Not included in base model			-0.47**	0.22	0.63
Number of observation			349			349
Log-likelihood function value: Constant only model			-73.78			-73.78
Log-likelihood function value: Parameterised model			-49.63			-47.15
Goodness of fit (McFadden rho squared)			**0.33**			**0.36**
Model Improvement Test: -2*(log-likelihood of basic model - log-likelihood of expanded model)						4.95
Chi-critical based on 1 degree of freedom						3.84

Notes: ***: $P < 0.01$; **: $P < 0.05$; *: $P < 0.1$. Coefficients that are statistically insignificant ($P \geq 0.1$) are not shown in this table.

Table 5-2 shows only the variables that provided the best fitting model fit. For instance, gender, age, first mile and last mile walking times, network distance, transfer walking time and transfer waiting time were found not to be significant. The best-fitting basic model (Model I) incorporated seven independent variables, including individual weekly income and type of transfer (significant at the 0.1 level). The "car travel time" variable was found to be statistically insignificant in Model I. The expanded model included one additional variables: the cognitive transfer location (significant at the 0.05 level). As for socio-economic variables, the household size has a positive effect on the utility of transit, whereas the number of cars in the household has a negative effect on the transit utility. The bus travel time factor was found significant (at the 0.01 level) among other journey attributes. The negative coefficient indicates that the transit utility will decrease as the bus travel time increases. Similar results can be found in the literature (Cervero, 2002; Guo & Ferreira, 2008; Schwanen & Mokhtarian, 2005).

As for the transfer-related variables, only the in-vehicle bus travel time factor was found to be significant in both the base and expanded models (significant at the 0.01 level). The Exp. β coefficient relating the in-vehicle transit travel to the likelihood of using transit is 1.18 and 1.20 in the base model and the expanded model, respectively. These results imply that travellers are more likely to choose transit as the expected in-vehicle bus travel time increases. This finding is consistent with the literature that shorter in-vehicle transit travel times could lead travellers to perceive the walking time and waiting time for transfer more onerous and eventually increases the relative attractiveness of private vehicles (Ceder et al., 2013; Frank et al., 2008; Guo & Wilson, 2011; Hadas & Ceder, 2010).

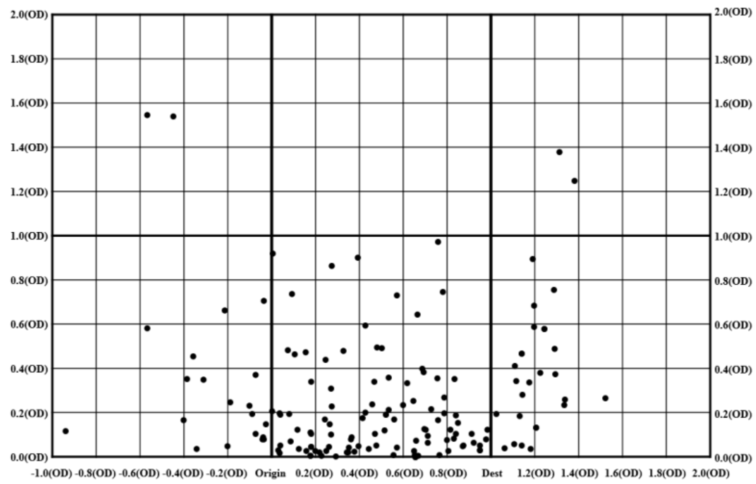
The expanded model (Model II) included the cognitive transfer location variable. This new variable was found to be significant at the 95% confidence level. The negative coefficient suggests that a transfer location farther from the origin to destination connection (in Euclidean space) will decrease the utility of bus and thus the probability to choose the bus mode. In fact, it turns out that the cognitive transfer location factor is one of the most important determinants in the travel mode choice. Exp. β shows the effect of the independent variable on the odds ratio. This variable has the Exp. β value of 0.63, which shows that a change in the transfer location from a more preferred cluster to a less preferred cluster (e.g.: from Cluster A to Cluster B) would decrease the probability of using a bus to 0.39, and increase the probability of using a private vehicle to 0.61. Having the "transfer location" variable in an ordinal scale could be the limitation of this study, yet there is not a single continuous variable that could capture the effect of deviation and direction of travel. Figure 5-5 and Figure 5-6 show that the frequency of service transfers located near to the origin and the destination is compatible to those locations that are on the way to the destination with a slight deviation (Cell F2 to J2), though it involves backtracking (Cell E1 and Cell K1). A continuous variable that measures the deviation from the OD straight route over-penalises the impact of transfer for those transfer journeys that involve backtracking.

The model predictabilities of Model I and II were conducted to test whether the newly added "cognitive transfer location" factor influences bus riders' mode choice. Both models were compared, using McFadden rho squared to measure the goodness of fit. Model I has a pseudo R-squared, ρ^2 of 0.33, while for Model II, it increases to 0.36. McFadden suggested ρ^2 values of between 0.2 and 0.4 should represent a very good fit of the model (Louviere et al., 2000). The increase in ρ^2 of Model II demonstrates that with the inclusion of the new variable, Model II has a better explanatory power on mode choice as compared to Model I.

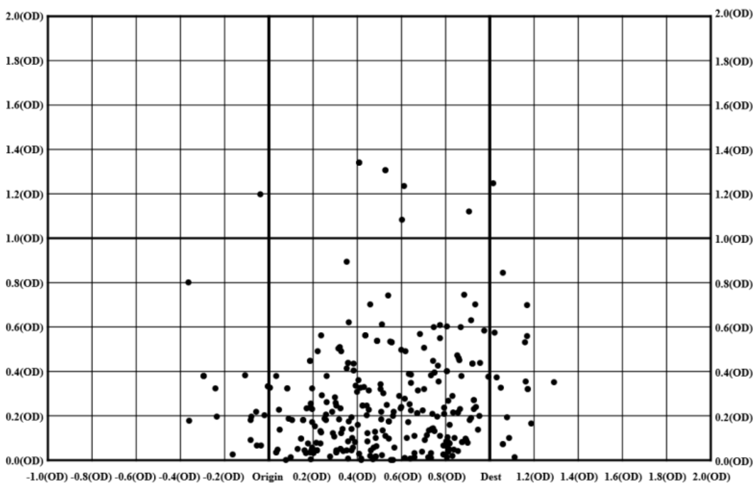
The chi-squared (χ^2) test was conducted to investigate the statistical improvement between Model I and Model II, by gauging the change in the log-likelihood function relative to the change in degrees of freedom. The chi-squared, χ^2 value of 4.95 exceeds the critical chi-squared of 1 degree of freedom of 3.84, at the 0.05 significant level. This gives sufficient evidence to reject the null hypothesis that Model II is no better than Model I. With the inclusion of the "cognitive transfer location" variable into Model II, it outperforms Model I (base model).

5.5 DISCUSSION AND APPLICATIONS

The concept to quantify transfer location is not foreign in route choice analysis (Raveau et al., 2011). However, to incorporate "transfer location" into mode choice analysis has its novelty value. Every transfer is unique and distinct. In order to discover meaningful patterns on transfer location among these transit journeys, each of these single-transfer journeys is transformed into a standardised Euclidean space. The frequency of single-transfer transit journey decreases when transit users are required to conduct a transfer at locations which have deviated far from the OD straight route. In any conventional mode choice model, this factor is often considered under the umbrella of “door-to-door travel time”, based on the assumption that conducting a transfer near to the OD straight route will incur a relatively shorter travel time, as compared to a more circuitous route. This research challenges this assumption, and discovered that transfer location is not correlated to travel time, and it can be visualised through Figure 5-9.



More than 90 minutes



Less than 15 minutes

Figure 5-9: The distribution of transfer location for different door-to-door travel time period

Figure 5-9 shows the random distribution of transfer location for two different door-to-door transit travel time period: less than 15 minutes (left) and more than 90 minutes (right). If the assumption is valid, those transit journeys that are less than 15 minutes will have transfer locations clustering near to OD straight route, while those longer journeys will have transfer locations clustering farther away from OD straight route. If a transit modeller were to assume that shorter journey time represents good transit connectivity between an origin and a destination, it will overestimate transit connectivity. For example, in Figure 5-9, some of the transit journeys required a transfer at less convenient locations. In the conventional mode choice model, transit travel time is not capable to capture the effect of transfer location.

This study provides a new approach to visualise the complex relationship between transfer location and OD journeys. This new technique is useful for many applications in social and geographical research, such as transit accessibility studies. The conventional method defines the transit accessibility using door-to-door travel time, where the impedance of transfer is modelled simply as an extra travel time. In a radial transit network orientation, travelling to neighbouring suburbs often require a transfer at downtown, when there is no direct transit route connecting the two suburbs. In this case, from the perspective of the transit choice users (private vehicle is available), transit users may deem the destinations as inaccessible using transit. Integrating the transfer location variable to the traditional door-to-door travel time approach could definitely give a more realistic representation of transit spatial coverage.

When transit planners could better quantify travellers' behaviour, the implication of this new approach is beyond quantifying the spatial limitation of transit coverage. Transit planners could quantify the transit demand for each OD pair to identify service gaps so that public investment could be channelled to underserved zones. In terms of redesigning transit network, transit planners should look into the trunk and feeder service. Identifying convenient and strategic transfer locations is essential so that scare resources (i.e.: government funds) can be channelled effectively to improve the quality of transfer experience in those major hubs, such as providing shelters, lifts and air-conditioned stations. Minimising the perceived transfer impedance in those major transfer stations will increase the transit utility, and eventually the transit ridership. For urban planners, this concept could inform them to make better decision to locate hospitals and retirement villages, especially for the benefits of those transit disadvantaged population groups (i.e.: the elderly).

5.6 CONCLUSION

This chapter proposes a new approach to take into account the transfer impact on travel mode choice. By mapping the transfer locations on the standardised two-dimensional Euclidean space using the smart card data, the "preferred" cognitive transfer location is observed. This study discovered that a transfer service located in those "preferred locations" is likely to increase the utility of bus and this cognitive transfer location factor is one of the most important determinants in the travel mode choice. If a traveller is required to make a transfer in order to complete a journey, they would actually consider the location of the transfer point. If it has deviated from the "preferred transfer locations", it will decrease the utility of transit, and eventually deter the use of transit. This will be more evident in cities with a radial transit network because passengers are required to make a transfer only at downtown or major transit hubs where they can catch other transit lines or modes.

Findings of this study present a new approach to explain transfer behaviours, and contribute to the current state-of-the-art of transfer and mode choice studies. This study should be viewed as an exploratory effort to develop and test the new transfer concept: the cognitive transfer location. In this study, an emphasis is only given to bus journeys with a single transfer. Future research could build upon this concept to consider multimodal transit journeys and those journeys with more than a single transfer.

Chapter 6: Transit Network Connectivity

6.1 INTRODUCTION

In this study, the network connectivity illustrates the service coverage of the transit network from a designated area. In other words, it shows the spatial limitation that would influence an average traveller in making a trip using transit. The network connectivity is quantified for each analysis zone and thus, normalising these connectivity levels provides an indicative measure of the transit connectivity level of the whole study area. Section 6.2 discusses the quantification method of transit network connectivity using smart card data. Section 6.3 demonstrates the processes to define the transit network connectivity of a small study area. Section 6.4 shows the application of the new connectivity measure to the entire city of Brisbane. Section 6.5 concludes the findings of this research phase.

6.2 QUANTIFICATION OF TRANSIT NETWORK CONNECTIVITY

This study seeks to understand how well a transit network serves a zone in connecting to other zones based on the transit travel time and transfer location as the main impacting factors. This study uses the go-card data during the morning peak hours (from the first bus service until 8:30 a.m.). In any transport system modelling, the geographic area is subdivided into smaller and discrete traffic analysis zones. This research used SA2 as the basic analysis zone.

Ideally, the transit connectivity must be able to show the estimated service coverage of the transit network from a point of reference (e.g.: state library). However, this is impossible for modelling zone-based transport network connectivity. In transport modelling literature, the transit network connectivity is commonly illustrated using a zone centroid to represent the whole area of interest (Cascetta, 2009), with the assumption that all trips start and end at the centroid (Chang et al., 2002). In reality, these origins and destinations are spatially distributed within the zone. Using centroids to represent zones could potentially distort the analysis especially for transit trips, when the access mode is usually walking (Furth et al., 2007).

In this research, points of origin and destination for each SA2 are represented by the largest bus stop in each SA2, identified by the most transit routes that pass through a stop, to replace the existing centroid reference point. This gives a better representation to the analysis zone, and a better fit to the purpose of this research. This research is interested in incorporating the impact of transfer location to quantify transit network connectivity. Using the largest bus stop as the point of reference could eliminate the walking components to and from transit stops, and minimise the random effect of intra-zone transfer, based on the assumption that transit riders would often assess stops with more frequent and consistent service. Figure 6-1 shows the point of reference for each SA2 and the major transit route.

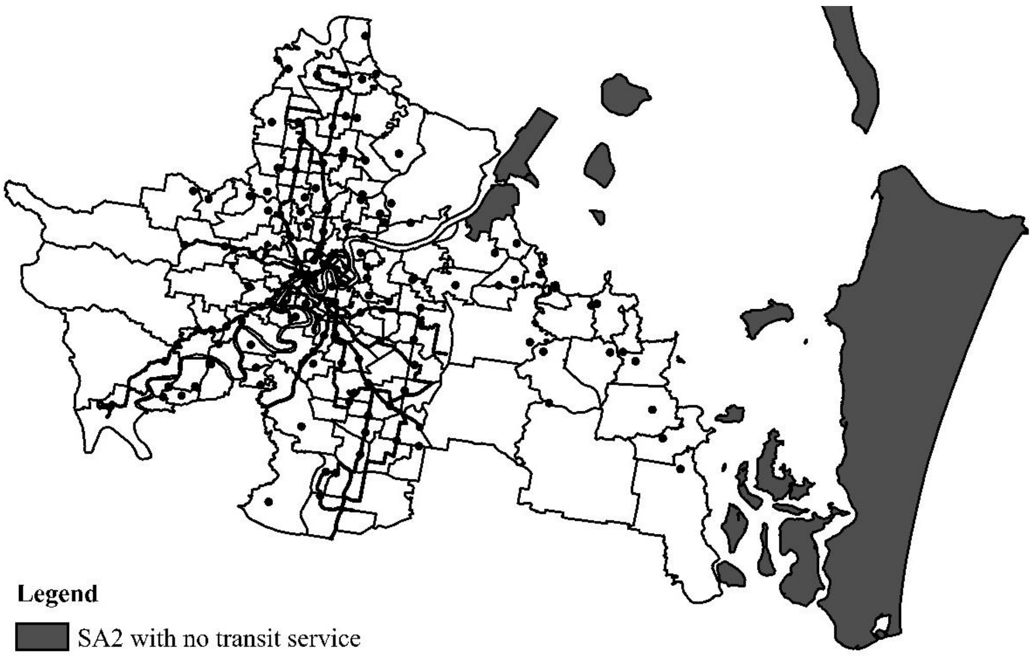


Figure 6-1: Point of reference (largest bus stop) for each SA2 and the major transit route

6.2.1 Transit Travel Time

In the literature, travel time has been used to define the level of connectivity instead of travel distance (Lam & Schuler, 1982; Lee & Lee, 1998; Lei & Church, 2010; Salonen & Toivonen, 2013). Travel distance would not have the ability to capture transit waiting time and transfer time, which are perceived more onerous than in-vehicle travel time. Number of transit users (or transit demand) will decrease as the time required to complete a trip using transit increases. This relationship has been modelled using a decay function by Mamun et al. (2013), which was motivated by the literature on walking distance decay function for transit demand estimation (Chia et al., 2016; Kimpel et al., 2007; Zhao et al., 2003).

In this study, a total of 137,503 morning peak transit journey data (five consecutive weekdays), regardless of the number of transfers, was collected to study transit travel demand based on travel time. Transit travel time of a bus journey is defined as the time when the transit rider boards the first bus to the time when the transit rider alights from the last bus to destination. Many public bus journeys involve transfer(s) from one route to another, which includes walking from one stop to another and waiting for the next service. Figure 6-2 illustrates the definition of transit travel time in this study.

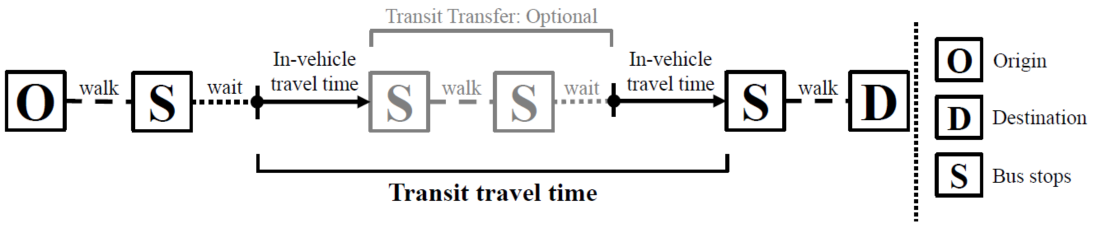


Figure 6-2: Definition of transit travel time

Zhao et al. (2003) adopted a negative exponential function to study the relationship between transit use and walking distance to transit stops. Kimpel et al. (2007) discovered that negative logistic function better estimates the probability of transit use based on walking distance to transit stops. Halás et al. (2014) used a negative logistic function to study the relationship between daily travel flow and distance to regional centres in the Czech Republic. Similarly, Mamun et al. (2013) utilised a logistic function to estimate the transit connectivity level based on door-to-door transit travel time. The relationship between the transit demand and the transit travel time is displayed in the form of negative exponential decay function and logistic decay function, as illustrated in Figure 6-3.

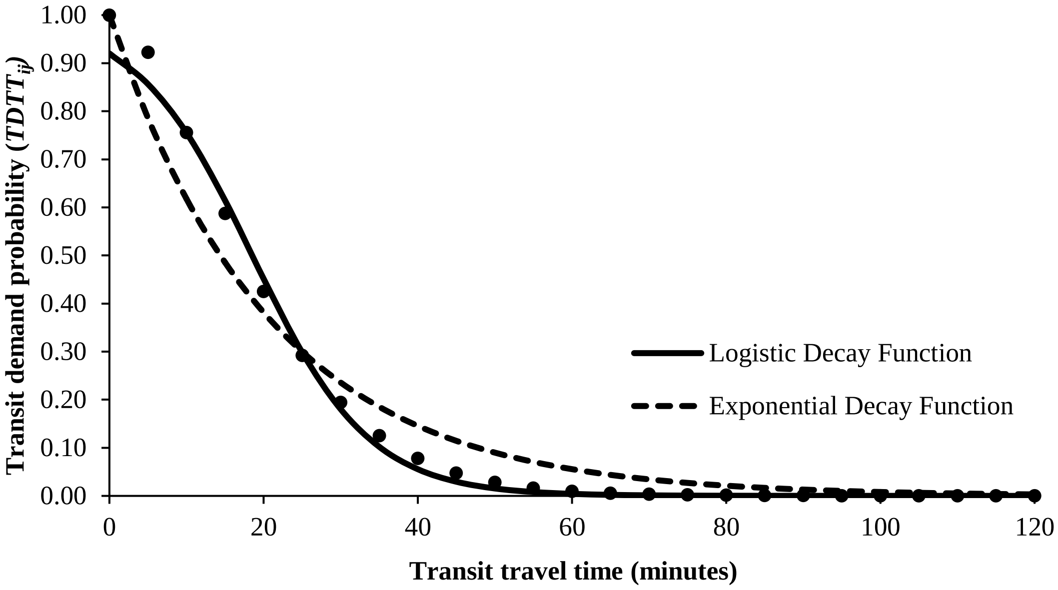


Figure 6-3: Transit travel time decay function

From Figure 6-3, it is clear that the negative logistic decay function has a better goodness of fit as compared to the exponential decay function. Unlike the exponential function, a negative logistic function has the ability to reflect a more gradual rate of reduction of transit use at the initial stage (as bus travel time increases up to 10 minutes), followed by a steeper decline until 30 minutes of bus travel time. The transit demand continues to decrease gradually up to 60 minutes. Once the bus travel time exceeds 60 minutes, the transit demand is near to 0. This is consistent with the findings from other studies (Lee et al., 2015; Mamun et al., 2013) that transit use will begin to deteriorate as transit travel time increases.

The functional form of the logistic decay function is expressed in Equation 6-1, of which the coefficient values of α and β are estimated using the cumulative transit demand. This transit demand decay function is later applied to reflect the probability of transit use as transit travel time increases. Transit demand probability refers to the probability of an individual choosing to take transit, based on transit demand analysis, to reflect the choices and behaviours of transit users.

$$TDTT_{ij} = \frac{L}{1 + \alpha e^{-\beta t}} \qquad \text{Equation 6-1}$$

where:

$TDTT_{ij}$ = Transit demand probability based on travel time from origin i to destination j

L = The upper limit of the logistic decay curve (assumed to be 1.0 in this study)

α = 0.0755443

β = – 0.1383489

t = Transit travel time (minutes)

6.2.2 Transit Transfer Location

The previous chapter has established that in general, if a traveller is required to make a transfer in order to complete a trip, the traveller would consider the location of transfer. If the transfer location is substantially deviated from the “preferred cognitive transfer locations”, it will decrease the utility of transit, and eventually deter the use of transit. Table 6-1 shows the composition of bus journey trips based on the number of transfers and corresponding transit demand probability. Out of 137,503 morning peak bus journeys, 87.91% of them did not involve any service transfer and 11.47% of them involved one transfer. Journeys with no transfer and one transfer amounted to 99.38% of the total five days’ trip data. Since the number of bus journeys with more than one service transfer was negligibly small (less than 0.62%), those trips were excluded from the analysis.

Table 6-1: Composition of journeys based on number of transfers

Number of Transfers	Number of Journeys	Percentage	Transit demand probability
0	120,874	87.91%	1.00
1	15,777	11.47%	Varied based on cognitive transfer location mapping
2	800	0.58%	0.00
3	52	0.04%	0.00
4	0	0.00%	0.00
Total	137,503	100.00%	-

As shown in Table 6-1, if there is a direct service connecting one SA2 to another SA2, the transit demand probability will be 1.00; otherwise, if it requires more than one transfer, the transit demand probability will be reduced to 0.00. When there is only one transfer required to complete any bus journey, each journey triangle OTD will undergo a series of Euclidean transformation, in reference to the OD unit distance, to determine which cell the transfer location falls into, and to take the cell density value as the representation of the probability of taking the public bus as shown in Equation 6-2.

$$TDTL_{ij} = \frac{CD}{CD_{max}} \qquad \text{Equation 6-2}$$

where:

$TDTL_{ij}$ = Transit demand probability based on transfer location from origin i to destination j (one transfer journey only)

CD = Cell density of the respective cell

CD_{max} = The highest value of cell density among all cells

The transfer locations of the 15,777 one transfer journeys were mapped out on a standardised Euclidean space to infer transit users' preference for travel direction towards transfer location in reference to the OD straight route distance. Figure 6-4 shows the cognitive transfer location mapping, and Figure 6-5 reiterates the grid density in the 3-D surface plots. The cell density of each 0.2 OD grid is shown in Figure 6-6.

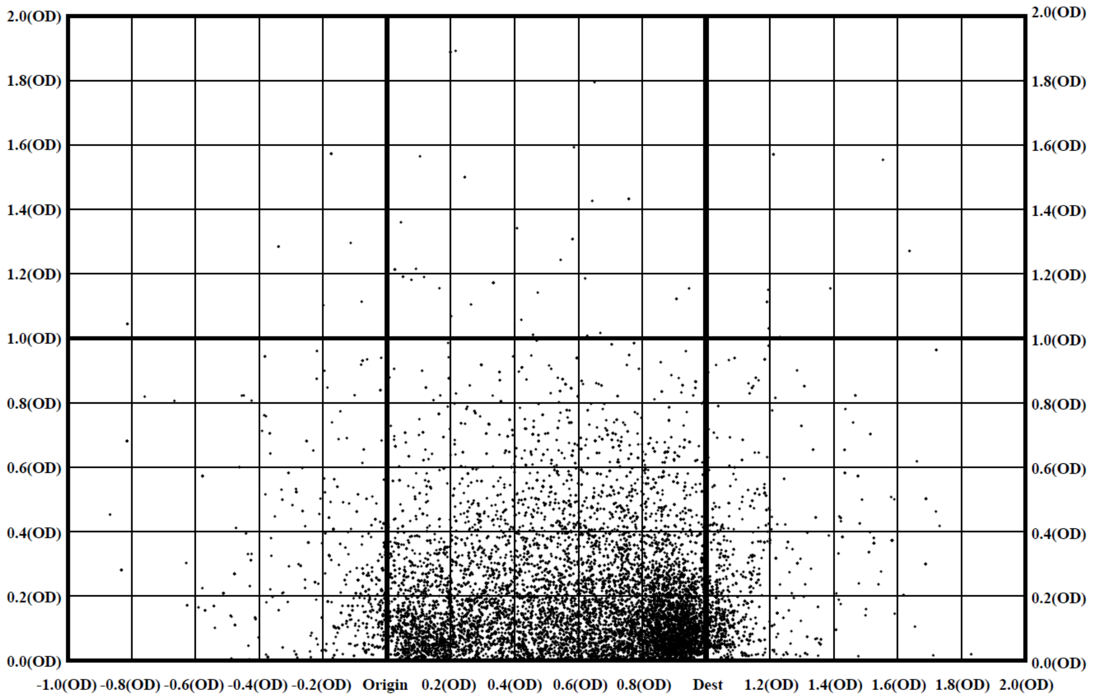


Figure 6-4: Grid structure on cognitive transfer location map

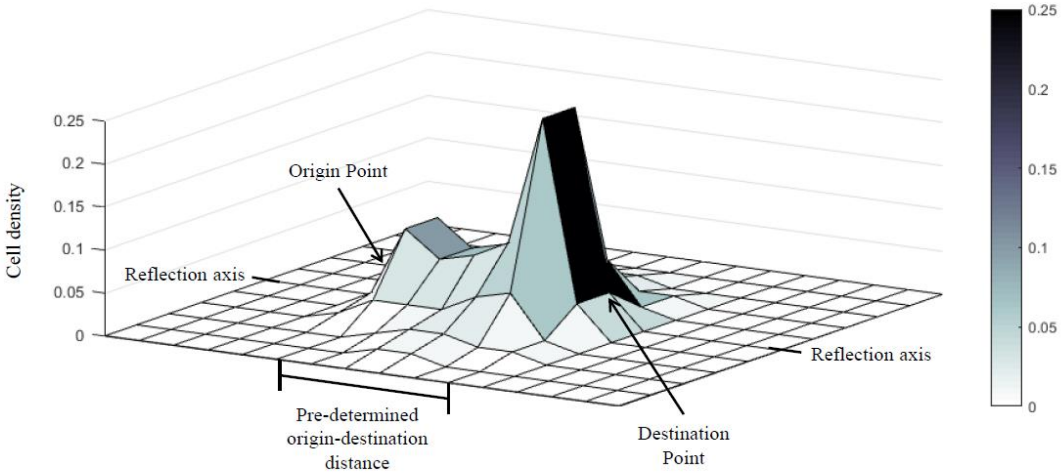


Figure 6-5: 3-D surface plot of cell density

	A	B	C	D	E	F	G	H	I	J	K	L	M	N	O	
10	0.00%	0.00%	0.00%	0.00%	0.00%	0.02%	0.01%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	10
9	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.01%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	9
8	0.00%	0.00%	0.00%	0.00%	0.02%	0.01%	0.01%	0.01%	0.03%	0.00%	0.00%	0.02%	0.01%	0.00%	0.00%	8
7	0.00%	0.00%	0.00%	0.01%	0.01%	0.03%	0.00%	0.03%	0.00%	0.00%	0.00%	0.00%	0.00%	0.01%	0.00%	7
6	0.02%	0.00%	0.00%	0.01%	0.01%	0.04%	0.05%	0.02%	0.02%	0.03%	0.03%	0.04%	0.01%	0.00%	0.00%	6
5	0.00%	0.01%	0.02%	0.03%	0.08%	0.10%	0.11%	0.24%	0.11%	0.17%	0.12%	0.03%	0.01%	0.02%	0.00%	5
4	0.03%	0.00%	0.01%	0.07%	0.05%	0.21%	0.40%	0.56%	0.68%	0.46%	0.11%	0.03%	0.04%	0.01%	0.00%	4
3	0.01%	0.00%	0.03%	0.13%	0.30%	0.45%	0.86%	1.57%	1.67%	1.36%	0.61%	0.06%	0.10%	0.04%	0.00%	3
2	0.03%	0.01%	0.13%	0.14%	0.82%	2.59%	2.74%	3.34%	5.01%	5.66%	1.40%	0.13%	0.18%	0.05%	0.00%	2
1	0.00%	0.01%	0.16%	0.16%	1.53%	9.57%	7.13%	7.79%	10.38%	24.52%	4.41%	0.33%	0.05%	0.01%	0.01%	1

Origin

Destination

Figure 6-6: Cell density of transfer locations

Compared to the all-day data mapping in Chapter 5, the morning peak transfer pattern concentrates towards the destination point. The most concentrated cell is J1, which is followed by I1, where a total of 34.09% of transfer points are gathered. These two cells may be regarded as the most preferred cognitive transfer location during the morning peak hours. Transit journeys that require a transfer service in those cells will be perceived as viable, as this increases the likelihood of making a transfer as compared to other cells.

Out of the total bus journeys with one service transfer, 59.40% of them had the transfer location, close to the straight path from origin to destination (i.e., F1, G1, H1, I1, and J1) out of the total 150 cells in the map. It implies that most travellers prefer the cognitive transfer point, located along the direction of their trip destination. Moving slightly away from the straight path (cell F2 to J2) has an average cell density of 3.87%. It is observed that bus riders would not mind travelling a little farther from the origin and destination path to make a transfer, respectively at 1.53% (cell E1), 4.41% (cell K1) and 1.40% (cell K2) of the total transfer points. The maximum distance bus riders are willing to travel to make a transfer is to cells H3, I3 and J3, and the average value of 1.53% of total bus users transferred in those cells. All the transfer points in those 16 cells account for 90.67% of the total transfers. The average density (in terms of the number of transfer points) of the remaining cells (134 out of 150 cells) is negligible at 0.07%.

6.3 THE CONNECTIVITY MAPPING PROCESS

This section illustrates the quantification of transit network connectivity level, as a function of transit travel time and transfer location. To illustrate the new approach and method, this study considers a small area in Brisbane (10 zones), as shown in Figure 6-7.

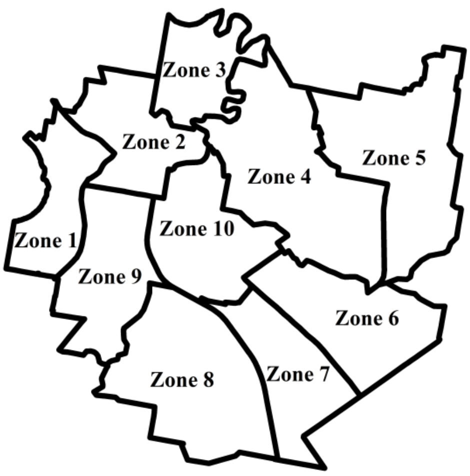


Figure 6-7: Sample study area

The first step is to determine the point of reference for each zone, represented by bus stops with the most transit routes that pass through them. Next, travel time of each OD pair is retrieved based on real-time information using GTFS data, departing at 8.00am in the morning. Table 6-2 shows the bus travel time from one zone to another.

Table 6-2: Bus travel time from zone to zone of the 10-zone study area

To / From	**Zone to zone bus travel time (minutes)**									
	1	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**
1		5	17	21	24	35	9	15	3	7
2	10		12	7	10	13	4	12	19	2
3	16	11		13	13	20	15	28	10	13
4	14	5	15		4	7	14	24	26	12
5	15	8	13	4		18	17	28	30	15
6	30	14	30	12	23		22	14	27	20
7	15	5	15	15	24	22		7	20	3
8	29	15	24	39	45	46	3		13	22
9	7	7	14	27	30	40	24	13		22
10	12	2	11	13	21	10	2	19	21	

Using the transit demand probability function developed using transit smart card data, the probability to choose bus from one zone to another zone based on transit travel time is estimated, as shown in Equation 6-3.

$$TDTT_{ij} = \frac{1}{1 + \ 0.0755443e^{0.1383489t}} \qquad \text{Equation 6-3}$$

where:

$TDTT_{ij}$ = Transit demand probability based on bus travel time from origin i to destination j

t = Transit travel time (minutes)

For example, it takes 7 minutes to travel from Zone 9 to Zone 1 using bus, and 40 minutes from Zone 9 to Zone 6. The probability of choosing public bus as the mode of travel from Zone 9 to Zone 1, and Zone 9 to Zone 6 can be calculated as follows:

$$TDTT_{91} = \frac{1}{1+0.0755443e^{0.1383489\,(7)}} = 0.90$$

$$TDTT_{96} = \frac{1}{1+0.0755443e^{0.1383489\,(40)}} = 0.13$$

From the calculation, when the bus travel time increases from 7 minutes to 40 minutes, the probability of using bus decreases from 90% to 13%. Table 6-3 shows the probability of using bus for each OD pair based on the zone-to-zone bus travel time. Those probability values are a good representation of the network connectivity for each pair of zones, which shows the likelihood of travelling using bus. Figure 6-8 shows the transit network connectivity based on bus travel time, originating from Zone 9. Zone 9 is selected as the origin zone for illustration purposes.

Table 6-3: Transit demand probability based on bus travel time

To / From	Zone to zone transit demand probability based on bus travel time									
	1	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**
1		0.92	0.72	0.61	0.52	0.22	0.87	0.77	0.94	0.90
2	0.86		0.83	0.90	0.86	0.81	0.93	0.83	0.67	0.94
3	0.75	0.84		0.81	0.81	0.64	0.77	0.40	0.86	0.81
4	0.79	0.92	0.77		0.93	0.90	0.79	0.52	0.46	0.83
5	0.77	0.89	0.81	0.93		0.70	0.72	0.40	0.34	0.77
6	0.34	0.79	0.34	0.83	0.55		0.58	0.79	0.43	0.64
7	0.77	0.92	0.77	0.77	0.52	0.58		0.90	0.64	0.94
8	0.37	0.77	0.52	0.15	0.08	0.07	0.94		0.81	0.58
9	0.90	0.90	0.79	0.43	0.34	0.13	0.52	0.81		0.58
10	0.83	0.94	0.84	0.81	0.61	0.86	0.94	0.67	0.61	

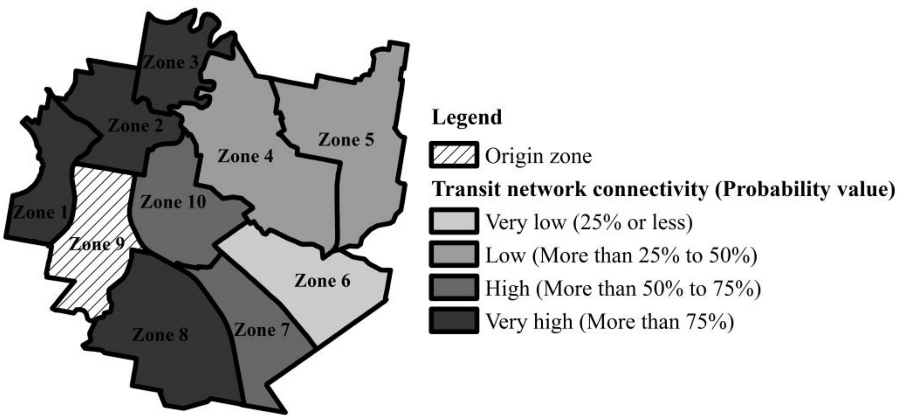


Figure 6-8: Transit network connectivity based on bus travel time

Figure 6-8 shows an example of the network connectivity based on bus travel time from Zone 9. In general, the transit connectivity of neighbouring zones is higher as the travel times to those zones are relatively short. For example, from Zone 9 to Zone 1, Zone 2, Zone 3 and Zone 8 have a very high connectivity level. Although Zone 10 is located next to Zone 9, the connectivity level is lower (than the first four zones), because a transfer is required. When transfer is involved, it significantly increases the travel time due to additional waiting time, walking time, and in-vehicle travel time. Table 6-4 shows the total number of transit transfers required to travel from one zone to another.

Table 6-4: Total number of transit transfers required

To / From	**Zone to zone total transit transfers required**									
	1	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**
1		0	1	1	1	1	0	0	0	0
2	1		1	0	0	0	0	0	1	0
3	1	1		0	0	0	1	1	0	1
4	1	0	0		0	0	1	1	1	1
5	0	0	0	0		1	1	1	1	1
6	1	0	0	0	1		1	0	1	1
7	1	0	1	1	1	1		0	0	0
8	1	0	1	1	1	1	0		0	1
9	0	0	0	1	1	1	1	0		1
10	1	0	1	1	1	0	0	1	1	

According to Table 6-4, there is no direct bus service connecting Zone 9 and Zone 10. The literature formulates the transfer impacts in terms of additional time and cost incurred during transfer (Sharaby & Shiftan, 2012; Wardman et al., 2001). Findings from the previous chapter support the hypothesis that transit users have a preference for the direction of travel towards transfer points, which will influence their travel mode choice.

In reference to Table 6-1 and Equation 6-2, the probability of choosing bus based on the cognitive transfer location will be 1.00, if there is a direct service connecting two zones; the probability will be 0.00, if the travel requires more than one transfer. If one service transfer is required, the corresponding transit demand probability is determined by comparing the transfer location with the cognitive transfer map. For example, travelling from Zone 9 to Zone 5 using bus requires one service transfer. In this journey, the transfer point is located in cell G3 in the cognitive transfer map (refer to Figure 6-6). Similarly, travelling from Zone 9 to Zone 6 requires a transfer at cell F4. The probability to choose public bus to travel from Zone 9 to Zone 5, and Zone 9 to Zone 6, can be calculated as follows:

$$TDTL_{95} = \frac{0.86}{24.52} = 0.03$$

$$TDTL_{96} = \frac{0.21}{24.52} = 0.01$$

Applying the calculation, Table 6-5 shows the transit demand probability based on transfer location. The transit demand probability drops as the transfer location deviates more from the origin and destination path. For example, the demand probability is 3% when the transfer location is in cell G3. The probability further drops to 1% in cell F4.

Table 6-5: Transit demand probability based on transfer location

To / From	Zone to zone transit demand probability based on transfer location									
	1	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**
1		1.00	0.03	0.02	0.11	0.03	1.00	1.00	1.00	1.00
2	0.07		0.00	1.00	1.00	1.00	1.00	1.00	0.00	1.00
3	0.02	0.00		1.00	1.00	1.00	0.06	0.03	1.00	0.01
4	1.00	1.00	1.00		1.00	1.00	0.02	0.11	0.01	0.06
5	1.00	1.00	1.00	1.00		0.01	0.02	0.06	0.03	0.23
6	0.29	1.00	1.00	1.00	0.02		0.00	1.00	0.23	0.02
7	1.00	1.00	0.18	0.06	0.02	0.00		1.00	1.00	1.00
8	0.01	1.00	0.06	0.00	0.00	0.00	1.00		1.00	0.00
9	1.00	1.00	1.00	0.02	0.03	0.01	0.00	1.00		0.00
10	0.06	1.00	0.02	0.06	0.11	1.00	1.00	0.00	0.00	

As shown next, the travel time and transfer location factors are integrated for the final presentation of the transit network connectivity. Transit demand probability is formulated as a function of transit travel time and transfer location, as shown in Equation 6-4.

$$TD_{ij} = TDTT_{ij} * TDTL_{ij} \quad \text{Equation 6-4}$$

where:

TD_{ij} = Transit demand probability from origin i to destination j

$TDTT_{ij}$ = Transit demand probability based on bus travel time from origin i to destination j

$TDTL_{ij}$ = Transit demand probability based on transfer location from origin i to destination j

Table 6-6 shows the transit demand probability by taking into consideration both transit travel time and transfer location. The greater the probability, the better the bus service is between the origin and destination zones. Figure 6-9 shows the final transit network connectivity of the study area, originating from Zone 9.

Table 6-6: Transit demand probability based on transit travel time and transfer location

To / From	**Zone to zone transit demand probability**									
	1	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**
1		0.92	0.02	0.01	0.06	0.01	0.87	0.77	0.94	0.90
2	0.06		0.00	0.90	0.86	0.81	0.93	0.83	0.00	0.94
3	0.01	0.00		0.81	0.81	0.64	0.05	0.01	0.86	0.01
4	0.79	0.92	0.77		0.93	0.90	0.01	0.06	0.00	0.05
5	0.77	0.89	0.81	0.93		0.01	0.02	0.03	0.01	0.18
6	0.10	0.79	0.34	0.83	0.01		0.00	0.79	0.10	0.02
7	0.77	0.92	0.14	0.04	0.01	0.00		0.90	0.64	0.94
8	0.00	0.77	0.03	0.00	0.00	0.00	0.94		0.81	0.00
9	0.90	0.90	0.79	0.01	0.01	0.00	0.00	0.81		0.00
10	0.05	0.94	0.02	0.05	0.07	0.86	0.94	0.00	0.00	

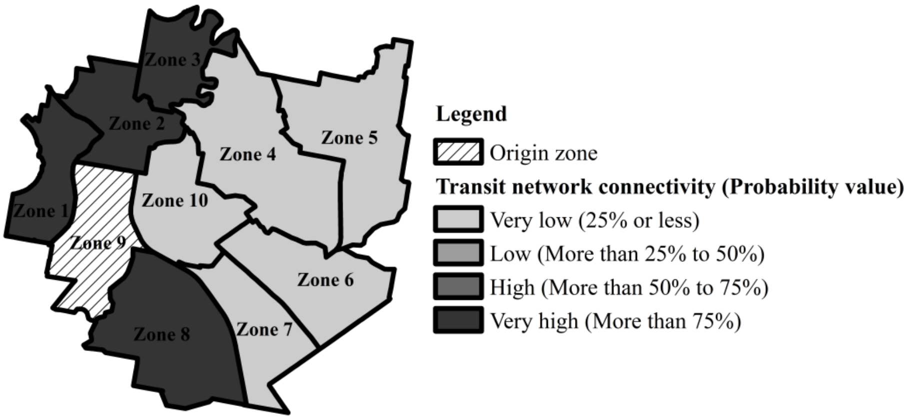


Figure 6-9: Transit network connectivity based on transit travel time and transfer location

Figure 6-9 shows that when transfer location is considered, the connectivity level from Zone 9 to Zone 7 and Zone 10 decreases from high to very low. Similarly, it reduces the connectivity level from low to very low for the trips from Zone 9 to Zone 4 and Zone 5. When a transfer is needed to complete a journey, it reduces the probability of travel using bus. It does impose a greater inconvenience to transit users, if transit users are required to conduct a transfer at less convenient transfer locations. This gives a better representation of how well a transit network is connecting each zone.

The network connectivity of one zone is expressed as the average of all transit demand probabilities from the zone to each of the other zones. In order to provide a relative transit network connectivity level, the average transit demand probability for each zone is normalised by the highest value from all the zones in the study area, as shown in Equation 6-5.

$$Network\ Connectivity_i = \frac{\overline{TD}_{ij}}{(\overline{TD}_{ij})_{max}} \qquad \text{Equation 6-5}$$

where:

$\overline{TD}_{ij}$ = Average transit demand probability from origin i to destination j

$Network\ Connectivity_i$ = Transit network connectivity level for origin zone i

For example, the transit network connectivity of Zone 9 is calculated as follows:

$$Network\ Connectivity_9\ (Based\ on\ transit\ travel\ time\ only) = \frac{0.60}{0.85} = 0.71$$

$$Network\ Connectivity_9\ (Based\ on\ transit\ travel\ time\ and\ transfer\ location) = \frac{0.38}{0.59} = 0.64$$

Figure 6-10 shows two connectivity maps of the sample study area. The map on the left shows the network connectivity based only on the transit travel time. The map on the right incorporates the cognitive transfer location factor.

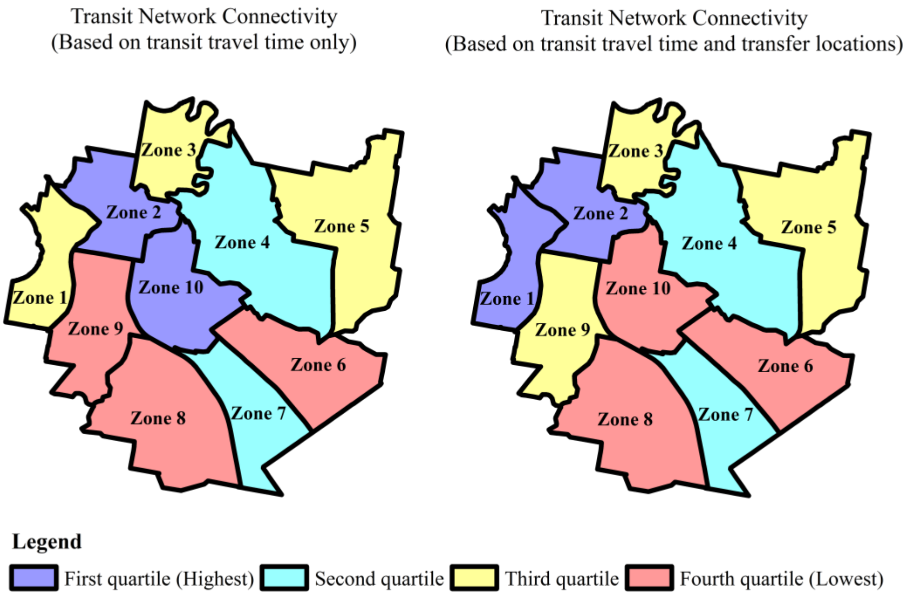


Figure 6-10: Transit network connectivity of the 10-zone study area

The level of connectivity is illustrated as a relative measure in quartiles. When only the travel time is considered, the network connectivity level of Zone 2 and Zone 10 is the highest. These two zones have the greatest spatial coverage. Zone 10 is located at the centre of the study area, where all trips originating from Zone 10 have relatively short travel time. By incorporating transfer location, the connectivity level of Zone 10 drops from the first quartile to the fourth quartile. This implies that most trips originating from Zone 10 to other destination zones require a service transfer at a less convenient location.

If a transit network connectivity level is quantified solely based on transit travel time, the connectivity level of Zone 1 belongs to the third quartile. Zone 1 is located on the fringe of the study area, which takes longer time to reach all the other destination zones. By integrating transfer location to the connectivity measure, it improves from the third quartile to the first quartile. Most likely, one of the major transit hubs is located in Zone 1. This new measure is extended to Brisbane, Australia.

6.4 BRISBANE TRANSIT NETWORK CONNECTIVITY MAPPING

6.4.1 Statistical Areas Level 2 (SA2s) Specific

The transit travel time and cognitive transfer location (if applicable) for each OD pair (137 SA2s in total) was collected based on real-time information using GTFS data. For demonstration, SA2-31055 (Greenslopes) is chosen as the origin zone to show the transit network connectivity to the remaining zones. The first map in Figure 6-11 shows the network connectivity based on transit travel time only. The second map integrates the cognitive transfer location factor. These maps show the transit network connectivity from Greenslopes (i.e.: how far can a person travel from Greenslopes using bus).

Figure 6-11: Transit network connectivity of Greenslopes

The first map in Figure 6-11 shows that based on transit travel time alone, all the neighbouring zones of Greenslopes have relatively high connectivity. In general, the farther two zones are from each other, the longer the transit travel time. As travel time increases, the transit network connectivity decreases. The transit connectivity level in the first map is consistent with existing studies (Lee et al., 2015; Mamun et al., 2013); destination zones that are located close to the origin zone have greater connectivity, and as the distance between zones increases, the connectivity level decreases.

The second map shows a new connectivity map by incorporating the cognitive transfer location factor. A main difference is that the connectivity level of some SA2s neighbouring to Greenslopes decreases substantially from very high to very low. To better illustrate, Figure 6-12 shows the high frequency bus routes in Greenslopes and neighbouring zones.

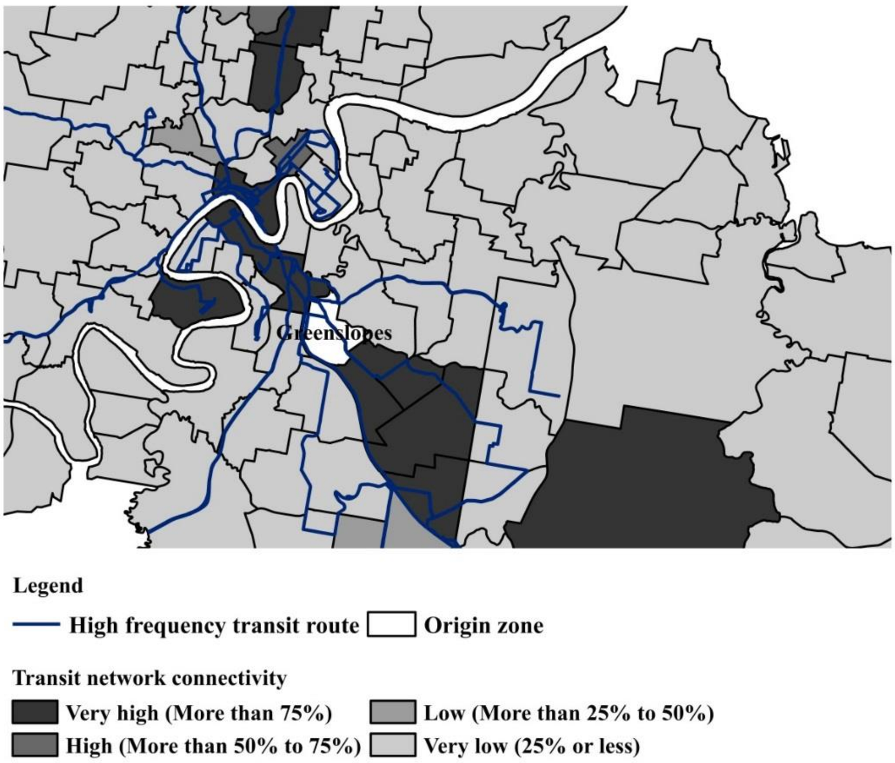


Figure 6-12: Validation of transit network connectivity

In Figure 6-12, a major bus route connects Greenslopes and neighbouring zones located northwest and southeast of Greenslopes. This bus route is the South East Busway, which has very high service frequency. Travelling to those SA2s located on the east and west of Greenslopes requires a transfer and the transfer location is not convenient based on its cognitive location. As a result, the connectivity to those zones is very low. Figure 6-13 shows two examples of how the current transit network orientation could affect the network connectivity.

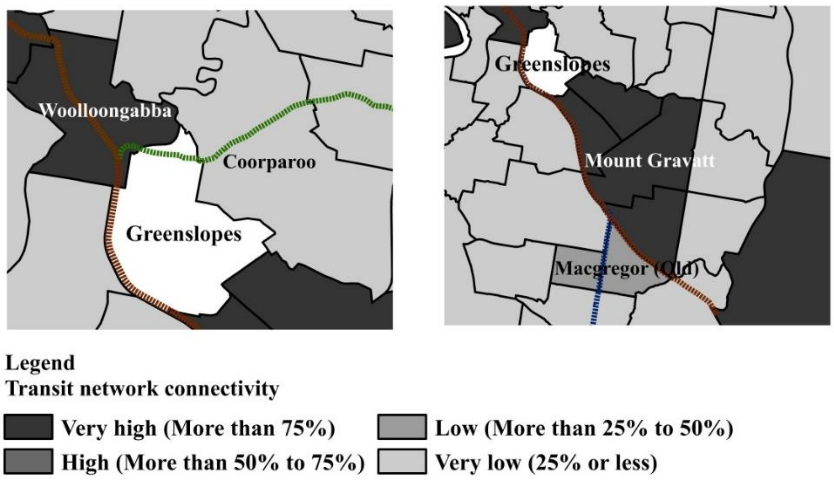


Figure 6-13: Transit network from Greenslopes to Coorparoo and Macgregor

The map on the left shows the transit route from Greenslopes to Coorparoo (east of Greenslopes), and the map on the right shows the transit route connecting Greenslopes with Macgregor (south-west of Greenslopes). In terms of travel time, it takes less time to travel from Greenslopes to Coorparoo, as compared to Macgregor, mainly due to the distance between those zones. The conventional measures of using transit travel time alone to quantify transit network connectivity (first map in Figure 6-11) shows that the transit network connectivity level between Greenslopes and Coorparoo is very high, while the connectivity level between Greenslopes and Macgregor is low.

Figure 6-13 shows that transit journeys originating from Greenslopes going to Coorparoo require a transfer in Woolloongabba (north of Greenslopes). The travel direction to Woolloongabba (northward) is not “on the way” to Coorparoo. This may impose a significant inconvenience to transit users and disadvantage the use of transit. Greenslopes and Coorparoo are neighbouring suburbs, yet transit service between those two zones are not very well connected (very low connectivity level) when the cognitive transfer location factor is incorporated to the measure.

The map on the right-hand side shows the transit routes connecting Greenslopes with Macgregor. Similarly, the transit travel between these two zones requires a transfer at Mount Gravatt. A main difference from the previous example is that the transfer location is on the travel direction to the destination. In this case, the cognitive transfer location factor does not penalise much on the connectivity level. The transit network connectivity level between Greenslopes and Macgregor is better than between Greenslopes and Coorparoo, although the travel time to Macgregor is longer than the travel time to Coorparoo.

The conventional approach to measure the transit network connectivity based only on transit travel time may overestimate the connectivity level compared to the new approach by incorporating the transfer location. The cognitive transfer location factor could provide a more realistic indication of the transit network connectivity by reflecting the inconvenience of transfer location resulting from the transit system configuration.

6.4.2 Transit Network Connectivity Mapping for City of Brisbane

Figure 6-14 shows the transit network connectivity maps for all SA2s in the city of Brisbane. The first map shows the network connectivity based on transit travel time only, while the second map integrates the cognitive transfer location factor.

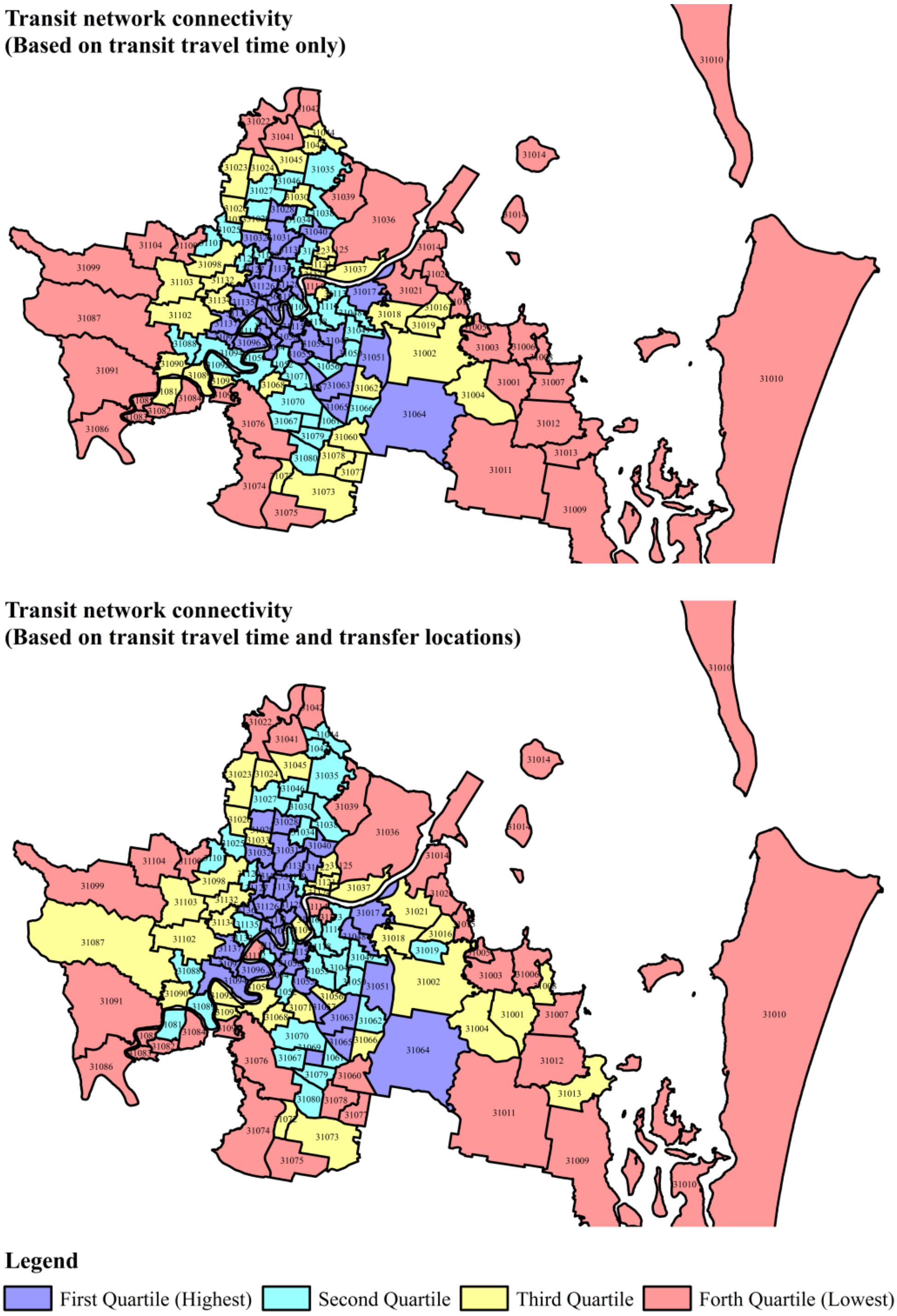


Figure 6-14: Transit network connectivity of all SA2s in Brisbane

When only the travel time is considered, the suburbs in or near the city-centre have higher connectivity levels (first and second quartiles), while the outer suburbs generally have lower transit network connectivity levels (third and fourth quartile). By incorporating the transfer location factor to measure transit network connectivity, it is observed that those suburbs located along major bus corridors to have a relatively high connectivity level. Some suburbs in or near to the city-centre are assessed to have a lower connectivity level compared to the first map. For example, West End (31112) and Highgate Hill (31107) are both located next to the city-centre, but the connectivity level is low in those zones. To travel from those two zones, to other areas, transit users are required to transfer in South Brisbane, which is a major transit hub. The travel direction towards the transfer location may not be "on the way" to destinations. Similarly, SA2s such as Bulimba (31114) and Balmoral (31113) are located close to the city-centre, but their connectivity levels are assessed as the lowest connectivity.

As aforementioned, Brisbane's transit network has strong radial configuration where transit users are required to transfer in the city-centre to travel. Those SA2s located along major bus corridors and near major transit hubs are assessed to have the highest transit network connectivity level (first quartile), such as Carindale (31051 at south-east of Brisbane), Rochedale (31064 at south of Brisbane), Indooroopilly (31094 at west of Brisbane), Chermside (31028 at north of Brisbane) and Murarrie (31017 at east of Brisbane). Some SA2s located in or close to the city-centre do not have the high connectivity level when the transfer location is considered, and this is the main difference from the conventional approach to quantify the transit network connectivity.

6.5 CONCLUSION

This chapter proposes a new approach to quantify the transit network connectivity. The conventional transit network connectivity measure considers only the transit travel time, and this approach could potentially overestimate the transit network connectivity. By incorporating the cognitive transfer location factor, the transit network connectivity could be better captured by reflecting the preference of transit users on travel direction to transfer. It is well established in literature that the increase of transit travel time will reduce the probability of taking transit as the mode of travel. Likewise, this research demonstrates that individuals have preferences in terms of transfer location. The findings suggest that if transfer(s) is required to complete a journey, an individual would actually consider the position of a transfer location. If it has deviated from the "preferred transfer locations", it will decrease the utility of transit. This factor will be more evident in cities with a radial transit network, because passengers are often required to make a transfer only in city-centre or major transit hubs to catch other transit lines or modes.

Using Brisbane as the case study, this study demonstrated that those SA2s in or near to the city-centre would have a relatively high transit connectivity level over those outer SA2s located on the fringe of Brisbane, when only the transit travel time is considered. However, findings are different when transfer location is considered in addition to transit travel time. SA2s with better transit network connectivity are more dispersed to the north, south, east and west of Brisbane along major bus corridors. In a relative measure, those SA2s that are located near to the city-centre may require shorter transit travel time to reach different destination SA2s, however, that does not mean that they have a direct transit service to other zones in the study area. Some SA2s neighbouring to the city-centre or major transit hubs are assessed to have relatively low transit connectivity, mainly because they do not have direct bus services to the neighbouring zones.

As an extension to this research, future study could quantify the transit demand for each OD pair to identify service gaps so that public investment could be channelled to underserved zones. This study should be viewed as an exploratory work to develop new bus connectivity mapping. The emphasis of this study is only given to the bus network; future works could expand to accommodate the multi-modal transit system. A similar approach could be employed to map how far a traveller would travel from a specific point of origin, given a specific time period. In order to be more accurate in quantifying transit network connectivity, in reaching destinations, a smaller spatial unit should be used (i.e.: SA1 instead of SA2).

Chapter 7: Conclusions

7.1 INTRODUCTION

This chapter summarises and concludes the thesis by revisiting the main aim and objectives (Section 7.2). Section 7.3 reiterates the main findings from each phase of the research. Section 7.4 discusses the theoretical and methodological contributions of this research. Section 7.5 provides recommendations for future research.

7.2 SUMMARY OF RESEARCH AIM AND OBJECTIVES

The long-standing goal of transit agencies and planners is to encourage transit use. Various studies in the literature have identified different travel behaviours and associated factors that affect people's mode choice. Due to the inherent complexity of human behaviours, it is challenging to comprehensively and accurately predict travel mode choice. This study is built on the hypothesis that individual would consider using transit if (1) a transit service is accessible to transit users, and (2) a transit service provides a reasonably well connection between intended trip origin and destination, before even considering the other factors such as comfort and convenience.

This research identifies and addresses three research gaps. Firstly, the "one size fits all" solution (400m) to define bus catchment area is unlikely to be effective due to the complexity of walking behaviours. Next, this research investigates the cost of transfer. Existing studies formulate transfer impacts in terms of additional time and cost incurred during transfer, and ignores the impact of travel direction towards transfer location. Thirdly, this research identifies the need for a more realistic measure to quantify the ease to travel from one location to another using transit, as a function of directness of the route between origin and destination, and transit travel time.

This research uses Brisbane, Australia, as the case study. Bus is the dominant transit mode in Brisbane. The benefit of bus over other transit modes, such as train and ferry, is that it has the flexibility to access almost all locations where a road network is present. The bus system in Brisbane is built in a radial orientation, which fits the purpose of this research. This research investigates the impact of travel direction towards transfer location, which is even more significant in a radial transit network. This research seeks to inform transit planners and agencies in evaluating the current transit network, as well as planning and designing for future transit network and service.

7.3 SUMMARY OF RESEARCH FINDINGS

This thesis is organised to ensure the coherent flow of information, and to demonstrate the consistent chain of logic in achieving the research aim and objectives. This research has identified three research objectives, and this section discusses the findings of this research, in reference to research objectives.

Objective 1: To better understand the variation in the practical walking accessibility to bus stop for different homogeneous population groups.

Using the conventional linear regression method to study the relationship between dependent walking access variables and independent explanatory variables is ineffective to capture the distinct differences in walking behaviours across different socio-economically homogeneous groups. To better explain the large variations in walking time to transit among individuals, this study adopted two market segmentation methods to identify relatively independent groups who share the similar characteristics across the general continuum of choice. The first and conventional segmentation method divided bus users into true transit captive users and choice users based on car ownership and driver's licence. This analysis induced insignificant difference between the walking time of these two groups. True transit captive users were excluded from the analysis to increase the accuracy since they do not have a choice of alternative modes of transport, other than to take transit. The second segmentation categorised the choice users into eight socio-economically homogeneous groups based on age, labour force and personal income.

The results showed that walking times vary across these eight groups. The walking time decay functions illustrated that part time workers, full-time high income earners and the elderly transit riders have the lowest walking time and thus are the most sensitive groups to walking time. The next groups include mid-aged working parents, full-time post-secondary students, teenagers studying and working, and young working adults. Young adults, who are studying and working at the same time, have the longest walking time to bus stops and thus are the least sensitive to walking time in choosing their travel mode. The affordability factor seems to be an important factor affecting the walking access to transit facilities. Trip complexity (due to caregiving responsibility) and physical limitations may deter the use of transit when they are required to walk for a longer time. In general, despite the few disparities among different socio-economically homogeneous groups, the aggregate approach of using 5 minutes or 400m walking access to bus stops is likely to work for most groups in the society.

Objective 2: To better understand and quantify the transit service connectivity and potential impact of transfer location on mode choice.

This research developed a new approach to investigate transit users' preference for travel direction towards transfer location. By mapping the transfer location on the standardised two-dimensional Euclidean space using the smart card data, the "preferred" cognitive transfer location was observed, especially those that are near to the points of origin and destination. Generally, transit riders are reluctant to make a transfer if transfer location is located far from the straight route connecting origin to destination. A logistic regression model was conducted to test whether the new variable (transit users' preference for transfer location) would affect individual's mode choice. This study discovered that a transfer service located in those "preferred locations" is likely to increase the utility of bus. This new variable is one of the most important determinants in the travel mode choice. These findings suggested that if transfer(s) is required in order to complete a trip, traveller would actually consider the location of the transfer point. If it has deviated from the "preferred transfer locations", it will decrease the utility of transit, and eventually deter the use of transit. This will be more evident in cities with a radial transit network because passengers are required to make a transfer only at downtown or major transit hubs to catch other transit lines or modes.

Objective 3: To account for the transfer location factor in quantifying the transit network connectivity.

The conventional way to measure how well transit connects one zone to other zones is based on transit travel time. The transit network connectivity to neighbouring zones would have a relatively high connectivity level using this approach because of shorter travel times to those zones, as compared to other zones that are farther apart. This approach is not able to account for the impact of transfer location, because the impedance of transfer is only considered as an increase in travel time. In a radial transit network, transit service to neighbouring zones could be not very efficient in terms of the transfer location. This study incorporates the preference for transfer location in quantification of transit network connectivity to capture more realistic travel behaviour.

The case study of Brisbane shows that those SA2s in or near to the city-centre would have higher transit network connectivity, as compared to those SA2s located on the fringe, if only transit travel time is considered. Findings are different when transfer location is considered. Better performing SA2s are more dispersed to the north, south, east and west of Brisbane, along major bus corridors. SA2s located near to the city-centre do not necessarily have good connectivity, especially when a transfer is required to travel to the destination. Using transit travel time alone to quantify transit network connectivity may overestimate the actual service coverage by omitting the transfer location factor.

7.4 STATEMENT OF RESEARCH CONTRIBUTIONS

7.4.1 Theoretical Contributions

This research contributes to a number of academic discussions. First, it challenges the current use of the 400m as the rule of thumb to define bus catchment areas. The ‘one size fits all’ solution to define transit catchment is deemed to be too simple, despite the rising realisation of the complexity of walking behaviours to a transit system. This research found a significant variation in the walking time to bus service across different socio-economically homogenous groups. Next, it adds to the literature that the current measure to quantify the inconvenience of transfer is insufficient. The conventional approach of quantifying the impact of transfer in terms of additional travel time may overestimate the spatial coverage of transit service. It must involve transit users’ perception, such as the travel direction towards transfer locations. The impact of this factor will be more significant in a radial transit network. In fact, to the author’s knowledge, this is the first study in transit literature to consider the inconvenience of transfer based on travel direction towards transfer location. In mode choice analysis, the cognitive transfer location factor is identified as one of the most important determinants. The finding suggests that if a transfer is required in order to complete a transit journey, the direction towards transfer location is an important factor determining the travel mode choice.

7.4.2 Methodological Contributions

Conventionally, linear regression is used to study the impact of different socio-economic factors on walking distance. This approach is not effective to capture the distinct differences across different socio-economically homogenous groups. This study used a cluster analysis technique to define different socio-economically homogenous groups, and to analyse their walking time for individual group. To study the impact of transfer location, this research presents a new approach to extract the transfer pattern using the smart card data. This research first transformed each journey triangle (OTD) from a spherical earth's surface to a 2D plan. Later, this study projected each journey triangle to a standardised two-dimensional Euclidean space. This allows comparison to be made across all transfer locations, and to derive the preferred transfer locations. Finally, this study develops a new approach to quantify transit network connectivity by incorporating the cognitive transfer location variable to the existing transit travel time measures. This gives a more realistic quantification of network connectivity level, and contributes to developing a new approach for the connectivity mapping of a radial transit network system.

7.5 RECOMMENDATIONS

7.5.1 Recommendations for Practice

Good accessibility to transit is a highly dominant factor to attract potential transit users. However, it is often difficult to determine the optimum bus stop spacing. When the distance between bus stops increases, the distance to walk to and from a bus stop would increase. However, increasing bus stop spacing will shorten the in-vehicle transit travel time. This research challenges transit planners and agencies to reconsider the bus stop spacing of 400m. In fact, it is suggested that it does not need to be a "one size fits all" measure. Transit planners and agencies should tailor the design of bus stop spacing for each suburb, especially those socio-economically distinct areas such as retirement villages and university dormitories.

Providing seamless connection between origins and destinations has always been the goal for transit agencies. Conventional radial transit orientation focuses on providing direct connections from outer suburbs to the city-centre. This type of transit network orientation is no longer effective to meet increasingly diversifying travel needs. Establishing easy and efficient transfers is necessary to expand the transit service. This study found that the radial configuration of the Brisbane's bus network system may have a negative consequence on the network connectivity due to the inconvenience of transfer location. The local government may consider improving the transit network by providing more multi-destination transit services such as circle bus routes. Other major cities in Canada, Switzerland and Mexico embrace long cross-suburban routes on key arterials, not necessarily trying to circle the city. These cross-town routes bypass the city centre, and found to result in monetary and time savings for transit users (El-Hifnawi, 2002). Similarly, Currie and Loader (2010) discovered the success of SmartBus in Melbourne, Australia, which focuses on the cross-suburban routes with high frequency and long service spans. This is a transit planning-based policy, which seeks to restructure the transit network around dispersed locations where people live and work (Thompson et al., 2012). Restructuring of routes into grid or spider web orientation will provide more direct connections between the dispersed population and employment clusters, as compared to the more traditional radial routing.

7.5.2 Research Limitations and Recommendations for Future Works

There are a few limitations in this research, primarily due to the research timeframe and the scope. These limitations provide opportunities for future studies to build upon and extend the scope of this research.

This research focused on bus only. Future study could adapt a similar framework to analyse other transit modes, such as train, tram and ferry, or even multi-model transit systems. The analysis of walking accessibility relied on the household travel survey data without taking into consideration the quality of transit service at the place of origins, such as the walkability of the neighbourhood. This research also considered the socio-economic characteristics as dominant factors for individuals to determine their walking time to access transit. Due to the limitation of the dataset, this study acknowledges that those travellers who walk more do not necessarily mean that they are forced to walk; rather it could be their choice to walk more, for example, as a form of exercise. This study should be viewed as an exploratory effort to study the variation of walking access across different socio-economically homogenous groups. Future study may conduct interviews with transit users to address this issue. In this study, only the walking access to bus stop from the home location (first mile) was considered. Some studies adapt the same walking time (or distance) value for walking from a transit stop to the trip destination (last mile), as they share similar walking properties and behaviours. It could be interesting to analyse the last-mile walking behaviour by the socio-economic standings of individuals by applying a similar analysis approach.

This study developed the cognitive transfer location mapping to derive transit users' preference for transfer location. Chapter 5 used one week data of 125,215 single-transfer journeys to develop the cognitive mapping, whilst Chapter 6 used only 15,777 one-transfer morning peak transfer journeys. Significant distinctive transfer behaviour between these two cognitive transfer location mappings was observed. Future studies should expand on this concept to study the variation of transfer behaviours for different origin zones. The transfer behaviours in each zone could be tested against different socio-economic variables of the zone, to explore the possible relationship to transfer behaviour.

The quantification of transit network connectivity used only weekday morning peak hour data and excluded weekends and public holidays. Travellers' behaviour during off peak may be substantially different as compared to weekday commuting trips. For example, trips during off peak period could be more for recreational and shopping purposes. It is expected that the choice users would be more sensitive to transit travel time and the inconvenience of transfer based on transfer location. The private vehicle mode will be more competitive for recreational and shopping trips, because of the benefits that a private vehicle can offer (i.e.: free parking at shopping centres, shorter travel time and possibly saving the trouble of walking long distance carrying bags of groceries). Future study could conduct a comparative research across different major cities, by employing similar method to discover meaningful transfer patters. This could also verify the findings, to see if the results are particularly skewed by Brisbane's bus network, or if it occurs elsewhere.

In this study, quantification of the transit network connectivity used the largest bus stop in each SA2, defined in terms of the number of bus services, to represent the whole zone. This definitely gives a better representation of the reference point as compared to the centroid of each zone, based on the assumption that more transit users will have direct access to the largest bus stop. The downside of this assumption is that an SA2 is relatively large in size. If the largest bus stop is located on the fringe of an SA2, it is almost impossible for traveller to directly access to the bus stop by walking. In order quantify transit network connectivity more accurately; a smaller spatial unit could be used, for example, SA1 instead of SA2. As an extension to this research, future study could also quantify the transit demand for each zone to the remaining zones in the study area, to identify service gaps so that public investment could be channelled more effectively to underserved zones.

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